NASA SBIR 2020 Phase I Solicitation

Human Exploration and Operations

H3.01 Advancements in Carbon Dioxide Reduction: Critical Subsystems and Solid Carbon Repurposing

Lead Center: GRC

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

Technology Area: TA15 Aeronautics

Scope Title

Carbon Dioxide Reduction System Components and Unit Processes

Scope Description

NASA has invested in many carbon dioxide reduction technologies over the years to increase the percentage of oxygen recovery from carbon dioxide in human spacecraft for long duration missions. Examples of technologies include, but are not limited to, Series-Bosch, Continuous Bosch, Methane Pyrolysis and Microfluidic Carbon Dioxide Electrolysis. Significant technical challenges still face these process technologies and are impeding progress in technology maturation. Critical technical elements of these technologies have a high degree of technical difficulty. Examples where additional technology development is needed include (this is a partial list):

- High temperature gas purification and/or separation for CO, H₂, and hydrocarbon rich streams.
- Nuisance particulate carbon contamination.
- Solid carbon clogging of frits and filters in recycle gas streams.
- Safe collection, removal and disposal of solid carbon while reactors are in operation.
- Subsystems to recharge reactors with new catalyst and to efficiently use or recycle consumable catalysts.

This subtopic is open to consider novel ideas that address any of the numerous technical challenges that face development of carbon dioxide reduction hardware with particular attention to those listed above. Specifics on two of these challenges are provided below.

Gas Purification and/or Separation for Carbon Monoxide, Hydrogen and Hydrocarbon Rich Streams

Many process technologies currently under development have challenging multi-component streams which could benefit from improved gas separation technology. High purity, high yield and continuous supply of separated gases are all desirable features of a proposed technology. The targeted process streams that may benefit from improved gas separations are the following:

- Producing a high-purity hydrogen product from a hydrogen-rich gas stream containing acetylene (as high as 6.4 mole%), trace amounts of other hydrocarbons (ethylene, ethane, benzene), unreacted methane, carbon monoxide, carbon dioxide and water vapor. It is imperative that the proposed separation technologies do not hydrogenate hydrocarbons, such as acetylene. This separation is directed at methane pyrolysis technologies including the Plasma Pyrolysis Assembly (PPA).
• Hydrogen separation from an ethylene-rich stream. This separation is directed at the effluent stream from a Microfluidic Electrochemical Reactor which consists of ethylene, hydrogen, methane, carbon monoxide, carbon dioxide and water vapor.
• Recovery of unreacted carbon dioxide and hydrogen from a carbon monoxide-rich stream. This separation is needed for a Bosch/Reverse Water Gas Shift (RWGS) Reactor.

Technology solutions could include, but not be limited to, filtration, mechanical separation or novel sorbents. If novel sorbents are developed the proposed technology solution should also address issues with scale-up to kg quantities (difficult for some novel sorbents). Technology solutions proposed in this subtopic could potentially be leveraged for In-Situ Resource Utilization (ISRU) applications.

Separation of Particulate Carbon and Hydrocarbons from Process Gas Streams

Oxygen recovery technology options, including carbon formation reactors and methane pyrolysis reactors almost universally result in particulates in the form of solid carbon or solid hydrocarbons. Mitigation for these particulates will be essential to the success and maintainability of these systems during long duration missions. Techniques and methods leading to compact, regenerable devices for removing, managing and disposing of residual particulate matter within ECLSS process equipment are sought. Separation performance approaching HEPA rating is desired for ultrafine particulate matter with minimal pressure drop. The separator should be capable of operating for hours at high particle loading rates and then employ techniques and methods to restore its capacity back to nearly 100% of its original clean state through in-place and autonomous regeneration or self-cleaning operations using minimal or no consumables (including media-free hydrodynamic separators). The device must minimize crew exposure to accumulated particulate matter and enable easy particulate matter disposal or chemical repurposing.

State of the Art and Critical Gaps

Future long duration human exploration missions may benefit from further closure of the Atmosphere Revitalization System (ARS). The state-of-the-art Sabatier system, which has flown on the International Space Station as the Carbon Dioxide Reduction Assembly (CRA), only recovers about half of the oxygen from metabolic carbon dioxide. This is because there is insufficient hydrogen to react all available carbon dioxide. The Sabatier reacts hydrogen with carbon dioxide to produce methane and water. The methane is vented overboard as a waste product causing a net loss of hydrogen. Mars missions target >75% oxygen recovery from carbon dioxide, with a goal to approach 100% recovery. NASA is developing several alternate technologies that have the potential to increase the percentage of oxygen recovery from carbon dioxide, toward fully closing the ARS loop. Methane pyrolysis recovers hydrogen from methane, making additional hydrogen available to react with carbon dioxide. Other technologies under investigation process carbon dioxide, recovering a higher percentage of oxygen than the Sabatier. All of these alternative systems, however, need additional technology investment to reach a level of maturity necessary for consideration for use in a flight environmental control and life support system (ECLSS).

Scope Title

Solid Carbon Repurposing

Scope Description

Solid carbon is produced as a major by-product from many candidate oxygen recovery technologies under consideration for long-duration missions, including Bosch, Series Bosch, Methane Pyrolysis by Carbon Vapor Deposition, and technologies containing carbon formation reactors. Based on metabolic CO₂ production for a crew of 4, 1.135 kg of solid carbon, with a volume as high as 2.8 liters, may be produced each day by oxygen recovery technologies, which then must be disposed of or repurposed. Repurposing of this carbon reduces logistical challenges associated with its disposal and may ultimately result in materials or processes advantageous for long-duration missions. The produced solid carbon may include nanofibers, microfibers and amorphous material with varying particle size, with the smallest in the micrometer range (10-50 µm). It may contain quantities of metals including, but not limited to, iron, nickel and cobalt. The solid carbon may be in the form of a loose powder or a densified cake with densities ranging from 0.4 to 1.8 g/cc and will vary by technology. Venting or disposal of this carbon to space will present considerable logistical challenges and will result in large volumes of space debris. Disposal of this carbon on a planetary surface may result in concerns for planetary protection or planetary science.
NASA is seeking technologies and/or processes that repurpose solid carbon and its contaminants resulting in useful products for transit, deep space or planetary surface missions. The technology and/or process must limit crew exposure to the raw carbon.

References for All Scopes

"Hydrogen Recovery by Methane Pyrolysis to Elemental Carbon" (49th International Conference on Environmental Systems, ICES-2019-103)

"Evolving Maturation of the Series-Bosch System" (47th International Conference on Environmental Systems, ICES-2017-219)


"Methane Post-Processing and Hydrogen Separation for Spacecraft Oxygen Loop Closure" (47th International Conference on Environmental Systems, ICES-2017-182)


NASA-STD-3001, VOLUME 2, REVISION A, Section 6.4.4.1 “For missions longer than 14 days, the system shall limit the concentration in the cabin atmosphere of particulate matter ranging from 0.5 ?m to 10 ?m (respirable fraction) in aerodynamic diameter to <1 mg/m3 and 10 ?m to 100 ?m to <3 mg/m3.”


Expected TRL or TRL range at completion of the project for Phase I: 3

Expected TRL or TRL range at completion of the project for Phase II for All Scopes: 4 to 5

Desired Deliverables of Phase II for All Scopes

Prototype, Analysis, Hardware, Research

Desired Deliverables Description for All Scopes

Phase I Deliverables - Reports demonstrating proof of concept, test data from proof of concept studies, concepts and designs for Phase II. Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II. Conceptual solution in Phase I should look ahead to satisfying the requirement of limiting crew exposure to the raw carbon dust.

Phase II Deliverables - Delivery of technologically mature hardware, including components and subsystems that demonstrate performance over the range of expected spacecraft conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, test data and analysis. Prototypes must be full scale unless physical verificiation in 1-g is not possible. Robustness must be demonstrated with long term operation and with periods of intermittent dormancy. System should incorporate safety margins and design features to provide safe operation upon delivery to a NASA facility.

State of the Art and Critical Gaps

No existing operational technology exists in this focused technical area. A crew of 6 during a 540 day Mars surface mission could potentially generate 920 kg of solid carbon - this will be a significant storage or disposal issue and may be a considerable raw product resource for potential utilization. Very limited research and development have been performed in this area. Some studies added carbon to plastic trash which subsequently was processed by a heat melt compactor to make "tiles", which encapsulated the carbon. Although these tiles are a safe way to get rid of trash waste, they were also studied for potential benefit for use as spacecraft radiation shielding. Other work included adding binders to make rudimentary bricks for structural use.
Relevance / Science Traceability

These technologies would be essential and enabling to long duration human exploration missions, in cases where closure of the atmosphere revitalization loop will trade over alternate ECLSS architectures. The atmosphere revitalization loop on the ISS is only about 50% closed when the Sabatier is operational. These technologies may be applicable to Gateway, Lunar surface, and Mars, including surface and transit. This technology could be proven on the ISS.

This subtopic is directed at needs identified by the Life Support Systems Capability Leadership Team (CLT) in areas of water recovery and environmental monitoring, functional areas of Environmental Control and Life Support Systems (ECLSS).

The Life Support Systems (LSS) Project, under the Advanced Exploration Systems (AES) Program, within the Human Exploration and Operations Mission Directorate (HEOMD), is the expected customer. The LSS Project would be in position to sponsor Phase III and technology infusion.

H3.02 Microbial Monitoring for Spacecraft Cabins

Lead Center: GRC

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

Technology Area: TA15 Aeronautics

Scope Title

Spacecraft Microbial Monitoring for Long Duration Human Missions

Scope Description

With the advent of molecular methods, emphasis is now being placed on nucleic acids to rapidly detect microorganisms. However, the sensitivity of current gene-based microbial detection systems is low (~100 gene copies per reaction), requires elaborate sample processing steps, involves destructive analyses, and requires fluids to be transferred and detection systems are relatively large size. Recent advancements in the metabolomics field have potential to substitute (or augment) current gene-based microbial detection technologies that are multi-stepped, destructive and labor intensive (e.g. significant crew time). NASA is soliciting non-gene based microbial detection technologies and systems that target microbial metabolites and that quantify the microbial burden of surfaces, air and water inside future long-duration deep space habitats.

Potable Water:
A simple integrated, microbial sensor system that enables sample collection, processing and detection of microbes or microbial activity in the crew potable water supply is sought. A system that is fully-automated and can be in-line in an Environmental Control and Life Support Systems (ECLSS)-like water system is preferred.

Habitat Surfaces:
Future crewed habitats in cis-lunar space will be crew-tended and thus unoccupied for many months at a time. When crew reoccupies the habitat they will want to quickly, efficiently, and accurately assess the microbial status of the habitat surfaces. A microbial assessment / monitoring system or hand-held device that requires little to no consumables is sought.

Airborne Contamination:
Future human spacecraft, such as Gateway and Mars vehicles, may be required to be dormant while crew is absent from the vehicle, for periods that could last from 1 to 3 years. Before crews can return, these environments must be verified prior to crew return. These novel methods have the potential to enable remote autonomous microbial monitoring that does not require manual sample collection, preparation or processing.
References

A list of targeted contaminants for environmental monitoring can be found at "Spacecraft Water Exposure Guidelines for Selected Waterborne Contaminants" located at: https://www.nasa.gov/feature/exposure-guidelines-smacs-swegs [2]

Advanced Exploration Systems Program, Life Support Systems Project: https://www.nasa.gov/content/life-support-systems [3]


Expected TRL or TRL range at completion of the project for Phase I: 3

Expected TRL or TRL range at completion of the project for Phase II: 4 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Research

Desired Deliverables Description

Phase I Deliverables - Reports demonstrating proof of concept, test data from proof of concept studies, concepts and designs for Phase II. Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II.

Phase II Deliverables - Delivery of technologically mature hardware, including components and subsystems that demonstrate performance over the range of expected spacecraft conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, test data and analysis. Prototypes must be full scale unless physical verification in 1-g is not possible. Robustness must be demonstrated with long term operation and with periods of intermittent dormancy. System should incorporate safety margins and design features to provide safe operation upon delivery to a NASA facility.

State of the Art and Critical Gaps

The State of the Art (SOA) on ISS for microbial monitoring is culturing and counting, as well as grab samples which are returned to earth. NASA has invested DNA-based (PCR) systems, partially robotic in some cases, to eliminate the need for on-orbit culturing. However, a fully automated system is still not ready and there is still a gap for a low- or no-crew time detection system.

Relevance / Science Traceability

The technologies requested could be proven on the ISS and would be useful to long duration human exploration missions away from earth, where sample return was not possible. The technologies are applicable to Gateway, Lunar surface, and Mars, including surface and transit. This subtopic is directed at needs identified by the Life Support Systems Capability Leadership Team (CLT) in areas of water recovery and environmental monitoring, functional areas of Environmental Control and Life Support Systems (ECLSS). The Life Support Systems (LSS) Project, under the Advanced Exploration Systems Program, Human Exploration and Operations Mission Directorate (HEOMD), is the expected customer. The LSS Project would be in position to sponsor Phase III and technology infusion. The ISS Program will have interest in successful awards for potential flight demonstrations.
H3.03 Lunar Dust Management Technology for Spacecraft Atmospheres and Spacesuits

Lead Center: JPL

Participating Center(s): JSC, MSFC

Technology Area: TA15 Aeronautics

Scope Description

Upon their return to Earth one of the Apollo astronauts commented that “dust is probably one of our greatest inhibitors to a nominal operation on the Moon.” Advances in spacecraft atmospheric quality management are sought to address the intrusion and containment of lunar dust in pressurized volumes and compartments in spacecraft systems. This will require the development of particle filtration and separation techniques, barrier techniques and monitoring instruments. For space suits, the challenge is to prevent dust intrusion, while at the same time providing the capability to mate and de-mate connectors and suit components as well as enabling venting to the environment for certain components. This will require the development of specialized dust covers for a variety of connections.

Specifics Regarding Areas of Interest in Spacecraft Atmospheric Quality Management are the Following:

Particle Filtration and Separation Techniques

Techniques and methods are sought leading to compact, low power, autonomous, regenerable bulk particulate matter separation and collection techniques suitable for general spacecraft cabin air purification and removal of planetary lunar dust in main cabin quarters and airlock compartments. The particulate matter removal techniques and methods must accommodate high volumetric flow rates up to 11.3 m$^3$/minute and minimized pressure drop (typically <125 Pa). The filter and separation system needs to meet both the requirements for internally generated particulate matter, such as derived from materials, ECLSS and other processes, and biological matter and debris generated by the crew, and lunar dust intrusion. Permissible levels of suspended particulate matter total dust must be maintained to <3 mg/m$^3$, and the respirable fraction of the total dust to <2.5 ?m in aerodynamic diameter to <1 mg/m$^3$, as per the standards in the NASA-STD-3001 Vol 2, Rev. B. More specifically lunar dust needs to be maintained to a time-weighted average of 0.3 mg/m$^3$ for particles < 10 ?m during intermittent daily exposure periods that may persist up to 30 days in duration for the Gateway or Habitat, and an average of 1.6 mg/m$^3$ for particles < 10 ?m for a 7 day exposure period on the lander. Filtration performance should be at minimum 99.97 % collection efficiency for particles 0.3 micron in diameter and larger (or HEPA efficiency standard). The filter and separation system needs to also provide microbial and fungal control as outlined in the NASA-STD-3001 Vol 2, Rev. B requirements.

Barrier Techniques

Specialized particulate matter management systems specifically designed to collect and remove lunar dust from airlocks or suit preparation compartments or areas that provide a > 99.5% effective barrier to lunar dust transfer between different volumes or compartments are also of interest. The barrier technique can include filtration, separation and mitigation techniques used within these smaller pressurized compartments and/or techniques that prevent the transport or transfer of lunar dust between compartments or to main cabin areas.

Monitoring Instruments

Instruments, or instrument technology, that measure particulate matter concentrations and particle sizes to verify compliance with particulate matter cleanliness levels (stated above) are desired. In addition, the instrument will need to monitor lunar dust intrusion in airlocks and into main cabin areas. Real-time measurement instruments must be compact and low power, requiring minimal maintenance and be able to maintain calibration for years. The instrument also needs to be compatible with the microgravity, reduced gravity and reduced pressure environments (26.2 kPa < pressure ? 103 kPa) in the cabin and airlocks of the transit and lander vehicles. The different environmental parameters may necessitate different modes of operation within one instrument (preferred to
minimize payload and operational resources) or it may require different sensor types. Particle sensors that are capable of distinguishing between different material types (lunar vs generic dust) when measuring particulate matter concentration and particle sizes will be highly desirable.

**Specifics Regarding Areas of Interest in Spacesuit Components are the Following:**

**Garment Protection:**

A lunar space suit requires a dedicated Environmental Protection Garment (EPG) to protect the pressure garment and crewmember from the extreme lunar surface conditions. The extreme conditions include but are not limited to:

1. Extreme cold scenarios
2. Extreme hot scenarios
3. Highly abrasive lunar regolith

Not only does the EPG have to protect against the conditions above, but it must also not inhibit the space suit mobility. It would be beneficial if space suit solutions provide protection for the crew member in the highly abrasive lunar regolith environment along with accommodating the extreme cold and hot conditions.

**Venting Portable Life Support System (PLSS) Covers:**

There are several spacesuit components that require access to the environment for gas flow, both in nominal and off-nominal operations. These components require specialized covers that prevent dust intrusion while at the same time allowing for sufficient gas flow. These components are:

1. **PLSS Shell Vent Ports**

   The PLSS shell has two ports to allow the evaporated water from the spacesuit water membrane evaporator (SWME) and its backup the Mini Membrane Evaporator (Mini-ME) to escape. The operation of these components is dependent on a low back pressure and each of the vent ports must have a flow through area of at least 7 in² to maintain the appropriate pressure for evaporation within the PLSS shell. The vents need to accommodate a water vapor mass flow of at least 2.6 lb/hr. The total area available for the vent ports is approximately 10 by 2.5 inches on either side.

1. **PLSS Rapid Cycle Amine (RCA) System Vent Quick Disconnect**

   The RCA system for water vapor and CO₂ removal requires vacuum access for the desorption of these constituents. This is accomplished via a Quick Disconnect (QD) on the PLSS backplate. For efficient desorption, the pressure in the vacuum access line needs to decrease quickly and allow the flow of 0.65 L of ullage gas to the environment. The ullage gas can be assumed to be 100 % O₂ at 2.15 psi. Without a specialized cover, this gas dissipates within about 2 seconds. After the ullage gas has dissipated, the desorbed gas consists of CO₂ and H₂O with a mass flow of 325 to 360 g/min depending on the bed loading and metabolic rate of the crew member. Between 210 to 230 g/min of that flow is CO₂. The rapid decompression of the vacuum line is essential for efficient operation of the RCA, as is the following diffusion of desorbed gas away from the absorber beds, both of which must not be impeded by the specialized dust cover.

1. **Suit Purge Valve (SPV) and Low Flow Purge Valve (LFPV)**

   The SPV is located on top of the Display and Control Unit and is used during nitrogen purge operations in the airlock. The LFPV is used during off-nominal operations to ensure sufficient CO₂ washout in the helmet and to provide some gas flow through the pressure garment. While similar in design, both valves require different flow rates. The SPV requires 3.15-3.38 lb/hr and the LFPV requires 1.55-1.69 lb/hr of O₂ flow rate at 3.5 psi. Both valves are exposed on the outside of the spacesuit to enable crew member access and thus need specialized covers in order to tolerate large amounts of dust exposure.
1. Positive and Negative Pressure Relief Valves (PPRV and NPRV)

The PPRV and NPRV are located on the hard upper torso (HUT) and exposed to vacuum and dust. The full open flow rate requirement for the PPRV is 7.49 lb/hr of dry O\textsubscript{2} at 70°F with suit internal pressure of 10.1 psia and vacuum as the external reference. The requirement for the NPRV is 60.4 lb/hr of dry air at 70°F, with the airlock pressure at 4.15 psia and a suit pressure at 3.65 psia. Specialized covers are needed in order to tolerate dust exposure.

Non-Venting Portable Life Support (PLSS) Covers:

Two other connectors are on the exterior of the suit that do not need vacuum access and are nominally covered during an Extravehicular Activity (EVA). However, they need to be accessed at the conclusion of an EVA at which point they may be covered in dust. Specialized covers for these connectors are needed to both protect the connectors from dust intrusion during the EVA as well as during the removal of the covers. The connectors are as follows:

1. An 85-pin receptacle that serves as the battery charge connector and is located on the bottom corner of the PLSS.
2. The Spacesuit Common Connector (SCC) contains high pressure oxygen lines, water lines, an electrical connector as well as mechanical mounting features. The SCC is located on the front of the spacesuit and is integrated with the Display and Control Unit (DCU). The connector is flat and has a surface area of approximately 2.5 by 4 inches.

References

NASA-STD-3001 Vol 2, Rev. B.


Apollo 17 Technical Crew Debrief, Page 20-12, NASA Manned Spacecraft Center, January 4, 1973, MSC-07631

Expected TRL or TRL range at completion of the project: 3 to 4

Desired Deliverables of Phase II

Prototype, Analysis, Hardware

Desired Deliverables Description

Phase I Deliverables - Reports demonstrating proof of concept, test data from proof of concept studies, concepts and designs for Phase II. Phase I tasks should answer critical questions focused on reducing development risk prior to entering Phase II.

Phase II Deliverables - Delivery of technologically mature hardware, including components, subsystems or treatments that demonstrate performance over the range of expected suit and spacecraft conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, test data and analysis. Robustness must be demonstrated with long term operation and with periods of intermittent dormancy. System should incorporate safety margins and design features to provide safe operation upon delivery to a NASA facility.

State of the Art and Critical Gaps

The state of the art in spacecraft filtration are HEPA filters used on the ISS, known as Bacterial Filter Elements (BFE).
There are currently no viable airborne particle sensors for pressurized volumes on the ISS or slated for future missions. Commercial sensors are only compatible with standard conditions (1 atmosphere) and terrestrial gravity levels. Also there are no commercial particle sensors that can discriminate between material types or particle shapes that may be used to distinguish between lunar dust and generic cabin dust.

**Relevance / Science Traceability**

Lunar and Martian human surface missions (Artemis/lander/spacraft) will be required to address and provide methods of controlling the intrusion of lunar dust into pressurized volumes.

The Life Support Systems (LSS) Project, under the Advanced Exploration Systems Program, Human Exploration and Operations Mission Directorate (HEOMD), is the expected customer for spacecraft cabin dust management technologies. The LSS Project would be in position to sponsor Phase III and technology infusion.

For Exploration EVA System Development, the xEMU Project is the expected customer.

**H4.01 Exploration Portable Life Support System Component Challenges**

**Lead Center: GRC**

**Technology Area: TA15 Aeronautics**

As the design for the new Exploration Extra-vehicular Mobility Unit (xEMU) is developed, there are obvious gaps in technologies, which need to be fulfilled to meet the new exploration requirements. Various Exploration Portable Life Support System (xPLSS) Hatch components are at a stall in technology development and require new innovative ideas. These xPLSS Hatch Components (through three scopes) are the focus areas for this solicitation in an attempt to integrate new technologies into the xPLSS. NASA has plans to go to the moon and as the mission extends further out of Lower Earth Orbit, durability and extensibility will become some of the most important requirements.

This subtopic is relevant to the Exploration Extravehicular Mobility Unit (xEMU), ISS, as well as commercial space companies. As a new Space Suit Exploration Portable Life Support System (xPLSS) is being designed, built, integrated and tested at JSC and integrated into the xEMU, solutions will have a direct infusion path as the xPLSS is matured to meet the design and performance goals.

**Scope Title**

Feedwater Supply Assembly

**Scope Description**

Sterile compliant bladder, capable of storing ultrapure feedwater with a relatively high cycle life: In order for the thermal control loop to operate properly, a water source is needed. An effective, efficient, sterile and durable feedwater bladder is essential. The suit pressure acts on this bladder and as water evaporates, the bladder resupplies the loop. The bladder must be clean and not leak particulates or polymer chains over long periods of quiescence. The water in the control loop contains a biocide and the bladder must not react with these chemicals to form potential contaminants. The maximum design pressure (MDP) for the system at a lunar environment will be 16 psid with a cycle life of $4 \times 156 = 624$ MDP. Having a bladder with these qualities not only buys down the safety risk of rupture, it promotes reliability at higher pressures and provides an avenue to extend Extravehicular Activity (EVA) length.

**References**

Feedwater Supply Assembly Requirements

Note to vendor: The following two drawings referenced in the above specification shall be provided if vendor is
selected for award.

1. Feedwater Supply Assembly (FSA 431) Drawing SLN 13102397

2. Auxiliary Feedwater Supply Assembly (FSA 531) Drawing SLN 13102398

Scope Title
Bypass Relief Valve

Scope Description
Material dependent Relief Valve (RV) capable of re-calibration: The bypass relief valve cracks and flows from the pump outlet to the pump inlet, short-circuiting the pump when there is a blockage in the line. It is a safety feature designed to limit the head pressure that could be generated by the positive displacement pump, which is used in the primary and auxiliary thermal control loops. Materials, design pressures and re-calibration capabilities are a priority for this design. The desired housing material is titanium, which is a difficult metal to work with, but is a requirement as a preventative measure to avoid galvanic coupling between interfacing metals. To ensure the thermal loop pressure stays within a safe range, the crack and reseat pressures must be between 14-15 psid with a full flow of 220 lb/hr at <18 psid. The design should also include a method of setting or re-calibrating the cracking pressure in case there is drift over time. Replacement of the entire unit is not preferred due to accessibility and operational concerns.

References
Thermal Loop Bypass Relief Valve Requirements

Note to vendor: The following drawing referenced in the above specification shall be provided if vendor is selected for award.

- Bypass Relief Valve Assembly (RV-424/RV-524) SLN13102925

Scope Title
Trace Contaminant Control

Scope Description
Trace contaminant removal capability: Non-regenerable activated carbon is the current state of the art for trace contamination control. However, this provides a logistics impact to future missions. The primary trace contaminants that must be removed include ammonia (NH$_3$), carbon monoxide (CO), formaldehyde (CH$_2$O), and methanethiol (also known as methyl mercaptan) (CH$_3$SH). The minimum objective would be to remove all of the significant compounds that threaten to exceed the 7-day Spacecraft Maximum Allowable Concentrations (SMAC) values during an EVA. The ideal solution would be a vacuum-regenerable sorbent that could be integrated with the Exploration Portable Life Support System (xPLSS) CO$_2$/H$_2$O removal system. This system performs regeneration
or desorption by exposing the sorbent to a pressure swing from 4.3 psia to <1 torr over approximately 2 minutes. Temperatures remain in the 60-80°F range with a small amount of heat flux from the cross-coupled adsorbing bed. Additional heat input requirements from resistance heaters or other sources would negatively impact the system trade the more significant the value becomes.

References

Trace Contamination Control Cartridge Requirements

Note to vendor: The following drawing referenced in the above specification shall be provided if vendor is selected for award.

- Trace Contamination Control (TCC-360) Specification Control Drawing SLN13102266
  

Expected TRL or TRL range at completion of the project for all scopes: 3 to 5

Desired Deliverables of Phase II for all scopes

Prototype

Desired Deliverables Description for all scopes

Phase I products: By the end of Phase I, it would be beneficial to have a concept design for infusion into the Exploration Portable Life Support System (xPLSS). 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 xPLSS or in a representative loop of the PLSS is desired.

State of the Art and Critical Gaps

As the design for the new Exploration Extra-vehicular Mobility Unit (xEMU) is developed, there are obvious gaps in technologies, which need to be fulfilled to meet the new exploration requirements. Various Exploration Portable Life Support System (xPLSS) Hatch components are at a stall in technology development and require new innovative ideas. These xPLSS Hatch Components are the focus areas for this solicitation in an attempt to integrate new technologies into the xPLSS. NASA has plans to go to the moon and as the mission extends further out of Lower Earth Orbit, durability and extensibility will become some of the most important requirements.

Relevance / Science Traceability

It is relevant to the Exploration Extravehicular Mobility Unit (xEMU), ISS, as well as commercial space companies. As a new Space Suit Exploration Portable Life Support System (xPLSS) is being designed, built, integrated, and testing at JSC and integrated into the xEMU, solutions will have a direct infusion path as the xPLSS is matured in to meet the design and performance goals.

H4.05 Liquid Cooling and Ventilation Garment Connector Upgrade and Glove Humidity Reduction

Lead Center: GRC

Technology Area: TA15 Aeronautics

Scope Title

Liquid Cooling and Ventilation Garment (LCVG) water loop connector upgrade and glove humidity reduction
Scope Description

LCVG water connector upgrade: The connector of the liquid cooling and ventilation garment (LCVG) for the space suit has been a source of failures in the current extra-vehicular mobility unit (EMU). Increased reliability and durability are needed for future space suits that will be used during long-duration missions, which include periods (up to 6 months) of quiescence. Two primary design problems can be addressed:

1) Cold flow of the ethyl-vinyl acetate tubing at the connection to the LCVG connector, which causes leaks to form

2) Sticking of the poppet seal, which allows the LCVG connector to leak. The poppet seal sticks after the seal lubricant is washed away.

A requirement that increases the challenge in designing a non-sticking poppet seal is, because the poppet seal is in the water loop of the space suit, the seal material used must maintain the high water quality requirements for the space suit water loop. Water leakage from the LCVG thermal loop connectors shall be less than 0.5 cc/hr when running at nominal operating pressure of 15 psid.

The connector should not generally leach material into the water flowing through it. Therefore, the connector needs to maintain water quality to the following levels in order to avoid affecting the performance of other equipment within the space suit water loop. In addition, galvanic corrosion in the water loop is of concern. Therefore the connector wetted surfaces, and in general the body should be constructed out of Titanium 6Al-4V wherever possible and stainless steel when necessary. Aluminum alloys should be avoided. Other wetted materials, such as seals or gaskets would preferably be constructed out of currently-used materials such as silicones.

The connector would also need to be compatible with the water solution of Iodine at concentrations of 0.5 – 5 ppm.

 Additionally, the connector would need to be compatible with inlet water containing contaminants such as those listed below:

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Amount (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barium</td>
<td>0.1</td>
</tr>
<tr>
<td>Calcium</td>
<td>1</td>
</tr>
<tr>
<td>Chlorine</td>
<td>5</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.05</td>
</tr>
<tr>
<td>Copper</td>
<td>0.5</td>
</tr>
<tr>
<td>Iron</td>
<td>0.2</td>
</tr>
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<td>Lead</td>
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<td>Potassium</td>
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<td>Sulfate</td>
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Glove humidity reduction: Onycholysis due to humidity and water in space suit gloves during Neutral Buoyancy Laboratory (NBL) training and during extra-vehicular activity is a common observation. Ventilation in gloves is poor allowing moisture to accumulate, which contributes to onycholysis and results in nail bed damage, skin damage, and fungal infections. NASA seeks solutions to reducing moisture in space suit gloves. LCVG ventilation improvements that could ventilate the glove are difficult due to ducting required that would cross the elbow. This ducting is undesirable since it impedes mobility of the elbow joint. Alternative solutions are desired that will prevent onycholysis during suited operations.

The LCVG ventilation ducting consists of a ducting network with one duct running down each arm and each leg. See “Liquid Cooling and Ventilation Garment” description and images at [8]. The ventilation ducts end just above the elbows for the arms and at the feet for the legs. The ventilation gas enters the spacesuit at helmet and flows over the body because the ends of the ducts at the elbows and feet are open. The fan in the portable life support subsystem (PLSS) pulls the ventilation from these open ends and sends the gas to be processed before recycling it back to the helmet. Since the ventilation duct in the arms end at the elbows, the wrist and hand areas are not well ventilated.

References

“Liquid Cooling and Ventilation Garment” description and images located at the following link: [8].

A high-level schematic of the LCVG connector [9]

Expected TRL or TRL range at completion of the project: 2 to 5

Desired Deliverables of Phase II

Hardware, Research

Desired Deliverables Description

The phase 1 needs to deliver a detailed design solution with information that provides confidence that hardware fabricated in the Phase II will resolve the current design challenges.

State of the Art and Critical Gaps

The 30+ history of the EMU has demonstrated these two design weaknesses as a potential for space suit failures for the exploration space suit. Without new design solutions, the exploration space suit will be limited by these weaknesses. In preparation for the exploration space suit, solving these problems are critical.

Relevance / Science Traceability

This subtopic is relevant across the Moon to Mars portfolio. Any mission in which an extra-vehicular activity suit is utilized will benefit from the increased reliability of a suit in which the current connector flaws are rectified.
H5.01 Lunar Surface Solar Array Structures

Lead Center: MSFC

Participating Center(s): GRC

Technology Area: TA15 Aeronautics

Scope Description

NASA intends to land near the lunar south pole (between 85-90 S latitude) by 2024 in Phase 1 of the Artemis Program, and then to establish a sustainable long-term presence by 2028 in Phase 2. At exactly the lunar south pole (90 S), the Sun elevation angle varies between -1.5 deg and 1.5 deg during the year. At 85 S latitude, the elevation angle variation increases to between -6.5 deg and 6.5 deg. These persistently shallow sun grazing angles result in the interior of many polar craters never receiving sunlight while some nearby elevated ridges and plateaus receive sunlight up to 100% of the time in the summer and up to about 70% of the time in the winter. For this reason, these elevated sites are promising locations for human exploration and settlement because they avoid the excessively cold 14-day nights found elsewhere on the Moon while providing nearly continuous sunlight for site illumination, moderate temperatures, and solar power [Refs. 1-2].

This subtopic seeks structural and mechanical innovations for 10+ kW lightweight solar arrays near the south pole for powering landers, In-Situ Resource Utilization (ISRU) equipment, lunar bases, and rovers, and that can deploy and retract at least 5 times. Retraction will allow solar array hardware to be relocated, repurposed, or refurbished and possibly also to minimize nearby rocket plume loads and dust accumulation. Also, innovations to raise the bottom of the solar array by up to 10 m to reduce shadowing from local terrain are of interest [Ref. 3]. Suitable innovations and variations of existing array concepts [e.g., Ref. 4] are of special interest.

Design guidelines for these deployable/retractable solar arrays are:

- Deployed area: 35 m² (10 kW) initially; up to 140 m² (40 kW) eventually per unit.
- Single-axis sun tracking about the vertical axis.
- Adjustable leveling to within 10 deg of vertical.
- Retractable for relocating, repurposing, or refurbishing.
- Number of deploy/retract cycles in service: >5; stretch goal >10.
- Optional 10 m height extension boom to reduce shadowing from local terrain.
- Lunar dust, radiation, and temperature resistant mechanical and electrical components.
- Factor of safety of 1.5 on all components.
- Specific mass: >150 W/kg at 35 m²; >100 W/kg at 140 m².
- Specific packing volume: >60 kW/m³ at 35 m²; >40 kW/m³ at 140 m².
- Lifetime: >15 years.

Suggested areas of innovation include:

- Novel packaging, deployment, retraction, and modularity concepts.
- Lightweight, compact components including booms, ribs, substrates, and mechanisms.
- Novel actuators for telescoping solar arrays with tubular segments of ~4 m length and ~0.2 m diameter such as gear/rack, piezoelectric, ratcheting, or rubber-wheel drive devices.
- Mechanisms with exceptionally high resistance to lunar dust.
- Load-limiting devices to avoid damage during deployment, retraction, and solar tracking.
- Optimized use of advanced lightweight materials (but not materials development).
- Validated modeling, analysis, and simulation techniques.
- High-fidelity, functioning laboratory models and test methods.
- Scaled flight hardware for demonstration on small or mid-size landers.
- Modular and adaptable solar array concepts for multiple lunar surface use cases.
- Completely new concepts; e.g., thinned “rigid panel” or 3D printed solar arrays, non-rotating telescoping “chimney” arrays, or lightweight reflectors to redirect sunlight onto solar arrays or into dark craters.

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 are proposed, strong arguments must be developed to justify why this approach is better from technical, cost, and risk points of view over unconcentrated planar solar arrays.

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). TRL at the end of Phase II of 4 or higher is desired.

NASA has plans to purchase services for delivery of payloads to the Moon through the Commercial Lunar Payload Services (CLPS) contract. Under this subtopic, proposals may include efforts to develop payloads for flight demonstration of relevant technologies in the lunar environment. The CLPS payload accommodations will vary depending on the particular service provider and mission characteristics. Additional information on the CLPS program and providers can be found at this link: https://www.nasa.gov/content/commercial-lunar-payload-services [10]. CLPS missions will typically carry multiple payloads for multiple customers. Smaller, simpler, and more self-sufficient payloads are more easily accommodated and would be more likely to be considered for a NASA-sponsored flight opportunity. Commercial payload delivery services may begin as early as 2020 and flight opportunities are expected to continue well into the future. In future years it is expected that larger and more complex payloads will be accommodated. Selection for award under this solicitation will not guarantee selection for a lunar flight opportunity.

References


Expected TRL or TRL range at completion of the project: 4 to 5

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

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 4 or higher are desired.

State of the Art and Critical Gaps

Deployable solar arrays power almost all spacecraft, but they primarily consist of hinged, rigid panels. This traditional design is too heavy and packages too inefficiently for larger sizes of arrays above about 20 kW. Furthermore, there is usually no reason to retract the arrays in space, so self-retractable solar array concepts are unavailable except for rare exceptions such as the special-purpose International Space Station (ISS) solar array wings. In recent years, several lightweight solar array concepts have been developed but none of them have motorized retraction capability either. The critical technology gap filled by this subtopic is a lightweight, vertically deployed, retractable 10+ kW solar arrays for the surface power for ISRU, lunar bases, dedicated power landers and rovers.

Relevance / Science Traceability

Robust, lightweight, redeployable solar arrays for lunar surface applications are a topic of great current interest to
NASA on its path back to the moon. New this year, the subtopic extends the focus area from landers to other powered elements of the lunar surface architecture along with refined design guidelines. There are likely several infusion paths into ongoing and future lunar surface programs, both within NASA and also with commercial entities currently exploring options for a variety of lunar surface missions. Given the focus on the lunar South Pole, NASA will need vertically deployed and retractable solar arrays that generate 10-40 kW of power. 10 kW class solar array structures are also applicable for Science Mission Directorate (SMD) ConOps on the Moon to charge a Mars Science Laboratory (MSL)-class rover.

H5.02 Hot Structure Technology for Aerospace Vehicles

Lead Center: MSFC

Participating Center(s): AFRC, JSC, LaRC

Technology Area: TA15 Aeronautics

Scope Title
Hot Structure Technology for Aerospace Vehicles

Scope Description
This subtopic encompasses the development of reusable hot structure technology for structural components exposed to extreme heating environments on aerospace vehicles. A hot structure system is a multi-functional structure that can reduce or eliminate the need for a separate thermal protection system (TPS) or active cooling system. 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 (Space Shuttle Orbiter, Hyper-X, and X-37) on control surfaces and wing leading edges, as well as in Department of Defense programs. Additionally, the development of hot structure technology for combustion-device liquid rocket engine propulsion systems is of great interest.

This subtopic seeks to develop innovative low-cost, damage tolerant, reusable and lightweight hot structure technology applicable to aerospace vehicles exposed to extreme temperatures between 1093\(^\circ\) to 2204\(^\circ\)C (2000\(^\circ\) to 4000\(^\circ\)F). These aerospace vehicle applications are unique in requiring the hot structure to carry primary structure vehicle loads and to be reusable after exposure to extreme temperatures during atmospheric entry and/or liquid rocket engine firings. The material systems of interest for use in developing hot structure technology include: advanced carbon-carbon (C-C) materials, ceramic matrix composites (CMC’s), or advanced high-temperature refractory metals. Potential applications of hot structure technology include: primary load-carrying aeroshell structures, control surfaces, leading edges, and propulsion system components (such as hot gas valves, combustion chambers, and passively- or actively-cooled nozzle extensions).

Proposals should present approaches to address the current need for improvements in operating temperature capability, toughness/durability, reusability and material system properties. Focus areas should address one or more of the following:

- Improvements in manufacturing processes and/or material designs to achieve repeatable and uniform material properties that should be scalable to actual vehicle components: specifically, material property data obtained from flat-panel test coupons should represent the properties of prototype and flight test articles.
- Material/structural architectures and multifunctional systems providing significant improvements over typical 2D inter-laminar mechanical properties while maintaining in-plane and thermal properties when compared to state-of-the-art C-C or CMC materials. Examples include: incorporating through-the-thickness stitching, braiding or 3D woven preforms.
- Functionally-graded manufacturing approaches to optimize oxidation protection, damage tolerance and structural efficiency, in an integrated hot structure concept that extends performance for multiple cycles up to 2204\(^\circ\)C (4000\(^\circ\)F).
• Manufacturing process methods that enable a significant reduction in the time required to fabricate materials and components. There is a great need to reduce processing time for hot structure materials and components -- current state-of-the-art fabrication times are often in the range of 6 to 12 months, which can limit the use of such materials. Approaches enabling reduced manufacturing times should not, however, lead to significant reductions in material properties.

Under this subtopic, research, testing, and analysis should be conducted to demonstrate technical feasibility during Phase I and show a path towards Phase II hardware demonstrations. Phase I feasibility studies should also address cost and risk associated with the hot structures technology. At the completion of the Phase I project, in addition to the final report, deliverables should include at least one of the following to aid assessment of technical feasibility: (a) coupons appropriate for thermal and/or mechanical material property tests, (b) arc-jet test specimens, or (c) a subscale nozzle extension test article or analog component. Emphasis should be placed on the delivery of manufacturing demonstration units for NASA testing at the completion of the Phase II contract. In addition, Phase II studies should address scale-up and integration with vehicles that could make use of the developed technology.

Hot structure technology is relevant to the Human Exploration and Operations Mission Directorate (HEOMD), where the technology can be infused into spacecraft and launch vehicle applications. Such technology should provide either improved performance or enable advanced missions requiring re-usability, increased damage tolerance and the durability to withstand long-term space exploration missions. The ability to allow for delivery of larger payloads to various space destinations, such as the lunar south pole, is also of great interest.

The Advanced Exploration Systems (AES) Program would be ideal for further funding a prototype hot structure system and technology demonstration effort. Commercial Space programs, such as Commercial Orbital Transportation Services (COTS), Commercial Lunar Payload Services (CLPS), and Next Space Technologies for Exploration Partnerships (NextSTEP), are also interested in this technology for flight vehicles. Additionally, NASA HEOMD programs that could use this technology include the Space Launch System (SLS) and the Human Landing System (HLS) for propulsion applications.

Potential NASA users of this technology exist for a variety of propulsion systems, including the following:

• Upper stage engine systems, such as those for the Space Launch System,
• In-space propulsion systems, including nuclear thermal propulsion systems,
• Lunar/Mars lander descent/ascent propulsion systems,
• Solid motor systems, including those for primary propulsion, hot gas valve applications, and small separation and/or attitude-control systems, and
• Propulsion systems for the Commercial Space industry, which is supporting NASA efforts.

Finally, the U.S. Air Force is interested in such technology for its Evolved Expendable Launch Vehicle (EELV), ballistic missile and hypersonic vehicle programs. Other non-NASA users include the U.S. Navy, the U.S. Army, the Missile Defense Agency (MDA) and the Defense Advanced Research Projects Agency (DARPA). The subject technology can be both enhancing to systems already in use or under development, as well as enabling for applications that may not be feasible without further advancements in high temperature composite technology.

References

Hypersonic Hot Structures:


Liquid Rocket Propulsion systems:
“Carbon-Carbon Nozzle Extension Development in Support of In-Space and Upper-Stage Liquid Rocket Engines” paper; Paul R. Gradl and Peter G. Valentine; 53rd AIAA/SAE/ASEE Joint Propulsion Conference, Atlanta, GA;

Note: The above references are open literature references. Other references exist regarding this technology, but they are International Traffic in Arms Regulations (ITAR) restricted. Numerous online references exist for the subject technology and projects/applications noted, both foreign and domestic.

Expected TRL or TRL range at completion of the project: 2 to 4

Desired Deliverables of Phase II

Prototypes or components suitable for testing by NASA or Commercial Space partners.

Desired Deliverables Description

At the completion of Phase I project deliverables should include at least one of the following: coupons appropriate for thermal/mechanical material property tests, arc-jet test specimens, or a subscale nozzle extension test article. Emphasis should be on the delivery of manufacturing demonstration units, with representative structural features, for NASA testing at the completion of the Phase II contract.

State of the Art and Critical Gaps

The current state of the art for composite hot structure components is limited primarily to applications with maximum use temperatures in the 1093° – 1600°C (2000° – 2912°F) range. While short excursions to higher temperatures are possible, considerable degradation may occur. Reusability is limited and may require considerable inspection before reuse. Critical gaps or technology needs include: (a) increasing operating temperatures to 1700° – 2204+°C (3092° – 4000+°F); (b) increasing resistance to environmental attack (primarily oxidation); (c) increasing manufacturing technology capabilities to improve reliability, repeatability and quality control; (d) increasing durability/toughness and interlaminar mechanical properties (or introducing 3D architectures); and (e) decreasing overall manufacturing time required.

As an alternative to composites, metallic hot structures may reduce operating temperature requirements to near 1000°C (1832°F) in some applications, while offering greater structural reliability, and should also be pursued. Unfortunately advancements in high temperature metals have been a significant gap.

Relevance / Science Traceability

Hot structure technology is relevant to the Human Exploration and Operations Mission Directorate (HEOMD), where the technology can be infused into spacecraft and launch vehicle applications. Such technology should provide either improved performance or enable advanced missions requiring reusability, increased damage tolerance and the durability to withstand long-term space exploration missions. The ability to allow for delivery of larger payloads to various space destinations, such as the lunar south pole, is also of great interest.

The Advanced Exploration Systems (AES) Program would be ideal for further funding a prototype hot structure system and technology demonstration effort. Commercial Space programs, such as Commercial Orbital Transportation Services (COTS), Commercial Lunar Payload Services (CLPS), and Next Space Technologies for Exploration Partnerships (NextSTEP), also are interested in this technology for flight vehicles. Additionally, NASA HEOMD programs that could use this technology include the Space Launch System (SLS) and the Human Landing System (HLS) for propulsion applications.

Potential NASA users of this technology exist for a variety of propulsion systems, including the following:

- Upper stage engine systems, such as those for the Space Launch System,
- In-space propulsion systems, including nuclear thermal propulsion systems,
- Lunar/Mars lander descent/ascent propulsion systems,
- Solid motor systems, including those for primary propulsion, hot gas valve applications and small separation and/or attitude-control systems, and
- Propulsion systems for the Commercial Space industry, which is supporting NASA efforts.

Finally, the U.S. Air Force is interested in such technology for its Evolved Expendable Launch Vehicle (EELV), ballistic missile, and hypersonic vehicle programs. Other non-NASA users include the U.S. Navy, the U.S. Army, the Missile Defense Agency (MDA), and the Defense Advanced Research Projects Agency (DARPA). The subject technology can be both enhancing to systems already in use or under development, as well as enabling for applications that may not be feasible without further advancements in high temperature composite technology.

**H6.04 Model Based Systems Engineering for Distributed Development**

**Lead Center:** GRC

**Technology Area:** TA15 Aeronautics

**Scope Title**

Model Based Systems Engineering for Distributed Development

**Scope Description**

Systems Engineering technology is both a critical capability and a bottleneck for NASA human exploration development. NASA looks to a sustainable return to the Moon to enable future exploration of Mars, components such as Lunar Gateway and Commercial Lunar Payload Services (CLPS) will require partnerships with a wide variety of communities. Building from the success of the international partnerships for International Space Station (ISS), space agencies from multiple governments are looking for roles on the Gateway. A particular focus has been made to include the rapidly growing commercial space industry to provide an important role in supporting a sustained presence on the Moon. All of these potential partners will have their own design capabilities, their own development processes and internal constituencies to support. Integrating and enabling disparate systems built in different locations by different owners to all work cohesively together will require a significant upgrade to the core systems engineering capabilities.

In the last decade Model-Based Systems Engineering (MBSE) technology has matured as evidenced by the development of Systems Modeling Language (SysML) tools and frameworks that support engineers in development efforts from requirements through hardware and software implementation. MBSE holds considerable promise for accelerating, reducing overhead labor, and improving the quality of systems development. However, a remaining bottleneck is the coordination and integration of system development across distributed organizations, such as the multiple partners developing lunar gateway and eventual Mars exploration. This subtopic seeks technology to fill this gap.

**Areas of particular need include:**

- Methodologies that support integration among tools and exchange of information between multidisciplinary artifacts using automated intelligent reasoning.
- The definition of open interface standards and tools to enable inspection of distributed models across engineering domains.
- Tools or systems that allow models to be shared across development environments and trace the resulting system model back to contributions from multiple partners.
- Modeling environments that facilitate user interaction from multiple stakeholders of varying expertise in MBSE.
- Continuous integration and verification of safety critical system requirements that depend on disparate development sources.

**References:**
Ensuring information exchange of digital artifacts are transferable and up to date among multiple stakeholders.

- Computational tools to augment human decision making and reasoning on complex systems with large amounts of data from disparate sources
- Automated formal specification, formal verification, and test case generation of requirements with linked data and traceability to discipline specific (CAD, CAE, etc.) tools, particularly requirements with safety properties.
  - ReqIF: https://www.omg.org/reqif/ [21]
  - SysPhs: https://www.omg.org/spec/SysPhS/ [22]
  - FMI: https://fmi-standard.org [23]
- Lightweight and intuitive cloud-based interfaces for CRUD (create, read, update, delete) operations on models particularly for users with limited MBSE experience.
- OSLC: https://open-services.net/ [25]

Expected TRL or TRL range at completion of the project: 4 to 6

**Desired Deliverables of Phase II**

Prototype, Software

**Desired Deliverables Description**

Methodologies and tools that support distributed development efforts

**State of the Art and Critical Gaps**

For distributed development, the state-of-the-art tends to be laboriously negotiated interface control documents and manual integration processes that are inherently slow and labor intensive. In an effort to overcome these challenges MBSE and SysML in particular has seen significant adoption at NASA (Gateway, Resource Prospector, Europa Clipper, Space Communications and Navigation [SCaN], Space Launch System [SLS]) especially after the MBSE Pathfinder (’16/’17) and MBSE Infusion And Modernization Initiative (MIAMI, ’18/’19) studies. However, these pilot programs and a survey of NASA's use of MBSE conducted by NASA Independent Verification & Validation (IV&V) and Ames Research Center identified areas of critical need, including:

1. Sharing and version control of models.
2. Integration of SysML of domain specific tools
3. Steep learning curve for users with limited MBSE experience
4. Testing, Verification and Validation with SysML have limited use
5. No tools exist for formally specifying requirements and linking to model properties

With programs such as Gateway and Artemis that require coordination among multiple NASA centers, international space agencies, and commercial partnerships these needs will be amplified. Tool infrastructures that enable integrated support of requirements tracing, design reference points, intelligent reasoning of data and interface constructs are generally not available except within proprietary boundaries. We need tools that support integrated development and model sharing across development environments and that support use across multiple vendors.

**Relevance / Science Traceability**

This subtopic would be of relevance to all Human Exploration and Operations Mission Directorate (HEOMD)
missions, but of particular interest will be Gateway and Artemis development. Those systems have already adopted the use of MBSE tools and tools sought help reduce potential system integration bottlenecks. Over the next 3 to 5 years, there will be considerable opportunity for small business contributions to be matured and integrated into the support infrastructure as Gateway evolves from concept to development program.

H6.22 Deep Neural Net and Neuromorphic Processors for In-Space Autonomy and Cognition

Lead Center: GRC

Participating Center(s): ARC

Technology Area: TA15 Aeronautics

Scope Title

Neuromorphic Capabilities

Scope Description

The Neuromorphic Processors for In-Space Autonomy and Cognition subtopic specifically focuses on advances in signal and data processing. Neuromorphic processing will enable NASA to meet growing demands for applying artificial intelligence and machine learning algorithms on-board a spacecraft to optimize and automate operations. This includes enabling cognitive systems to improve mission communication and data processing capabilities, enhance computing performance, and reduce memory requirements. Neuromorphic processors can enable a spacecraft to sense, adapt, act and learn from its experiences and from the unknown environment without necessitating involvement from a mission operations team. Additionally, this processing architecture shows promise for addressing the power requirements that traditional computing architectures now struggle to meet in space applications.

The goal of this program is to develop neuromorphic processing software, hardware, algorithms, architectures, simulators and techniques as enabling capability for autonomous space operations. Emerging memristor and other radiation-tolerant devices, which shows potential for addressing the need for energy efficient neuromorphic processors and improved signal processing capability, is of particular interest due to its resistance to the effects of radiation.

Additional areas of interest for research and/or technology development include: a) spiking algorithms that learn from the environment and improve operations, b) neuromorphic processing approaches to enhance data processing, computing performance, and memory conservation, and c) new brain-inspired chips and breakthroughs in machine understanding/intelligence. Novel memristor approaches which show promise for space applications are also sought.

This subtopic seeks innovations focusing on low size, weight and power (SWaP) applications suitable lunar orbital or surface operations, enabling efficient on-board processing at lunar distances. Focusing on SWaP-constrained platforms opens up the potential for applying neuromorphic processors in spacecraft or robotic control situations traditionally reserved for power-hungry general purpose processors. This technology will allow for increased speed, energy efficiency and higher performance for computing in unknown and un-characterized space environments including the Moon and Mars.

Phase I will emphasize research aspects for technical feasibility and show a path toward a Phase II proposal. Phase I deliverables include concept of operations of the research topic, simulations and preliminary results. Early development and delivery of prototype hardware/software is encouraged.

Phase II will emphasize hardware and/or software development with delivery of specific hardware and/or software products for NASA, targeting demonstration operations on a low-SWaP platform. Phase II deliverables include a working prototype of the proposed product and/or software, along with documentation and tools necessary for NASA to use the product and/or modify and use the software. In order to enable mission deployment, proposed prototypes should include a path, preferably demonstrated, for fault tolerance and mission tolerance.
References
Several reference papers that have been published at the Cognitive Communications for Aerospace Applications (CCAA) workshop are available at: http://ieee-ccaa.com [26].

Expected TRL or TRL range at completion of the project 4 to 6

Desired Deliverables of Phase II
Prototype, Hardware, Software

Desired Deliverables Description
Phase 2 deliverables should include hardware/software necessary to show how the advances made in the development can be applied to a cubesat, small sat, and rover flight demonstration.

State of the Art and Critical Gaps
The current State-of-the-Art (SOA) for in-space processing is the High Performance Spaceflight Computing (HPSC) processor being developed by Boeing for NASA GSFC. The HPSC, called the Chiplet, contains 8 general purpose processing cores in a dual quad-core configuration. Delivery is expected by December 2022. In a submission to the STMD Game Changing Development (GCD) program, the highest computational capability required by a typical space mission is 35-70 GFLOPS (million fast logical operations per second).

The current SOA does not address the capabilities required for artificial intelligence and machine-learning applications in the space environment. These applications require significant amounts of multiply and accumulate operations, in addition to a substantial amount of memory to store data and retain intermediate states in a neural network computation. Terrestrially, these operations require General-Purpose Graphics Processing Units (GP-GPUs), which are capable of teraflops (TFLOPS) each -- approximately 3 orders of magnitude above the anticipated capabilities of the HPSC.

Neuromorphic processing offers the potential to bridge this gap through a novel hardware approach. Existing research in the area shows neuromorphic processors to be up to 1000 times more energy efficient than GP-GPUs in artificial intelligence applications. Obviously the true performance depends on the application, but nevertheless the architecture has demonstrated characteristics that make it well-adapted to the space environment.

Relevance / Science Traceability
The Cognitive Communications Project, through the Human Exploration and Operations Mission Directorate (HEOMD) Space Communications and Navigation (SCaN) Program, is one potential customer of work from this subtopic area. Neuromorphic processors are a key enabler to the cognitive radio and system architecture envisioned by this project. As communications become more complex, cognition and automation will play a larger role to mitigate complexity and reduce operations costs. Machine learning will choose radio configurations, adjust for impairments and failures. Neuromorphic processors will address the power requirements that traditional computing architectures now struggle to meet and are of relevance to lunar return and Mars for autonomous operations, as well as of interest to HEOMD and SMD for in-situ avionics capabilities.

H8.01 Utilization of the International Space Station (ISS) to Foster Commercial Development of Low-Earth Orbit (LEO)
Lead Center: JSC
Participating Center(s): ARC, GRC, JPL, KSC, LaRC, MSFC
Technology Area: TA15 Aeronautics
This subtopic seeks proposals that could aid in achieving NASA’s newly-stated objective of leveraging International Space Station (ISS) capabilities to stimulate demand and catalyze markets leading to a broad commercial demand for Low Earth Orbit (LEO). The ISS SBIR program has particular interest in technologies and flight projects that could lead to valuable terrestrial applications due to development in microgravity, which can aid in fostering an economy in LEO. Use of the ISS will facilitate validation and enable development of the minimal viable product required to attract significant capital and lead to growth of new and emerging commercial markets in the following areas: in-space manufacturing, regenerative medicine, bioengineering and advanced materials production. Additionally, leveraging existing ISS facilities for new research and commercial product development which could improve, enhance and/or augment investigations being conducted, or planned to be conducted, on ISS is a high priority.

References

- Space Station Research & Technology at: https://www.nasa.gov/mission_pages/station/research/experiments/explorer [27]
- Center for the Advancement of Science In Space, Inc. at: https://www.issnationallab.org/ [28]
- LEO Economy: https://cms.nasa.gov/leo-economy/low-earth-orbit-economy [29]

Expected TRL or TRL range at completion of the project: 3 to 7

Desired Deliverables of Phase II

Prototype, Analysis, Hardware, Software, Research

Desired Deliverables Description

Desired deliverables at the end of Phase II would be engineering development units and/or software packages for NASA-sponsored testing that could be turned into proof-of-concept systems suitable for flight demonstrations.

State of the Art and Critical Gaps

The ISS is being used to stimulate both the supply and demand of commercial marketplace as NASA supports the development of the LEO space economy.

Relevance / Science Traceability

This subtopic is in direct support of NASA’s recent policy to enable commercial and marketing activities to take place aboard the ISS. The ISS capabilities will be used to further stimulate the demand for commercial products development.

H9.01 Long Range Optical Telecommunications

Lead Center: GSFC

Participating Center(s): GRC, GSFC

Technology Area: TA15 Aeronautics

Scope Title

Free-Space Optical Communications Technologies

Scope Description
This Free-space Long Range Optical Communications subtopic seeks innovative technologies for advancing free-space optical communications by pushing future data volume returns to and from space missions in multiple domains with return data-rates > 100 Gbit/s (cis-lunar, i.e. Earth or lunar orbit to ground), > 10 Gbit/s (Earth-sun L1 and L2), >1 Gbit/s per AU-squared (deep space), and >1 Gbit/s (planetary lander to orbiter) and forward data-rates > 25 Mb/s at ranges extending from the Moon to Mars. Innovative technologies should target improved efficiency, reliability, robustness, and longevity for existing or novel state-of-the-art flight laser communication systems. Photon-counting sensitivity, near infrared (NIR), space-flight worthy detectors/detector arrays for supporting laser ranging for potential navigation and science are of particular interest. Ground-based technologies targeting high power, NIR and intensity-modulated lasers with fast rise times and low timing jitter (sub-nanosecond) are needed to support high forward data-rates and laser ranging.

Proposals are sought in the following specific areas:

**Flight Laser Transceivers**

Low-mass, high-Effective Isotropic Radiated Power (EIRP) laser transceivers for links over planetary distances with:

- 30 to 50 cm clear aperture diameter telescopes for laser communications
- Targeted mass of opto-mechanical assembly per aperture area, less than 100 kg/square-meter
- Cumulative wave-front error and transmission loss not to exceed 2 dB.
- Advanced thermal-mechanical designs to withstand planetary launch loads and flight temperatures by the optics and structure, at least -20° C to 70° C operational range
- Design to mitigate stray light while pointing transceiver 3 degrees from edge of sun
- Survive direct sun pointing for extended duration

Transceivers fitting the above characteristics should support robust link acquisition tracking and pointing characteristics, including point-ahead implementation from space for beacon assisted and/or "beaconless" architectures. Innovative solutions for mechanically stiff, light-weighted thermally stable structural properties are sought.

- Pointing loss allocations not to exceed 1 dB (pointing errors associated loss of irradiance at target less than 20%)
- Receiver field-of-view of at least 1 milliradian angular radius for beacon assisted acquisition, tracking and pointing
- As a goal additional focal plane with field-of-view to support on-board astrometry is desired
- Beaconless pointing subsystems for operations beyond 3 AU
- Assume integrated spacecraft micro-vibration angular disturbance of 150 micro-radians (<0.1 Hz to ~500 Hz)

Low complexity small footprint agile laser transceivers for bi-directional optical links (> 1-10 Gbit/second at a nominal link range of 1000-20000 km) for planetary lander/rover to orbiter and/or space-to-space cross links.

- Disruptive low Size, Weight and Power (SWaP) technologies that can operate reliably in space over extended mission duration
- Vibration isolation/suppression systems that will integrate to the optical transceiver in order to reject high frequency base disturbance by at least 50 dB
- Desire integrated launch locks and latching mechanism
- Low burden (mass, power, volume)
- Robust for space flight
- Should afford limited +/- 5 mrad - +/-12 mrad actuated field-of-regard for the optical line of sight of the transceiver

**Flight Laser Transmitters**

High-gigabit/s laser transmitters
- 1550 nm wavelength
- Lasers, electronics and optical components ruggedized for extended space operations
- High rate 10-100 Gb/s for cis-lunar
- 1 Gb/s for deep-space
- Integrated hardware with embedded software/firmware for innovative coding/modulation/interleaving schemes that are being developed as a part of the Consultative Committee for Space Data Systems (CCSDS)

High peak-to-average power laser transmitters for regular or augmented M-ary PPM modulation with M=4, 8, 16, 32, 64, 128, 256 operating at NIR wavelengths, preferably 1550 nm with average powers from 5 - 50 W

- Sub-nanosecond pulse
- Low pulse jitter
- Long lifetime and reliability operating in space environment ( > 5 and as long as 20 years)
- High modulation and polarization extinction ratio with 1-10 GHz line width

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

- >20% wall-plug efficiency (DC-to-optical, including support electronics) with description of approach for stated efficiency of space-qualifiable lasers. Multi-watt Erbium Doped Fiber Amplifier (EDFA), or alternatives, with high gain bandwidth (> 30nm, 0.5 dB flatness) concepts will be considered.
- Radiation tolerance better than 50 krad is required (including resilience to photo-darkening).

**Receivers/Sensors**

Space-qualifiable high-speed receivers and low light level sensitive acquisition, tracking, pointing, detectors, and detector arrays

- NIR wavelengths: 1064nm and/or 1550 nm
- Sensitive to low irradiance incident at flight transceiver aperture (~ fW/m2 to pW/m2) detection
- Low sub-nanosecond timing jitter and fast rise time
- Novel hybridization of optics and electronic readout schemes with in-built pre-processing capability
- Characteristics compatible with supporting time-of-flight or other means of processing laser communication signals for high precision range and range rate measurements
- Tolerant to space radiation effects, total dose > 50 krad, displacement damage and single event effects

**Novel technologies and accessories**

**Narrow Bandpass Optical Filters**

- Space-qualifiable, sub-nanometer to nanometer, noise equivalent bandwidth with ~90% throughput, large spectral range out-of-band blocking (~ 40 dB)
- NIR wavelengths from 1064 – 1550 nm region, with high transmission through Earth’s atmosphere
- Reliable tuning over limited range

Novel Photonics Integrated Circuit (PIC) devices targeting space applications with objective of reducing size, weight and power of modulators, without sacrificing performance. Proposed PIC solutions should allow improved integration and efficient coupling to discrete optics, when needed.

Concepts for offering redundancy to laser transmitters in space
Optical fiber routing of high average powers (10’s of watts) and high peak powers (1-10 kW)
Redundancy in actuators and optical components
Reliable optical switching

Ground Assets for Optical Communication

Low cost 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
- Better than 10 micro radian spot size (excluding atmospheric seeing contribution)
- Desire demonstration of low-cost primary mirror segment fabrication to meet a cost goal of less than $35 K per square meter
- Low-cost techniques for segment alignment and control, including daytime operations
- Partial adaptive correction techniques for reducing the field of view required to collect signal photons under daytime atmospheric "seeing" conditions
- Innovative adaptive techniques not requiring a wavefront sensor and deformable mirror of particular interest
- Mirror cleanliness monitor and control systems
- Active metrology systems for maintaining segment primary figure and its alignment with secondary optics
- Large core diameter multi-mode fibers with low temporal dispersion for coupling large optics to detectors remote (30-50 m) from the large optics

1550 nm sensitive photon counting detector arrays compatible with large aperture ground collectors with a means of coupling light from large aperture diameters to reasonably- sized detectors/detector arrays, including optical fibers with acceptable temporal dispersion

- Integrated time tagging readout electronics for >5 giga-photons/s incident rate
- Time resolution <50 ps at 1-sigma
- Highest possible single photon detection efficiency, at least 50% at highest incident rate
- Total detector active area > 0.3 - 1 mm²
- Integrated dark rate < 3 mega-count/s.

Cryogenic optical filters

- Operate at 40 K with sub-nanometer noise equivalent bandwidths
- 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 - 5 microns.

Multi-kilowatt laser transmitters for use as ground beacon and uplink laser transmitters

- Near infrared wavelengths in 1.0 or 1.55 micrometer spectral region
- Capable of modulating with narrow nanosecond and sub-nanosecond rise times
- Low-timing jitter and stable operation
- High speed real-time signal processing of serially concatenated pulse position modulation operating at a few bits per photon with user interface outputs
- 15-60 MHz repetition rates

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.

References

**Expected TRL or TRL range at completion of the project:** TRL 2-3 Phase I for maturation to TRL 3-5 in Phase II

**Desired Deliverables of Phase II**

Prototype, Hardware, Software

**Desired Deliverables Description**

Models of components or assemblies for flight laser transceivers or Ground receivers

**State of the Art and Critical Gaps**

The State Of the Art (SOA) for Free-Space Optical Communications (FSOC) can be subdivided into near-earth (extending to cis- and trans-lunar distances) and planetary ranges with the Lagrange points falling in between.

Near Earth FSOC technology has completed a number of technology demonstrations from space and is more mature. Nonetheless, low size-weight power novel high speed 10-100 Gb/s space-qualified laser transmitters and receivers are sought. These transmitters and receivers can possibly be infused for deep space proximity links, such as landed assets on planetary surfaces to orbiting assets with distances of 5000-100000 km or inter-satellite links. Innovative light-weight space-qualified modems for handling multiple optical modulation schemes.

A technology demonstration for deep space FSOC is anticipated in the next decade. Critical gaps following a successful technology demonstration will be light-weighted 30-50 cm optical with a wide operational temperature range -20C to 50C over which wave front error and focus is stable. High peak-to-average power space qualified lasers with average powers of 20-50 W. Single photon-sensitive radiation-hardened flight detectors with high detection efficiency, fast rise times low timing jitter. The detector size should be able to cover 1 milliradian Field-Of-View (FOV) with an instantaneous FOV comparable to the transmitted laser beam width. Laser pointing control systems that operate with dim laser beacons transmitted from earth or use celestial beacon sources.

For Deep Space Optical Communications (DSOC) ground laser transmitters with high average power (kW class) but narrow line-widths (< 0.3 nm) and high variable repetition rates are required. Innovative optical coatings for large aperture mirrors that are compatible with near-sun pointing applications for efficiently collecting the signal and lowering background and stray light.

**Relevance / Science Traceability**

A number of FSOC-related NASA projects are ongoing with launch expected in the 2019-2022 time frame. The Laser Communication Relay Demonstration (LCRD) is an earth-to-geostationary satellite relay demonstration to launch in late 2019. The Illuma-T Project will extend the relay demonstration to include a Low Earth Orbit (LEO) node on the ISS in 2021. In 2022 the EM-2 Optical to Orion (O2O) demonstration will transmit data from the Orion crewed capsule as it travels to the Moon and back. In 2022 the DSOC Project technology demonstration will be hosted by the Psyche Mission spacecraft extending FSOC links to astronomical unit distances.

These missions are being funded by NASA's Space Technology Mission Directorate (STMD) Technology Demonstration Mission (TDM) Program and Human Exploration Operations Mission Directorate (HEOMD) Space Communications and Navigation (SCaN) Program.
Participating Center(s): JSC, MSFC

Technology Area: TA15 Aeronautics

Scope Title

Advanced Techniques for Trajectory Optimization

Scope Description

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 navigation, guidance and control. This sub-topic 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 autonomous onboard navigation, guidance, and control, and trajectory optimization are solicited. See Reference 1 below for NASA Technical Area (TA) roadmaps:

- 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)
- Tools and techniques for orbit/trajectory design for distributed space missions including constellations and formations (TA 11.2.6)

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 (GMAT), Copernicus, Evolutionary Mission Trajectory Generator (EMTG), Mission Analysis Low-Thrust Optimization (MALTO), Monte, and Optimal Trajectories by Implicit Simulation (OTIS), or other available 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.

References

4. Copernicus: https://www.nasa.gov/centers/johnson/copernicus/index.html [37]
5. Mission Analysis Low-Thrust Optimization (MALTO): https://software.nasa.gov/software/NPO-43625-1 [38]

Expected TRL or TRL range at completion of the project: 3 to 6

Desired Deliverables of Phase II

Prototype, Analysis, Software, Research

Desired Deliverables Description

Phase 1 research should be conducted to demonstrate technical feasibility, with preliminary software being delivered for NASA testing, as well as show a plan towards Phase 2 integration. Phase 2 new technology development efforts shall deliver components at the Technology Readiness Level (TRL) 5-6 level with mature algorithms and software components complete and preliminary integration and testing in an operational
environment.

**State of the Art and Critical Gaps**

Algorithms and software for rapid and robust preliminary and high-fidelity design and optimization of low thrust trajectories in a multi-body dynamical environment (such as cislunar space) currently do not exist. Designing trajectories for these types of missions relies heavily on hands-on work by very experienced people. That works reasonably well for designing a single reference trajectory but not as well for exploring trade spaces or when designing thousands of trajectories for a Monte-Carlo or missed-thrust robustness analysis.

**Relevance / Science Traceability**

- Lunar Orbital Platform-Gateway
- WFIRST
- Europa Clipper
- Lucy
- Psyche

Trajectory design for these complex missions can take weeks or months to generate a single reference trajectory. Providing algorithms and software to speed up this process will enable missions to more fully explore trade spaces and more quickly respond to changes in the mission.

**Scope Title**

Autonomous Onboard Spacecraft Navigation, Guidance and Control

**Scope Description**

Future NASA missions require precision landing, rendezvous, formation flying, proximity operations (e.g., servicing and assembly), non-cooperative object capture and coordinated platform operations in Earth orbit, cislunar space, libration orbits and deep space. These missions require a high degree of autonomy. The subtopic seeks advancements in autonomous spacecraft navigation and maneuvering technologies for applications in Earth orbit, lunar, cislunar, libration and deep space to reduce dependence on ground-based tracking, orbit determination and maneuver planning. See Reference 1 for NASA Technical Area (TA) roadmaps:

- Advanced autonomous spacecraft 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 (TA 5.4.2.4, TA 5.4.2.6, TA 5.4.2.8).
- Onboard spacecraft trajectory planning and optimization algorithms for real-time mission re-sequencing, onboard 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), including the concept of robust onboard trajectory planning and optimization algorithms that account for system uncertainty (i.e., navigation errors, maneuver execution errors, etc.).
- Onboard relative and proximity navigation (TA 5.4.4) multi-platform relative navigation (relative position, velocity and attitude or pose) which support cooperative and collaborative space operations such as satellite servicing and in-space assembly.
- Rendezvous targeting (TA 4.6.2.1) Proximity Operations/Capture/ Docking Guidance (TA 4.6.2.2)
- Advanced filtering techniques (TA 5.4.2.4) that address rendezvous and proximity operations as a multi-sensor, multi-target tracking problem; handle non-Gaussian uncertainty; or incorporate multiple-model estimation.
- Advanced algorithms for safe precision landing on small bodies, planets and moons, including real-time three-dimensional (3D) terrain mapping (TA 9.2.8.1, 9.2.8.3), autonomous hazard detection and avoidance (TA 9.2.8.4), terrain relative navigation (TA 9.2.8.2), small body proximity operations (TA 9.2.8.8).
- Machine vision techniques to support optical/terrain relative navigation and/or spacecraft rendezvous/proximity operations.
Proposals that leverage state-of-the-art capabilities already developed by NASA, or that can optionally integrate with those packages, such as the Goddard Enhanced Onboard Navigation System (GEONS) ([https://software.nasa.gov/software/GSC-14687-1](https://software.nasa.gov/software/GSC-14687-1)), Navigator ([http://itpo.gsfc.nasa.gov/wp-content/uploads/gsc_14793_1_navigator.pdf](http://itpo.gsfc.nasa.gov/wp-content/uploads/gsc_14793_1_navigator.pdf)), NavCube ([https://goo.gl/bdobb9](https://goo.gl/bdobb9)) or other available NASA 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.

**References**

1. NASA Space Technology Roadmaps (2015): [https://www.nasa.gov/offices/oct/home/roadmaps/index.html](https://www.nasa.gov/offices/oct/home/roadmaps/index.html) [34]
2. Goddard Enhanced Onboard Navigation System (GEONS), ([https://software.nasa.gov/software/GSC-14687-1](https://software.nasa.gov/software/GSC-14687-1)), ([https://goo.gl/TbVZ7G](https://goo.gl/TbVZ7G))

**Expected TRL or TRL range at completion of the project:** 3 to 6

**Desired Deliverables of Phase II**

Prototype, Analysis, Hardware, Software, Research

**Desired Deliverables Description**

Phase 1 research should be conducted to demonstrate technical feasibility, with preliminary software being delivered for NASA testing, as well as show a plan towards Phase 2 integration. For proposals that include hardware development, delivery of a prototype under the Phase 1 contract is preferred, but not necessary. Phase 2 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.

**State of the Art and Critical Gaps**

Currently navigation, guidance and control functions rely heavily on the ground for tracking data, data processing and decision making. As NASA operates farther from Earth and performs more complex operations requiring coordination between vehicles, round trip communication time delays make it is necessary to reduce reliance on Earth for navigation solutions and maneuver planning. Spacecraft that arrive at a near-Earth asteroid (NEA) or a planetary surface, may have limited ground inputs and no surface or orbiting navigational aids. NASA currently does not have the navigational, trajectory and attitude flight control technologies that permit fully autonomous approach, proximity operations and landing without navigation support from Earth.

**Relevance / Science Traceability**

- Lunar Orbital Platform-Gateway
- Orion Multi-Purpose Crew Vehicle
- Wide Field Infrared Survey Telescope (WFIRST)
- Europa Clipper
- Lucy
- Psyche

These complex, deep space missions require a high degree of autonomy. The technology produced in this subtopic enables these kinds of missions by reducing or eliminating reliance on the ground for navigation and maneuver planning. The subtopic aims to reduce the burden of routine navigational support and communications.
requirements on network services, increase operational agility, and enable near real-time re-planning and opportunistic science. It also aims to enable classes of missions that would otherwise not be possible due to round-trip light time constraints.

**Scope Title**

Conjunction Assessment Risk Analysis (CARA)

**Scope Description**

The U.S. Space Surveillance Network currently tracks more than 22,000 objects larger than 10 centimeters and the number of objects in orbit is steadily increasing which causes an increasing threat to human spaceflight and robotic missions in the near-Earth environment. The NASA Conjunction Assessment Risk Analysis (CARA) team receives screening data from the 18th Space Control Squadron concerning predicted close approaches between NASA satellites and other space objects. CARA determines the risk posed by those events and recommends risk mitigation strategies, including collision avoidance maneuvers, to protect NASA non-human-spaceflight assets in Earth orbit. The ability to perform CARA more accurately and rapidly will improve space safety for all near-Earth operations. This subtopic seeks innovative technologies to improve the CARA process including (see Reference 1 for NASA Technical Area (TA) roadmaps):

- Event evolution prediction methods, models and algorithms with improved ability to predict characteristics for single and ensemble risk assessment, especially using artificial intelligence/machine learning (TA 5.5.3).
- Methods for combining commercial data (observations or ephemerides) with 18 SPCS–derived solutions (available as Vector Covariance Messages, Conjunction Data Messages, or Astrodynamics Support Workstation output) to create a single improved orbit determination solution including more data sources.

**References**

1. NASA Space Technology Roadmaps (2015): [https://www.nasa.gov/offices/oct/home/roadmaps/index.html](https://www.nasa.gov/offices/oct/home/roadmaps/index.html) [34]

**Expected TRL or TRL range at completion of the project:** 2 to 5

**Desired Deliverables of Phase II**

Prototype, Analysis, Software, Research

**Desired Deliverables Description**

Phase 1 research should be conducted to demonstrate technical feasibility, with preliminary software being delivered for NASA testing, as well as show a plan toward Phase 2 integration. Phase 2 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 a quasi-operational environment.
State of the Art and Critical Gaps

Current state of the art has been adequate in performing conjunction assessment and collision mitigation for space objects that fall under the high interest events (HIE). With the incorporation of the Space Fence, the number of objects tracked and assessed for conjunctions will increase by one or more orders of magnitude, this presents a critical gap in which current approaches may not suffice. Thus, smarter ways to perform conjunction analysis and assessments such as methods for bundling events and performing ensemble risk assessment, Middle-duration risk assessment (longer duration than possible for discrete events but shorter than decades-long analyses that use gas dynamics assumptions), Improved Conjunction Assessment (CA) event evolution prediction, Machine learning / Artificial Intelligence (AI) applied to CA risk assessment parameters and/or event evolution are needed. The decision space for collision avoidance relies on not only the quality of the data (state and covariance) but also the tools and techniques for conjunction assessment.

Collision avoidance maneuver decisions are based on predicted close approach distance and probability of collision. The accuracy of these numbers depend on underlying measurements and mathematics used in estimation. Current methods assume Gaussian distributions for errors and that all objects are shaped like cannon balls for non-gravitational force computations. These assumptions and others cause inaccurate estimates which can lead decision makers to perform unnecessary collision avoidance maneuvers, thus wasting propellant. Better techniques are needed for orbit prediction and covariance characterization and propagation. Better modeling of non-gravitational force effects is needed to improve orbit prediction. Modeling of non-gravitational forces relies on knowledge of individual object characteristics.

Relevance / Science Traceability

This technology is relevant and needed for all human spaceflight and robotic missions in the near-Earth environment. The ability to perform CARA more accurately will improve space safety for all near-Earth operations, improve operational support by providing more accurate and longer term predictions and reduce propellant usage for collision avoidance maneuvers.

H9.05 Transformational Communications Technology

Lead Center: GSFC

Participating Center(s): GSFC

Technology Area: TA15 Aeronautics

Scope Title: Revolutionary Concepts

Scope Description

NASA seeks revolutionary transformational communications technologies, for lunar exploration and beyond, that emphasize not only dramatic reduction in system size, mass and power but also dramatic implementation and operational cost savings while improving overall communications architecture performance. 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 transformational communications technology development will focus research in the following areas:

- Systems optimized for energy efficiency (information bits per unit energy)
- Hybridization of communications and sensing systems to maximize performance and minimize Size, Weight and Power (SWaP), especially for harsh environments
- Advanced materials; smart materials; electronics embedded in structures; functional materials; graphene-
based electronics/detectors

- Techniques to overcome traditional analog-to-digital converter speed and power consumption limitations
- 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.
- Energy harvesting technologies to enhance space communication system efficiency
- Human/machine and brain-machine interfacing to enable new communications paradigms; the convergence of electronic engineering and bio-engineering; neural signal interfacing
- Quantum communications, methods for probing quantum phenomenon, methods for exploiting exotic aspects of quantum theory.

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.

References

https://sbir.nasa.gov/sites/default/files/Presentation15_CharlesNiederhaus.pdf [49]

https://www.nasa.gov/pdf/675092main_SCaN_ADD_Executive_Summary.pdf [50]

Expected TRL or TRL range at completion of the project: 2 to 4

Desired Deliverables of Phase II

Prototype, Analysis, Research

Desired Deliverables Description

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.

State of the Art and Critical Gaps

While according to the Business R&D and Innovation Survey of the $323 billion of research and development performed by companies in the United States in 2013, Information and Computing Technology industries accounted for 41%. But it must be understood that the majority of these investments seek short term returns and that most of the investment is in computer technology, cloud computing and networking, semiconductor manufacturing, etc. - not new and futuristic "over-the-horizon" technologies with uncertain returns-on-investment. As a concrete example, deep-space mission modeling indicates a need for a 10X improvement in data rate per decade out to 2040. How will that be achieved? To some extent that goal will be achieved by moving to Ka-band and optical communications and perhaps antenna arraying on a massive scale. But given the ambitiousness of the goal, disruptive technologies like what is being sought here, will be required.

Relevance / Science Traceability

NASA seeks revolutionary, transformational communications technologies that emphasize not only dramatic reduction in system size, mass, and power but also dramatic implementation and operational cost savings while improving overall communications architecture performance. This is a broad sub-topic 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.

H9.07 Cognitive Communication

Lead Center: GSFC

Participating Center(s): GSFC, JPL

Technology Area: TA15 Aeronautics

Scope Title

Lunar Cognitive Capabilities

Scope Description

NASA’s Space Communication and Navigation (SCaN) program seeks innovative approaches to increase mission science data return, improve resource efficiencies for NASA missions and communication networks and ensure resilience in the unpredictable space environment. The Cognitive Communication subtopic specifically focuses on advances in space communication driven by on-board data processing and modern space networking capabilities. A cognitive system is envisioned to sense, detect, adapt, and learn from its experiences and environment to optimize the communications capabilities for the user mission satellite or network infrastructure. The underlying need for these technologies is to reduce both the mission and network operations burden.

Examples of these cognitive capabilities include:

- Link technologies - reconfiguration and autonomy, maximizing use of bandwidth while avoiding interference
- Network technologies - robust inter-satellite links, data storage/forwarding, multi-node routing in unpredictable environments
- System technologies - optimal scheduling techniques for satellite and surface relays in distributed and real-time environments

Through Space Policy Directive-1, NASA is committed to landing American astronauts on the Moon by 2024. In support of this goal, cognitive communication techniques are needed for lunar communication satellite and surface relays. Cognitive agents operating on lunar elements will manage communication, provide diagnostics, automate resource scheduling, and dynamically update data flow in response to the types of data flowing over the lunar network. Goals of this capability are to improve communications efficiency, mitigate channel impairments, and reduce operations complexity and cost through intelligent and autonomous communications and data handling.

Examples of research and/or technology development include:

- On-board processing technology and techniques to enable data switching, routing, storage, and processing on a relay spacecraft
- Data-centric, decentralized network data routing and scheduling techniques that are responsive to quality of service metrics
- Simultaneous wideband sensing and communications for S-, X-, and Ka-bands, coupled with algorithms that learn from the environment
- Artificial intelligence and machine learning algorithms applied to optimize space communication links, networks, or systems
- Flexible communication platforms with novel signal processing technology to support cognitive approaches
- Other innovative, related areas of interest to the field of cognitive communications

Proposals to this subtopic should consider application to a lunar communications architecture consisting of surface assets (e.g., astronauts, science stations, surface relays), lunar communication relay satellites, Gateway, and ground stations on Earth. The lunar communication relay satellites require technology with low size, weight, and
power attributes suitable for small satellite (e.g., 50kg) or cubesat operations. Proposed solutions should highlight advancements to provide the needed communications capability while minimizing use of on-board resources such as power and propellant. Proposals should consider how the technology can mature into a successful demonstration in the lunar architecture.

References

Several related reference papers and articles include:

- "NASA Explores Artificial Intelligence for Space Communications"
  - [https://www.nasa.gov/feature/goddard/2017/nasa-explores-artificial-intelligence-for-space-communications][51]
- "Implementation of a Space Communications Cognitive Engine"
  - [https://ntrs.nasa.gov/search.jsp?R=2018002166][52]
- "Reinforcement Learning for Satellite Communications: From LEO to Deep Space Operations"
  - [https://ieeexplore.ieee.org/document/8713802][53]
- "Cognitive Communications and Networking Technology Infusion Study Report"
  - [https://ntrs.nasa.gov/search.jsp?R=20190011723][54]
- "Multi-Objective Reinforcement Learning-based Deep Neural Networks for Cognitive Space Communications"
  - [https://ntrs.nasa.gov/search.jsp?R=20170009153][55]
- "Assessment of Cognitive Communications Interest Areas for NASA Needs and Benefits"
  - [https://ntrs.nasa.gov/search.jsp?R=20170009386][56]
- "Architecture for Cognitive Networking within NASAs Future Space Communications Infrastructure"
  - [https://ntrs.nasa.gov/search.jsp?R=20170001295][57]
- "Modulation Classification of Satellite Communication Signals Using Cumulants and Neural Networks"
  - [https://ntrs.nasa.gov/search.jsp?R=20170006541][58]

A related conference, co-sponsored by NASA and the Institute of Electrical and Electronics Engineers (IEEE), the Cognitive Communications for Aerospace Applications Workshop, has additional information available at: [http://ieee-ccaa.com/][59]

Expected TRL or TRL range at completion of the project: 4 to 6

Desired Deliverables of Phase II

Prototype, Hardware, Software

Desired Deliverables Description

Phase I will study technical feasibility, infusion potential for lunar operations, clear/achievable benefits and show a path towards a Phase II implementation. Phase I deliverables can include a feasibility assessment and concept of operations of the research topic, simulations and/or measurements, validation of the proposed approach to develop a given product (TRL 3-4) and a plan for further development of the specific capabilities or products to be performed in Phase II. Early development, integration, test, and delivery prototype hardware/software is encouraged but not necessary.

Phase II will emphasize hardware/software development with delivery of specific hardware or software product for NASA targeting demonstration operations on a small satellite or cubesat platform. Phase II deliverables include a working prototype (engineering model) of the proposed product/platform or software, along with documentation of development, capabilities, and measurements, and related documents and tools as necessary for NASA to modify and use the cognitive software capability or hardware component(s). Hardware prototypes shall show a path towards flight demonstration, such as a flight qualification approach and preliminary estimates of thermal, vibration, and radiation capabilities of the flight hardware. Software prototypes shall be implemented on platforms that have a clear path to a flight qualifiable platform. Opportunities and plans should be identified for technology commercialization. Software applications and platform/infrastructure deliverables for software defined radio platforms shall be compliant with the latest NASA standard for software defined radios, the Space Telecommunications Radio System (STRS), NASA-STD-4009 and NASA-HNBK-4009.
State of the Art and Critical Gaps

To summarize NASA Technology Roadmap TA5: "As human and science exploration missions move further from Earth and become increasingly more complex, they present unique challenges to onboard communications systems and networks...Intelligent radio systems will help manage the increased complexity and provide greater capability to the mission to return more science data...Reconfigurable radio systems...could autonomously optimize the RF links, network protocols, and modes used based on the needs of the various mission phases. A cognitive radio system would sense its RF environment and adapt and learn from its various configuration changes to optimize the communications links throughout the system in order to maximize science data transfer, enable substantial efficiencies, and reduce latency. The challenges in this area are in the efficient integration of different capabilities and components, unexpected radio or system decisions or behavior, and methods to verify decision-making algorithms as compared to known, planned performance."

The technology need for the lunar communication architecture includes:

- Data routing from surface assets to a lunar communication relay satellite, where data is unscheduled, a-periodic, and ad-hoc
- Data routing between lunar relay satellites as necessary to conserve power, route data to Earth, and meet quality of service requirements
- Efficient use of lunar communication spectrum while co-existing with future/current interference sources
- On-demand communication resource scheduling
- Multi-hop, delay tolerant routing

Critical gaps between the state of the art and the technology need include:

- Implementation of artificial intelligence and machine learning techniques on SWaP-constrained platforms
- Integrated wide-band sensing and narrow-band communication on the same radio terminal
- Inter-satellite networking and routing, especially in unpredictable and unscheduled environments
- On-demand scheduling technology for communication links
- Cross-layer optimization approaches for optimum communication efficiency at a system level

Relevance / Science Traceability

Cognitive technologies are critical for the lunar communications architecture. The majority of lunar operations will be run remotely from Earth, which could require substantial coordination and planning as NASA, foreign space agencies, and commercial interests all place assets on the Moon. As lunar communications and networks become more complex, cognition and automation are essential to mitigate complexity and reduce operations costs. Machine learning will configure networks, choose radio configurations, adjust for impairments and failures, and monitor short and long term performance for improvements.

H10.01 Advanced Propulsion Systems Ground Test Technology

Lead Center: KSC

Participating Center(s): KSC

Technology Area: TA15 Aeronautics

Scope Title

Advanced Propulsion Test Technology Development

Scope Description
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, in-space propulsion and so forth. It involves a combination of component and engine-level testing to demonstrate the propulsion devices were designed to meet the specified requirements for a specified operational envelope over robust margins and shown to be sufficiently reliable prior to its first flight.

This topic area seeks to develop advanced ground test technology components and system level ground test systems that enhance Chemical and Advanced Propulsion technology development and certification. The goal is to advance propulsion ground test technologies to; enhance environment simulation, minimize test program time, cost and risk; and meet existing environmental and safety regulations. It is focused on near-term products that augment and enhance proven, state-of-the-art propulsion test facilities. This project 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 stable combustion of oxygen and hydrogen in a low pressure duct, developing robust materials, and advanced instruments and monitoring systems capable of operating in extreme temperature and harsh environments.

This subtopic seeks innovative technologies in the following areas:

- Design of technology/techniques for oxygen injection into a duct that assures stable combustion with hot (>1700°R) hydrogen at low pressure (<25 psia), having an oxidizer to fuel mixture ratio of 9 for an oxygen flow rate of approximately 2.7 lbm/sec. This technology solution must be extensible to a system having an oxygen flow rate of approximately 270 lbm/sec.
- 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 that integrate simple interfaces with detailed design and/or analysis software, are required. Stennis Space Center (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 and 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.

References

https://www.nasa.gov/centers/stennis/home/index.html [60]

https://technology.ssc.nasa.gov/ [61]

Expected TRL or TRL range at completion of the project: 4 to 6

Desired Deliverables of Phase II
Prototype, Hardware, Software

**Desired Deliverables Description**

For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I and show a path toward 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.

**State of the Art and Critical Gaps**

This subtopic seeks to provide technological advances that provide the ability to test next generation rocket propulsion systems while reducing costs, increasing efficiencies and improving safety/reliability within the static rocket engine test environment. Specifically, the goal is to reduce costs of propellants and other fluids; reduce logistics costs; reduce times required for ground processing and launch; reduced mission risk; and reduced hazards exposure to personnel.

There is a broad range of technologies needed to support rocket propulsion testing. Dynamic fluid flow simulation is used to characterize and model the facility performance in a highly dynamic environment with NASA, Department of Defense (DoD) and commercial customers. Multiple issues remain with modeling combustion instabilities and component/facility performance. These issues can have catastrophic results if not understood completely. New test programs will require the materials to withstand extreme temperatures and harsh environments. Next generation testing requires the ability to produce very high temperature hydrogen at high near-continuous flow rates to verify component and facility performance. The extreme and harsh environment also requires advancements in mechanical components and instrumentation.

**Relevance / Science Traceability**

Subtopic is relevant to the development of liquid propulsion systems development and verification testing in support of the Human Exploration and Mission Operations Directorate (HEOMD), all test programs at SSC and other propulsion system development centers.

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H10.02 Autonomous Operations Technologies for Ground and Launch Systems

**Lead Center:** KSC

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

**Technology Area:** TA15 Aeronautics

**Scope Description**

Autonomous Operations Technologies (AOT) are required to reduce operations and maintenance (O&M) costs of ground and payload processing operations on ground, and to increase ground systems availability to support mission operations. These technologies will also be required for extended surface O&M on the Moon and Mars. Furthermore, AOT are required in activities where human intervention/interaction/presence needs to be minimized, such as in hazardous locations/operations and in support of remote operations.

AOT performs functions such as systems and components’ fault prediction and diagnostics, anomaly detection, fault detection and isolation, and enables various levels of autonomous control and recovery from faults, where recovery may include system repair and/or reconfiguration. AOT are enabled by Health Management (HM) technologies, methodologies, and approaches; command, monitoring and control architectures; computing architectures; software for decision-making and control; and intelligent components and devices.

AOT will be integrated in activities performed by rocket engine test facilities, propellant servicing systems, and processing and launch of vehicles and payloads. AOT will complement In-Situ Resources Utilization (ISRU) operations. AOT will enable surface O&M, which requires high degree of autonomy and reliability for unattended
operations during extended periods of time. AOT enables Autonomous Propellant Management (APM), which requires unattended or minimally attended storage, transfer, monitoring, and sampling of cryogenic propellants, or other propellants use in launch systems. APM includes pre-planned nominal processes, such as vehicle fill and drain, as well as contingency and off-nominal processes, such as emergency safing, venting and system reconfiguration.

AOT will enable the autonomous command, monitoring and control of the overall system, resulting from the integration of loading systems and all other associated support systems involved in the loading process. AOT will also support tasks such as systems 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.

The AOT autonomy software will include 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.

Specifically, this subtopic seeks the:

- Standardization of architectures and interfaces
- Standardization of ground systems design (design for maintainability, commonality, reusability)
- Development of ground technologies for automated/autonomous cryogenic loading and servicing of commodities for ground and lunar payloads
- Development of high-fidelity physics-based cryogenic-thermal models and simulations capable of real-time and faster than real-time performance
  - Development of high-fidelity models and simulations for complex payload systems
  - Development of automated/autonomous algorithms for ground systems applications
  - Development of Test and Evaluation (T&E), and verification and validation (V&V) methods for automated/autonomous algorithms, models and simulations
- Development of technologies for ground systems Health Determination and Fault Management
  - Prediction, prognosis and anomaly detection algorithms and applications
  - Detection, isolation, and recovery of systems and components faults and degradation
  - Development of Test and Evaluation (T&E), and verification and validation (V&V) methods for Health Determination and Fault Management algorithms and applications
- Development of technologies for automated/autonomous Planning and Scheduling (P&S)
  - Automated/Autonomous Assets management tools and applications
  - Scheduling and prioritization algorithms and applications
  - Human-machine information interactions
- Development of technologies for automated/autonomous Inspection, Maintenance and Repair
  - Use of robotic caretakers for inspection, maintenance and repair needs
  - Self-diagnosis in systems and components (Condition Based Maintenance)
- Development of technologies for enhanced Logistics and Reliability
  - Optimization/Reduction of logistics needs (design for maintainability, commonality, reusability)
  - Commonality of maintenance equipment, tools and consumables
  - Automated/autonomous assets and personnel location and condition
  - Intelligent Devices (sensors, actuators and electronics with self-diagnosis capabilities, calibration on demand, self-healing capabilities, etc.)

For all above technologies, research should be conducted to demonstrate technical feasibility during Phase I; show a path toward Phase II demonstration; deliver a demonstration package for NASA testing in operational or analog test environments at the completion of the Phase II contract. Successful Phase II technologies will be candidates for integration and demonstration in the existing Advanced Ground Systems Maintenance (AGSM) Integrated Health Management (IHM) Architecture, deployed at Kennedy Space Center (KSC).
References

NASA Technology Roadmaps (https://www.nasa.gov/offices/oct/home/roadmaps/index.html [34])

NASA Strategic Space Technology Investment Plan (https://www.nasa.gov/sites/default/files/atoms/files/strategic_space_technology_investment_plan_508.pdf [62])

Expected TRL or TRL range at completion of the project: 5 to 8

Desired Deliverables of Phase II

Prototype, Hardware, Software

Desired Deliverables Description

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.

State of the Art and Critical Gaps

There are presently critical gaps between state-of-the-art and needed technology maturation levels as follows:

1) High-fidelity, physics-based, cryogenic-thermal simulations with real-time and faster than real-time performance (Current TRL is 5; Required TRL is 9)

2) Simulation Component libraries to support rapid prototyping of cryogenic-thermal models (Current TRL is 5; Required TRL is 9)

3) Supervisory control software for autonomous control and recovery of propellant loading systems and infrastructure (Current TRL is 5; Required TRL is 9)

4) Software development tools to support rapid prototyping of autonomous control applications (Current TRL is 5; Required TRL is 9)

5) Architecture for integrated autonomous operations (Current TRL is 5; Required TRL is 9)

Relevance / Science Traceability

In addition to reducing O&M costs in ground operations, this subtopic provides Human Exploration Operations Mission Directorate (HEOMD) with an on-ramp for technologies that enable the unattended setup, operation and maintenance of ground systems and systems on the surfaces of other planets and moons. With the recently directive from the President to accelerate the landing of astronauts on the Moon and provide sustainable presence after 2028, these technologies have become more relevant. These types of technology development are identified in the NASA Strategic Technology Area (TA) roadmaps, published by the Office of the Chief Technologist, under TA4 - Robotics and Autonomous Systems, and TA13- Ground and Launch Systems roadmaps.
This subtopic produces technologies which will also be of use to the Space Technology Mission Directorate (STMD) program. Autonomous strategies have crosscutting value in other applications and with other mission directorates.

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

Lead Center: JSC

Technology Area: TA15 Aeronautics

Scope Title
Radioprotectors and Mitigators of Space Radiation-Induced Health Risks

Scope Description
Space radiation is a significant obstacle when sending humans on long-duration missions beyond low earth orbit. Although various forms for radiation exist in space, astronauts during Lunar or Mars missions will be exposed constantly to galactic cosmic radiation (GCR), which consists of high energy particles ranging from protons to extremely heavy ions. Astronaut health risks from space radiation exposure are categorized into cancer, late and early central nervous systems (CNS) effects, and degenerative risks, which include cardiovascular diseases and premature aging. With the current exposure limits for cancer risks, few female astronauts will be able to fly long duration missions without countermeasures.

This subtopic solicits proposals to develop biological countermeasures that mitigate one or several of the radiation risks associated with space travel. Compounds that target common pathways (e.g., inflammation) across aging, cancer, cardiovascular disease and neurodegeneration would be preferred. Most of the countermeasure developments in the medical arena have focused on mitigating the effects of X- or gamma rays. The proposed project should focus on re-purposing of technology and compounds for high-energy charged-particle applications. Compounds that are under current development or have been proven effective for other applications are both suitable for this subtopic.

In Phase I of the project, the company should test radioprotectors or mitigators using protons or other charged particles at doses simulating exposure to space radiation. This testing can be done with cell models at the location of choice. Deliverables for the Phase I will be data generated from this exposure with the radioprotector selected. After contract award, due to the nature of this research, the contractor should immediately coordinate with their technical monitor for any special considerations for testing. In Phase II of the project, we would expect the company to expand testing radioprotectors or mitigators with combinations of different particles and energies that simulate the space radiation environment. Appropriate animal models, which may include chimeric humanized mouse models, should be used for the Phase II project.

This subtopic seeks technology development that benefits the Space Radiation Element of the NASA Human Research Program (HRP). Biomedical countermeasures are needed for all of the space radiation risks.

References
The following references discuss the different health effects NASA has identified in regard to space radiation exposure:

- Evidence report on central nervous systems effects - https://humanresearchroadmap.nasa.gov/evidence/reports/CNS.pdf [63].
- Evidence report on degenerative tissue effects - https://humanresearchroadmap.nasa.gov/evidence/reports/Degen.pdf [64].
**Expected TRL or TRL range at completion of the project** 5 to 8

**Desired Deliverables Description**

Phase I will test radioprotectors or mitigators using protons or other charged particles at space relevant doses. This testing can be done with cell models at the location of choice. After contract award, due to the nature of this research, the contractor should immediately coordinate with their technical monitor for any special considerations for testing.

Phase II will test effective radioprotectors or mitigators in space radiation simulated environments (HZE) to determine if they are able to minimize or prevent space radiation risks. Companies should provide a test plan for in vivo evaluation that describes the expected effect from the compound. Testing in NASA-owned space radiation simulation facilities will be an option for Phase II.

**State of the Art and Critical Gaps**

Exposure of crew members to space radiation during Lunar and Mars missions can potentially impact the success of the missions and cause long-term diseases. Space radiation risks include cancer, late and early CNS effects, cardiovascular diseases, and accelerated aging. Abiding by the current exposure limits for cancer risks, few female astronauts will be able to fly long-duration missions. Mitigation of space radiation risks can be achieved with physical (shielding) and biomedical means. This subtopic addresses development of drugs that mitigate one or several of the identified space radiation risks. Countermeasures for adverse health effects from radiation exposure are of interest to Department of Defense (DoD), Department of Homeland Security (DHS) and the radiation therapy community as well.

**Relevance / Science Traceability**

This subtopic seeks technology development that benefits the Space Radiation Element of the NASA Human Research Program (HRP). Biomedical countermeasures are needed for all of the space radiation risks.

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**H12.05 Autonomous Medical Operations**

**Lead Center:** JSC

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

**Technology Area:** TA15 Aeronautics

**Scope Title**

Autonomous Medical Operations

**Scope Description**

Current medical operations on the International Space Station (ISS) rely significantly on the Mission Control Center (MCC) and telemedicine to enable Crew Health and Performance (CHP). Near real-time communications allow MCC staff (Flight Surgeons, Flight Controllers, etc.) to guide the crew when a medical scenario exceeds the crew’s knowledge, skills or abilities. Prior to launch, crew are trained in the basic operation of the medical assets on the ISS and use detailed procedures to respond to a variety of planned and unplanned events. The training and procedures, however, are limited and do not adequately address the breadth of medical situations that may arise in flight. MCC expertise extends these capabilities allowing the crew to respond to an even larger set of events. Despite this, it is possible that some events will exceed the crew's and MCC’s ability to respond and will require the crew to rapidly return to earth and seek definitive medical care in a hospital.

Mars missions, however, will not have real-time communications with MCC nor will they have a rapid return capability. Round trip communications between the surface of Mars and Earth is approximately 40 minutes and the return trip will be months, which significantly complicates NASA’s current medical operations. Communication bandwidth considerations may also limit data transmission between the crew and MCC even in the event of high
acuity medical situations. More specifically, a variety of existing ISS medical operations require the crew to ‘Contact MCC’ or ‘Notify Surgeon’ for additional instructions, a capability that will be significantly reduced on Mars. Examples of existing ISS medical operations can be found within the links found in the references section.

NASA requires new technologies that will enable a greater degree of autonomy and self-reliance for the crew and allow them to operate in a progressively Earth independent manner. These technologies should also be dual-purposed to enable MCC to better monitor and predict adverse conditions. Ideally, these solutions should require minimal mass, volume, power and/or crew time. Examples of technology developments can include, but are not limited to, advanced just-in-time training modalities, enhanced procedure execution technologies (augmented reality), autonomous physiologic monitoring and trend prediction, automated and in-situ diagnostic and image interpretation, multipurpose medical supplies and devices, etc. The best technology solutions will 1) maximize crew autonomy and self-reliance across a wide range of medical operations, 2) demonstrate how technology could be leveraged to prevent adverse medical conditions, and 3) extend the amount of time needed before MCC intervention is required.

References

http://spaceref.com/iss/medical.ops.html [66]
https://www.nasa.gov/hrp/elements/exmc [67]

Expected TRL or TRL range at completion of the project 2 to 4

Desired Deliverables of Phase II

Prototype, Hardware, Software

Desired Deliverables Description

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

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

State of the Art and Critical Gaps

There are a variety of innovative technologies that are being developed, but the bulk of this technology is either not yet in clinical practice or has not been translated to a clinical domain.

Relevance / Science Traceability

A significant portion of ISS Medical Operations procedures require MCC to properly execute a medical procedure. Contacting MCC on Mars will be significantly limited and technologies need to be developed that allow the crew to operate for longer periods of time without direct MCC interaction.