NASA SBIR 2018 Phase I Solicitation

Human Exploration and Operations

H1.01 Mars Atmosphere ISRU for Mission Consumables

Lead Center: JSC

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

Technology Area: TA15 Aeronautics

In-Situ Resource Utilization (ISRU) involves collecting and converting local resources into products that can be used to reduce mission mass, cost, and/or risk of human exploration. ISRU products that provide significant mission benefits with minimal infrastructure required are propellants, fuel cell reactants, and life support consumables. Production of mission consumables from in-situ Mars resources is enabling and critical for human exploration of the Mars surface and for minimizing the number and size of landers and the crew ascent vehicle. Innovative technologies and approaches are sought related to ISRU processes associated with collecting, separating, pressurizing, and processing gases collected from the Mars atmosphere. State of the art (SOA) technologies for these ISRU processes either do not exist, are too small of scale, or are too complex, heavy, inefficient, or consume too much power.

Specific areas of technology interest include the following:

Mars Atmosphere Collection and Separation:

- *Inlet Gas Dust Measurement* - To understand both the dust concentration before filtration as well as the effectiveness of dust filtration techniques, NASA is interested in a dust sensor to measure dust particles in the Mars atmosphere acquired for processing. Measurements need to be made in a flow of carbon dioxide (CO_2) up to 2.5 SLPM at Mars atmosphere pressure. The measurement technique should produce minimal modifications to the flow. The dust sensor needs to discriminate over a minimum of three particle sizing bins from 0.1 to 5.0 micron and detect particle concentrations from a few to hundreds of particles per cubic centimeter. The sensor needs to provide an analog or digital output to allow for remote monitoring and storage of particle counting data.
- *Rapid Cycle Adsorption Pump (RCAP)* - This process operates through adsorption and desorption of carbon dioxide (CO_2). The cycle time between absorption and desorption should be in terms of minutes to minimize adsorption material mass. To achieve this, the proposal must include the thermal management system to perform the adsorption/desorption cycle with a minimum of thermal energy loss. The proposals also must consider all the valving and an active flow device to move the Mars atmosphere through the unit during the CO_2 adsorption cycle.
- *CO_2 Freezing including active cooling (direct cryocooler or cryogenic fluid loop) and thermal management of freezing/heating that minimizes overall electrical energy* - Active cooling is required to achieve a minimum of ?123° C (150) K during the freezing process. The design must state and withstand pressures potentially up to 1000 psi during CO_2 feeding.
- *Cryocooler for in-house NASA design that operates at 150 K with a thermal lift in the 200-300 W range* - The cold fingers and flanges must be capable of 1000 psi to handle the liquid CO_2 pressures. The cryocooler would also need to be able to operate under Mars conditions with cooling supplied by the lander system.

- *Separation and storage of nitrogen (N_2) from Mars atmosphere* - Two options can be considered. Option one is separation of N_2 after the CO_2 has been removed at Mars atmosphere pressures based on the use of RCAP or CO_2 Freezing. Option two is separation of N_2 after the Mars atmosphere has been compressed up to 517 KPa (75 psi).

Carbon Dioxide (CO_2) Processing:

- *Microchannel Reverse Water Gas Shift (RWGS)* - The technology must demonstrate a CO_2 conversion efficiency to >50% in a single pass before any separation and recirculation occurs. The technology proposed should include inlet/outlet gas heat exchange and reactor thermal management to minimize thermal energy losses. The proposer needs to define the design and performance aspects associated with operating pressures ranging from a nominal pressure of 103 KPa (15 psi) up to 517 KPa (75 psi).
- *Solid Oxide Electrolysis (SOE)* - The technology must demonstrate a temperature ramp rate of >15° C/min. and redox stable electrodes for the production durations and rates below. The technology must be able to electrolyze dry CO_2, water (H_2O), or a combination of both CO_2 and H_2O. The proposer needs to define the design and performance aspects associated with operating pressures ranging from a nominal pressure of 55 KPa (8 psi) up to 103 KPa (15 psi), and the design impact associated with differential pressures from inside to outside and across the electrolyte during different phases of operation. In Phase I the technology must demonstrate ? 20 thermal cycles, and ? 70 thermal cycles for Phase II. The technology proposed should include thermal management of the SOE stack and inlet/outlet gas heat exchange to minimize thermal energy losses. Information and performance of the proposed technology in a second application as a fuel cell using previously produced oxygen and carbon monoxide is also of interest to NASA.
- *Alternative O_2 from CO_2 conversion technologies* - Besides RWGS and SOE, NASA is interested in alternative CO_2 conversion technologies as well. These technologies must exhibit >50% CO_2 to CO conversion in single pass, and the proposer must clearly state benefits in mass, power, volume, operating life, and/or complexity compared to RWGS or SOE.
- *Separation and recirculation of CO_2 from CO_2/CO streams* - Most O_2 to CO conversion processes have a significant amount of unreacted CO_2 in the exhaust stream after a single pass. NASA is interested in technologies that allow the unreacted CO_2 to be separated and recirculated back to the process inlet. RWGS and SOE reactors operate at high temperatures (>650° C) so exhaust gases may be at high temperature. The proposal must include both the recirculation pump and separation technologies required for the separation and recirculation system and define the temperatures, pressures, and separation efficiencies associated with these technologies.
- *Regenerable gas drying* - Oxygen and methane (CH_4) produced from Mars CO_2 must be dried before it is liquefied and stored. Also, hydrogen (H_2) from water electrolysis must be dried before delivery to fuel/chemical production reactors. NASA is interested in regenerable gas drying technologies that can remove water from O_2, H_2, and CH_4 streams. No service should be required for these units prior to completion of the ISRU plants operation. Recuperation of the removed water for subsequent use is highly desired.
- *Humidity Sensor for dry oxygen and methane* - Oxygen and methane produced from Mars CO_2 must be dried before it is liquefied and stored. NASA is interested in technologies for water vapor sensing down to 20 ppmv of water in oxygen and methane streams.
- *Dehydration resistant Proton Exchange Membrane (PEM) for water electrolysis and gas/water separators* - ISRU plants sent to Mars may be required to be for launch and during the cruise and landing phases before the system is activated. NASA is interested in dehydration resistant PEM materials for water electrolyzers and gas/water vapor separator membranes to allow for long term dry storage and delivery of ISRU systems.

Technology work in Phase I and hardware to be delivered at the conclusion of Phase II will be designed and built to operate under lunar polar shadowed crater and/or Mars surface environmental conditions, so thermal management during operation of the proposed technology will need to be specified in the Phase I proposal.

ISRU technologies for Mars missions must operate continuously (day and night) for very long durations (480 days) and at all possible atmosphere pressures, 700 to 1000 Pa (0.1 to 0.14 psi) and surface temperatures, which may reach a high of about 20° C (293 K) at noon, at the equator, to a low of about ?153° C (120 K) at the poles, with the potential for significant temperature differences between day and night depending on the season and latitude.

The total production rate for initial human missions to Mars for ascent propellant are 2.2 kg/hour for O_2 production alone and 2.7 kg/hour oxygen and 0.68 hg/hour of methane for oxygen and fuel production. This correlates to

approximately needing 6.6 kg/hr CO_2 for O_2 only and 2 kg/hr for O_2/CH_4 production. Since carbon dioxide processing may occur between 55 and 517 KPa (8 and 75 psi) and nominally at 103 KPa (15 psi) depending on the processing technology selected, proposers must state how the technology proposed changes in mass, power, volume, and complexity as a function of CO_2 delivery and process operating pressure. Proposers are allowed to consider the use of multiple units to achieve these production rates, but should justify the number of units proposed based on overall mass, power, thermal, and/or operation duration requirements. Power needed for the proposed technology operation should be differentiated between electrical and thermal, and consideration should be given on how the thermal management system and the Mars environment could minimize the need for electrical-to-thermal energy conversion. Proposals will be evaluated on mass, power, volume, complexity, and technical feasibility.

H2.01 Lunar Resources

Lead Center: JSC

Participating Center(s): GRC, JPL, JSC

Technology Area: TA15 Aeronautics

Whereas the Moon was once thought to be dry, more recent discoveries indicate that there are a variety of resources that exist on the Moon in an embedded or frozen state in the regolith. When acquired and exposed to higher temperatures and vacuum, these resources will change state into the vapor phase and are known as volatiles. Examples are polar water ice or Hydrogen and Helium 3 embedded in the regolith grains by the sun.

Lunar volatiles are a meaningful first focus area for a space exploration strategy because:

- Use of local space resources, including lunar volatiles, for propellant, life support, etc. will improve the sustainability of human space exploration.
- Technologies and methods for accessing lunar volatiles are relevant to potential future Mars resource utilization.
- Volatiles are of great interest to the science community and provide clues to help understand the solar wind, comets, and the history of the inner solar system.

NASA is interested in this proposal solicitation for small payloads up to 5 kg in mass which are needed to characterize and map the lunar volatiles resources, so that they can be included in a future lunar ISRU strategy, as listed in selective NASA Strategic Knowledge Gaps (SKG) below. This payload may be delivered to the surface of the Moon on a small commercial lunar lander and could be stationary on the lander, mobile on a mobility device, or it may itself be mobile and/or deployable. The Phase I proposal shall indicate the type of lunar surface assets, interfaces and commodities that are required to carry and support the payload. Impactors and other devices that are used or released in lunar orbit are not within the scope of this solicitation.

The goal of this subtopic is to develop the technologies necessary for small payloads delivered to the Moon on a commercial lander to characterize and map the lunar volatiles resources. All proposals need to identify the state-of-the-art of applicable technologies and processes and Technology Readiness Level (TRL) expected at the end of Phase I, with a credible development plan. By the end of Phase I, feasibility of the proposed payload technology should be established with a notional payload packaging concept and evidence that the payload is feasible. If a Phase II is awarded, then further development of the payload technologies and payload packaging shall be required, including a payload prototype delivered to NASA at the end of the two-year project with a goal of achieving TRL 6. Due to the fact that lunar volatiles primarily exist in permanently shadowed craters, the prototype hardware proposed will need to operate under lunar vacuum conditions and either need to be designed to operate and be tested at extremely low temperatures (down to 40 K) or include estimates on thermal management and power to operate under these temperatures. Methods to collect the volatiles without significant loss to sublimation are of high interest. Proposals for innovative technologies and processes must include the design and test of critical attributes or high-risk areas associated with the proposed payload technology or process to achieve the objectives of potential SBIR Phase II proposed Lunar payload hardware. At the end of Phase II, successful payload designs will be considered for funding applied to a commercial lunar lander flight in a potential Phase III award.

Proposals will be evaluated on the basis of feasibility, mass, power, volume, and complexity. All proposals shall

identify the SKG(s) from the list below that will be met. Payloads with a proposed mass of greater than 5 kg shall not be considered in this subtopic.

The following information is provided so proposers understand the context and purpose of the small payloads being solicited for a robotic lunar landing mission.

Recent data from NASA's Lunar CRater Observation and Sensing Satellite (LCROSS), and Lunar Reconnaissance Orbiter (LRO) missions indicate that as much as 20% of the material kicked up by the LCROSS impact was volatiles, including water, methane, ammonia, hydrogen gas, carbon dioxide and carbon monoxide. The instruments also discovered relatively large amounts of light metals such as sodium, mercury and possibly even silver.

The following criteria are relevant to this SBIR solicitation, as reported by the Lunar Exploration Analysis Group (LEAG):

Significant uncertainties remain regarding to the distribution of volatiles at the 10 to 100 m resolution scales accessible to near term orbital missions. Data and models are clear that volatiles are distributed unevenly at this scale and mission success scenarios should accommodate this likelihood. We also found that a range of new orbital missions and science support activities could reduce this risk by improving both the empirical data upon which site selections are based upon, and the scientific understanding of polar volatile evolution. Regarding landed experiments, there are several key measurements-- such as compositional variation and soil geotechnical and thermal properties--within the capabilities of small near-term missions that would greatly improve the understanding of polar volatiles; obtaining any of the needed quantities would benefit subsequent missions.

There are sufficient data to support near-term landing site selections – Enhanced hydrogen is widespread across the polar regions and is sometimes concentrated in permanently shadowed regions (PSRs). Data show that average annual surface temperatures below 110K are also widespread, including both PSRs and areas sometimes illuminated. This characteristic allows preservation of shallow buried ice for geologic time. LCROSS demonstrated hydrogen and water do occur at shallow depths at the LCROSS target site PSR. However, arguments derived from lunar surface processes suggest volatiles will be distributed irregularly and high water abundance observed by LCROSS was not consistent with the regional H abundance indicating sampling of a local concentration.

The expected patchy nature of hydrogen distributions constitutes significant risk to missions requiring detection and sampling of hydrogen. Higher resolution definitive hydrogen data would reduce this risk.

LEAG Volatiles Specific Action Team (SAT) Landed Measurements Finding #1

Small near-term missions can provide critical data to resolve important unknowns regarding polar volatile science and resource utilization:

- Lateral and vertical distribution of volatiles.
- Chemical phases that contain volatile elements.
- Geotechnical and thermal properties of polar soils.
- Mobility of volatiles and associated timescale(s).
    - Landed experiments obtaining any of the important quantities are of great science and exploration value.

LEAG Volatiles Specific Action Team (SAT) Landed Measurements Finding #2

Early characterization of the variation in volatile abundance at ISRU and scientifically relevant spatial scales would greatly benefit all future missions:

- Current understanding of the spatial variation of volatile abundance at the scale of landers and small rovers is a major uncertainty. This ignorance is a strong inhibitor for the use of static landers.
- Several studies suggest that near surface volatiles will be very unevenly distributed due to the impact process and other mechanisms.
- A small rover traversing several hundred meters could characterize the variation in volatiles at this scale

with simple instrumentation. A rover traverse of several hundred meters to several kilometers is required. The minimum distance for ground truthing is 20 km. Minimum distance to confirm if there are volatiles present is likely to be ~1 km.
- This would provide ground-truth for orbital volatile measurements by beginning to close the gap in scales.

LEAG Volatiles Specific Action Team (SAT) Landed Measurements Finding #3

The physical and chemical forms of abundant volatile elements are critical to understanding the resource and its origins:

- Early measurements should include unambiguous determination of the chemical phase of volatiles present to a depth of one or more meters.
- Measurements should not be restricted to the detection of water, but include other volatile species.
- Profiling is desirable, but a bulk analysis would be of very high value.
- It is necessary to measure the isotopic composition of volatile elements. Both with respect to fundamental volatile science and with respect to assessing quantitatively potential landing-induced contamination of the surface materials.

LEAG Volatiles Specific Action Team (SAT) Landed Measurements Finding #4
Successful exploitation of in-situ resources requires knowledge of the physical (geotechnical) and thermal properties of polar regolith in addition to the volatile abundance:

- The utility of a resource is highly dependent on the cost of extraction that is in turn dependent on the physical and chemical state of the volatile and its refractory matrix.
- The ISRU community should develop specific measurement objectives for geotechnical and temperature dependent properties.
- Thermal analysis of polar soils such as differential scanning calorimetry would greatly enhance the ability to develop ISRU regolith processing strategies, even in a volatile poor polar target:
    - Thermal analysis can also be made sensitive to volatiles found in the LCROSS plume that could cause significant concerns for contamination and degradation of ISRU hardware including H_2S, Hg, and Na.
- Physical and thermal properties of polar regolith should be measured. The potential effect of some volatile compounds such as Hg and Na on instrument degradation should be quantified.

LEAG Volatiles Specific Action Team (SAT) Landed Measurements Finding #8

In addition to ISRU goals, landed experiments should include measurements of current volatile flux to aid understanding volatile transport mechanism:

- Apollo surface experiments revealed a dynamic exosphere and produced a lengthy list of potential volatile atmospheric species.
- Measurements might include:
    - Pressure.
    - Atmospheric species.
    - Flux directions.
    - Measurements at PSR contacts to measure the volatile flux into cold traps.

The relevant lunar Strategic Knowledge Gaps (SKG's) for this subtopic are listed below:

- I-C. Regolith 2: Quality/ quantity/distribution/form of H species and other volatiles in mare and highlands regolith (requires robotic precursor missions). Robotic in-situ measurements of volatiles and organics on the lunar surface and eventual sample return of "pristine" samples. Enables prospecting for lunar resources and ISRU. Feeds forward to Near Earth Asteroids (NEA)-Mars. Relevant to the Planetary Science Decadal survey.
- I-D-1. Composition/quantity/distribution/form of water/H species and other volatiles associated with lunar

cold traps. Required "ground truth" in-situ measurement within permanently shadowed lunar craters or other sites identified using LRO data. Technology development required for operating in extreme environments. Enables prospecting of lunar resources and ISRU. Relevant to Planetary Science Decadal survey.

- I-D-3 Subsection c: Geotechnical characteristics of cold traps Landed missions to understand regolith densities with depth, cohesiveness, grain sizes, slopes, blockiness, association and effects of entrained volatiles.
- I-D-7 Subsection g: Concentration of water and other volatiles species with depth 1-2 m scales Polar cold traps are likely less than ~2 Ga, so only the upper 2-3 m of regolith are likely to be volatile-rich.
- I-D-9 Subsection I: mineralogical, elemental, molecular, isotopic make up of volatiles. Water and other exotic volatile species are present; must know species and concentrations.
- I-D-10 Subsection j: Physical nature of volatile species (e.g., pure concentrations, inter-granular, globular) Range of occurrences of volatiles; pure deposits (radar), mixtures of ice/dirt (LCROSS), H_2-rich soils (neutron).
- I-E. Composition/volume/distribution/form of pyroclastic/dark mantle deposits and characteristics of associated volatiles. Required robotic exploration of deposits and sample return. Enables prospecting for lunar resources and ISRU. Relevant to Planetary Science Decadal survey.

H3.01 Process Technologies for Water Recycling in Space

Lead Center: JSC

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

Technology Area: TA15 Aeronautics

Water Processors for Planetary Surface Systems

NASA seeks concepts for the development of water systems on a planetary surface that take advantage of the partial gravity on Mars or the lunar surface while implementing robust technologies with minimal consumables. The technologies should focus on the following potential waste streams: urine, humidity condensate, Sabatier product water, waste hygiene, and waste laundry water. Consideration should be given to planetary protection, for both forward and backward contamination. Technologies must be compatible with a delivery schedule to Mars (6-12-month transit) in which the system will be dormant, operational periods exceeding 500 days, followed by dormancy periods between uses for 2 or more years.

Total Organic Carbon Analyzer for Exploration Missions

Over the past 10+ years, we've learned the importance of real-time on-board monitoring of total organic carbon (TOC) in product water from the ISS wastewater recycling system (Water Processor Assembly - WPA). TOC along with conductivity provides a means to predict when multi-filtration beds require replacement. This data allows controllers and engineers to monitor both impending break through and recovery of upsets in water quality once appropriate remedial action is taken. Having measurement of TOC helps to optimize the life of consumable WPA elements. The hardware for monitoring TOC on the ISS is called the "Total Organic Carbon Analyzer" or TOCA. The Size, Weight and Power (SWaP) of TOCA is as follows: 67 L, 34 kg, and 64 W. Water recycling and therefore a TOCA will be required on future long duration gateway/deep space missions. The ISS TOCA design is simply too large for exploration vehicles and habitats. Any design effort toward an advanced TOCA should reduce the SWaP of the ISS TOCA by at least an order of magnitude. New technology development is sought in measuring TOC and conductivity in a miniaturized, automated system that can be plumbed into the WPA. Ideally, the TOCA requires no hazardous reagents, has long-term calibration stability, and requires very little crew time to operate and maintain. TOCA functionality is one of the critical water monitoring needs for future spacecraft based on the requirements assessment. Studies are currently being performed to explore alternative oxidation and detection techniques, as well as system simplifications and repackaging to shrink its size. In-line measurement is desired as a capability above the SOA, but it is not critical.

Silver-based Microbial Check Valve

NASA has interest in in-line microbial check valve (MCV) technologies for spacecraft potable water systems. The MCV should add 300 to 500 ug/L of silver to the water at a flow rate of 0.1 to 0.15 L/min to maintain the microbial control of the system in accordance with typical spacecraft potable water specifications. In addition, the device should be able to operate at ambient temperature, pH ranges between 4.5 - 9.0, and system pressures up to 30 psig. In addition, the MCV should prevent the passage and/or grow through of microbes across the MCV device when there is no flow. The MCV device should be capable of easy installation and be maintainable. The devices should also be small, robust, lightweight, and have minimal power and consumable mass requirements. In addition, candidate technologies should be microgravity compatible, have no adverse effects on the potability of the drinking water system, and not require removal of the imparted biocide prior to crew consumption. Of particular interest are microbial check valve technologies that are either silver-based and/or fully compatible with ionic silver disinfection strategies. Finally, MCV technologies should also be capable of providing continuous, stable and autonomous operation, and be fully functional following periods of long-term system dormancy – up to 1 year.

H3.02 Waste Management and Resource Recovery

Lead Center: JSC

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

Technology Area: TA15 Aeronautics

There are two areas of focus in this subtopic:

Collection and Recovery of High TOC Water from Feces and Trash

Wet trash contains ~25% and feces contains ~75% water by mass that is currently not recovered on ISS. Currently wet trash and feces are collected and stored in relatively impermeable containers for short term storage (1-3 months) and disposed of in departing logistics vehicles. There have been crew comments about odor generation during storage. Trash and fecal material must be stabilized for Mars transit and surface missions. Drying and thermal processing of trash can reduce odor generation and prevent microbial proliferation. Past Heat Melt Compactor (HMC) technology development has indicated >80 volatile compounds elute from trash and recovered water can exceed 3,500 ppm total organic carbon (TOC). Innovations are requested for technologies that can recover water from a gas stream with a wide range of volatile gas contaminants for long periods. Technologies must be able to recover >80% of the gas stream water content. Captured water should have minimal free gas and should be below 2% by volume for eventual delivery to a waste water tank. Purification of the water is not requested. Technologies must be able to accommodate a wide range of condensable and non-condensable mass flow rates as trash/fecal processing systems dry and process the material. Water recovery from a variety of processes (i.e., HMC, Trash to Gas, freeze drying) should be accommodated directly or with an assumed regenerative heat exchanger to recover energy prior to phase separation. Process gas temperatures will range from -80° C to 200° C and 6-110 kPa absolute. Condensable gas will range from 0-100% by volume with a maximum water flow rate of 15 g/min. Air cooling using cabin air 18-30° C is preferred but water cooling is acceptable. Systems must be capable of microgravity operation over a 6-month transit to Mars, an 18-month dormancy period, and 6-month operation on return to Earth with minimal crew maintenance. It is highly desirable that maintenance items consider fabrication by on-demand manufacturing (i.e., additive manufacturing and post finishing). Technologies must consider accumulation of organics and microbial proliferation between normal waste processing cycles and extended dormancy and any change in performance should be characterized. Technologies shall demonstrate comparison to previous SOA condensing heat exchangers.

Low Consumable Low Residual Waste Gasification

Past trash gasification technologies focused on producing gases (methane, water, oxygen, or CO_2) for secondary purposes using supplemental oxygen, water, or other consumables. The current request focuses on the minimal total mass (combined consumables and residual mass). Recent trash storage vs processing trade studies have indicated trash jettison during the transit results in the lowest total vehicle mass. It is possible to reduce overall vehicle mass by ~6% (10,800 kg) via trash jettison. Approximately 70% of the savings is due to reduced chemical propulsion fuel and tankage for orbit departures and insertions. Innovations are requested for technologies that can convert trash to gas suitable for venting to the space craft exterior for the purpose of reducing vehicle mass. Technologies must be capable of processing the wide range of crew logistical trash and metabolic

waste. Processing technologies must decompose at least a portion of the hydrocarbon waste. Technologies that only recover water are not requested. Residuals material plus processing consumables (lost gas, oxygen, water, and carrier gases) must be less than 10% of the starting trash material. Processes must be capable of serial waste loading, processing, and residual removal without complete shutdown. Systems must be capable of microgravity operation over a 6-month transit to Mars, an 18-month dormancy period, and 6-month operation on return to Earth with minimal crew maintenance. It is highly desirable that maintenance items consider fabrication by on-demand manufacturing (i.e., additive manufacturing and post finishing). Technologies must consider containment of high pressure/temperature/hazardous gases for crew safety and operational robustness. Characterization of produced gases is required with emphasis on identification of condensable gases and acid/caustic gases that can adversely affect exterior glass and metallic vehicle surfaces. Technologies shall demonstrate comparison to previous state-of-the-art Trash to Gas (TtG) systems. If water is recovered (desirable but not required) chemical contaminants within the recovered water should be characterized.

H4.01 Advanced Space Suit Portable Life Support System (PLSS)

Lead Center: JSC

Technology Area: TA15 Aeronautics

NASA plans to continue using the current EMU/spacesuit for the life of ISS. However, with the anticipation of a replacement suit for ISS or other future mission, the plan for an Advanced EMU is underway. Technology gaps remain for the PLSS. The following is a list of technology focus areas specifically for the Advanced PLSS:

- *Continuous trace contaminant removal capability* - Activated charcoal is the state of the art and provides a logistics impact to future missions. The primary trace contaminants to remove include ammonia (NH_3), carbon monoxide (CO), formaldehyde (CH_2O), and methanethiol (also known as methyl mercaptan) (CH_3SH). The minimum objective would be to remove all of the significant compounds that threaten to exceed the 7-day SMAC[2] during an EVA. For continuous removal, the most advantageous integration with the current state of the art CO_2/H_2O removal system would be integrated such that regeneration or desorption occurs with a pressure swing from 4.3 psia to <1 torr over a ~2min period half-cycle at temperatures in the 60-80° F range. A small amount of heat flux is available from the cross-coupled adsorbing bed; additional heat input requirements from resistance heaters, etc. would negatively impact the system trade the more significant the value becomes.
- *Small, oxygen compatible gas flow meter for suit operations* - Small, oxygen compatible gas flow meter for suit operations: The current state of the art for flow measurement on the ISS EMU space suit is a flapper valve attached to a microswitch which is limited to a single set-point. The accurate measurement ranges required for the sensor are 2-8 acfm +/- 1% with a pressure drop of less than 0.68 in-H_2O in a 100% oxygen (O_2) environment (traces of NH_3, H_2O, CO_2); suit pressure from 3.5-25 psia, temperature from 50-90° F, relative humidity (RH) 0-50%, and CO_2 from 0-15mmHg. This flow meter needs to fit within a volume/shape factor of approximately 2.5 in x 1.5in x 3in or less including fluid ports and electrical connectors; if added as an in-line flow, 1 in inlet/outlet porting will be necessary. Operating life objective is 8 years without calibration and 5000 hours of powered operation.
- *Small hermetic micro switch* - Current state of the art is 3-5 times larger than needed. Honeywell MicroSwitch HM-1 series is a typical state of the art. Combining Single Pole Double Throw (SPDT) circuits that add additional toggle mechanisms would further grow the size of the switch. Hermetic is defined as leakage <10-8 atm-cc/sec. Switching currents for these switches are signal level at <500mA.
- *Multi-gas monitoring within the suit* -Multi-gas monitoring: Advanced suit could benefit from measuring Oxygen (O_2), carbon dioxide (CO_2), water (H_2O), ammonia (NH_3), carbon monoxide (CO), formaldehyde (CH_2O), methanethiol (also known as methyl mercaptan) (CH_3SH), etc. The measurement of trace contaminants becomes even more important if an alternate approach (e.g., pressure or temperature swing adsorption) to the traditional activated charcoal cartridge is used. There is a need to measure the following major constituents and trace contaminants ranges in the gas stream across a total pressure range of 3.5 – 23.5 psia and temperature range of 35-125F: O_2 = 20-100%; CO_2 = 0-30 torr over 3.5-23.5 psia; H_2O = 5-90% RH; NH_3 = 0-50 ppm; CO = 0-400 ppm; CH_2O = 0-5 ppm; and CH_3SH = 0-5 ppm.
- *Power* -Current state of the art is lithium-ion batteries with cell level energy densities of 200 W-h/kg but packaged energy densities of ~130W-h/kg after addressing mitigation for thermal runaway. Safe, high-energy density power sources are needed which are rechargeable post-EVA.

- *Heat Transport Improvements* - Several improvements are needed in this focus area including:
  - Improvement in the Liquid Cooling and Ventilation Garment (LCVG) state of the art.
  - Improvement in the UA such that warmer water can be used to sink the waste heat from the human and hence reduce the evaporator size.
  - Drastically alter the human-to-cooling loop interfaces such as a fluid-filled suit with directly pumped cooled water.
  - Alter the Thermal Micrometeoroid Garment (TMG) such that the emissivity/absorptivity can be dynamically altered to improve thermal.
- *Human-Machine Interface Improvements* - Current state of the art for this focus area includes mechanical switches and a 16 x 2 Liquid Crystal Display (LCD). Low power, wide thermal range, rad tolerant high definition graphics displays that can be integrated with the suit soft goods or hard goods such as heads-displays.

These technology gaps were detailed during the 2017 SBIR/STTR Industry Day (https://sbir.nasa.gov/events/sbir-industry-day [1]).

Phase I Products - By the end of Phase, it would be beneficial to have a concept design for infusion into the Advanced PLSS. Testing of the concept is desired at this Phase.

Phase II Products - By the end of Phase II, a prototype ready for system-level testing in the PLSS or in a representative loop of the PLSS is desired.

H4.02 Controllable, Tinting, Polycarbonate Compatible Coatings for Advanced EVA Spacesuit Visor

Lead Center: JSC

Technology Area: TA15 Aeronautics

For the next generation of NASA's space suits, being able to enable an architecture for microgravity and planetary capabilities is required. To support these future missions, we will need support hardware to be designed, such as a new extravehicular visor assembly (EVVA) to protect the astronaut's eyes from the damaging UV rays of the sun. The EMU has an EVVA that is a sun visor that can be manually deployed by the crew members. This changes the radiation protection from just UV via the clear helmet to a reflective visor that blocks visible light and IR via the gold visor. Unlike the EMU EVVA design, the new EVVA will need to integrate with the exploration space suit helmet bubble, which is a 10"x13" hemi-ellipsoid dome. We feel that in this new design we have a unique opportunity to integrate the new technologies in the field of actively controlled coatings that affect tint-ability, UV protection, and optimized transmittance through our EVVA. Focus areas of coating technology that appeal to the team are electrochromics and solar variable reflectance, but we are open to other novel solutions.

The goal at the end of Phase I SBIR is to have a tabletop prototype helmet bubble that is coated with a controllable tint that would demonstrate the technology needed to replace the EVVA reflective visor.

Phase I Performance Targets:

- Transmittance requirements in off state: 450 nm N/A, 550 nm 70% min, 1100 N/A.
- Transmittance requirements in on state: 450 nm 10+/-4%, 550 16+/-4%, and 1100 nm 10% max.
- Cannot hinder visibility in a failed state.
- Must be thermally stable in the space environment.
- Concepts of how to make it operable with a gloved hand.
- If required, low power consumption.

Phase II would require the coating to meet the same requirements as seen in Phase I, but to deliver a full helmet bubble prototype that could interface with NASA's Z-2 spacesuit for a suited demonstration. Examples of Phase II performance targets would include ability to autosense UV/light with the ability to turn on/off the coating automatically, integrating a scratch resistant coating, a packaged power supply (if needed) that is dust resistant and tolerant to the space environment, and packaged controls for the crew member that are operable with a gloved hand.

H4.03 Mass Produced, Minimal Capability, Disposable EVA Life Support System

Lead Center: JSC

Technology Area: TA15 Aeronautics

NASA's plans for Exploration EVA Operational Concepts and Architectures currently lead to conceptual design solutions optimized for relatively long EVA's and extensive re-use of the PLSS over the course of many missions. From an economics perspective, that is one way to solve the question of "value" – by amortizing the development and manufacturing cost of a relatively small amount of production units across a relatively long period of use (many years, many EVAs or many separate missions).

However, it is possible that alternative ways of solving the Suit and PLSS problems, including cost, could be acceptable – by reducing the capability inside the EVA PLSS to a point where it might only enable a relatively short EVA (perhaps ~2 hours instead of ~8) and relatively few EVAs (perhaps ~10 instead of ~100) one might be able to construct a schematic and design that was affordably "mass produced".

Embracing innovative suit garment technologies and concepts such as novel material layups, self-healing/self-repair bladders and restraints, Shape Memory Alloy (for adjustable sizing and fit geometry, ballistic projectile mitigation (for secondary eject from MMOD strikes on nearby natural surfaces), electrochromics, Mechanical Counter Pressure (MCP) concepts, and hybrid designs and manufacturing approaches may lead to cost effective suits that could inform NASA future plans as well as support future commercial space needs. Ultimately, concepts, technologies and design solutions leading to the capability of "low-cost customization" is vital to NASA's future exploration capabilities in many ways.

The potential benefits of these approaches could include the ability to more regularly incorporate emerging technologies and minor feature updates to continuous reduction of cost through refinement and modernization of the production system. Such an approach might also stimulate or otherwise support the adoption of EVA as a viable, cost effective feature in commercial spaceflight systems for non-NASA customers.

Design solutions might look significantly different from current/historic EVA PLSS and suit designs, including features similar to the emergency breathing systems used for short periods by firefighters, first responders and Hazardous Material teams. Parallels with such terrestrial applications offer opportunities for existing commercial product lines to be adapted or modified for the "hazardous environment" of EVA and could further grow existing sectors of the economy. Such innovative design solutions would also provide NASA technical data that NASA could then integrate into analysis of alternative "Mission Design" scenarios where the total spaceflight architectural impact of mass, volume, reliability, spares and contingency scenarios are assessed. These types of analysis currently only use the conventional PLSS design solution parameters as inputs, but running the same models by adapting Operational Concepts to use a "mass produced" EVA PLSS might reveal surprising alternative approaches that NASA should be aware of.

Phase I products:

- A paper report on the concept highlighting the design's minimal capabilities.
- A manufacturability analysis explaining why it is mass-producible at an extremely low cost (including an estimate of the number of units needed to achieve a minimal unit price).
- A comparison of the proposed concept with existing commercially available terrestrial life support systems such as firefighter breathing apparatus':
    - The comparison highlights commonality or differences in the technical design and the economies of scale found in available terrestrial life support systems and the proposed concept.
    - This information should clearly support the manufacturability analysis by providing evidence to the costs of existing product lines and why those are relevant analogies to the proposal.
- Prototype suit subsystem manufacture, up to and including a full suit, which could be used in testing.

Phase II would require the product development, further characterization of the limits of the design's performance and additional financial analysis on the cost of mass production.

H5.01 Mars Surface Solar Array Structures

Lead Center: LaRC

Participating Center(s): GRC

Technology Area: TA15 Aeronautics

Human missions to the Mars surface will require tens of kilowatts of electrical power for life support, science, in-situ resource utilization (ISRU), and other equipment. Possible power sources include nuclear reactors and solar arrays with batteries or regenerative fuel cells. Solar arrays are a mature, reliable technology used on most spacecraft and increasingly for Earth terrestrial power, and also at small sizes up to ~3 m^2 for several successful Mars landers and rovers. However, human missions will need thousands of square meters of solar cells to generate the required power. Furthermore, the solar arrays must survive inevitable dust storms and possibly months of dormancy before and between crew visits.

This subtopic seeks structural and mechanical innovations for solar arrays with at least 1000 m^2 of total area that autonomously deploy from Mars landers. Design guidelines for these large deployable solar arrays are:

- Solar arrays must self-deploy.
- Total area: 1000 m^2. Extensibility to 1500+ m^2 is desirable.
- Mass goal: < 1.5 kg/m^2 including all mechanical and electrical components. Packaging goal: < 10 m^3 per 1000 m^2 of deployed area.
- Launch loads: 5 g axial, 2 g lateral, 145 dB OASPL.
- Lander may not have azimuth control (i.e., guaranteed landing clocking angle). State all assumptions concerning array orientation and sun pointing.
- Solar arrays deploy in Mars 0.38 gravity and low winds (use 0.5 g for preliminary design). Solar arrays operate in Mars 0.38 gravity and wind gusts (use 1.0 g for preliminary design).
- Must survive peak winds of 50-100 m/s and simultaneous upward winds of 25-50 m/s (dust devils) with maximum air density of 0.023 kg/m^3.
- Deployable on terrain with up to 0.5 m obstacles/depressions, 15 degree slopes, and potentially hidden hazards (e.g., sand-filled holes). Operating height > 0.5 m to avoid wind-blown sand collection.
- Time to deploy: < 8 hrs.
- Deployed strength: Ideally > 1 g to allow unconstrained Earth deployment qualification.
- Integrated dust abatement or removal methods. Dust accumulation is the #1 design risk issue for sustained solar power production on Mars.
- Tolerant of daily thermal cycling from -100° C to 25° C over a lifetime of 10-15 years.
- Describe the concept of operations (ConOps) including all packaging, deployment, and operating assumptions.

This subtopic seeks innovations in the following areas for Mars solar array structures:

- Novel packaging, deployment, retraction, terrain-following ground supports, or in-situ assembly or manufacturing concepts.
- Lightweight, compact components including booms, ribs, substrates, and mechanisms.
- Load-limiting devices to avoid damage during extreme winds.
- Optimized use of advanced ultra-lightweight materials (but not materials development).
- Validated modeling, analysis, and simulation techniques.
- High-fidelity, functioning laboratory models and test methods.

Proposals should emphasize structural and mechanical innovations, not photovoltaics, electrical, or energy storage innovations, although a complete solar array systems analysis is encouraged. If solar concentrators or solar tracking are proposed, strong arguments must be developed to justify why this approach is better from technical, cost, and risk points of view over fixed planar solar arrays. Of special interest are design innovations that improve NASA's proposed solar array concepts using multiple Compact Telescoping Arrays (CTAs) as depicted on Charts

16-19 of Reference 2. Load alleviation methods to avoid damage during extreme winds are also of high interest.

In Phase I, contractors should prove the feasibility of proposed innovations using suitable analyses and tests. In Phase II, significant hardware or software capabilities that can be tested at NASA should be developed to advance their Technology Readiness Level (TRL). TRLs at the end of Phase II of 3-4 or higher are desired.

References:

1. Joseph Appelbaum and Geoff Landis, "Photovoltaic Array for Martian Surface Power," 43rd Congress of the International Astronautical Federation, NASA TM-105827, August 28, 1992, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19920024655.pdf [2].

2. Richard Pappa and Tom Kerslake, "Mars Surface Solar Arrays," FISO telecon seminar with recorded audio, June 7, 2017, http://spirit.as.utexas.edu/~fiso/telecon/Pappa-Kerslake_6-7-17/ [3].

3. Lee Mason, "Mars Surface Power" panel, AIAA Propulsion and Energy Forum with recorded video, July 12, 2017, https://livestream.com/AIAAvideo/PropEnergy2017/videos/159709334 [4].

H5.02 Hot Structure Technology for Atmospheric Entry Vehicles

Lead Center: LaRC

Participating Center(s): AFRC, JSC, MSFC

Technology Area: TA15 Aeronautics

This subtopic encompasses the development of reusable, hot structure technology for primary structure that is exposed to extreme heating environments on atmospheric entry vehicles. A hot structure system is a multifunctional structure that can reduce or eliminate the need for a separate thermal protection system (TPS). The potential advantages of using a hot structure system in place of a TPS with underlying cool structure are: reduced mass, increased mission capability such as reusability, improved aerodynamics, improved structural efficiency, and increased ability to inspect the structure. Hot structure is an enabling technology for reusability between missions or mission phases, such as aerocapture followed by entry, and has been used in prior NASA programs (HyperX and X-37) on control surfaces and leading edges, and Department of Defense programs.

This subtopic seeks to develop innovative low-cost, damage tolerant, reusable and lightweight hot structure technology applicable to atmospheric entry vehicles, exposed to extreme temperatures between 1000° C to 2200° C. The material systems of interest for use in developing the hot structure technology include: advanced carbon-carbons (C-C), ceramic matrix composites (CMC), or advanced high temperature metals. Potential applications of the hot structure technology include: primary load-carrying aeroshell structure, control surfaces, and propulsion system components (such as hot gas valves and passively-cooled nozzle extensions). Proposals should address one or more of the following:

- Employing advanced materials in novel structural system concepts for thermal management associated with atmospheric entry and/or hypersonic flight.
- Utilizing preceramic polymers for producing advanced material systems with tailored chemical, mechanical, and physical properties. Of particular interest are polymers yielding ceramics in the SiOC, SiNBC, SiNC or SiC families in the form of ceramic foams, fibers, coatings, and fiber-reinforced CMC, for use in a hot structure concept.
- Material/structural architectures and multifunctional systems providing significant improvements of interlaminar mechanical properties while maintaining in-plane and thermal properties compared to state-of-the-art C-C or CMC. Examples include: incorporating through the thickness stitching or 3D woven preforms.
- Improvements in manufacturing process and/or material design to achieve repeatable and uniform material properties, scalable to actual vehicle components; specifically, data obtained from flat-panel test coupons should represent the properties of future flight vehicles.
- High temperature oxidation resistant coating integrated with a hot structure concept to extend performance for multiple cycles up to 2200° C.

For proposals to this subtopic, research, testing, and analysis should be conducted to demonstrate technical feasibility during Phase I and show a path towards Phase II hardware demonstration. Phase I feasibility studies should also address cost and risk associated with the hot structures technology. At completion of Phase I, project deliverables should include: coupon specimens of components adequate for thermal/mechanical and/or arc-jet testing and a final report that is acceptable for publication as a NASA Technical Memorandum. Emphasis should be on the delivery of a manufacturing demonstration unit for NASA testing at the completion of the Phase II contract. In addition, Phase II studies should address vehicle integration. Opportunities and plans should also be identified and summarized for potential commercialization.

H6.01 Integrated System Health Management for Sustainable Habitats

Lead Center: JSC

Participating Center(s): GRC, JSC, LaRC

Technology Area: TA15 Aeronautics

Habitation systems provide a safe place for astronauts to live and work in space and on planetary surfaces. They enable crews to live and work safely in deep space, and include integrated life support systems, radiation protection, fire safety, and systems to reduce logistics and the need for resupply missions. Innovative health management technologies are needed in order to increase the safety and mission-effectiveness for future space habitats on other planets, asteroids, or lunar surfaces. For example, off-nominal or failure conditions occurring in safety-critical life support systems may need to be addressed quickly by the habitat crew without extensive technical support from Earth due to communication delays. If the crew in the habitat must manage, plan and operate much of the mission themselves, operations support must be migrated from Earth to the habitat. Enabling monitoring, tracking, and management capabilities on-board the habitat and related EVA platforms for a small crew to use will require significant automation and decision support software.

This subtopic seeks to broaden the scope of traditional caution and warning systems, which are typically triggered by out-of-bounds sensor values, by including machine learning and data mining techniques. These methods aim to reveal latent, unknown conditions while still retaining and improving the ability to provide highly accurate alerts for known issues. The performance targets for known faults and failures will be based upon false alarm rate, missed detection rate, and detection time (first time prior to the adverse event that the algorithm indicates an impending fault/failure). Methods should explore the trade space for ISHM data and processing needs in order to provide guidance for future habitat sensor and computational resource requirements.

Proposals may address specific system health management capabilities required for habitat system elements (life support systems, etc.). In addition, projects may focus on one or more relevant subsystems such as water recycling systems, photovoltaic systems, electrical power systems, and environmental monitoring systems. Proposals that involve the use of existing testbeds or facilities at one of the participating NASA centers (e.g., Sustainability Base at ARC) for technology validation, verification, and maturation are strongly encouraged. Technology Readiness Levels (TRL) of 4 to 6 or higher are sought.

Key features of Sustainability Base that make it relevant to deep space habitat technology are its use of a grey water recycling system and a photovoltaic array. Data logged from other facility management/building automation systems include environmental data (temp, CO_2, etc.) and facility equipment sensors (flowrates, differential pressures, temperatures, etc.). Also, information on power consumption (whole building, plug load, other loads metered at the panel/circuit level) can be made available. These remaining systems, while conventionally "green," have no unique feature that can't be exclusively used for terrestrial purposes. However, the fact that all such systems require less power to support human occupancy can be used as a focal point to serve as a testbed for deep space habitats that will need to operate within finite energy budgets.

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

- Machine learning and data mining techniques that are capable of learning from operations data to identify statistical anomalies that may represent previously unknown system degradations. Methods should facilitate the incorporation of human feedback on the operational significance of the statistical anomalies using

techniques such as active learning.
- Demonstration of advanced predictive capability using machine learning or data mining methods for known system fault or failure modes, within prescribed performance constraints related to detection time and accuracy.
- Prognostic techniques able to predict system degradation, leading to system robustness through automated fault mitigation and improved operational effectiveness. Proposals in this area should focus on systems and components commonly found in space habitats or EVA platforms.
- Innovative human-system integration methods that can convey a wealth of health and status information to mission support staff quickly and effectively, especially under off-nominal and emergency conditions.

H6.02 Resilient Autonomous Systems

Lead Center: ARC

Participating Center(s): JPL, JSC, MSFC

Technology Area: TA15 Aeronautics

Future human spaceflight missions will place crews at large distances and light-time delays from Earth, requiring novel capabilities for crews with limited ground support to manage spacecraft, habitats, and supporting equipment to prevent Loss of Mission (LOM) or Loss of Crew (LOC) over extended duration missions. In particular, these capabilities are needed to handle faults leading to loss of critical function or unexpected expenditure of consumables. Expanded flight control functionality will be on-board spacecraft with significant automation, autonomy, and decision support software. The increasingly complex interconnectivity of these elements introduces new vulnerabilities within space systems that are sometimes impossible to predict. In that context, one key property of the respective system is its resilience to unforeseen events.

Resilience, as defined by the U.S. National Academy of Sciences [1] (NAS), is the ability to plan and prepare for, absorb, recover from, and more successfully adapt to adverse events. This definition encompasses principles such as robustness, redundancy, modularity, and adaptability.

To enable resilient behavior of a system (such as a vehicle, a habitat, a rover, etc.), "resilience" needs to be built-in during the design phase of the system development. To that end, the operational states of a system's component need to be considered in conjunction with the intended function of the component and its possible failure modes throughout the vehicle's life cycle. Where possible, critical failures are eliminated during the design stage. For failure modes that cannot be eliminated, a mechanism needs to be devised that considers how to have optimal state awareness during operations and to mitigate the fault. Mitigation can be accomplished through fault avoidance, fault masking, or Fault Detection, Identification, and Recovery (FDIR). For the latter, system reconfiguration leveraging functional redundancies is of particular interest. Since a vehicle is made up of many components, a system-of-system's approach needs to be considered in a multi-objective optimization context to account for interdependencies and to realize possible mutually beneficial mitigation solutions for resiliency.

Proposals to this subtopic should specify innovation and approaches toward two goals:

- Development of methods and tools that allow the assessment and optimization of system resilience during its conceptual design stage, while simultaneously maximizing reliability and safety.
- Development of measures and metrics that quantify the degree of resilience of a system with respect to a mission ConOps and hazard analysis.

Resilience measures and metrics must be general enough to support broad applications, yet precise enough to measure system-specific qualities. Such metrics are necessary to make resource and operations decisions. Risk metrics tend to assess risks to individualcomponents, ignoring system functionality as the result of interacting components. Resilience measures and metrics also ideally need to account for uncertainty in the planned operation of the system, and focus on integrating statistical methods for uncertainty propagation into resilience-based design. Rather than the static view of systems and networks in risk assessment, resilience adopts a dynamic view. This means resilience metrics must also consider the ability of a system to plan, prepare, and adapt as adverse events

occur, rather than focus entirely on threat prevention and mitigation. Finally, resilience depends upon specific qualities that risk assessment cannot quantify, such as system flexibility and interconnectedness.

Proposed solutions are expected to have characteristics including, but not limited to:

- Life-cycle models that encapsulate cost/benefit of envisioned design solution and that can be used to inform about the resilience of the system.
  - Models may need to be built at the appropriate fidelity level to capture relevant fault behavior.
  - Models may need to assess behavior and consequences during degraded (or faulted) state.
  - Models should also be able to assess mitigation actions that are part of an integrated health management approach.
- Design optimization methodology that can systematically incorporate health management solutions.
  - Methods that integrate optimal decision-making into the design concept.
  - Methods that make use of both system health models and observations to provide the best decision given the information available.
  - Methodology to allows bi-directional exchange between a model and the analysis tool.
  - Methods that systemically include desired levels of resilience in the design optimization process.

Desired, but not necessary:

- Uncertainty management:
  - Identify the various sources of uncertainty that affect system performance, and quantify their combined effect on both system failure and resilience.
  - Systematically incorporate uncertainty in the design process, thereby incorporating both resilience and likelihood of failure directly during the design stage.

This SBIR work aims to generate a practical toolkit for space systems that can deliver solutions with assured levels of performance, reliability and resilience. Emphasis is on the design for resilience methodology, not on delivering entire systems.

Metrics for success include:

- Development of generic quantitative measures and metrics that evaluate system resilience, and their application to space relevant systems or subsystems.
- Demonstrated improvement of resilience over baseline design for at least two different space relevant systems or subsystems (In-space applications are preferred, but terrestrial analogues will be considered).
- Consideration of at least 3 different fault modes.
- Software tools must be able to accept other systems or subsystems through appropriate interface.

SBIR work is expected to deliver mainly software in the form of tools used during the design stage and also prototype software that would manage resiliency during autonomous operations. For the latter, the SBIR effort should analyze sensors, computational hardware, and software stack.

Proposals must demonstrate mission operations risk reduction through appropriate metrics.

Deliverables: tools developed, algorithms and any data generated in simulations or experiments.

Below are a few links to documents on resilience that may be useful to understand the context:

- Resilience Engineering and Quantification for Sustainable Systems Development and Assessment: Socio-technical Systems and Critical Infrastructure - https://www.irgc.org/wp-content/uploads/2016/04/Haering-et-al.-Resilience-Engineering-and-Quantification.pdf [5].
- The New Resilience Paradigm - Essential Strategies for a Changing Risk Landscape - https://www.irgc.org/wp-content/uploads/2016/04/Fiksel-The-New-Resilience-Paradigm.pdf [6].

References:

Kash Barker, Jose Emmanuel Ramirez-Marquez, Claudio M. Rocco, "Resilience-based network component importance measures", Reliability Engineering and System Safety 117 (2013) pp.89–97.

Daniel A. Eisenberg, Igor Linkov, Jeryang Park, Matthew E. Bates, Cate Fox-Lent, Thomas P. Seager**, Resilience Metrics: Lessons from Military Doctrines.** http://www.thesolutionsjournal.org/node/237200 [7].

[1] Committee on Increasing National Resilience to Hazards and Disasters; Committee on Science, Engineering, and Public Policy (COSEPUP); Policy and Global Affairs (PGA); The National Academies. Disaster Resilience: A National Imperative. The National Academies Press. http://www.nap.edu/catalog.php?record_id=13457 [8] (2012).

H6.03 Spacecraft Autonomous Agent Cognitive Architectures for Human Exploration

Lead Center: ARC

Participating Center(s): JSC, MSFC

Technology Area: TA15 Aeronautics

This subtopic develops intelligent autonomous agent cognitive architectures that are open and modular such that they can feasibly be certified for use on deep space missions to interact both with the mission control operators, the crew, and most if not all of the spacecraft subsystems. With such a cognitive agent that has access to all onboard data and communications, the agent could continually integrate this dynamic information and advise the crew and mission control accordingly by multiple modes of interaction including text, speech, and animated images. This agent could respond to queries and recommend to the crew courses of action and direct activities that take into account all known constraints, the state of the systems, availability resources, risk analyses, and goal priorities.

Future human spaceflight missions will place crews at long distances from Earth causing significant communication lag due to the light distance as well as occasional complete loss of communication with Earth. Novel artificial intelligence capabilities augmenting crews will be required for them to autonomously manage spacecraft operations and interact with Earth mission control under these conditions, including spacecraft and systems health, crew health, maintenance, consumable management, payload management, training, as well as activities such as food production and recycling.

Autonomous agents with cognitive architectures would be able to interface directly with the crew as well as with the onboard systems and mission control, thus reducing the cognitive loads on the crew as well as performing many tasks that would otherwise require scheduling crew time. In addition, this cognitive computing capability is necessary in many circumstances to respond to off-nominal events that overload the crew; particularly when the event limits crew activity, such as high-radiation or loss of atmospheric pressure events.

In deep space, crews will be required to manage, plan, and execute the mission more autonomously than is currently done on the International Space Station (ISS); which from Low Earth Orbit has instantaneous ground support. NASA expects to migrate significant portions of current operations functionality from Earth flight control to deep-space spacecraft to be performed autonomously. These functionalities will be performed jointly by the crew and cognitive agents supervised by the crew; so, the crew is not overburdened. Cognitive agents that can effectively communicate with the crew could perform tasks that would otherwise require crew time by providing assistance, directly operating spacecraft systems, providing training, performing inspections, and providing crew consulting among other tasks.

Due to the complexity of such cognitive agents and the need for them to be continually updated, their software architecture is required to be modular. A requirement for these cognitive software architectures is that modules can dynamically be added, removed, and enhanced. Types of modules would likely include a smart executive, state estimator, planner/scheduler, diagnostics and prognostics, goal manager, etc. Other modules that may be supported include a dialog manager, risk manager, image recognition, instructional drawing, crew task manager, etc. This type of modular cognitive architecture is consistent with that proposed by Prof. Marvin Minsky in "The Society of Mind", 1988, and subsequent proposals and realizations of cognitive agents. Recent venues for cognitive architectures include: ICCM (http://iccm-conference.org/2017/ [9]) and AAAI-17 Special Track on Special

Track on Cognitive Systems http://www.aaai.org/Conferences/AAAI/2017/aaai17cognitive.php [10].

Due to NASA's need for fail-safe capabilities, such as continued functionality during high-radiation events, the cognitive architecture will be required to be capable of supporting multiple processes executing on multiple processors, in order to meet the expected computational loads as well as be robust to processor failure. Cognitive architectures capable of being certified for crew support on spacecraft are also required to be open to NASA with interfaces open to NASA partners who develop modules that integrate with other modules on the cognitive agent in contrast to proprietary black-box agents. Note that a cognitive agent suitable to provide crew support on spacecraft may also be suitable for a variety of Earth applications, but the converse is not true; thus, requiring this NASA investment.

The emphasis of proposed efforts is expected to be on analyzing and demonstrating the feasibility of various configurations, capabilities, and limitations of a cognitive architecture suitable for crew support on deep space missions. The software engineering of a cognitive architecture is to be documented and demonstrated by implementing a prototype goal-directed cognitive agent that interacts with simulated spacecraft systems and humans.

For Phase I, a preliminary cognitive architecture, preliminary feasibility study, a cognitive agent prototype that supports a human operating a simulated complex system that illustrates a candidate cognitive agent architecture, and a detailed plan to develop a comprehensive cognitive architecture feasibility study are expected. For Phase II, it is expected that the proposed detailed feasibility study plan is executed.

In Phase II it is expected that a comprehensive cognitive architecture will be generated, along with a demonstration of an agent prototype that instantiates the architecture. The agent prototype should interact with a spacecraft simulator and humans executing a plausible HEOMD design reference mission beyond cis-lunar (e.g., Human Exploration of Mars Design Reference Mission: https://www.nasa.gov/pdf/373665main_NASA-SP-2009-566.pdf [11]). Phase II deliverables are also expected to include a comprehensive feasibility study report, and a detailed plan to develop a fully instantiated robust cognitive architecture suitable for proposing to NASA and other organizations interested in funding a flight capability. A Phase II prototype suitable for a compelling flight experiment or simulation interfacing with the ISS or a spacecraft-relevant robotic system is encouraged.

H7.01 Development of Higher Strength Feedstocks for In-Space Manufacturing

Lead Center: MSFC

Participating Center(s): LaRC

Technology Area: TA15 Aeronautics

There is a substantial rift between the properties of 3D printed thermoplastics (that can be produced with the current printers on the International Space Station) and the aerospace metals traditionally used in critical space systems. However, processes compatible with metals are more challenging from the perspective of operations in the space environment, often having volumes, powers, and safety hazards that may be incompatible with ISS requirements. As an alternative to adapting traditional AM of metals process to microgravity, this topic seeks development of higher strength feedstocks compatible with the FDM process that would uniquely enable NASA applications, facilitating sparing and/or palliative repair scenarios (the latter is where FDM would provide a stopgap solution until a more permanent fix could be developed). This work also has clear terrestrial benefits, as it stands to stands to significantly enhance the properties achievable with FDM techniques and expand the use of FDM processes for manufacturing beyond low-criticality applications. Proposers must clearly state how their development work under this opportunity advances the state of the art and enables new applications of AM.

This SBIR subtopic is intended to investigate development of materials and/or post-processing techniques that will:

- Narrow the gap between the properties of materials produced using FDM techniques and metals.
- Result in much higher strength plastics with isotropic properties and improved dimensional tolerances.
- Homogenize material by reducing presence of pores.

The solution may be obtained by a variety of approaches, including but not limited to:

- Novel post-processing or heat treatment techniques. Any techniques developed must be adaptable to the microgravity environment of ISS. Post-processing techniques must also preserve the characteristic dimensions of the part.
- Incorporation of nano or microfibers into filament feedstock.
- Benchtop materials development of high strength feedstock materials that are also extrudable with FDM. Feedstock materials which incorporate in-situ materials (such as those found on a planetary surface) and/or materials which represent polymer trash recyclables are of strong interest.
- Materials testing activities must be undertaken to demonstrate and quantify improvements in mechanical properties, densification, and dimensional accuracy possible with a proposed approach. Complementary modeling efforts are not required, but will be value added in establishing predictive relationships between processing conditions and material outcomes.

Phase I SBIR is a feasibility demonstration and should provide:

- Development and implementation of new materials in FDM systems that represent a significant improvement over current material options.
- Materials testing and characterization to quantify material improvement over traditional FDM techniques or FDM manufactured material in the as-built condition.
- Proposed design approach for integrating methods developed into current or future ISM payloads for FDM as well as ground based machines and processes.
- Verification that material approaches or exceeds key mechanical performance targets for polymeric feedstocks sought under this opportunity: tensile strength of at least 200 MPa, specific strength of at least 100 kN-m/kg, Poisson's ratio of 0.20-0.45, and fracture toughness of at least 5 MPa/m$^{1/2.}$ Ability to meet these requirements will be demonstrated as part of the materials development activities in Phase I.

H7.02 In-situ monitoring and development of in-process quality control for in-space manufacturing (ISM) applications

Lead Center: MSFC

Participating Center(s): KSC, LaRC

Technology Area: TA15 Aeronautics

The ability to ensure production of parts with repeatable quality is critical for ISM implementation. There are essentially two approaches to ensure consistency in the parts and the manufacturing process: a traditional qualification and certification (which may be difficult for ISM due to constraints on crew time and equipment size limitations) and online quality control (i.e., process monitoring, where in-situ monitoring of process signals provides information about the quality of the part produced by the process).

Qualification and certification processes for ISM require better machine and feedback control than is currently available with off the shelf printers and other small manufacturing systems. While traditional approaches to qualification and certification are also being pursued, a more immediate solution is that of online/off-line quality control techniques that are adaptable to ISM.

This SBIR seeks approaches to real-time, in-situ quality assurance of parts manufactured in the space environment and specifically focuses on manufacturing platforms similar to those used on ISS. The solicitation seeks methods that can be demonstrated for FDM or nonmetallic additive processes initially but are also broadly applicable to other candidate manufacturing processes for ISM, including AM of metallics and potentially even CNC machining. The latter technologies will likely be incorporated in to the Fabrication Laboratory in some capacity.

Development of in-situ techniques for quality control applicable for ISM may utilize the following approaches or leverage other techniques not listed here:

- Online layer/trace monitoring would allow for rapid identification of defects as they are generated and well before the part is finished. In turn, this would allow for stoppage of the production run (thus conserving feedstock and lowering processing/recycling energy) or for the correction of defects by introducing layer compensation algorithms. Ideally, evaluation should occur with every layer (enabling corrective actions to be taken right away) but can also be done after a batch of layers. This approach may require:
    - A multi-sensor approach and the ensuing data fusion and signal processing to extricate sensor data signatures that point to anomalies in the current print layer. This might include a combination of vision, structured light profilometry, thermography (IR), temperature, etc. Sensors and measurement methods are needed for:
        - Dimension and geometry.
        - Roughness and general surface finish.
        - Defects, porosity and flaws.
        - Feedstock tolerance.
        - Energy source.
        - Microstructure and mesostructured.
        - Strength of the interlayer bonding.
        - Residual stresses.
    - Collection of extensive data that will help develop feedback systems, predictive processing and modeling capabilities. Defect taxonomies (type, frequency and size quantification) and algorithms will be needed to map the functional correlation between the type and size of defects and the potential impact on material composition and microstructure (thus mechanical and functional properties).
    - Validation of modeling with process measurements to enable robust process control (e.g., vision system identifies a defect/pore and process control system corrects and eliminates defect).
    - Use of statistical process control.
    - Measurement of in-situ materials properties.
    - In-situ, monitoring of operating conditions (e.g., temperature management and others) to reduce and control residual stresses and distortion.
    - On-demand/adaptive post-processing based on actual thermal history of part
- Off-line quality control (nondestructive testing), including traditional finished part inspection and verification. Less desirable because it is *post-mortem*. Must be non-destructive testing. Computer Tomography (CT) and X-Ray analyses have become the norm for aerospace components. Others include visual and instrument-based inspection of dimensional accuracy, surface finish and perhaps some mechanical/physical properties. Likely to be intensive on crew time and limited by size of equipment.

Phase I is a feasibility demonstration and should provide:

- Approach for in-situ quality control and verification of parts manufactured in space with clear adaptability to current and future ISM systems.
- Demonstration of approach:
    - Sensors integrated into a ground based AM system (can be FDM initially), but has high extensibility to other processes that operate in a similar volume.
    - Demonstrate that process signals acquired during build are correlated with and predictive of material outcomes (density, mechanical properties, other metrics) through a combination of material testing and statistical analysis.

Phase II would focus on integration of the system in a NASA ground-based ISM platform as a demonstration and development of closed-loop control systems. Phase III would integrate the technique/NDE system into an ISM platform on ISS and verify its efficacy for V&V applications.

H7.03 Plasma Jet Printing Technology for Printable Electronics in Space

Lead Center: MSFC

Participating Center(s): MSFC

This emerging alternative needs further maturation before it can be used in space missions. Common inks and dispersions used in inkjet printing and aerosol systems must be usable in plasma jet printers with proper nebulizers for extended deposition times. Throughput vs. plasma cylinder/nozzle diameter needs to be optimized with possibility of multiple nozzles that can be arranged in a showerhead configuration either to increase throughput or mix various types of feedstock for alloy-type materials.

In Phase I, a print head that can print materials using plasma and tailor oxidation states of materials should be developed. The print head should have an integrated fluid delivery system that can work in microgravity environment and should use low weight power supply. A preliminary prototype printer demonstrating basic features of plasma printing is a preferred deliverable.

In Phase II, the technology should be advanced by showing capability of printing a wide range of materials including organics, inorganics and others. The system also should be advanced by using appropriately sized electrical components, flow controllers etc. for meeting space operation needs and including an enclosure for trapping any airborne materials that would ensure safe use in closed environments such as the International Space Station.

Atmospheric pressure plasma jet systems have cross cutting applications in sterilization and plasma treatment of surfaces as well. Phase II should demonstrate in-situ resource utilization applications of the plasma jet including in-space printable electronics, removal of biological contaminations in science tools, etc. The completed system at the end of the effort should have integrated hardware and software.

H8.01 ISS Utilization and Microgravity Research

Lead Center: JSC

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

Technology Area: TA15 Aeronautics

NASA continues to invest in the near- and mid-term development of highly-desirable systems and technologies that provide innovative ways to leverage existing ISS facilities for new scientific payloads and to provide on orbit analysis to enhance capabilities. Additionally, NASA is supporting commercial science, engineering, and technology to provide low earth orbit commercial opportunities utilizing the ISS. Utilization of the ISS is limited by available up-mass, down-mass, and crew time as well as by the capabilities of the interfaces and hardware already developed and in use. Innovative interfaces between existing hardware and systems, which are common to ground research, could facilitate both increased and faster payload development and subsequent utilization. Technologies that can be matured rapidly for flight demonstration on the International Space Station are of particular interest. Desired capabilities that will continue to enhance improvements to existing ISS research and support hardware, with the potential of reducing crew time needs, and those that promote commercial enterprise ventures include but are not limited to, the below focus areas:

- Projects that improve, enhance and/or augment science investigations being conducted or planned to be conducted on the ISS.
- Projects leading to the development of new research facilities and the enhancement of others in focus areas involving material science for polymerization, soldering, thermal diffusivity of organic liquids, particles suspension in plasma, and safe containment of samples while undergoing microscopy imaging. Facility enhancements that are efficient and enable high experiment throughput are of major importance.
- Technologies and flight projects that can enable significant terrestrial applications from microgravity development and lead to private sector and/or government agency product development within a number of discipline areas, including biotechnology, medical applications, material sciences, electronics, and pharmaceuticals. This includes modifications to existing flight instruments as well as the development of novel flight hardware for deployment on the ISS.

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

H9.01 Long Range Optical Telecommunications

Lead Center: GRC

Participating Center(s): GRC, GSFC

Technology Area: TA15 Aeronautics

The Long Range Optical Communications subtopic seeks innovative technologies in free-space optical communications for increased data volume returns from space missions in multiple domains: >100 gigabit/s cis-lunar (Earth or lunar orbit to ground), >10 gigabit/s Earth-sun L1 and L2, >1 gigabit/s per AU-squared deep space, and >100 megabit/s planetary lander to orbiter.

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

Flight Laser Transceivers:

- Low-mass, high-effective isotropic radiated power (EIRP) laser transceivers: 30 to 100 cm clear aperture diameter telescopes for laser communications. Targeted mass less than 65 kg/square-meter with wavefront errors less than 1/25th of a wavelength at 1550 nm. Cumulative wavefront error and transmission loss not to exceed 3-dB in the far field. Advanced thermal and stray light design so that transceiver can survive direct sun-pointing and operate while pointing 3-degrees from the edge of the sun; wide range of allowable flight temperatures by the optics and structure, at least -20° C to 50° C operational range, wider range is preferred.
- Diffraction limited field-of-view at focal plane of at least 1 milliradian radius, provision for point-ahead implementation from space.
- Beaconless pointing subsystems for operations beyond 3 A.U.: Point 20 to 100 cm lasercomm transmitter aperture to an Earth-based receiver with a 1-sigma accuracy of better than 100 nanoradians with an assumed integrated spacecraft micro-vibration angular disturbance of 150 micro-radians (<0.1 Hz to ~500 Hz) without requiring a dedicated laser beacon transmission from Earth; lowest subsystem mass and power is a primary selection factor.
- Low mass/low power/cold survivable optical transceivers for planetary lander to orbiter links [7]: bi-directional optical terminals with data rates from >100 megabit/second at a nominal link range of 1000 km, with an individual terminal mass <5 kg and operational power < 25W, including a pointing system for at least full hemisphere coverage.
- Terminals shall be capable of operationally surviving >500 cycles of unpowered temperature cycling from -40° C to +40° C and a 100 krad TID. Discussion of acquisition and tracking con-ops and requirements is a must.

Flight Laser Transmitters and Receivers:

- High-gigabit/s laser transmitter and receiver optical-electronic subsystems: space qualifiable 1550 nm laser transmitter and receiver optoelectronic modulator, detection, and forward-error-correction (FEC) assemblies for data rates from 1 gigabit/s to >200 gigabits/s with power efficiencies better than 10W per gigabit/s and mass efficiencies better than 100 g per gigabit/s.
- Radiation tolerance better than 50 Krad is required.
- Technologies for efficient waveform modulation, detection, and synchronization and on-board low-gap-to-capacity forward-error-correction decoding are of interest.
- Also of interest are hybrid RF-optical technologies.
- Integrated photonic circuit solutions are strongly desired.
- High efficiency (>20% DC-to-optical, including support electronics) space qualifiable (including resilience to

photo-darkening) multi-watt Erbium Doped Fiber Amplifier (EDFA) with high gain bandwidth (> 30nm, 0.5 dB flatness) concepts will be considered. Detailed description of approaches to achieve the stated efficiency is a must. High peak-to-average powers for supporting 7-ary to 8-ary pulse position modulation (PPM).

- Space qualifiable wavelength division multiplexing transmitters and amplifiers with 4 to 20 channels and average output power > 20W and peak-to-average power ratios >200 with >10 Gb/s channel modulation capability are also desired.

Narrow Band Pass Optical Filters:

- Flight qualified optical narrow band pass filters with 1 to 2 cm clear aperture and 0.5 1 nm noise equivalent bandwidth with less than 1 dB transmission loss around 1064 nm or optical c-band are also required.

Ground Assets for Optical Communication:

- Large aperture receivers for faint optical communication signals from deep space, subsystem technologies: Demonstrate innovative subsystem technologies for >10 m diameter deep space ground collector capable of operating to within 3 degrees of solar limb with a better than 10 microradian spot size (excluding atmospheric seeing contribution). Desire demonstration of low-cost primary mirror segment fabrication to meet a cost goal of less than $35K per square meter and low-cost techniques for segment alignment and control, including daytime operations.
- 1550 nm sensitive photon counting detector arrays compatible with large aperture ground collectors with integrated time tagging readout electronics for >5 gigaphotons/s incident rate. Time resolution <100 ps 1-sigma and highest possible single photon detection efficiency, at least 50% at highest incident rate, and total detector active area > 0.2 mm^2. Integrated dark rate < 5 megacount/s.
- Cryogenic optical filters for operation at 40K with sub-nanometer noise equivalent bandwidths in the 1550 nm spectral region, transmission losses < 0.5 dB, clear aperture >35 mm, and acceptance angle >40 milliradians with out-of-band rejection of >65 dB from 0.4 to 5 microns.

For all technologies, lowest cost for small volume production (5 to 20 units) is a driver. Research must convincingly prove technical feasibility (proof-of-concept) during Phase I, ideally with hardware deliverables that can be tested to validate performance claims, with a clear path to demonstrating and delivering functional hardware meeting all objectives and specifications in Phase II.

H9.03 Flight Dynamics and Navigation Technology

Lead Center: GRC

Participating Center(s): MSFC

Technology Area: TA15 Aeronautics

Future NASA missions will require precision landing, rendezvous, formation flying, cooperative robotics, proximity operations (e.g., servicing), and coordinated platform operations. This drives the need for increased precision in absolute and relative navigation solutions, and more advanced algorithms for both ground and onboard guidance, navigation, and control. This subtopic seeks advancements in flight dynamics and navigation technology for applications in Earth orbit, lunar, and deep space that enables future NASA missions. In particular, technology relating to navigation, autonomous onboard guidance, navigation and control, and trajectory optimization are solicited.

Autonomous, On-Board Guidance, Navigation and Control**:**

- Advanced autonomous navigation techniques including devices and systems that support significant advances in independence from Earth supervision while minimizing spacecraft burden by requiring low

power and minimal mass and volume.

- Onboard trajectory planning and optimization algorithms, for real-time mission re-sequencing, on-board computation of large divert maneuvers (TA 5.4.2.3, TA 5.4.2.5, TA 5.4.2.6, TA 9.2.6) primitive body/lunar proximity operations and pinpoint landing (TA 5.4.6.1).
- Rendezvous targeting (TA 4.6.2.1) Proximity Operations/Capture/ Docking Guidance (TA 4.6.2.2).

Advanced Techniques for Trajectory Optimization**:**

- Tools and techniques for distributed space missions including constellations and formations (TA 11.2.6).
- Low-thrust trajectory optimization in a multi-body dynamical environment (TA 5.4.2.1).
- Advanced deep-space trajectory design techniques. (TA 5.4.2.7) and rapid trajectory design near small bodies (TA 5.4.5.1).

Additional Scope Clarification

Efforts must demonstrate significant risk or cost reduction, significant performance benefit, or enabling capability. Note that implementation of well understood GN&C algorithms into hardware/software, and high TRL activities, are not in scope.

Proposals that leverage state-of-the-art capabilities already developed by NASA, or that can optionally integrate with those packages, such as the General Mission Analysis Tool (http://sourceforge.net/projects/gmat/ [12]), Goddard Enhanced Onboard Navigation System (GEONS) (https://software.nasa.gov/software/GSC-14687-1 [13]), GPS-Inferred Positioning System and Orbit Analysis Simulation Software, (http://gipsy.jpl.nasa.gov/orms/goa/ [14]), Optimal Trajectories by Implicit Simulation (http://otis.grc.nasa.gov/ [15]) , and Navigator (http://itpo.gsfc.nasa.gov/wp-content/uploads/gsc_14793_1_navigator.pdf [16]), or other available hardware and software tools are 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.

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. 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.

H9.05 Transformational/Over-the-Horizon Communications Technology

Lead Center: GRC

Participating Center(s): GSFC

Technology Area: TA15 Aeronautics

The proposer is expected to identify new ideas, create novel solutions and execute feasibility demonstrations. Emphasis for this subtopic is on the far-term (?10yrs.) insofar as mission insertion and commercialization but it is expected that the proposer proves fundamental feasibility via prototyping within the normal scope of the SBIR program. The over-the-horizon communications technology development will focus research in the following areas:

- Systems optimized for energy efficiency (information bits per unit energy).
- Advanced materials; smart materials; electronics embedded in structures; functional materials; graphene-based electronics/detectors.
- Technologies that address flexible, scalable digital/optical core processing topologies to support both RF and optical communications in a single terminal.
- Nanoelectronics and nanomagnetics; quantum logic gates; single electron computing; superconducting devices; technologies to leapfrog Moore's law.
- Quantum communications, methods for probing quantum phenomenon, methods for exploiting exotic

aspects of quantum theory.
- Human/machine and brain-machine interfacing; the convergence of electronic engineering and bio-engineering; neural signal interfacing.

The research should be conducted to demonstrate theoretical and technical feasibility during the Phase I and Phase II development cycles and be able to demonstrate an evolutionary path to insertion within approximately 10 years. Delivery of a prototype of the most critically enabling element of the technology for NASA testing at the completion of the Phase II contract is expected.

Phase I deliverables shall include a final report describing theoretical analysis and prototyping concepts. The technology should have eventual commercialization potential. For Phase II consideration, the final report should include a detailed path towards Phase II prototype hardware.

H10.01 Advanced Propulsion Systems Ground Test Technology

Lead Center: KSC

Participating Center(s): KSC

Technology Area: TA15 Aeronautics

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

This topic area seeks to develop advanced ground test and launch environment technology components and system level ground test systems that enhance Chemical and Advanced Propulsion technology development and certification. The goal is to advanced propulsion ground test technologies to enhance environment simulation, minimize test program time, cost and risk and meet existing environmental and safety regulations. It is focused on near-term products that augment and enhance proven, state-of-the-art propulsion test facilities. This subtopic is especially interested in ground test and launch environment technologies with potential to substantially reduce the costs and improve safety/reliability of NASA's test and launch operations.

In particular, technology needs include producing large quantities of hot hydrogen, and developing robust materials, advanced instruments and monitoring systems capable of operating in extreme temperature and harsh environments. Harsh environments include high vibration and ablative.

This subtopic seeks innovative technologies in the following areas:

- Efficient generation of high temperature (>2500° R), high flowrate (<60 lb/sec) hydrogen.
- Devices for measurement of pressure, temperature, strain and radiation in a high temperature and/or harsh environment.
- Development of innovative rocket test facility components (e.g., valves, flowmeters, actuators, tanks, etc.) for ultra-high pressure (>8000 psi), high flow rate (>100 lbm/sec) and cryogenic environments.
- Robust and reliable component designs which are oxygen compatible and can operate efficiently in high vibro-acoustic, environments.
- Advanced materials to resist high-temperature (<4400° F), hydrogen embrittlement and harsh environments.
- Tools using computational methods to accurately model and predict system performance are required that integrate simple interfaces with detailed design and/or analysis software. SSC is interested in improving capabilities and methods to accurately predict and model the transient fluid structure interaction between cryogenic fluids and immersed components to predict the dynamic loads, frequency response of facilities.
- Improved capabilities to predict and model the behavior of components (valves, check valves, chokes, etc.) during the facility design process are needed. This capability is required for modeling components in high

pressure (to 12,000 psi), with flow rates up to several thousand lb/sec, in cryogenic environments and must address two-phase flows. Challenges include accurate, efficient, thermodynamic state models; cavitation models for propellant tanks, valve flows, and run lines; reduction in solution time; improved stability; acoustic interactions; fluid-structure interactions in internal flows.

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.

H10.02 Autonomous Control Technologies (ACT) for Ground Operations

Lead Center: KSC

Participating Center(s): ARC, LaRC, SSC

Technology Area: TA15 Aeronautics

Autonomous Control Technologies (ACT) are needed to reduce operations and maintenance costs of ground and payload operations and to increase the availability of systems to support mission operations. These technologies perform functions such as anomaly and fault detection, fault isolation, diagnostics and prognostics and enable variable levels of autonomous control and recovery of system operations, where recovery may include reconfiguration or repair. Autonomous Control Technologies are enabled by intelligent systems health management component technologies, methodologies, and approaches; command and control architectures; computing architectures; software for decision-making and control; and intelligent devices.

ACT will be applied to operations such as autonomous propellant management, which includes the transfer, storage, measuring, and sampling of cryogenic, or other propellant for use in launch systems without requiring human interaction. Propellant management includes pre-planned nominal capabilities such as vehicle fill and drain as well as contingency and off-nominal capabilities such as emergency safing, venting and system reconfiguration. ACT capabilities will enable the autonomous monitoring and control of the integrated system resulting from the loading system and all other associated systems involved in the loading process. The system autonomy software itself includes both prerequisite control logic (PCL) and reaction control logic (RCL) programming, and may utilize some form of machine learning, neural network, or other form of artificial intelligence to adapt to degraded system components or other form of off-nominal conditions. In addition to cryogenic and other propellants, propellant management systems may utilize additional commodities to prepare a vehicle for launch, such as high-pressure gases for purges, pressurization, or conditioning, and may include power and data interfaces with the vehicle to configure vehicle valves or other internal systems and utilize on-board instrumentation to gain visibility into the vehicle during loading.

ACT must also support tasks such as setup, testing and checkout, troubleshooting, maintenance, upgrades and repair. These additional tasks drive the need for autonomous element to element interface connection and separation, multi-element inspection, and recovery of high value cryogenic propellants and gases to avoid system losses.

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

Phase I Deliverables - Research, identify and evaluate candidate technologies or concepts for systems and components fault detection, isolation and recovery, fault prediction and diagnosis, and decision-making algorithms for control to enable autonomy of ground systems. Demonstrate the technical feasibility, and show a path towards a demonstration. Concept methodology should include the path for adaptation of the technology, infusion strategies (including risk trades), and business model. It should identify improvements over the current state of the art for both operations and systems development and the feasibility of the approach in a multi-customer environment. Bench or lab-level demonstrations are desirable. Deliverables must include a report documenting findings.

Phase II Deliverables - Emphasis should be placed on developing, prototyping and demonstrating the technology under simulated operational conditions using analog earth-based systems including dynamic events such as

commodity loading, disconnect or engine testing. Deliverables shall include a report outlining the path showing how the technology could be matured and applied to mission-worthy systems, functional and performance test results and other associated documentation. Deliverable of a functional prototype (software and hardware) is expected at the completion of the Phase II contract. The technology concept at the end of Phase II should be at a TRL of 6 or higher.

H12.01 Radioprotectors and Mitigators of Space Radiation-induced Health Risks

Lead Center: LaRC

Participating Center(s): JSC

Technology Area: TA15 Aeronautics

Space radiation is a significant obstacle to sending humans on long duration missions beyond low earth orbit. NASA is concerned with the health risks to astronauts following exposures to galactic cosmic rays (GCR), the high-energy particles found outside Earth's atmosphere. Astronaut health risks from GCR are categorized into cancer, late and early central nervous systems (CNS) effects, and degenerative risks, which includes cardiovascular diseases (CVD) (see references below for more detail).

This subtopic is for biological countermeasures to minimize or prevent adverse health effects from space radiation: chronic, low dose, low dose-rate, mixed field (high LET and low LET) and mission relevant doses (0.25 to 0.5 Gy). Radioprotectors or mitigators are needed that can target common pathways (e.g., inflammation) across cancer, cardiovascular disease, and neurodegeneration. The focus of this subtopic will be to address CVD and late CNS effects through a medical countermeasure that can provide cross-risk mitigation (addressing both CVD and CNS late effects).

This subtopic will consider:

- FDA approved drugs.
- FDA Off-label usage drugs.
- FDA IND Status drugs.

Biological countermeasures under development for acute radiation syndrome or prevention of secondary radiation-induced diseases from radiation therapy may be ideal for this topic and allow the company to expand its product line to space radiation, carbon ion therapy and ground based late effects from nuclear fallout. Additionally, countermeasures must be acceptable for use as a radioprotectant in an otherwise healthy population with consideration given to safety, risks, and benefits of possible long-term usage over the course of a mission and/or post mission timeframe. Benefits should clearly outweigh risks.

The biological countermeasure criteria:

- Medical products and regimens that prevent and/or mitigate adverse health effects due to space radiation with emphasis on broad activity (i.e., multi-tissue).
- Mechanism of action well known.
- Independent of sex.
- Capable of being delivered chronically for the period of the mission (potentially up to 3 years).
- Easily administered; capable of self-administration (e.g., Oral, inhaled).
- Known/potential benefits greater than known potential risks; minimal adverse events.
- No contraindications with other drugs used for treating other symptoms or diseases during the mission.
- Long shelf-life.

Phase I will test radioprotectors or mitigators using mixed radiation fields that must include a low LET source such as gamma combined with high LET radiation such as neutrons or alpha particles to determine efficacy in mixed fields at space relevant doses. This testing can be done at the location of choice. Companies should provide a test plan that will demonstrate the compound being proposed provides protection or mitigation of radiation-induced

injury for normal tissues and does not protect cancer cells. A kickoff meeting with NASA is mandatory prior to the start of this award.

Phase II will test effective radioprotectors or mitigators in space radiation simulated environments (HZE) to determine if they are able to minimize or prevent late effects directly related to the development of neurodegeneration or cardiovascular disease. Companies should provide a test plan for in vivo evaluation that describes the expected effect from the compound. Access and funding to support testing in space radiation simulated facilities will be provided for Phase II in addition to the standard award.

The following references discuss the different health effects NASA has identified as areas of concern as a result of space radiation:

- Evidence report on central nervous systems effects - https://humanresearchroadmap.nasa.gov/evidence/reports/CNS.pdf [17].
- Evidence report on degenerative tissue effects - https://humanresearchroadmap.nasa.gov/evidence/reports/Degen.pdf [18].
- Evidence report on carcinogenesis - https://humanresearchroadmap.nasa.gov/evidence/reports/Cancer.pdf [19].

H12.03 Crew Worn Accelerometers in spaceflight environment

Lead Center: LaRC

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

Technology Area: TA15 Aeronautics

NASA needs an all-in-one data collection system to record crewmember dynamics and kinematics during dynamic phases of flight including launch, pad or ascent abort, atmospheric reentry, descent, and landing. These phases of Soyuz and Commercial vehicle flights are of particular interest due to the sustained vibration (launch), sustained accelerations (launch and reentry), transient accelerations (aborts, descent and landing), and rotational velocities (abort, descent and landing). The sensors must:

- Be self-powered with non-volatile memory (onboard data storage).
- Be able to collect at least 30 minutes of data in a 5-hour time span of launch (including time on the pad).
- Be able to sustain the stresses of launch and then be powered off for 6 months to 1 year (with the possibility of charging and off-loading launch data while in-flight).
- Be capable of collecting ?1 hour of data in at least an 8-hour period during entry, descent, and landing (including loiter time).
- Have a customizable trigger based on timing or acceleration sensing.
- Be capable of accurately measuring and storing linear accelerations and angular velocities with sufficient temporal resolution to capture the relevant dynamics in each event (linear X, Y, Z axis; ±200g range, 0-3000Hz bandwidth, 10,000 Hz sampling rate; angular X & Z - ±2,000 rad/sec range, 0-300 Hz bandwidth, 5,000 Hz sampling rate, Y - ±5,000 rad/sec range, 0-300 Hz bandwidth, 5,000 Hz sampling rate).
- Be crew-worn without interfering with other crew-worn equipment.
- Meet SAE J211-1 and SAE J2570 specifications.

The data collected will be used to quantify crew loading during each phase of flight and improve NASA's ability to predict dynamic environments through the use of numerical simulation and models. Such sensors could be used to quantify crewmember head and neck dynamics, chest kinematics, and helmet kinematics in relation to the head and neck. These data have not been previously collected during spaceflight and are important to understanding how humans respond to the unique dynamics present in the spaceflight environment.

H12.04 Wash System to Disinfect Fresh Fruit & Vegetables Grown in Spaceflight

Lead Center: JSC

Participating Center(s): KSC

Technology Area: TA15 Aeronautics

Fresh fruits and vegetables grown in spaceflight may provide critical nutritional and behavioral benefits, but introduce unacceptable microbiological risk that could lead to foodborne illness. It is critical that a produce disinfection method be identified to prevent foodborne illness. A water wash method would impact vehicle design, and requirements must be determined in time to inform transit vehicle designs. The Pro-San wipes currently used to disinfect space-grown produce require continual up-mass and create trash. Other novel methods that have been investigated, including hydrogen peroxide and cold plasma chambers, generated a noticeable quality reduction during disinfection. Crewmembers will be harvesting and processing produce themselves, and it is imperative that quality is not reduced during disinfection. Some examples of items of interest:

- Development of a water wash system that can directly integrate in a closed loop with the spacecraft water system.
- Use of food grade sanitizers. No soaps or detergents. Residuals should not exceed approved food amounts.
- Systems that disinfect and dry a range of fruit and vegetable amounts (0.25 - 2 kg) and types (leafy greens, tomatoes, radishes, green peppers) in both microgravity and reduced gravity environments.
- Proposals that use the least amount of crew time (both active and passive) will be given greater consideration.
- Proposals that use the least amount of water for both disinfecting and rinsing will be given greater consideration. Note, crew currently receive less than 3 L of water a day each for consumption.
- Demonstrate greater than a 3 log reduction in Aerobic Plate Count, Yeast and Mold, and both *Bacillus cereus* ATCC 14579, a common contaminant on fresh produce, and in *Escherichia coli* ATCC 11775, a non-pathogen used as a surrogate for other gram negative organisms that have been associated with foodborne illness.
- Demonstrate that produce quality is not noticeably reduced from the beginning of the process to the end.
- Systems that are lowest in mass, power, volume, crew time, etc. will be given greater consideration.
- Reliability; capable of operation for up to 2-5 years and withstand launch loads and gravity changes.

Proposals for novel approaches or systems other than a water solution wash system that meet the success criteria may be considered. Note, systems that require pressurized gases or that generate toxic byproducts will not be considered at this time.

Phase I Deliverables - Prototype system design and evaluation. Final report detailing resource use (crew time, water, mass, volume), sanitizer compatibility, microbial reduction achieved and initial quality results.

Phase II Deliverables - Completed first generation unit that integrates with the ECLSS water system and detailed data regarding resource use, microbial testing, and quality evaluations.