NASA SBIR 2022 Phase I Solicitation

Space Technology

Z1.05 Lunar and Planetary Surface Power Management and Distribution

Lead Center: GRC

Participating Center(s): GSFC, JSC

Scope Title

Innovative Ways to Transmit Power over Long Distances for Lunar and Mars Missions

Scope Description

The Global Exploration Roadmap (January 2018) and the Space Policy Directive (December 2017) detail NASA’s plans for future human-rated space missions. A major factor in this effort involves establishing bases on the lunar surface and eventually Mars. Surface power for bases is envisioned to be located remotely from the habitat modules and must be efficiently transferred over significant distances. The International Space Station (ISS) has the largest and highest power (100 kW) space power distribution system, with eight interleaved microgrids providing power functions similar to a terrestrial power utility. Planetary bases will be similar to the ISS, with expectations of storage, science, and habitation modules and multiple power sources, but at higher power levels and with longer distribution networks providing interconnection. In order to enable high-power (>100 kW) and longer distribution systems on the surface of the Moon or Mars, NASA is in need of innovative technologies in the areas of lower mass/higher efficiency power electronic regulators, switchgear, connectors, wireless sensors, power scavenging, and power management control. The technologies of interest would need to operate in extreme temperature environments, including lunar night, and could experience temperature changes ranging from -153 to 123 °C for lunar applications and -125 to 80 °C for Mars bases. In addition to temperature extremes, technologies would need to withstand (have minimal degradation from) lunar dust/regolith, Mars dust storms, and space radiation levels.

While this subtopic would directly address the lunar and Mars base initiatives, technologies developed could also benefit other NASA Mission Directorates, including SMD (Science Mission Directorate) and ARMD (Aeronautics Research Mission Directorate). Specific projects that could find value in the technologies developed herein include Gateway, In-Situ Resource Utilization (ISRU), Advanced Modular Power Systems (AMPS), In-Space Electric Propulsion (ISP), planetary exploration, and Electrified Aircraft Propulsion Technology. The power levels may be different, but the technology concepts could be similar, especially when dealing with temperature extremes and the need for electronics with higher power density and efficiency.

Specific technologies of interest would need to address the lunar or Mars environment and include:

- Application of wide-bandgap electronics in direct current (DC)-to-DC isolating converters with wide-temperature (-70°C to 150°C), high-power-density (>2 kW/kg), high-efficiency (>96%) power electronics and associated drivers for voltage regulation.
- Distribution components of a three-phase/1,200-Hz permanent magnet alternator, 480-VAC to 650-VDC
power management and distribution with direct drive to Hall thrusters. Key components of the distribution include rotary alternators and alternating current (AC) transmission, including alternator voltage, step-up/step-down transformers, and rectifiers.

NOTE: See Subtopic Z13.02, Mechanisms for Extreme Environments, to propose power connection/termination-related technologies that are impervious to environmental dust and enable robotic deployment, such as robotically enabled high-voltage connectors and/or near-field wireless power transfer in the 1- to 10-kW range.

Expected TRL or TRL Range at completion of the Project

3 to 6

Primary Technology Taxonomy

Level 1

TX 03 Aerospace Power and Energy Storage

Level 2

TX 03.3 Power Management and Distribution

Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description

Typically, deliverables under Phase I proposals are geared toward a technology concept with associated analysis and design. A final report usually suffices in summarizing the work, but a prototype is preferred. Phase II hardware prototypes will have opportunities for infusion into NASA technology testbeds and commercial landers.

State of the Art and Critical Gaps

While high-power terrestrial distribution systems exist, there is no equivalent to a lunar or planetary base. Unique challenges must be overcome in order to enable a realistic power architecture for these future applications, especially when dealing with the environmental extremes that will be encountered. Operability in environments subject to temperature swings will be a critical requirement for any technology developed, from power converters to cabling or power-beaming concepts. In addition, proposals will have to consider lunar regolith and Mars dust storms. To enable a new Mars transportation capability for human exploration, new technology development must be started soon to address the unique needs of a mixed alternating current/direct current (AC/DC) space-rated power system to prove feasibility and provide realistic performance metrics for detailed vehicle design concepts and mission trade studies.

Relevance / Science Traceability

This subtopic would directly address a remaining technology gap in the lunar and Mars surface mission concepts and Mars human transportation needs. There are potential infusion opportunities with SMD (Science Mission Directorate), Commercial Lander Payload Services (CLPS), HEOMD (Human Exploration and Operations Mission Directorate), and Flexible Luna Architecture for Exploration (FLARE). In addition, technologies developed could benefit other NASA missions, including Gateway. The power levels may be different, but the technology concepts could be similar, especially when dealing with temperature extremes.

References
Z1.06 Radiation-Tolerant High-Voltage, High-Power Electronics

Lead Center: GRC

Participating Center(s): GRC, JPL, LaRC

Scope Title

Radiation-Tolerant High-Voltage, High-Power Electronics

Scope Description

NASA’s directives for space exploration and habitation require high-performance, high-voltage transistors and diodes capable of operating without damage in the natural galactic cosmic ray space radiation environment and induced neutron environment. Recently, significant progress has been made in the research community in understanding the mechanisms of heavy-ion-radiation-induced single-event effect (SEE) degradation and catastrophic failure of wide bandgap (WBG) power transistors and diodes. This subtopic seeks to facilitate movement of this understanding into the successful development of radiation-hardened gallium nitride high-voltage transistors and gallium nitride and/or silicon carbide rectifiers to meet NASA mission power needs reliably in the space environment. These needs include:

- **High-voltage, high-power solutions:** Taxonomy Area (TX) 03.3.4 (Power Management and Distribution (PMAD) - Advanced Electronic Parts) calls out the need for development of radiation-hardened high-voltage components for power systems. NASA has a core need for diodes and transistors that meet the following specifications:
  - Diodes: Minimum 1200 V, 40 A, with fast recovery <50 ns. Forward voltage drop should not exceed 150% of that in state-of-the-art (SOA) unhardened diodes.

- **High-voltage, low-power solutions:** In support of TX 8.1.2 (Sensors and Instruments - Electronics), radiation-hardened high-voltage transistors are needed for low-mass, low-leakage, high-efficiency applications such as lidar Q-switch drivers, mass spectrometers, and electrostatic analyzers. High-voltage, fast-recovery diodes are needed to enhance performance of a variety of heliophysics and planetary science instruments.
  - Diodes: 2 kV to 5 kV, <50-ns recovery time. Forward voltage drop should not exceed 150% of that in SOA unhardened diodes.
  - Transistors: Minimum 1000 V, <50-ns turn-on and turn-off times.

- **High-voltage, low- to medium-power solutions:** In support of peak-power solar tracking systems for planetary spacecraft and small satellites, transistors and diodes are needed to increase buck converter efficiencies through faster switching speeds.
  - Transistors: Minimum 600 V, <50-ns turn-on and turn-off times, current ranging from low to >20 A.

Successful proposal concepts should result in the fabrication of GaN transistors and/or GaN or SiC diodes that meet or exceed the above performance specifications without susceptibility to damage due to the galactic cosmic ray heavy-ion space radiation environment (SEEs resulting in permanent degradation or catastrophic failure) and the fission reactor environment. These diodes and/or transistors will form the basis of innovative high-efficiency, low-mass, and low-volume systems and therefore must significantly improve upon the electrical performance.
available from existing heavy-ion SEE radiation-tolerant devices. Lower TRL (technology readiness level) semiconductor technologies are not solicited at this time.

**Expected TRL or TRL Range at completion of the Project**

4 to 5

**Primary Technology Taxonomy**

**Level 1**

TX 03 Aerospace Power and Energy Storage

**Level 2**

TX 03.3 Power Management and Distribution

**Desired Deliverables of Phase I and Phase II**

- Hardware
- Prototype
- Analysis

**Desired Deliverables Description**

Phase I deliverables must state the initial SOA for the proposed technology and justify the expected final performance metrics. Well-developed plans for validating the tolerance to heavy-ion radiation must be included, and the expected total ionizing dose tolerance should be indicated and justified or test plans included. Target radiation performance levels will depend upon the device structure due to the interaction of the high electric field with the ionizing particle.

**Heavy-ion SEE susceptibility:**

- For vertical-field power devices: No heavy-ion-induced permanent destructive effects upon irradiation while in blocking configuration (in powered reverse-bias/off state) with ions having a silicon-equivalent surface-incident linear energy transfer (LET) of 40 MeV·cm²/mg and sufficient energy to maintain a rising LET level throughout the epitaxial layer(s).
- For all other devices: No heavy-ion-induced permanent destructive effects upon irradiation while in blocking configuration (in powered reverse-bias/off state) with ions having a silicon-equivalent surface-incident LET of 75 MeV·cm²/mg and sufficient energy to penetrate to the substrate interface prior to the ions reaching their maximum LET value (Bragg peak).

**Induced radiation effect susceptibility:**

- All devices should maintain performance requirements at neutron dose levels of $10^{11}$ to $10^{13}$ cm⁻² total 1-MeV neutron equivalent fluence, and between 100 and 1,000 krad(Si) total ionizing gamma-ray dose under worst-case bias conditions.

Deliverables in Phase II shall include prototype and/or production-ready semiconductor devices (diodes and/or transistors); and device electrical and radiation performance characterization (device electrical performance specifications, heavy-ion SEE test results, and neutron and gamma total-dose radiation analyses or test results).

**State of the Art and Critical Gaps**

High-voltage silicon power devices are limited in current ratings and have limited power efficiency and higher
losses than do commercial WBG power devices. Efforts to space-qualify WBG power devices to take advantage of
their tremendous performance advantages revealed that they are very susceptible to damage from the high-
energy, heavy-ion space radiation environment (galactic cosmic rays), which cannot be shielded against. Higher
voltage devices are more susceptible to these effects. Space-qualified GaN transistors are currently available, but
these are limited to 300 V. Recent radiation testing of 600-V and higher GaN transistors has shown failure
susceptibility at about 50% of the rated voltage, or less. Silicon carbide power devices have undergone several-
generation advances commercially, improving their overall reliability, but catastrophically fail at less than 50% of
their rated voltage.

Specific needs in STMD (Space Technology Mission Directorate) and SMD (Science Mission Directorate) areas
have been identified for spacecraft PMAD, and science instrument power applications and device performance
requirements to meet these needs are included in this subtopic nomination. In all cases, there is no alternative
solution that can provide the mass and power savings sought to enable game-changing capability. Current PPUs
(power processing units) and instrument power systems rely on older silicon technology with many stacked devices
and efficiency penalties. In NASA's move to do more with less (smaller satellites), and its lunar/planetary habitation
objectives requiring up to 100 kW power production, the technology sought by this subtopic is truly enabling.

State-of-the-art, currently available heavy-ion SEE-tolerant silicon power devices include a Schottky diode capable
of 600 V, 30 A, and 27-ns recovery time, and a power MOSFET (metal-oxide semiconductor field-effect transistor)
capable of 650 V, 28 A, with on-state resistance of 116 mohm and >50 ns turn-off time. Commercial (non-SEE
tolerant) GaN and SiC offerings are available that meet the electrical performance needs indicated in this subtopic,
but that cannot meet the heavy-ion SEE requirements indicated.

Relevance / Science Traceability

Power transistors and diodes form the building blocks of numerous power circuits for spacecraft and science
instrument applications. This subtopic therefore feeds a broad array of space technology hardware development
activities by providing SEE (heavy-ion) and total-dose radiation-hardened SOA device technologies that achieve
higher voltages with lower power consumption and greater efficiency than is presently available.

TX 03.3.4, Power Management and Distribution (PMAD) – Advanced Electronic Parts, calls out the need for
development of radiation-hardened high-voltage components for power systems. This subtopic serves as a feeder
to the subtopic Lunar and Planetary Surface Power Distribution, in which WBG circuits for PMAD applications are
solicited. The solicited developments in this subtopic will also feed systems development for the NASA Kilopower
project due to the savings in size/mass combined with radiation hardness.

TX 08.1.2, Sensors and Instruments – Electronics: Radiation-hardened high-voltage transistors are needed for low-
mass, low-leakage, high-efficiency applications such as lidar Q-switch drivers, mass spectrometers, and
electrostatic analyzers. These applications are aligned with science objectives including Earth science lidar needs,
Jovian moon exploration, and Saturn missions. Finally, mass spectrometers critical to planetary and asteroid
research and in the search for life on other planets such as Mars require high-voltage power systems and will thus
benefit from mass and power savings from this subtopic's innovations.

References

Partial listing of relevant references:

1. S. J. Pearton, A. Haque, A. Khachatrian, A. Ildefonso, L. Chernyak, and F. Ren, "Review—Opportunities in
2. E. Mizuta et al., "Single-Event Damage Observed in GaN-on-Si HEMTs for Power Control
4. C. Abbate et al., "Experimental Study of Single Event Effects Induced by Heavy Ion Irradiation in
   Effects on SiC Power Device Reliability," in 2021 IEEE International Reliability Physics Symposium (IRPS),

Z1.08 Space-Rated Fuel Cell Technologies

Lead Center: GRC

Participating Center(s): JSC

Scope Title
Reversible Proton Exchange Membrane (PEM) Cells for High-Pressure Oxygen and Hydrogen

Scope Description
Objective: Develop a PEM cell design that stably and efficiently operates in both electrolysis and fuel cell modes at high pressures with pure oxygen and hydrogen.

NASA needs energy storage technologies with very high specific energies (W·hr/kg) to maximize the intended science and exploration payloads. Packaged state-of-the-art lithium ion battery systems have a packaged specific energy of ~180 W·hr/kg. Regenerative fuel cell systems have the theoretical potential to more than double this specific energy, depending on the mission specifics and mission energy requirements. Current regenerative fuel cell (RFC) energy storage systems include a significant balance of plant to manage the discrete stack architecture necessitated by the water management requirements of the hydrogen-oxygen-water reaction triad. Detailed research into potential electrolyte chemistries for high-efficiency/low-mass RFC systems strongly indicates that the PEM technology includes the necessary ionic conductivity to support required reaction rates as well as the mechanical durability to survive the high pressures and dynamic thermal and mechanical environments. A unitized fuel cell that supports both the power-producing fuel cell reaction and the energy-storing electrolysis reaction has the potential to reduce the complexity of the RFC balance of plant. Recent developments by academia, Government, and industry have produced these unitized PEM cells for use in hydrogen/air systems. NASA operates in environments without access to air and must use pure oxygen. This call seeks to leverage the existing developments in the unitized PEM cell design that support high-pressure unitized PEM cell operation in air to utilize...
pure oxygen. As this application is critically limited by available power and mass, preference is given to solutions with lower parasitic power and mass.

- Working fluids: Oxygen, hydrogen, water.
- Operational life: >170 cycles (~10-yr life + flight qualification testing).
- Minimum round-trip efficiency: >48% based on higher heating value (HHV) when measured at 500 mA/cm$^2$ in fuel cell mode, 1,500 mA/cm$^2$ in electrolysis mode.
- Operation in fuel cell mode:
  - Minimum = 3 hr.
  - Target = 366 hr.
- Operation in electrolysis mode:
  - Minimum = 3 hr.
  - Target = 366 hr.
- Maximum time to cycle between modes: 3 min (lower preferred).
- Process fluid pressure range (oxygen and hydrogen):
  - Minimum = 35 to 250 psia.
  - Target = 35 to 2,500 psia.

**Expected TRL or TRL Range at completion of the Project**

2 to 4

**Primary Technology Taxonomy**

**Level 1**

TX 03 Aerospace Power and Energy Storage

**Level 2**

TX 03.2 Energy Storage

**Desired Deliverables of Phase I and Phase II**

- Research
- Prototype
- Hardware
- Analysis

**Desired Deliverables Description**

**Phase I Deliverables:**

1. Final report.
2. Testing up to 250 psia with both reactants.
3. Engineering data package including supporting analyses, design drawings, test plans, and reports.

**Phase II:**

1. Final report.
2. Testing up to 2,500 psia with both reactants.
3. Engineering data package including supporting analyses, design drawings, test plans, and reports.
4. Prototype reversible fuel cell stack of at least five cells with an active area of at least 50 cm$^2$ for testing at a NASA center.
State of the Art and Critical Gaps

Current regenerative fuel cell designs utilize discrete (separate) electrochemical stacks for the fuel cell and electrolysis reactions. A unitized cell has the possibility of significantly reducing the mass of a system by eliminating up to a third of the system components by incorporating both reactions within a single electrochemical stack. The Department of Energy has supported development of unitized cells for hydrogen/air systems. However, these cell designs utilize catalysts and other materials unsuitable for the H₂/O₂ systems required by space applications.

Relevance / Science Traceability

This technology would support any lunar or Mars mission that requires an energy storage system with a specific energy higher than the ~180 W·hr/kg offered by packaged lithium ion battery systems. This includes Science Mission Directorate (SMD) lunar sensor arrays or crewed lunar outposts.

References

The literature contains a large number of papers on the challenges associated with reversible PEM cells. These challenges include catalyst selectivity, amphiphilic/hydrophilic/hydrophobic surface treatments, and fluid versus electrode reversibility. Since the bulk of the recent research in this area was funded by the Department of Energy (DOE), see the DOE Reversible Fuel Cell Targets (https://www.hydrogen.energy.gov/pdfs/20001-reversible-fuel-cell-targets.pdf [3]) for the current terrestrial performance and life targets.

Scope Title

High-Efficiency Reversible Dehumidification Technology

Scope Description

Objective: Develop a desiccant material or other technical solution to manage dew point of bulk gases and recover separated water for later use.

Water management is a major concern on the lunar surface, and operational systems on the lunar surface need to conserve water whenever possible. Power-limited in situ resource utilization (ISRU) and regenerative fuel cell (RFC) energy storage systems generate water-saturated hydrogen and oxygen gases that need to be dehumidified prior to storing the gases. Nonregenerative desiccants or technologies that require dumping absorbed water onboard constitute unacceptable water-loss rates for ISRU and RFC systems. As this application is critically limited by available power and mass, preference is given to solutions with lower parasitic power and mass.

- Bulk fluid 1: Oxygen, saturated with water (noncondensing) at flow rates up to 50 SLPM.
- Bulk fluid 2: Hydrogen, saturated with water (noncondensing) at flow rates up to 100 SLPM.
- Target dew point: < -40 °C.
- Recovery rate (%): >99.3% per cycle.
- Operational life: >100 cycles (~6-yr life + flight qualification testing).
- Process fluid pressure range: 35 to 2,500+ psia.
- Process fluid temperature range: 4 to 85 °C.

Special notes:

- Desiccant materials to be compatible with bulk fluids.
- No slipstreams (any fluids that leave the system through a slipstream represent a loss of system capacity).
- Cannot release particulates to the system that could contaminate the electrochemical hardware.

Expected TRL or TRL Range at completion of the Project

3 to 5
Primary Technology Taxonomy

Level 1

TX 03 Aerospace Power and Energy Storage

Level 2

TX 03.2 Energy Storage

Desired Deliverables of Phase I and Phase II

- Research
- Prototype
- Hardware

Desired Deliverables Description

Phase I Deliverables:

1. Final report.
2. Engineering data package including supporting analyses, design drawings, test plans, and reports.

Phase II Deliverables:

1. Final report.
2. Engineering data package including supporting analyses, design drawings, test plans, and reports.
3. Two prototype sets of hydrogen and oxygen humidification control system for testing at a NASA Center.

State of the Art and Critical Gaps

Based on current research, there exists a gap for regenerative humidity regulation solutions for hydrogen and oxygen gas systems with long-term operation that exclude venting water or gases overboard.

Relevance / Science Traceability

This technology can apply to any NASA mission that produces hydrogen and oxygen from water. Examples include ISRU and power applications and, to a much lesser extent, life support applications.

References


Z2.01 Spacecraft Thermal Management
Scope Title

Spacecraft Thermal Management

Scope Description

NASA seeks new technologies that will facilitate low-mass and highly reliable thermal control systems for the exploration of our solar system. This solicitation specifically targets proposals for new technologies and methods that clearly address one of the following areas:

1. Lunar surface habitat thermal technologies
2. High-temperature heat acquisition and transport for nuclear electric propulsion (NEP)
3. Topology optimization of thermal control systems

These areas are considered of equal priority, and no award preference is expected for one area over another.

1. Lunar Surface Habitat Thermal Technology Development

NASA is seeking focused efforts to develop thermal control technologies that will enable crewed habitats for extended stays on the lunar surface. Technologies should address a gap associated to long-duration habitation on the lunar surface, where temperatures range from -193 °C or lower in shadow regions (including night) to 120° C at the equatorial subsolar point. Technologies are needed that allow a single mobile habitat to operate in all these environments. Technologies should address reduction in mass, volume, and power usage relative to current solutions. The addition of heaters can lead to increased vehicle mass due to additional power generation and storage requirements and is not considered a novel architecture approach. Proposed radiator technologies should also address micrometeoroid and orbital debris (MMOD) robustness and protection potential where appropriate.

Examples of other challenges to address in this area include the deposition of dust on radiators leading to degraded optical properties, contamination-insensitive evaporators/sublimators to enable long mission life, self-healing coolant tubes for MMOD-impact resilience, and passive gas traps for removing gas bubbles from internal thermal control system loops that use low-surface-tension nonwater coolants. Technologies should be suitable for use with habitats having variable heat loads averaging between 2 and 6 kW. All technologies should support a minimum operational duration of 5 years and be compatible with encountered environments.

Alternatively, technologies that utilize the conditions provided by the lunar environment to provide a critical function may also be considered; for example, air-water separator technologies that leverage the gravity field of the lunar surface, or concepts that explore the viability of utilizing the lunar surface regolith to provide long-duration thermal control function. As appropriate, such systems should also address functional capability in the microgravity environment that will be experienced prior to lunar surface operations.

2. High-Temperature Heat Acquisition and Transport for Nuclear Electric Propulsion (NEP)

NASA is seeking the development of thermal transport systems for NEP. This application requires the transfer of large amounts of thermal energy from a nuclear reactor to a power conversion system. NASA desires a high-temperature heat transfer system capable of transferring 4 to 10 MW of thermal power from a nuclear reactor, at a supply temperature of 1,200 to 1,400 K and a flux on the order of 0.3 MW/m² with a goal of 1 MW/m², to the hot-end heat exchangers of an electric power conversion system. The target distance for the power conversion system is 5 m from the reactor, but transport distances up to 10 m may be required. The system will need to be gamma- and neutron-radiation tolerant, be single-fault tolerant (a single leak should not render the system inoperable) and have an operating life of 15+ years. System mass and reliability should be addressed as part of the proposal.

Example solutions include, but are not limited to, liquid metal heat pipes or pumped fluid loops. Special consideration should be given to interfaces (both at the nuclear reactor and at the power conversion system) to
maximize heat transfer. Integration with the reactor may include solutions that run through the reactor core. For integration with the power conversion system, a helium-xenon working fluid in a Brayton cycle system may be assumed but is not required.

3. Topology Optimization of Thermal Control Systems

Advanced design and manufacturing are rapidly transforming engineered systems. The advent of reliable additive manufacturing techniques coupled with robust optimization algorithms is facilitating the development of new high-performance systems. To date, the advanced design community has primarily focused on optimized structural systems that minimize mass and volume while meeting structural performance requirements. While some work has been done to develop advanced design tools for thermal control systems, considerable work remains to make it standard practice. This solicitation requests the development of a topology optimization (TO) tool that can optimize a thermal-fluid component (e.g., a heat exchanger). Specific goals include minimizing component (heat exchanger) mass, minimizing pressure drop, and maximizing heat transfer efficiency. Because of the inherent multiphysics characteristics of the problem (coupled structural/thermal/fluids behavior), proposals are encouraged to leverage existing TO software (e.g., see Watkins (2019) and other TO references below) that can already handle structural and thermal conduction optimization, and extend the code to handle systems that include single-phase laminar convective heat transfer.

This solicitation requests the development of TO software capable of minimizing heat exchanger mass while meeting envelope volume, heat transfer, and pressure drop targets. The initial target is optimization for laminar single-phase flow. An extended goal is to be able to optimize a heat exchanger for turbulent single-phase flow while accommodating manufacturing constraints to ensure the heat exchanger design is manufacturable.

**Expected TRL or TRL Range at completion of the Project**

3 to 5

**Primary Technology Taxonomy**

Level 1

TX 14 Thermal Management Systems

Level 2

TX 14.2 Thermal Control Components and Systems

**Desired Deliverables of Phase I and Phase II**

- Analysis
- Prototype
- Hardware
- Software

**Desired Deliverables Description**

Phase I awards in this area are expected to demonstrate analytical and/or empirical proof-of-concept results that demonstrate the ability of the organization to meet the goals stated in the solicitation.

At the conclusion of a Phase II contract, deliverables are expected to include a functioning prototype (or better) that demonstrates the potential to meet the performance goals of the technology or software. Any delivered math models should include supporting data that validates the assumptions used within the model.

**State of the Art and Critical Gaps**

These focus areas strive to reduce mass, volume, and power of a thermal control system in the next generation of robotic and human-class spacecraft and to enable long-term missions to the Moon and Mars. These improvements
may come through either novel hardware solutions or modernization of software tools. The current state of the art in thermal control systems is vehicle power and mass impact of greater than 25 to 30% due to old technologies still in use. Furthermore, as missions become more variable (dormancy, environments, etc.), the need for intelligent design and control (both actively and passively) within the thermal control system becomes more apparent. For topology optimization (TO) in particular, it has become a well-established structural design tool, but it has yet to penetrate the thermal design community. Multiple research efforts have shown that TO of thermal-fluid systems is possible and can be successfully implemented to obtain optimized designs; however, a robust commercial code that is capable of doing this is yet to be demonstrated. Additionally, science payloads will continue to decrease in size, increase in power, and require precise temperature control, all of which cannot be readily provided by traditional thermal control methods due to vehicle-level impacts of overall performance, mass/volume, and power.

Relevance / Science Traceability

- Long-duration habitats (Moon, Mars, etc.).
- Lunar surface power.
- Mars transit vehicles.
- SmallSats/CubeSats.
- Rovers and surface mobility.
- Nuclear electric propulsion (NEP) systems.

References

Z2.02 High-Performance Space Computing Technology

Lead Center: JSC

Participating Center(s): GSFC

Scope Title
High-Performance Space Computing Technology

Scope Description
Most current NASA missions utilize 20-year-old space computing technology that is inadequate for future missions. Newer processors with improved performance are becoming available from industry but still lack the performance, power efficiency, and flexibility needed by the most demanding mission applications. The NASA High-Performance Spaceflight Computing (HPSC) project is addressing these needs. This subtopic solicits technologies that can enable future high-performance, multicore processors, along with the supporting technologies needed to fully implement avionics systems based on these processors.

- Fault-tolerant internet protocol (IP) core supporting Ethernet, Time-Sensitive Networking (TSN), Time-Triggered Ethernet (TTE), and remote direct memory access (RDMA) over converged Ethernet (RoCE) to support processor clustering.
- Compilers that support software-implemented fault tolerance (SIFT) capabilities (e.g., control flow checking, coordinated checkpoint/rollback, recovery block) for multicore processors are desired.
  - Compile-time fault tolerance is desired by NASA for reorganizing execution code to automatically build redundancy in stall cycles without requiring additional development from the user; this would be exceptional for performance optimization of code without putting additional burden on the developers. This is increasingly important with the adoption of more complex and commercial processors in future missions.
- Radiation-tolerant, point-of-load (POL) converters that feature multiple outputs, intelligent communication, or high power.
  - Modern and next-generation processors require multiple voltage supply levels, requiring multiple discrete POL converters occupying valuable processor card real estate. A multiple-output POL would enable smaller and more powerful spaceflight processing platforms.
  - Future spaceflight systems have increased needs for fault detection, tolerance, and command ability. A POL converter capable of communicating with command-and-control architectures to report health status, telemetry, or to adjust parameters is desired.
  - Future high-powered spaceflight processing applications will have a need for high-power POL converters. Specifically, converters capable of providing low voltage, but high currents (tens of amps) are desired.
- Coprocessors to (a) accelerate onboard artificial intelligence applications, or (b) perform digital signal processing (DSP) functions. Specifically, technologies are sought that either enable the reliable use of commercial off-the-shelf (COTS) coprocessors in space systems, or fault-tolerant IP cores that can be implemented in a radiation-hardened field-programmable gate array (FPGA).
- Radiation-tolerant solid-state memory drives (minimum 1-TB capacity) with Peripheral Component Interconnect Express (PCIe) interface, supporting file systems with industry-standard Non-Volatile Memory Express (NVMe) software stack.
- Checkpointing and recovery mechanism for single-process flight software applications.
Especially with increased use of COTS processors, single-event functional interrupts (SEFIs) have a high chance the processor will need to reset or incur a kernel panic. NASA desires a way for the flight software to be automatically checkpointed or have some sort of functional save-state to recover before the upset.

Current methodologies for resetting and recovering processors and flight software applications can incur considerable downtime and data loss. A more intelligent, rapid method for resetting and recovering is desired. NASA’s Core Flight Software (cFS) would be an ideal candidate software to implement this capability.

Expected TRL or TRL Range at completion of the Project

1 to 4

Primary Technology Taxonomy

Level 1
TX 02 Flight Computing and Avionics

Level 2
TX 02.X Other Flight Computing and Avionics

Desired Deliverables of Phase I and Phase II

- Analysis
- Prototype
- Hardware
- Software
- Research

Desired Deliverables Description

Phase I Deliverables:

For software and hardware elements, a solid conceptual design, plan for full-scale prototyping, and simulations and testing results to justify prototyping approach. Detailed specifications for intended Phase II deliverables.

Phase II Deliverables:

For software and hardware elements, a prototype that demonstrates sufficient performance and capability and is ready for future development and commercialization.

State of the Art and Critical Gaps

Most NASA missions utilize processors with in-space-qualifiable high-performance computing that has high power dissipation (approximately 18 W), and the current state-of-practice Technology Readiness Level 9 (TRL-9) space computing solutions have relatively low performance (between 2 and 200 DMIPS (Dhrystone million instructions per second) at 100 MHz). A recently developed radiation-hardened processor provides 5.6 GOPS (giga operations per second) performance with a power dissipation of 17 W. Neither of these systems provides the desired performance, power-to-performance ratio, or flexibility in configuration, performance, power management, fault tolerance, or extensibility with respect to heterogeneous processor elements. Onboard network standards exist that can provide >10 Gbps bandwidth, but not everything is available to fully implement them.

Relevance / Science Traceability

The high-performance spaceflight computing (HPSC) ecosystem is enhancing to most major programs in the Human Exploration and Operations Mission Directorate (HEOMD). It is also enabling for key Space Technology
Mission Directorate (STMD) technologies that are needed by HEOMD, including the Safe and Precise Landing - Integrated Capabilities Evolution (SPLICE) project. Within the Science Mission Directorate (SMD), strong mission pull exists to enable onboard autonomy across Earth science, astrophysics, heliophysics, and planetary science missions. There is also relevance to other high-bandwidth processing applications within SMD, including adaptive optics for astrophysics missions and science data reduction for hyperspectral Earth science missions.

References


Z2.03 Human Interfaces for Space Systems

Lead Center: JSC

Scope Title

Display Systems

Scope Description

NASA’s vision for human spaceflight requires the crew to execute increasingly complex tasks in more demanding and dangerous environments. As a result, advances in avionics technologies relevant to human interfaces for space systems are sought that can be infused into current and future human spaceflight programs, including orbiting spacecraft, surface habitats, surface mobility vehicles, and spacesuits. The 2022 subtopic goals are to advance technologies that increase the reliability of crew interface systems in the radiation environment beyond low Earth orbit (LEO), while also increasing the crew’s capabilities and effectiveness in performing mission tasks. Standards-based interfaces are of particular interest to promote interoperability and equipment reuse across spacecraft.

Successful proposal concepts should significantly advance the state of the art. Furthermore, proposals should indicate an understanding of the safety-critical operations performed by spaceflight crews, as well as the intended radiation environment. Note that environmental requirements vary significantly between space systems and missions, with some spacecraft and surface vehicles supporting human operations for days and others supporting periodic crewed missions for 15 or more years.

Specific technologies sought by this subtopic include display systems capable of supporting long-duration human
spaceflight beyond low Earth orbit. Multifunctional visual displays provide the highest bandwidth and most versatile means for crew to receive complex information, but unique component technologies with limited radiation performance data prevent high-reliability displays from being developed. The following design parameters and data are sought for display panel and pixel technologies:

- A scalable architecture that permits different levels of performance
- Radiation test data, analysis of failure modes, radiation-tolerant designs, and prototype hardware/software solutions
- A display panel diagonal measurement of at least 14 in. with the capability to render complex graphics, including high-definition video, at a frame rate of at least 20 frames per second.

Design and performance parameters are driven by use cases requiring crewmembers to directly control the spacecraft using live streaming video, such as in-space docking, controlled landing, robotic operations, and surface mobility.

**Expected TRL or TRL Range at completion of the Project**

3 to 7

**Primary Technology Taxonomy**

**Level 1**

TX 02 Flight Computing and Avionics

**Level 2**

TX 02.2 Avionics Systems and Subsystems

**Desired Deliverables of Phase I and Phase II**

- Prototype
- Hardware
- Software
- Analysis

**Desired Deliverables Description**

The desired Phase I deliverables include designs, simulations, and analyses to demonstrate the viability of proposed designs and components.

The desired Phase II deliverables for display systems include a prototype demonstration of a custom or modified display panel technology that mitigates radiation failure modes of electronic components. The proof-of-concept design should consider scalability and integration with other display components.

**State of the Art and Critical Gaps**

Commercial display technologies have been used in LEO on the International Space Station for decades, but radiation test data for complex electronics beyond LEO are very limited, and existing test data indicate displays may be more susceptible to radiation than other electronic components. As a result, spacecraft designers are forced to take an unquantified risk of equipment failure due to radiation effects and to include backup crew interface systems that take up valuable mass, volume, and power on the spacecraft. While ongoing Government and industry investments seek to improve processor and graphics processing unit (GPU) performance, quantifying and improving the radiation tolerance of display panel components remains unaddressed.
Relevance / Science Traceability

This subtopic is relevant to human spaceflight programs in the development and planning phases, including Gateway, HLS (Human Landing System), Orion, and xEMU (Exploration Extravehicular Mobility Unit), as well as to lunar and martian surface habitation systems and rovers. Technology solutions developed under this subtopic have the potential for a direct infusion path as these spacecrafts are designed and developed.

Electronic visual displays are required for human spaceflight (NPR 8705.2C, NASA Human-Rating Requirements for Space Systems) and will be at the center of any spacecraft’s crew interface architecture. By quantifying and improving the reliability of radiation-tolerant displays, spacecraft designers will be able to simplify this architecture by reducing the need for redundancy, sparing, and operational constraints while also reducing mass, volume, and power needs.

References


Scope Title

Audio Systems

Scope Description

NASA’s vision for human spaceflight requires the crew to execute increasingly complex tasks in more demanding and dangerous environments. As a result, advances in avionics technologies relevant to human interfaces for space systems are sought that can be infused into current and future human spaceflight programs, including orbiting spacecraft, surface habitats, surface mobility vehicles, and spacesuits. The 2022 subtopic goals are to advance technologies that increase the reliability of crew interface systems in the radiation environment beyond low Earth orbit (LEO), while also increasing the crew’s capabilities and effectiveness in performing mission tasks. Standards-based interfaces are of particular interest to promote interoperability and equipment reuse across spacecraft.

Successful proposal concepts should significantly advance the state of the art (SOA). Furthermore, proposals should indicate an understanding of the safety-critical operations performed by spaceflight crews, as well as the intended radiation environment. Note that environmental requirements vary significantly across space systems and missions, with some spacecraft and surface vehicles supporting human operations for days and others supporting periodic crewed missions for 15 or more years.

Specific technologies sought by this subtopic include audio systems that provide two-way voice communication between crew members and mission personnel on Earth through all mission phases and crew activities. These systems also must annunciate alarms and may provide a means of controlling systems by voice or record field notes. Robust audio system technologies are sought with the following design and performance parameters:

- Low-latency G.711 and G.729 audio encoding/decoding and routing from multiple simultaneous sources.
- Integrate with Ethernet-based spacecraft networks to route multiple simultaneous audio streams to each user.
- Support ad hoc addition and removal of end systems and in-flight configuration and extensibility.
- Leverage modular and standards-based hardware and software.
• Provide radiation tolerance and fault mitigation.
• Incorporate SOA microphones, speakers, and acoustic echo-canceling technologies that improve speech quality and intelligibility for voice communication and speech recognition in acoustically challenging environments, such as noisy habitable modules and spacesuits. NASA human spaceflight programs typically require a speech intelligibility score of 90% per the ANSI S3.2 standard using the Modified Rhyme Test (MRT) method.

Expected TRL or TRL Range at completion of the Project

4 to 7

Primary Technology Taxonomy

Level 1

TX 02 Flight Computing and Avionics

Level 2

TX 02.2 Avionics Systems and Subsystems

Desired Deliverables of Phase I and Phase II

• Prototype
• Hardware
• Software

Desired Deliverables Description

The desired Phase I deliverables include designs, tabletop hardware/software prototypes, and analyses to demonstrate the viability of proposed designs and components.

The desired Phase II deliverables for display systems include a prototype hardware and software audio system that can be tested in NASA network test facilities with at least three simultaneous audio endpoints. The audio system should be tested for radiation tolerance.

State of the Art and Critical Gaps

Audio systems are not currently available that meet NASA’s basic functional requirements and can perform reliably in the spaceflight radiation and acoustic environments.

Relevance / Science Traceability

This subtopic is relevant to human spaceflight programs in the planning phases, including human landing systems (HLSs) and lunar and martian surface habitation systems and rovers. Technology solutions developed under this subtopic have the potential for a direct infusion path as these spacecrafts are designed and developed.

Voice communication and auditory alarms have been included in NASA spacecraft since the Mercury Program, but this has not been sufficient to sustain a robust commercial market for space-rated audio systems. As NASA and commercial partners have increased new spacecraft development, the dearth of vendors has resulted in substantial schedule, cost, and technical integration risk.

References

• NASA Electronic Parts and Packaging Program: https://nepp.nasa.gov/ [6]
• NASA Cross-Program Design Specification for Natural Environments
Z4.05 Nondestructive Evaluation (NDE) Sensors, Modeling, and Analysis

Lead Center: LaRC

Participating Center(s): GSFC, MSFC

Scope Title

Nondestructive Evaluation (NDE) for In-Space and Additively Manufactured Materials/Structures

Scope Description

NASA's NDE SBIR subtopic will address a wide variety of NDE disciplines with a focus on in-space inspection. This SBIR solicitation will focus on aerospace structures and materials systems, including but not limited to Inconel, titanium, aluminum, carbon fiber, Avcoat, Alumina Enhanced Thermal Barrier (AETB), Phenolic Impregnated Carbon Ablator (PICA), and thermal blanket structures. Development efforts should target any set of these materials in common aerospace configurations, such as micrometeoroid and orbital debris (MMOD) shielding, truss structures, and stiffened structures. NDE can target material and material systems in a wrought state or additive manufacturing (AM). In-process or postproduction NDE techniques that could be used to inspect additively manufactured components will be favored. As NASA strives for longer duration space missions, these new tools need to be developed to support in-space manufacturing and assembly.

NDE Sensors and Data Analysis:

Technologies enabling the ability to perform automated inspections on large or complex structures are encouraged. Technologies should provide reliable rapid assessments of the location and extent of damage or defects. Methods are desired to perform inspections in areas with difficult access in pressurized habitable compartments and external environments for flight hardware. Many applications require the ability to see through assembled conductive and/or thermal insulating materials without contacting the surface.

Techniques that can dynamically and accurately determine position and orientation of the NDE sensor are needed to register NDE results to precise locations on the structure with little to no human intervention. Advanced processing and displays are needed to reduce the complexity of operation and interpretation for astronaut crews who need to make important assessments quickly. NDE inspection sensors are needed for potential use on free-flying inspection platforms. Integration of wireless systems with NDE may be of significant utility. It is strongly encouraged that proposals provide an explanation of how the proposed techniques and sensors will be applied to a complex structure. Examples of structural components include but are not limited to multiwall pressure vessels, batteries, tile, thermal blankets, micrometeoroid shielding, International Space Station (ISS) radiators, or aerospace structural components, including the lunar gateway.

Additionally, techniques for quantitative analysis of sensor data are desired. It is also considered highly desirable to develop tools for automating detection of material foreign object debris (FOD) such as lunar dust and/or defects and evaluation of bondline and in-depth integrity for ablative materials, like a heat shield. Typical internal void volume detection requirements for ablative materials are on the order of less than 6 mm, and bondline defect detection requirements are less than 25 mm.

Additive manufacturing is rapidly becoming a manufacturing method capable of producing fracture-critical components; as such, NDE requirements will become more stringent. Additively manufactured components represent a novel challenge for NDE due to the layering nature of the process and its effect on diffracting energy...
sources. Development of NDE techniques, sensors, and methods addressing these issues would be highly desired. Additionally, in situ inspection systems that support assessment of AM builds will be considered desirable. Most of the aerospace components will be metallic in nature, and critical flaws can be volumetric or fracture-like in nature.

In-Space Inspection:

Technologies sought under this SBIR include those related to in-space NDE. This includes on-orbit NDE (e.g., ISS or Gateway) as well as for future lunar, Mars, or other planetary missions. This could include new NDE tools for astronauts to use in a habitat or in the space environment (i.e., on an extravehicular activity (EVA)) or for automated inspection. Technologies may include fully functional NDE tools developed based on ground-use/laboratory equipment. Consideration will also be given to particularly promising technologies that may not provide turnkey operation, but enable the advancement of future NDE inspection capabilities in space (i.e., enabling technologies). Fully functional NDE “tool” designs must address considerations related to size, mass, power, safety, environment, operation and/or automation, and data transfer related to their proposed application. For example, an NDE tool designed for ISS must ultimately be able to meet (after final development) ISS design requirements, launch mass/payload limitations, operational guidelines for crew, etc. If no specific application is outlined in the design, or if the proposal is for development of an enabling technology, then consideration must still be given to system size, mass, power, and data rate, to the extent that it makes the technology feasible in the within the next decade. To that end, consideration may be given to technology developments that are specifically focused on minimizing (or optimizing) these system parameters (e.g., low-mass, compact microfocus x-ray sources).

This solicitation is aimed at technologies for conventional NDE inspection of relevant components in space, meaning detection of commonly known defects in materials (cracks, pores, delamination, FOD, impact damage, etc.), rather than analytical tools aimed at determining chemistry, composition, or other properties of materials. Relevant components to be inspected may include (but are not limited to) spaceflight hardware, protective gear, core/rock samples, structural components, electronics/wiring, pressure vessels, thermal protection systems, etc. Of particular interest are technologies that advance the inspection of AM parts in space. These parts may be manufactured in an AM cabinet system that fits in an ISS EXPRESS (EXpedite the PRocessing of Experiments for Space Station) rack, which results in parts on the scale of 6 in. AM technologies used in such a payload could include fused deposition modeling, bound metal deposition, wire arc additive manufacturing, or other technologies using wire feedstock. Large-scale space structures may be manufactured or assembled in the space environment using AM techniques. Inspection technologies may involve x-ray technology (such as computed tomography), ultrasonic imaging, thermography, or any other NDE methods adapted for space use. NDE tools or enabling technologies that are compact, easy to carry (by astronauts), and work on low or accessible power will be considered.

Expected TRL or TRL Range at completion of the Project

1 to 6

Primary Technology Taxonomy

Level 1

TX 08 Sensors and Instruments

Level 2

TX 08.X Other Sensors and Instruments

Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype
- Hardware
- Software
**Desired Deliverables Description**

Phase I Deliverables: For proposals focusing on NDE sensors: Lab prototype and feasibility study or software package, including applicable data or observation of a measurable phenomenon on which the prototype will be built. For proposals focusing on NDE modeling: Feasibility study, including demonstration simulations and data interpretation algorithms, proving the proposed approach to develop a given product (Technology Readiness Level (TRL) 2 to 4). Inclusion of a proposed approach to develop a given methodology to a TRL of 2 to 4. All Phase I proposals will include minimum of short description for Phase II prototype/software. It will be highly favorable to include a description of how the Phase II prototype or methodology will be applied to structures.

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

**State of the Art and Critical Gaps**

NASA and the SBIR program are preparing for the next phase of human deep space flight. As such, much of the materials, structures, and subsystem will have to be built or assembled in space. Quantitative and qualitative inspection of these components and structures will be critical to ensure safe spaceflight. Additionally, NDE sensors will be used to determine the health of structures as they age in space.

**Relevance / Science Traceability**

Several missions could benefit from technology developed in the area of NDE. Currently, NASA is returning to manned spaceflight. The Artemis program’s Orion spacecraft and Space Launch System have had inspection difficulties, and continued development and implementation of NDE tools will serve to keep our missions flying safely. Currently, Orion is using several techniques and prototypes that have been produced under the NDE SBIR topic. The Space Launch System is NASA’s next heavy-lift system, capable of sending hundreds of metric tons into orbit. Inspection of the various systems is ongoing and will continue to have challenges, such as verification of the friction stir weld on the fuel tanks. As NASA continues to push into deeper space, smart structures that are instrumented with structural health monitoring (SHM) systems can provide real-time mission-critical information on the status of the structure. NDE of spaceflight hardware and parts manufactured in space will be key enabling technologies for constant crew presence and long-duration missions.

**References**

- Cramer, K. E.: Current and Future Needs and Research for Composite Materials NDE. Presented at SPIE
Z4.07 Advanced Materials and Manufacturing for In-Space Operations

Lead Center: LaRC

Participating Center(s): MSFC

Scope Title

Manufacturing of Materials from Lunar Surface Resources

Scope Description

As humanity embarks on sustained deep space exploration, starting with the lunar surface, there will be a need for building infrastructure that is based on indigenous resources [1]. Usage of these resources will face limitations that include the available source materials, equipment, and power. Therefore, materials processing and manufacturing approaches are required that are operable within these constraints.

Operations on the lunar surface must consider types of materials available as well as their abundance. Various in situ resource utilization (ISRU) efforts are ongoing to extract and process the raw materials into usable forms. These include some SBIR topics that the prospective proposer is encouraged to look into. Elements available for extraction from regolith include oxygen, silicon, iron, calcium, aluminum, magnesium, and titanium. From these, and from other materials that may be available in smaller quantities, manufacturing methods are needed to produce components for construction and for the building, replication, and repair of equipment.

Proposals are invited for approaches that utilize the resources available on the Moon in order to be able to produce structural girders, beams, and pipes that can withstand both tensile and bending forces. These are required in addition to compacted cementitious and sintered materials that can carry mostly compressive loads.

Concepts can include, but are not limited to, production using various metallic materials as well as basalt-fiber-reinforced geopolymers and other combinations that can be produced from lunar resources. Manufacturing methods that capitalize on the lunar environment are of particular interest.

The selection of the material system must take into account the potential availability on the lunar surface and a demonstrated or projected ability to support tensile and bending loads. For example, proposed work may include an analysis of lunar material properties and processing methods that yield the required performance characteristics for relevant structures. An example beam would be a structural component for a crane with a 25-ft reach that can
support one metric ton (2,200 lb) in lunar gravity. Proposers are pointed to the references provided [2-6] as well as ongoing ISRU activities for the latest and detailed information on the potential availability of various materials on the Moon.

Proposals to the current solicitation can assume the materials extracted and processed in the ISRU activities to be available and ready to use at levels of purity that range from as-dug regolith to separated and refined metals. The quantities available will depend on the lunar abundance of the materials and the effort needed for the processing. As-dug regolith can be expected to be available in large amounts; more refined materials can be expected to be available in quantities that decrease with the level of refinement and the requirements for that refinement, such as energy and any Earth-sourced ingredients.

Proposal elements of interest include but are not limited to:

- Material concepts that can utilize various purities of feedstocks, e.g., concepts that might be able to use a metal at less than 100% purity.
- Manufacturing processes that can take advantage of the lunar environment, such as vacuum, radiation, reduced gravity, etc.
- Equipment required for the manufacturing, including the size scale, power requirements, production rates, and operating environments.
- Preliminary proof-of-concept experiments for feasibility of the proposed material systems, processing methods, and equipment.

**Expected TRL or TRL Range at completion of the Project**

4 to 5

**Primary Technology Taxonomy**

**Level 1**

TX 12 Materials, Structures, Mechanical Systems, and Manufacturing

**Level 2**

TX 12.X Other Manufacturing, Materials, and Structures

**Desired Deliverables of Phase I and Phase II**

- Research
- Analysis
- Prototype
- Hardware

**Desired Deliverables Description**

Phase I: Define the material system to be used for manufacturing of relevant components, the processes required, and the equipment needed to process that material. Provide one or more material systems, manufacturing processes, and equipment design concepts for the production of tensile- and bending-force-supporting components on the lunar surface using resources available from ISRU extraction and beneficiation activities. The concept will include analysis of how the material system(s) is/are able to meet the load-carrying requirements and the manufacturing parameters, and how the equipment that is required utilizes/succeeds in operating in the lunar environment.

Phase II would look at scaled/laboratory demonstrations of the material system(s), manufacturing processes, and equipment. These would include designing and building of relevant equipment and potential processing of commercially available regolith simulants or other materials that may match the materials expected to be available on the Moon, either in raw form or from other processes. Test coupons must be built and tested using as close an
analog as possible of the lunar material system and a prototype of the proposed manufacturing equipment. Documentation of requirements for the manufacturing process and operation of the equipment, such as power and mass that can be used to evaluate feasibility in trade studies, shall be included.

**State of the Art and Critical Gaps**

Sustainable long-term exploration of the Moon will be dependent on the utilization of lunar resources. While various efforts are looking at the excavation and extraction of those resources, there are currently gaps in manufacturing of the material feedstocks that may be available on the Moon into other useful products. Addressing these gaps requires understanding of the fabrication equipment and the full manufacturing cycle as well as the expected impact when the processes are run on the Moon.

**Relevance / Science Traceability**

The Artemis program envisions the start of a long-term human presence on the lunar surface for the exploration and development of the Moon by Government as well as commercial companies and international partners. In order to support these missions, it will be essential to utilize resources that can be sourced from the lunar surface. The current solicitation calls for proposals that provide the support for these exploration and development activities. Technologies that are developed in this solicitation may also feature on preparatory missions for Artemis, such as the Commercial Lunar Payload Services Programs, depending on the readiness of the technology.

**References**


**Scope Title**

Welding Testbed for Space Manufacturing

**Scope Description**

Technology development efforts are required to enable on-orbit servicing, assembly, and manufacturing (OSAM) for commercial satellites, robotic science, and human exploration. OSAM is an emerging national initiative to transform the way we design, build, and operate in space. The goal of the initiative is to develop a strategic framework to enable robotic servicing, repair, assembly, manufacturing, and inspection of space assets.

An in-space material welding capability is an important supporting technology for the long-duration, long-endurance space missions that NASA will undertake beyond the International Space Station (ISS). Historically, structures in space have been assembled using mechanical fastening techniques and modular assembly. Structural designs for
crewed habitats, space telescopes, antennas, and solar array reflectors are primarily driven by launch considerations such as payload fairing dimensions and vibrational loads experienced during ascent. An in-space welding capability will greatly reduce constraints on the system imposed by launch, enabling the construction of larger, more complex, and more optimized structures. Welding is an essential complementary capability to large-scale additive manufacturing technologies being developed by NASA and commercial partners. Welding is also a critical capability for repair scenarios (e.g., repair of damage to a structure from micrometeorite impacts).

The development of welding processes for a variety of materials and thicknesses is carried out via a welding destructive testing and nondestructive testing feedback loop. This ensures that a weld procedure is well understood and that it produces welds that have sufficient material properties for their end-use application. While weld procedures are developed on the ground in simulated space environments, it is also necessary to further develop and validate these procedures in the true space environment where they will be applied. To achieve this need, a fully autonomous welding testbed must be created and deployed in space.

This subtopic seeks innovative engineering solutions—both fully autonomous and semiautonomous—to robotically weld materials for manufacturing in the unpressurized space environment. Current state-of-the-art (SOA) terrestrial welding methods such as laser beam, electron beam, and friction stir should be modified with an effort to reduce the footprint, mass, and power requirements for on-orbit applications. Targeted applications for this technology include joining and repair of components at the subsystem level, habitat modules, trusses, solar arrays, and/or antenna reflectors. The need to repair a damaged structure or build new structures may require the need to not only weld material but to cut and remove material. A process that can weld material is the priority, but a robust process with cutting, removal, and testing capabilities adds value.

**Expected TRL or TRL Range at completion of the Project**

3 to 6

**Primary Technology Taxonomy**

**Level 1**

TX 12 Materials, Structures, Mechanical Systems, and Manufacturing

**Level 2**

TX 12.4 Manufacturing

**Desired Deliverables of Phase I and Phase II**

- Research
- Analysis
- Prototype
- Hardware
- Software

**Desired Deliverables Description**

Phase I is a feasibility study and laboratory proof of concept of a robotic welding process and system for on-orbit manufacturing applications. The Phase I effort should provide a laboratory demonstration of the welding process and its applicability to aerospace-grade metallic materials and/or thermoplastics, focusing on joint configurations that represent the priority in-space joining applications identified above. Work under Phase I will inform preliminary design of a mobile welding unit and/or in-space welding testbed. It will also inform a concept of operations for how the system would be deployed and operate in the space environment, with a focus on specific scenarios—for example, repair of a metal panel following micrometeorite damage, longitudinal welding of two metal curved panels, and welding of a truss to an adjacent truss. The Phase I effort should also provide an assessment of the proposed process operational capabilities (e.g., classes of materials that can be welded with the process, joint configurations that can be accommodated, and any expected impacts of the microgravity environment on joint efficiency relative to
terrestrial system operation), volume, and power budget. A preliminary design and concept of operations are also deliverables under Phase I. Concepts for ancillary technologies such as postprocess inspection, in situ monitoring, mechanical testing, or robotic arms for manipulation of structures to be welded may also be included in the Phase I effort.

Development of a prototype with detailed analysis, initial testing, and associated software is desired for Phase I.

Phase II should further develop the prototype from Phase I and provide substantial test data using the prototype in an environment similar to the end application.

State of the Art and Critical Gaps

A clear demonstrated understanding of the SOA is required. Any proposed technologies should not replicate the SOA and should instead advance the SOA or create an entirely different approach from the SOA. Welding in space has a multitude of applications, from repair to manufacturing, and is necessary to ensure a sustainable human presence in space. The development of space welding technologies is a substantial undertaking and requires years to perfect, so it is of the utmost importance that this process begins now. A welding testbed in space is an integral part of gaining weld property feedback data in an autonomous manner in a high-fidelity environment. The current SOA requires further advancement, and the growth of small business in the field of space welding is the best route to ensure that technological development is unique and that an array of technology providers exists in the future space economy.

Relevance / Science Traceability

Space welding is necessary for the future sustainability of the space economy. To both build and repair structures in space, on the lunar surface, or on Mars, welding is a valuable tool that will provide agility for astronauts in a location where resources are highly limited. The development of space welding is a significant undertaking, so early development must begin now. The development of systems to autonomously weld structures in space and the ability to develop welding parameters through a closed-feedback-loop space testbed are both required to ensure that welding may be sufficiently applied in space.

References


Z5.04 Intravehicular Robot (IVR) Technologies

Lead Center: ARC

Participating Center(s): JSC

Scope Title

Improve the Capability or Performance of Intravehicular Robots

Scope Description

To support human exploration beyond Earth orbit, NASA is developing Gateway, which will be an orbiting facility near the Moon. This facility will serve as a starting point for missions to cislunar space and beyond. It could enable assembly and servicing of telescopes and deep space exploration vehicles. It could also be used as a platform for astrophysics, Earth observation, heliophysics, and lunar science.
In contrast to the International Space Station (ISS), which is continuously manned, Gateway is expected to be occupied by humans only intermittently—perhaps only 1 month per year. Consequently, there is a significant need for Gateway to have autonomous capabilities for performing payload operations and spacecraft caretaking, particularly when astronauts are not present. Similar capabilities are needed for future lunar or planetary surface habitats. Intravehicular robots (IVR) can potentially perform a wide variety of tasks, including systems inspection, monitoring, diagnostics and repair, logistics and consumables stowage, exploration capability testing, aggregation of robotically returned destination surface samples, and science measurements and operations.

The objective of this subtopic is to develop technologies that can improve the capability or performance of IVR for science utilization and spacecraft caretaking.

Proposals must describe how the technology will make a significant improvement over the current state of the art (SOA), rather than just an incremental enhancement, for a specific IVR application.

Proposals are specifically sought to create IVR-relevant technologies in the following areas:

- Compact, lightweight robotic arms suitable for IVR free-flyers.
- Robotic tools.
- Compact, reliable, modular robotic actuators and controllers for IVR.
- Sensors and perception systems.
- Operational subsystems that enable extended robot operations (power systems, efficient propulsion, etc.).
- Improved robot autonomy (planning, scheduling, and task execution).
- Improved human-robot interaction between IVR and human teams on the ground under communications constraints, including low bandwidth and extended loss-of-signal periods (software architecture, remote operations methods, etc.).
- Improved management of robot operational and hardware faults such that the robot can “fail operational.” For example, the software may use algorithms to determine how to automatically respond to a failure in a motion planner for move to a commanded location by taking into account a projected collision and replanning to the next closest point not in collision.

The technologies must be applicable to required IVR capabilities, such as:

- Maintenance and housekeeping (installing and stowing cables or fluid lines, plugging and unplugging MIL-STD-38999 electrical connectors and fluid quick-disconnect connectors, opening panels, swapping out NASA AMPS (Advanced Exploration Systems (AES) Modular Power Systems) avionics cards, opening and closing hatches, cleaning or swapping air filters, cleaning or sterilizing surfaces, etc.).
- Logistics management (inventory tracking, cargo transport, packing and unpacking bags, kitting items, etc.).
- Science utilization (moving samples between cold storage and instruments, swapping out consumables cartridges, moving planetary samples or SmallSat experiments in and out of airlocks, installing items fabricated using in-space manufacturing, etc.).
- Emergency management (detecting and patching leaks, detecting fires, etc.).
- Localization and navigation.
- Environment monitoring, inspection, and modeling.

The technologies must have an infusion path to NASA missions where habitats require IVR support, such as the Gateway habitat, the Artemis lunar surface habitat, or transit vehicles or surface habitats for future Mars missions. To facilitate infusion, proposals are encouraged, but not required, to:

- Target near-term integration and testing with NASA IVR platforms and analogs, such as Astrobee and Valkyrie.
- Limit dependence on third-party proprietary technologies that might complicate NASA adoption of the technology.
- Use industry standard hardware and software interfaces, architectures, and frameworks that align with relevant NASA IVR technology development to reduce future integration technical effort.
Expected TRL or TRL Range at completion of the Project
4 to 5

Primary Technology Taxonomy

Level 1
TX 04 Robotics Systems

Level 2
TX 04.X Other Robotic Systems

Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description

Deliverables should focus on prototype components, subsystems, and the demonstration thereof. Specifically, Phase I awards shall deliver an interim and final report discussing these results. Phase II awards shall deliver demonstration reports along with supporting software, design information, and documentation.

State of the Art and Critical Gaps

The technology developed by this subtopic would both enable and enhance IVR such as the Astrobee free-flying robot, Robonaut 2, and Valkyrie humanoid mobile manipulators, which are the SOA for IVR. SBIR technology would improve the capability and performance of these robots to routinely and robustly perform IVR tasks, particularly internal spacecraft payload operations and logistics. New technology created by 2022 SBIR awards could potentially be tested with these, or other, robots in ground testbeds at Ames Research Center (ARC) and Johnson Space Center (JSC) in follow-on awards. These platforms make use of the ROS (Robot Operating System) software architecture. Likewise, on-orbit testing on the ISS may be possible during follow-on awards.

The technology developed by this subtopic would also fill technical gaps identified by the Game Changing Development (GCD) Integrated System for Autonomous and Adaptive Caretaking (ISAAC) project, which is maturing autonomy technology to support the caretaking of human exploration spacecraft. In particular, the SBIR technology would help provide autonomy and robotic capabilities that are required for in-flight maintenance (both preventive and corrective) of Gateway during extended periods when crew are not present.

Relevance / Science Traceability

This subtopic is directly relevant to the following STMD (Space Technology Mission Directorate) investments:

- Astrobot freeflying robot, GCD.
- Integrated System for Autonomous and Adaptive Caretaking (ISAAC), GCD.
- Smart Deep Space Habitats (SmartHabs), Space Technology Research Institutes (STRI).

This subtopic is directly relevant to the following HEOMD (Human Exploration and Operations Mission Directorate) investments:
• Astrobe facility, ISS.
• Gateway program, AES.
• Logistics Reduction project, AES. Autonomous Systems Operations project, AES.

References

• What is Astrobe? https://www.nasa.gov/astrobee [22]
• What is a Robonaut? https://www.nasa.gov/robonaut2 [23]
• The Robot Operating System (ROS) https://www.ros.org [24]

Z7.01 Entry, Descent, and Landing Flight Sensors and Instrumentation

Lead Center: JSC

Participating Center(s): ARC, GSFC, JPL, LaRC

Scope Title

Air Data Sensors to Support Entry, Descent, and Landing (EDL) Environment Characterization

Scope Description

Current NASA state-of-the-art air data sensors for EDL applications are very expensive to incorporate on planetary missions because they must meet functional and performance requirements during and after exposure to loads and environments associated with long-duration spaceflight and atmospheric entry. The dynamic loads and thermal environments encountered prior to arrival at the destination make flight qualification of air data sensors challenging and costly. Scarce commercial options exist for off-the-shelf products with the potential to meet NASA’s requirements for accuracy and survivability. In an effort to bring more commercial options for air data sensors that can be flown on EDL missions as part of an air data system, NASA seeks proposals in two distinct areas: pressure transducers and lidar sensors.

1. Air Data Pressure Transducers

The Mars Entry, Descent, and Landing Instrumentation 2 (MEDLI2) sensor suites flew supersonic-range pressure transducers on the heat shield that were developed in house at NASA Langley Research Center because there was no commercially available pressure sensor that met the mission’s requirements. The hypersonic pressure...
transducer on the heat shield was a flight spare from the first MEDLI suite, which flew on the Mars Science Laboratory Mission in 2012. In situ pressure measurements on the aerodynamic surfaces of an EDL vehicle capsule—such as the heat shield and backshell—are primarily used to reconstruct the free-stream density and vehicle attitude (angles of attack and sideslip) to isolate aerodynamic performance. NASA seeks pressure transducers that can meet the following requirements:

- **Configuration:** The pressure transducer shall be hermetically sealed. The design space should consider a nonamplified output configuration or a configuration with embedded electronics for an amplified output. The internal temperature shall be monitored. The pressure transducer shall measure absolute pressure, and the housing must be able to be connected to a flared tube fitting. The pressure transducer should have the capability of being mechanically mounted in a 2- or 3-point configuration.
- **Mass:** Less than 300 g if no active electronics; less than 400 g for a unit with active electronics.
- **Size:** Less than 442 cm³.
- **Electrical connections:** Electrical interface/connector should be configured for power, ground, analog signal, analog return, and temperature sensor accommodation. Electrical connector pin configurations should allow for interchangeability of mating connectors for all pressure transducers.
- **Parts, material, and processes used in the construction of the pressure transducer should be controlled by specification or procedure per AS9100 or equivalent. Any soldering should meet NASA-STD-8739.3 or IPC J-STD-001 with space addendum, and any fusion welding should follow AWSD17.1.
- **The pressure transducer should meet MIL-STD-461 for electromagnetic interference (EMI) compliance (amplified units only).**
- **Axial loading capability:** Minimum 15 g (Venus missions could require 100 g or higher).
- **Temperature capability:** Operating temperature range of -120 to 80 °C. It is desired that the unit can survive temperatures as cold as -130 °C in a nonoperating condition. It is also desired that the unit can survive a dry heat microbial reduction temperature of 104 °C for 200 hr, or 110 °C for 100 hr.
- **Functional characteristics:**
  - Input voltage: Up to 10 Vdc for a nonamplified unit or 12 to 36 Vdc for an amplified unit.
  - Input current: Should not exceed 7 mA for a nonamplified unit or 30 mA for an amplified unit.
  - Output impedance: Should not exceed 10 kilohms for a nonamplified unit or 1 kilohm for an amplified unit.
  - Output voltage: Minimum output of 1.2 mV/V (nonamplified unit).
  - Measurement range: 0 to 1.0 psia for a supersonic range pressure transducer; 0 to 5.0 psia for hypersonic range pressure transducer. Zero psia is considered to be less than 10⁻⁵ torr.
  - Accuracy: Provide a description of the approach to quantify and demonstrate accuracy of the pressure transducer.
    - Static error band should be no greater than +/- 0.3% of full scale based on an unweighted least-squares straight-line fit. The static error band includes errors due to nonlinearity, hysteresis, and nonrepeatability.
- **Cost:** Fully qualified first-unit target of ~$500K.

2. Air Data Lidar Sensors

Air data lidar sensors have the potential of providing more accurate velocimetry data than pitot tubes for Mars landing and Earth reentry vehicles. Furthermore, a lidar-based air data sensor can eliminate the aerodynamic influences of pitot tubes, particularly in the supersonic velocity regime. NASA seeks proposals for air data lidar sensors that can provide critical air-vector velocity data during the atmospheric entry and descent phases of the spacecraft. An ability to provide other relevant air data, such as atmospheric pressure, is viewed favorably if it can enhance and/or complement the air velocity measurement capabilities. The proposed lidar sensor must be compact and efficient with a clear path to spaceflight units meeting physical and environmental constraints of landing vehicles.

**Expected TRL or TRL Range at completion of the Project**

2 to 4
Primary Technology Taxonomy

Level 1

TX 09 Entry, Descent, and Landing

Level 2

TX 09.X Other Entry, Descent, and Landing

Desired Deliverables of Phase I and Phase II

- Analysis
- Prototype
- Hardware

Desired Deliverables Description

Phase I Goals: Design and proof of concept, including the production approach to achieve the cost goals.

Phase II Goals: Prototype/breadboard validation in laboratory environment.

State of the Art and Critical Gaps

NASA now requires instrumentation on all EDL missions, including competed science missions, and these cost- and mass-constrained missions cannot use the state-of-the-art instrumentation. Very few commercial options exist for air data sensors that can meet accuracy and survivability requirements.

Relevance / Science Traceability

EDL instrumentation directly informs and addresses the large performance uncertainties that drive the design, validation, and in-flight performance of planetary entry systems. Improved understanding of entry environments and real-time measurement knowledge could lead to reduced design margins, enabling a greater payload mass-fraction, and smaller landing ellipses for placing advanced payloads onto the surface of atmospheric and airless bodies.

References


Scope Title

Novel Lidar Component Technologies Applicable to Guidance, Navigation, and Control (GN&C) for Precise Safe
Landing

**Scope Description**

NASA is seeking the development of component technologies for advanced lidar sensors that will be utilized within entry, descent, and landing (EDL) and deorbit, descent, and landing (DDL) GN&C systems for precise safe landing on solid solar system bodies, including planets, moons, and small celestial bodies (e.g., asteroids and comets). The EDL phase applies to landings on bodies with atmospheres, whereas DDL applies to landings on airless bodies. For many of these missions, EDL/DDL represents one of the riskiest flight phases. NASA has been developing technologies for precision landing and hazard avoidance (PL&HA) to minimize the risk of the EDL/DDL phase of a mission and to increase the accessibility of surface science targets through precise and safe landing capabilities. One flight instrumentation focus of PL&HA technology has been in the development of lidar technologies that provide either terrain mapping (range point cloud) capability or direct velocity measurement. The continued maturation of these technologies is targeting (1) multimodal operation (i.e., combining mapping and velocimetry functions); (2) reduction of size, mass, and power; and (3) multicomponent integration.

This solicitation is requesting specific lidar system components and not complete lidar solutions. To be considered, all component technologies proposed must show a development path to operation within the applicable EDL/DDL spaceflight environment (radiation, thermal, vacuum, vibration, etc.). The specific lidar component technologies desired include the following (proposals can be to either or both):

1. Dense focal plane arrays for simultaneous ranging and Doppler velocimetry with the following characteristics:
   - Simultaneous measurements from each pixel or from subsets of pixels.
   - Functionality (when integrated into a lidar system) for measuring range up to 8 km.
     - Range precision less than 5 cm, 1-sigma, for 3D image frames up to 1 km.
     - Range precision less than 1 m, 1-sigma, for ranges up to 8 km.
   - Functionality (when integrated into a lidar system) for measuring velocity from 0 to 200 m/sec (or greater) along the line of sight (LOS).
     - Doppler velocity precision on order of 1 cm/sec, 1-sigma, from ranges of 4 km or greater.
   - Rejection of false locks on dust or plumes from the spacecraft exhaust.
   - Implementation for low power, mass, and size.

2. Readout integrated circuit (ROIC) consisting of preamplifiers and switching fabric, capable of operating at cryogenic temperatures, with the following characteristics:
   - Preamplifiers: Array of low-noise transimpedance preamplifiers, one for each detector element.
     - Electrical bandwidth: > 150 MHz.
     - Transimpedance gain: > 300 kV/A.
     - Input current noise: < 1.5 pA/Hz^{1/2}.
     - Input voltage noise: < 10 nV/Hz^{1/2}.
     - Output: Analog pulse waveforms, DC coupling.
     - Electrical power: < 2 mW per element.
   - Network switching fabric: Connection of a subarray of the detector elements to the output terminals.
     - Switch speed: > 5 MHz with settling time < 40 ns.
     - Number of input channels: Up to 2x320.
     - Number of output channels: Subarray of the input signals up to 16 channels.
     - Interchannel isolation: < -37 dB @ 1 GHz.
     - Insertion loss: < 1 dB.
     - Total electrical power: < 0.05 W.

**Expected TRL or TRL Range at completion of the Project**

4 to 6

**Primary Technology Taxonomy**
Level 1

TX 09 Entry, Descent, and Landing

Level 2

TX 09.X Other Entry, Descent, and Landing

Desired Deliverables of Phase I and Phase II

- Analysis
- Prototype
- Hardware
- Software

Desired Deliverables Description

The following deliverables are desired for Phase I: (1) Hardware demonstrations of sensor components and applicable support hardware and/or (2) Analysis and software simulations of component proofs of concept within simulated environments. Responses must show a path for the proposed capabilities to be compatible with the environmental conditions of spaceflight.

The following deliverables are desired for Phase II: (1) Hardware demonstrations of sensor components and applicable support hardware and (2) Analysis of components in laboratory or relevant environment (depending on TRL). Phase II products will need to demonstrate a path for the capabilities to be compatible with the environmental conditions of spaceflight.

State of the Art and Critical Gaps

For more than a decade, the EDL GN&C and sensors community has been developing the technologies to enable precise safe landing. Infusion of these capabilities into spaceflight missions and spinoff into the commercial sector remains the critical gap. Bridging this gap requires additional component technology advancements for specific lidar sensors that enhance operational performance, increase dynamic envelope, reduce size/mass/power/cost, and enable spaceflight qualification.

Relevance / Science Traceability

GN&C/PL&HA technologies for precise safe landing are critical for future robotic science and human exploration missions to locations with hazardous terrain and/or pre-positioned surface assets (e.g., cached samples or cargo) that pose significant risks to successful spacecraft touchdown and mission surface operations. The PL&HA technologies enable spacecraft to land with minimum position error from targeted surface locations, and they implement hazard-avoidance diverts to land at locations safe from lander-sized or larger terrain hazards (e.g., craters, rocks, boulders, sharp slopes, etc.). PL&HA has maintained consistent prioritization within the NASA and National Research Council (NRC) space technology roadmaps for more than a decade, and multiple planetary landers such as Mars 2020 and upcoming Commercial Lunar Payload Services (CLPS) are starting to infuse some of the PL&HA capabilities.
References


Z7.03 Entry and Descent System Technologies

Lead Center: JSC

Participating Center(s): ARC

Scope Title

Entry and Descent System Technologies

Scope Description

NASA is advancing deployable aerodynamic decelerators to enhance and enable robotic and human space missions. Applications include Mars, Venus, and Titan as well as payload return to Earth from low Earth orbit. The benefit of deployable decelerators is that the entry vehicle structure and thermal protection system are not constrained by the launch vehicle shroud. Deployable decelerators have the flexibility to more efficiently use the available shroud volume and can be packed into a much smaller volume for Earth departure, addressing potential constraints for payloads sharing a launch vehicle. For Mars, this technology enables delivery of a very large (20 metric tons or more) usable payload, which may be needed to support human exploration. The technology also allows for reduced-cost access to space by enabling the recovery of launch vehicle assets. Development of efficient gas generator technology is needed for inflation of large inflatable decelerators. NASA is also seeking development of domestic capability for fabricating custom stretch-broken carbon and polymer blended yarns for traditional thermal protection systems for other planetary entry missions. This subtopic area solicits innovative technology solutions applicable to both deployable and traditional entry concepts. Specific technology development areas include (1) gas generators for hypersonic inflatable aerodynamic decelerators (HIAD) and (2) blended phenolic/carbon yarn for 3D woven ablative thermal protection systems.

1. Gas Generators for HIAD

Development of gas generator technologies used as inflation systems that result in improved mass efficiency and system complexity over current pressurized cold gas systems for inflatable structures is desired. Inflation gas technologies can include warm or hot gas generators, sublimating powder systems, or hybrid systems; however, the final delivery gas temperature must not exceed 200 °C. Lightweight, high-efficiency gas inflation technologies capable of delivering gas at 250 to 10,000 standard liters per minute (SLPM) are sought. This range spans a number of potential applications. Thus, a given response need not address the entire range. Additionally, the final
delivery gas and its byproducts must not harm aeroshell materials such as the fluoropolymer liner of the inflatable structure. Minimal solid particulate is acceptable as a final byproduct. Water vapor as a final byproduct is also acceptable for lower flow (250 to 4,000 SLPM) and shorter duration missions, but it is undesirable for higher flow (8,000 to 10,000 SLPM) and longer duration missions. Chillers and/or filters can be included in a proposed solution, but they will be included in assessing overall system mass versus amount of gas generated. Gas delivery configurations that rely on active flow control devices are not desired. Long-term mission applications will have inflatable volumes in the range of 1,200 to 4,000 ft³ with final inflation pressures in the range of 15 to 30 psid. Initial concepts will be demonstrated with small-scale volumes to achieve the desired inflation pressures and temperatures. Focus of Phase I development can be subscale manufacturing demonstrations that demonstrate proof of concept and lead to Phase II manufacturing scaleup for applications related to human-scale Mars entry, Earth return, launch vehicle asset recovery, or the emergent small-satellite community.

2. Blended Phenolic/Carbon Yarn for 3D Woven Ablative Thermal Protection Systems

Development of domestic capability for fabricating custom stretch-broken carbon and polymer blended yarns is desired. Specifically, NASA is interested in the ability to twist and ply stretch-broken fibers into a 4-ply blended yarn of varying carbon/phenolic/thermoset resin ratios (phenolic or other nonbrittle fibers preferred). Challenges include maintaining an intimate blend ratio to maintain consistent linear weight while also fabricating a high-quality yarn free from breaks and large yarn defects (e.g., slubs and flames in the resin phase), with uniformity in diameter such that yarns are capable of being processed into 3D woven preforms for advanced thermal protection systems. Phase I effort shall identify the ability to fabricate these custom yarns and establish the characterization processes and controls that will be necessary to eventually fine-tune the blended yarn properties. Final composition of interest to NASA would be a carbon/phenolic blended yarn—any surrogate polymeric yarn should have similar stretch-breaking and blending performance such that any successful process shown with surrogate yarn is extensible to a carbon/phenolic blend with low risk. Notional Phase II effort would demonstrate blending of stretch-broken carbon/kynol fibers and detailed yarn testing—char, strength, yield, etc.—to meet the following established NASA specifications:

- Carbon to phenolic ratio in the yarn by mass shall be 63 ± 4% carbon to 37 ± 4% phenolic
- Blended yield shall be 1,140 yd/lb +/- 10%.
- Yarn shall have a minimum strength of >13,000 cN and elongation of >1%.
- Yarn shall have a twist in the “S” direction and shall be 115 +/- 15% T/m (twists per meter) (2.92 T/in.).
- Yarn shall be manufactured so as to reduce presence of surface features such as slubs or flames.

**Expected TRL or TRL Range at completion of the Project**

1 to 4

**Primary Technology Taxonomy**

**Level 1**

TX 09 Entry, Descent, and Landing

**Level 2**

TX 09.1 Aeroassist and Atmospheric Entry

**Desired Deliverables of Phase I and Phase II**

- Research
- Analysis
- Prototype
- Hardware
- Software

**Desired Deliverables Description**
Reports documenting analysis and development results, including description of any hardware or prototypes developed. Focus of Phase I development can be material coupons and/or subscale manufacturing demonstrations that demonstrate proof of concept and lead to Phase II scaleup and testing in relevant environments for applications related to Mars and other planetary entry, Earth return, launch asset recovery, or the emergent small-satellite community.

State of the Art and Critical Gaps

The current state of the art for deployable aerodynamic decelerators is limited due to novelty of this technology. Development of gas generator technologies that improve mass efficiency over current pressurized cold gas systems for inflatable structures is needed. Domestic capability for producing blended phenolic/carbon yarn for 3D woven thermal protection systems is nonexistent, and NASA is interested in developing this domestic capability for future missions.

Relevance / Science Traceability

NASA needs advanced deployable aerodynamic decelerators to enhance and enable robotic and human space missions. Applications include Mars, Venus, and Titan as well as payload return to Earth from low Earth orbit. NASA also needs domestic supply of blended phenolic/carbon yarn for 3D woven traditional thermal protection systems. HEOMD (Human Exploration and Operations Mission Directorate), STMD (Space Technology Mission Directorate), and SMD (Science Mission Directorate) can benefit from this technology for various exploration missions.

References


Z7.04 Landing Systems Technologies

Lead Center: JSC

Participating Center(s): GRC, LaRC

Scope Title

Plume-Surface Interaction (PSI) Instrumentation, Ground Testing, and Analysis
Scope Description

As NASA and commercial entities prepare to land robotic and crewed vehicles on the Moon, and eventually Mars, characterization of landing environments is critical to identifying requirements for landing systems and engine configurations, instrument placement and protection, and landing stability. The ability to predict the extent to which regolith is liberated and transported in the vicinity of the lander is also critical to understanding the effects on precision landing sensor requirements and landed assets located in proximity. Knowledge of the characteristics, behavior, and trajectories of ejected particles and surface erosion during the landing phase is important for designing effective sensor systems and PSI risk mitigation approaches. Mission needs to consider include landers with single and multiple engines, both pulsed and throttled systems, landed mass from 400 to 40,000 kg, and both lunar and Mars destinations.

NASA is seeking support in the following areas:

1. Ground test data, test techniques, and diagnostics across physical scales and environments, with particular emphasis on nonintrusive approaches and methodologies.
2. PSI-specific flight instrumentation, with particular emphasis on in situ measurements of particle size and particle velocity during the landing phase.
3. Solutions to alleviate or mitigate the PSI environments experienced by propulsive landers—not vehicle-specific solutions.
4. Validated, robust, and massively parallel computational fluid dynamics (CFD) models and tools for predicting PSI physics for plumes in low-pressure and rarefied environments, time-evolving cratering and surface erosion, and near-field and far-field ejecta transport.

NASA has plans to purchase services for payload delivery 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 PSI technologies in the lunar environment. The CLPS payload accommodations will vary depending on the service provider and mission characteristics, but the data to be obtained or mitigations to be demonstrated should be broadly applicable to other future landing systems. Additional information on the CLPS program and providers can be found at this link: [https://www.nasa.gov/content/commercial-lunar-payload-services](https://www.nasa.gov/content/commercial-lunar-payload-services) [29]. 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 are currently under contract, 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.

Expected TRL or TRL Range at completion of the Project

3 to 6

Primary Technology Taxonomy

Level 1

TX 09 Entry, Descent, and Landing

Level 2

TX 09.3 Landing

Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype
- Hardware
Desired Deliverables Description

Deliverables of all types can be infused into the prospect missions due to early design maturity.

For PSI ground test data, flight instrumentation, diagnostics, and mitigation approaches, Phase I deliverables should include detailed test plans, with prototype and/or component demonstrations as appropriate. Phase II deliverables should include complete data products, fully functional hardware, and validated performance in relevant environments.

For PSI modeling and simulation, Phase I deliverables should demonstrate proof of concept and a minimum of component-level verification, with detailed documentation on future data needs to complete validation of the integrated model and uncertainty quantification methodology. Phase II deliverables must demonstrate verification and validation beyond the component level, with validation demonstrated through comparisons with relevant data and documented uncertainty quantification. Significant attention should be applied to create highly robust and extremely high-performance computational simulation tool deliverables, exploiting leading-edge computational architectures to achieve this performance.

State of the Art and Critical Gaps

The characteristics and behavior of airborne particles during descent is important for designing descent sensor systems that will be effective. Furthermore, although the physics of the atmosphere and the characteristics of the regolith are different for the Moon, the capability to model PSIs on the Moon will feed forward to Mars, where it is critical for human exploration.

Currently, flight data are collected from early planetary landing, and those data are fed into developmental tools for validation purposes. The validation data set, as well as the expertise, grows as a result of each mission and is shared across and applied to all other missions. We gain an understanding of how various parameters, including different types of surfaces, lead to different cratering effects and plume behaviors. The information helps NASA and industry make lander design and operations decisions. Ground testing (“unit tests”) is used early in the development of the capability in order to provide data for tool validation.

The current postlanding analysis of planetary landers (on Mars) is performed in a cursory manner with only partially empirically validated tools because there has been no dedicated fundamental research investment in this area. Flight test data does not exist in the environments of interest.

Relevance / Science Traceability

Current and future lander architectures will depend on knowledge of PSI, such as:

- Artemis human landing system (HLS).
- Commercial robotic lunar landers (CLPS or other).
- Planetary mission landers (Mars Sample Retrieval Lander and others).
- Human Mars landers.

References

- Lander Technologies: [https://www.nasa.gov/content/lander-technologies](https://www.nasa.gov/content/lander-technologies) [30]
Scope Title

Landing Shock Attenuation, Reusability, and In Situ Landing Sensors

Scope Description

Novel and creative solutions will be required to attenuate the structural loads induced by the landing of crewed spacecraft, commercial cargo payloads, scientific payloads, critical surface assets, and surface habitats on the Moon and Mars. In principle, the mass and scale of these spacecraft, payloads, and assets could range from something akin to a small-satellite class, roughly 10 to 500 kg, to masses on the order of thousands of kg. This capability is critical for landing larger spacecraft near assets already in place.

Current landing system solutions include legs, shock absorbers, inflatables, crushables, sky cranes, pallets, etc., but new technologies, novel combinations of existing technologies, and/or the repurposing of current Earth-based technologies could enable new mission design and feasibility.

Mission concepts requiring the sustainability and reusability of assets and payloads on the surfaces of celestial bodies (including the Moon, Mars, moons of Mars, comets, and/or asteroids) will benefit from the development of reusable landing systems, including consideration of launch plumes for ascent vehicles. Reusability can also be interpreted to include the postlanding adaptation of landing systems to enable mobility or augmented capabilities (e.g., "touch-and-go" mobility, grappling, maneuverability, etc.).

In situ landing sensors that measure the induced loads and shocks experienced within these challenging environments will provide engineers and researchers with valuable in situ data, which will enable improved environmental modeling, landing structure design, and sensor design. Possible applications include advanced touchdown sensors, measurement of payload orientation, stability, and/or landing loads.

Also, of interest are approaches for achieving multifunctional components, repurposing landing structures for postflight mission needs such as payload placement or mobility, and incorporating design features that reduce operating complexity.

Under this subtopic, proposals may include efforts to develop prototypes for flight demonstration of relevant technologies in the lunar environment or in terrestrial testbeds. The Commercial Lunar Payload Services (CLPS) 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](https://www.nasa.gov/content/commercial-lunar-payload-services) [29]. 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 2022, 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.

Expected TRL or TRL Range at completion of the Project

3 to 6

Primary Technology Taxonomy

Level 1

TX 09 Entry, Descent, and Landing

Level 2

TX 09.3 Landing

Desired Deliverables of Phase I and Phase II
Desired Deliverables Description

Deliverables and/or prototypes of all types can be infused into the prospective missions due to early design maturity.

Phase I deliverables should include preliminary designs, end-product test plans, and component-level testing and/or demonstrations as appropriate, and Phase II should include a working prototype demonstration in a relevant environment.

State of the Art and Critical Gaps

Robust landing structures can enable lunar and Mars global access with 20-ton payloads to support human missions.

Mission risks related to hazard avoidance may be partially mitigated by robust landing system accommodation of landing hazards.

Development of exploration technologies to enable a vibrant space economy can be partially addressed with respect to landing technologies related to landing pads and protective and robust landing structures.

Construction and outfitting of assets on the Moon and Mars could be addressed by technologies related to multifunctional and adaptive landing structures for use after landing.

Relevance / Science Traceability

Current and future lander architectures will depend on landing shock attenuation, reusability, and intelligent landing sensors, such as:

- Artemis human landing system (HLS).
- Commercial robotic lunar landers (CLPS or other).
- Planetary mission landers (Mars Sample Retrieval Lander and others).
- Human Mars landers.
- Scientific investigations of comets and asteroids.

References

- Lander Technologies: https://www.nasa.gov/content/lander-technologies [30]
- Commercial Lunar Payload Services: https://www.nasa.gov/content/commercial-lunar-payload-services [29]
- Lunar Exploration and Transportation Services: https://www.nasa.gov/nextstep/humanlander3 [31]
- JPL ATHLETE Rover: https://wwwrobotics.jpl.nasa.gov/systems/system.cfm?System=11 [33]
- SLS-SPEC-159 Cross-Program Design Specification for Natural Environments (DSNE)

Z8.02 Communications and Navigation for Distributed Small Spacecraft Beyond Low Earth Orbit (LEO)

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

**Scope Title**

End-to-End Deep Space Communications

**Scope Description**

Develop enabling communications technologies for small spacecraft beyond low Earth orbit (LEO). These technologies will be required by spacecraft to conduct NASA lunar and deep space distributed spacecraft science missions. Innovations in communications technologies for distributed small spacecraft are essential to fulfill the science missions envisioned within the decadal surveys and contribute to the success of human exploration missions. To construct the lunar communications architecture [Ref. 11], it is appropriate to consider a hybrid approach of large and small satellite assets. Primary applications include lunar surface-to-surface data relay, data relay to Earth, and navigational aids to surface and orbiting users. Distributing these capabilities across multiple small satellites may be necessary because of limited size, weight, and power (SWaP), but also to enhance coverage.

Technologies for specific lunar architectures are especially needed. For example, landers near the lunar South Pole may not have—and landers on the far side of the Moon will not have—direct line-of-sight to Earth-based ground stations and will need to send data through a relay satellite (or Gateway) to return data to Earth. Small surface systems (including rovers or astronauts on extravehicular activities (EVAs)) on the Moon will likely not have the necessary system resources to close a direct link to Earth. Human surface operations may require surface-to-surface over-the-horizon communications through an orbital relay. Deployment of sufficient traditional communications assets to maintain persistent global coverage of the lunar surface may be prohibitively expensive. Analogous to emerging LEO communications constellations, small spacecraft can operate as local relays in cislunar space.

Considerations for technology and capability extension to the martian domain and other deep space applications are also solicited.

Interspacecraft networking is inherent to distributed mission and interoperable communications relay architectures. Enabling networking capabilities in small spacecraft requires low SWaP, low-cost hardware for radiofrequency (RF) and optical crosslinks. While network protocols developed for interoperable communications relays may be interchangeable with those for distributed missions, relay networks may not be scalable to very large-scale sensor webs of small spacecraft. As such, addressing interspacecraft networking gaps may require investment in both hardware crosslinks and networking protocols that scale to hundreds of nodes, and requires robustness for loss of nodes or as new nodes enter the network. Network management technologies may be needed due to the increased operational complexity.

An end-to-end system needs to be considered for the application of small satellites for deep space missions as described in preceding paragraphs. Therefore, enabling technologies also include non-NASA ground services that keep the operations cost commensurate with the lower costs of the small satellites themselves. Automation of the ground services as well as the small satellite constellations are needed.

Communications solutions can operate in optical or various RF bands; however, considerations must be given to bandwidth, public and Government licensing, network and data security, and compatibility with referenced candidate architectures.

**Expected TRL or TRL Range at completion of the Project**

2 to 5

**Primary Technology Taxonomy**

**Level 1**

TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
Level 2

TX 05.X Other Communications, Navigation, and Orbital Debris Tracking and Characterization Systems

Desired Deliverables of Phase I and Phase II

- Prototype
- Hardware
- Software

Desired Deliverables Description

Phase I: Identify and explore options for the deep space small-satellite missions, including ground services. Conduct trade analysis and simulations, define operating concepts, and provide justification for proposed multiple access techniques, frequency bands of operation, command and data handling, and networking solutions. Also identify, evaluate, and develop design for integrated communications payload(s) and one or more constituent technologies that enable distributed spacecraft operations in the relevant space environment beyond LEO. Integrated communications system solutions and constituent component deliverables should offer potential advantages over the state of the art, demonstrate technical feasibility, and show a path toward a hardware/software infusion into practice. Bench-level or laboratory-environment-level demonstrations or simulations are desirable. The Phase I proposal should outline a path that shows how the technology can be developed into space-qualifiable and commercially available small-spacecraft communications payloads through Phase II efforts and beyond.

Phase II: Demonstration of communication technology via prototype or high-fidelity emulation. The relevant deep space environment parameters should be simulated as much as possible.

State of the Art and Critical Gaps

Small-spacecraft missions beyond Earth require compact, low-power, high-bandwidth radios for use on the Moon, Mars, the rest of the inner planets, around asteroids or other small bodies, and at other deep space destinations. The current state of the art is the Iris radio (0.5U, 1.2 kg, and 35 W) [Ref. 12] that has been operationally used at Mars, and there is no known affordable, readily available competitor. Future missions require systems that are lower SWaP-C, can operate in multiple bands (S, X, Ka-band, and optical), and can reach uplink and downlink speeds in excess of 20 Mbps. Spectral, modulation, information layer, and protocol compatibility with current technologies (Space Communications and Navigation (SCaN)); licensing and spectrum approval; and planned Government or commercial deep space communication architecture must all be considered.

Communications among spacecraft in a distributed spacecraft mission (DSM) configuration and between the DSM configuration and the Earth become more challenging beyond LEO distances. Collaborative configurations of widely distributed (tens to hundreds of kilometers apart) small spacecraft (180 kg or less) will operate far into the near-Earth region of space and beyond into deep space, further stressing the already limited communications capabilities of small spacecraft. Alternative operational approaches with associated enabling hardware and/or software will be needed with the following:

- Uplinks (Earth-to-space) and downlinks (space-to-Earth): Alternatives for coordinated command and control of the DSM configuration and individual small spacecraft from Earth as well as return of science and telemetry data to Earth. Each spacecraft cannot rely on its own dedicated Earth link, consuming valuable ground infrastructure and operators.
- Integrated communications payload: Hardware and software designs for the common and unique capabilities of each small spacecraft in the DSM configuration. Spacecraft communication SWaP-C should be reduced by at least 25% from a non-DSM spacecraft.
- Small-spacecraft antennas: Development of antennas optimized for either intersatellite or uplink/downlink communications are sought across a broad range of technologies including but not limited to deployable parabolic or planar arrays, active electronically steered arrays, novel antenna steering/positioning subsystems, and others suitable for use in high data rate transmission among small spacecraft over large distances. SWaP-C should be reduced from state of the art, such as the recent 6U CubeSat MarCO
mission, which used a 0.2 m² X-band reflectarray to achieve 29 dBic gain and 42% efficiency [Refs. 13, 14]. Operations compatible with NASA's space communications infrastructure [Ref. 9] and Government-exclusive or Government/non-Government-shared frequency spectrum allocations is required [Refs. 6, 7, 8].

- Small-spacecraft RF solid-state power amplifiers and RF front ends with smart electronics that increase operational efficiencies.
- Compatibility and interoperability with lunar communications and navigation architecture plans [Refs. 1, 2, 3]. Application of the emerging lunar standards includes frequency allocations per link functionality, modulation, coding, and networking protocol standards. Ka-band frequencies and above are highly desired.
- Optical end-to-end considerations for Earth links. If a DSM design relies on an optical link to Earth, the needed ground infrastructure should be considered.

Relevance / Science Traceability

Several missions are being planned to conduct investigations/observations in the cislunar region and beyond. For example: Commercial Lunar Payload Services (CLPS); Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE); human exploration (Artemis) landing site and resource surveys; and communications and navigation infrastructure, including LunaNet, Mars communications relay, etc. Commercial and NASA small spacecraft, lunar surface assets, and manned vehicles in cislunar space and beyond will multiply within the decade. All these missions will depend on small-spacecraft communications relays, time reference transmissions, and navigation capabilities.

References:

1. International Communication System Interoperability Standard (ICSIS): https://www.internationaldeepspacestandards.com [34]
4. NASA Delay/Disruption Tolerant Networking (DTN): http://www.nasa.gov/content/dtn [37]
10. NASA Optical Communications: https://www.nasa.gov/directorates/heo/scan/opticalcommunications/overview [42]
Scope Description

Develop enabling technologies for beyond Low Earth Orbit (LEO) relative and/or absolute position knowledge. This situational awareness allows for autonomous control of small spacecraft as well as determining and maintaining position within a swarm or constellation of small spacecraft. In addition, timing distribution solutions for the SmallSats are important. Earth-independent and Global Positioning System- (GPS-) independent navigation and timing are enabling capabilities required by spacecraft to conduct NASA lunar and deep space distributed spacecraft science missions. Innovations in navigation technologies for distributed small spacecraft are essential to fulfill the science missions envisioned within the decadal surveys and contribute to the success of human exploration missions.

Multiple small spacecraft operating in coordinated orbital geometries or performing relative station-keeping can further expand human knowledge deeper into the universe by performing coordinated occultation, acting as virtual telescopes, and forming distributed apertures that would be prohibitively complex and expensive to launch into space as monolithic structures. Small-spacecraft formation flight can also enable swarm gravimetry, synchronized observation of transient phenomena, and proximity operations for inspection of other assets. Realizing these capabilities on affordable small spacecraft requires sensors and maneuvering systems that are low in mass, volume, power consumption, and cost.

Further expansion of small spacecraft use into deep space requires highly accurate position knowledge and precision timing that does not depend on GPS or other Earth-centric aids. Exploration mission operations that involve multiple-element distributed-mission architectures may involve 30 to 100 spacecraft, and the general expansion of the number of cislunar and deep space missions will stress or exceed current capacity of the Deep Space Network (DSN). Access to DSN ranging may not be available for multiple concurrent missions, may be blocked by terrain for surface operations, or may be limited by the radio capabilities of smaller missions. In concert with other available signals of opportunity and landed beacons, small spacecraft can provide relative ranging or triangulation to aid lunar navigation. Knowledge at the spacecraft of relative (between-spacecraft) situational awareness is needed for real-time station-keeping/relative position control where required rapid reaction speeds preclude human-in-the-loop operation.

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Future small-spacecraft missions will need to autonomously determine and transmit relative and absolute position as well as keep and exchange precise timing. These capabilities are required for small spacecraft to act as infrastructure for other missions and for distributed missions composed of small spacecraft beyond Earth. Navigation technologies and techniques may include inertial navigation combined with enhanced visual navigation capabilities (e.g., dual use of star-tracking instruments for relative navigation using surface features or other nearby spacecraft), x-ray emissions (from pulsars), and laser range finding to other spacecraft or surface landmarks. For use with small spacecraft, these systems must be compatible with the inherent size, weight, power, and cost (SWaP-C) constraints of the platforms.

Precise timekeeping and timing exchange is not only required for navigation but is fundamental to science data collection. Internetworked small spacecraft can help synchronize timing across multiple mission assets using an external timing source. Recently improved chip-scale atomic clocks that can be carried by the small spacecraft themselves can augment this capability to reduce the accumulation of errors over time or serve as the primary clock when other larger but more accurate reference sources are not available or feasible. The vast majority of current commercial interests and Government missions operate in near-Earth orbits. To date, both NASA and the commercial spaceflight industry have enjoyed strong investment in near-Earth situational awareness made possible by tracking and identification capabilities provided by the Department of Defense. As the number of cislunar missions grows and NASA encourages the development of the lunar service economy, similar investments in situational awareness capabilities in these new orbital regimes will be needed to help support NASA and commercial operations.

Primary applications include navigational aids to lunar surface and orbiting users. Distributing these capabilities across multiple SmallSats may be necessary because of limited SWaP, but also to enhance coverage. Technologies for specific lunar architecture are especially needed, but considerations of extension to the Martian domain are also solicited. Navigation solutions for deep space distributed spacecraft missions (DSMs) may be addressed via hardware or software solutions or a combination thereof.

Expected TRL or TRL Range at completion of the Project: 2 to 5
Primary Technology Taxonomy:
Level 1: TX 17 Guidance, Navigation, and Control (GN&C)
Level 2: TX 17.2 Navigation Technologies

Desired Deliverables of Phase I and Phase II:

- Prototype
- Software
- Hardware

Desired Deliverables Description:

Phase I: Identify and explore options for the deep space navigation technology, conduct trade analysis and simulations, define operating concepts, and provide justification for proposed techniques, frequency bands of operation, command and data handling, and networking solutions. Also identify, evaluate, and develop design for integrated navigation payload(s) and one or more constituent technologies that enable distributed spacecraft operations in the relevant space environment beyond LEO. Integrated navigation system solutions and constituent component deliverables should offer potential advantages over the state of the art, demonstrate technical feasibility, and show a path toward a hardware/software infusion into practice. Bench-level or laboratory-environment-level demonstrations or simulations are desirable. The Phase I proposal should outline a path that shows how the technology can be developed into space-qualifiable and commercially available small-spacecraft communications payloads through Phase II efforts and beyond.

Phase II: Demonstration of navigation technology via prototype or high-fidelity emulation. The relevant deep space environment parameters should be simulated as much as possible.

State of the Art and Critical Gaps:

Science measurements of distributed satellite missions (DSMs) are based on temporal and spatially distributed measurements where position knowledge and control are fundamental to the science interpretation. Current space navigation technologies are not adequate when relative or absolute position knowledge of multiple spacecraft is involved. State of the art (SOA) for attitude is the Jet Propulsion Laboratory's ASTERIA (Arcsecond Space Telescope Enabling Research in Astrophysics) 6U CubeSat demonstrated pointing stability of 0.5 arcsec (0.1 microdeg) rms over 20 min using guide stars. For position knowledge, missions still primarily use ranging transponders relying on a two-way Earth link. Examples of SOA for this ranging are the Iris transponder and the Small Deep Space Transponder (SDST) [Ref. 13].

Global navigation satellite services like the United States’ Global Positioning System (GPS) provide very limited services beyond geostationary Earth orbit distances, and no practical services in deep space. Autonomous navigation capabilities are fundamental to DSMs to ensure known topography of the configuration at the time of data acquisition. Control of the distributed configuration requires robust absolute and relative position knowledge of each spacecraft within the configuration and the ability to control spacecraft position and movement according to mission needs. Critical areas for advancement are:

- Long-term, high-accuracy attitude determination: In particular, low-SWaP absolute attitude determination using star trackers, etc., to achieve sub-arcsec accuracy.
- Optical navigation: Solutions are sought for visual-based systems that leverage advances in optical sensors (e.g., cameras, star trackers) to observe and track a target spacecraft and perform pose and relative position estimation. Opportunities for innovation include methods that do not require the execution of satellite maneuvers and/or the design of external satellite features that enhance observability. Innovations may be appropriate for only certain regimes, such as near, medium, or far range; however, this context should be described. Solutions for various lunar and deep space mission operations concepts are of interest.
Other novel navigation methods: Stellar navigation aids, such as navigation via quasars, x-rays, and pulsars, may provide enabling capabilities in deep space. Surface-based navigation aids, such as systems detecting radio beacons or landmarks, are invited. Emerging quantum-based technologies are of high interest.

Methods for autonomous position control are also of interest. Technologies that accomplish autonomous relative orbit control among the spacecraft are invited. Control may be accomplished as part of an integrated system that includes one or more of the measurement techniques described above. Of particular interest are autonomous control solutions that do not require operator commanding for individual spacecraft. That is, control solutions should accept as input swarm-level constraints and parameters and provide control for individual spacecraft. Opportunities for innovation include the application of optimization techniques that are feasible for small-satellite platforms and do not assume particular orbit eccentricities. State of the art in this area is the Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE), the first spacecraft to attempt to navigate to and maintain a near-rectilinear halo orbit around the Moon as a precursor for Gateway [Ref. 11]. NASA is also partnering with universities for use of surface-feature-based navigation and timing [Ref. 12].

NOTE: Small-spacecraft propulsion technologies are not included in this subtopic.

Relevance / Science Traceability:

Space communications and position knowledge and control are enabling capabilities required by spacecraft to conduct all NASA missions. The concept of distributed spacecraft missions (DSMs) involves the use of multiple spacecraft to achieve one or more science mission goals.

Several missions are being planned to conduct investigations/observations in the cislunar region and beyond. For example, CLPS; human exploration (Artemis) landing site and resource surveys; and communication and navigation infrastructure, including LunaNet, Mars communications relay, etc. All of these missions will benefit from improved communications and navigation capabilities.

References:

1. International Communication System Interoperability Standard (ICSIS): [https://www.internationaldeepspacestandards.com][34]
4. NASA Delay/Disruption Tolerant Networking (DTN): [http://www.nasa.gov/content/dtn][37]
7. National Telecommunications and Information Administration Tables of Frequency Allocations: [https://www.ntia.doc.gov/legacy/osmhome/allocdb/allocdb.html][39]
9. NASA Space Communications and Navigation Networks: [https://www.nasa.gov/directorates/heo/scan/services/networks/index.html][41]
10. NASA Optical Communications: [https://www.nasa.gov/directorates/heo/scan/opticalcommunications/overview][42]
Z8.09 Small Spacecraft Transfer Stage Development

Lead Center: GRC

Participating Center(s): AFRC, GRC, JSC

Scope Title
Small Spacecraft Transfer Stage Development

Scope Description
NASA and industry represent prospective customers for sending small-spacecraft payloads in the near term to the cislunar environment, with longer term potential for farther destinations such as near-Earth objects, Mars, or Venus. The lunar destinations in this case include the lunar surface, with specific interest in the South Pole, low lunar and frozen lunar orbits, and cislunar space, including Earth-Moon LaGrange points (e.g., E-M L3) and the lunar near-rectilinear halo orbit (NRHO) intended for Gateway. In future missions, NASA may transport small spacecraft to Venus for scientific discovery, to Mars to serve as precursors and infrastructure for human (and scientific) exploration, and on small-spacecraft missions to near-Earth objects for science measurements needed to understand prospective threats to Earth and perhaps even for resource extraction and return to Earth. The ultimate goal is to exploit the advantages of low-cost and rapidly produced CubeSats and small spacecraft, defined as total mass less than 180 kg fueled, by enabling them to reach these locations. Due to the current limits of SmallSat propulsion capabilities and the constraints of rideshare opportunities, NASA has an interest in the development of a low-cost transfer stage to guide and propel small spacecraft on trajectories to the vicinity of the Moon and enable their insertion into the above-referenced orbits. In addition, NASA has interest in the transfer stage being able to provide support services to the spacecraft post-deployment, such as communications relay or positioning, navigation, and timing (PNT) services. Advancement and extension of these capabilities will be needed for future planetary exploration.

Transfer stage designs shall be compatible with U.S. small launch vehicles that are currently flying or will be launching imminently. Proposals shall identify one or more relevant small launch vehicles, describe how their designs fit within the constraints of those vehicles, and define the transfer capability of the proposed system (i.e., from Low Earth Orbit (LEO), geosynchronous transfer orbit (GTO), etc., to low lunar orbit (LLO), NRHO, E-M L3, etc.). Establishment of a partnership or cooperative agreement with a launch vehicle provider is strongly encouraged. Transfer stage designs shall contain all requisite systems for navigation, propulsion, and communication to complete the mission. Novel propulsion chemistries and methods may be considered, including electric propulsion, as long as the design closes within the reference mission constraints. Transfer stages shall also include method(s) to deploy one or more SmallSat payloads into the target trajectory or orbit. Innovations such as novel dual-mode propulsion systems that enable new science missions or offer improvements to the efficiency, accuracy, and safety of lunar missions are of interest. Concepts that enable small cargo delivery and inspections to support on-orbit servicing, assembly, and manufacturing platforms are also desired. Additionally, technologies with dual-use potential (such as hypersonic or suborbital demonstrations) are applicable to this subtopic. The ability of the transfer stage to provide support services, such as Communications Relay or PNT, after spacecraft deployment is highly desirable.

This subtopic is targeting transfer stages for launch vehicles that have a capability range similar to that sought by the NASA Venture Class Launch Services. Rideshare applications that involve medium- or heavy-lift launch vehicles (e.g., Falcon 9, Atlas V) or deployment via the International Space Station (ISS) airlock are not part of this topic.

Lunar design reference mission:

- Launch on a small launch vehicle (ground or air launch).
Payload (deployable spacecraft) mass: at least 25 kg.
Provide sufficient delta-v and guidance to enter into trans-lunar injection (TLI) orbit after separation from small launch vehicle. An example mission is the Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE)/NRHO Pathfinder 12U (25 kg) CubeSat, which requires a TLI orbit with a $C_3$ (characteristic energy) of -0.6 km$^2$/s$^2$. (Alternative) Provide sufficient delta-v and guidance to place a 25- to 50-kg spacecraft directly into lunar NRHO or E-M L3 orbit.
Deploy spacecraft from transfer stage.
Perform transfer stage safing and disposal operations.

Stretch goals are:

1. Extensibility of the design for planetary design reference missions: Similar to the above, for Venus, Mars, or near-Earth object destinations.
2. Ability to provide postdeployment spacecraft support services such as Communications Relay and/or PNT. Proposer to outline the performance and duration these support services can achieve for applicable orbital environments.
3. Enable small-cargo delivery and inspections to support on-orbit servicing, assembly, and manufacturing platforms.

Expected TRL or TRL Range at completion of the Project:

4 to 6

Primary Technology Taxonomy:
Level 1: TX 01 Propulsion Systems
Level 2: TX 01.1 Chemical Space Propulsion

Desired Deliverables of Phase I and Phase II:

- Prototype
- Hardware
- Software
- Analysis

Desired Deliverables Description:

A Phase I effort should provide evidence of the feasibility of key elements of cost, assembly, integration, and operations through fabrication and testing demonstrations. A flight concept should reach sufficient maturity to be able to clearly define mission environments and performance requirements. A prototype system design should reach sufficient maturity to define test objectives and map key performance parameters (mass, power, cost, etc.) from the prototype to the flight design. Hardware development during the Phase I effort should provide confidence in the design maturity and execution of the Phase II effort. Lastly, the Phase I effort should identify potential opportunities for mission infusion and initiate partnerships or cooperative agreements necessary for mission execution.

The Phase II deliverable should provide significant evidence of the progress toward mission infusion (PMI) as outlined in the 2020 NASA Small Spacecraft Technology: State of the Art report. Phase II objectives should meet the intent of the In-Development or Engineering-to-Flight classifications, including demonstrations in a relevant
environment or execution of a qualification program. Efforts leading to Phase II delivery of an integrated system that could either be ground- or flight-tested as part of a post-Phase II effort are of particular interest.

State of the Art and Critical Gaps:

Many CubeSat/SmallSat propulsion units are designed for low delta-v maneuvers such as orbit maintenance, station-keeping, or reaction control. Larger delta-v systems are employed for larger satellites and science/exploration missions but are often costly and integrated as part of the satellite design. Systems typically range from cold-gas to bipropellant storables with electric systems also viable for very small systems. Rocket Lab has recently introduced an upgraded version of their monopropellant kick stage, which includes a bipropellant engine, advanced attitude control, and power subsystems. This system will be used for the first time for NASA's Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) mission and is suggested to have capability for orbits beyond the lunar environment. At the component level, suppliers of state-of-the-art (SOA) thrusters include Aerojet Rocketdyne, Moog Inc, and Bradford Space, among others, while companies like Blue Canyon Technologies offer spacecraft bus solutions absent dedicated propulsion elements. Advanced manufacturing, electric pumps, and actuators, nontoxic or nontraditional propellants, and electrospray thrusters all offer potential improvements in the flight capabilities of small propulsion systems. System concepts that enable improved spacecraft performance and control, such as dual-mode systems, provide potential advancements to the current SOA, especially those that enable new science missions and those that offer potential improvements to the efficiency, accuracy, and safety of future lunar manned missions. While many of these component technologies are reasonably mature, progress has been limited in the development and qualification of an integrated system as a rapid, low-cost solution for translunar or cislunar missions.

Deployment of small spacecraft beyond geosynchronous orbits typically exacerbates their limitations with respect to communications and navigation, by virtue of longer communication distances and limited ability to use Global Navigation Satellite System (GNSS) PNT services. This typically requires the spacecraft to throttle their communications and rely on more cumbersome ranging transponders with Earth for position knowledge, adversely affecting spacecraft designs and operations. Equipping transfer stages with such support services potentially allows for a less constraining environment for small spacecraft deployed in deep space. With respect to the current SOA, the Air Force Research Laboratory's EAGLE mission (Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) Augmented Geostationary Laboratory Experiment), launched into a near geosynchronous orbit, is an example of a host vehicle able to deploy smaller spacecraft as well as providing support services to hosted payload only.

Relevance / Science Traceability:

This subtopic extends the capabilities of the Flight Opportunities program and the Launch Services Program by seeding potential providers to establish lunar/cislunar transfer capabilities. The Small Spacecraft Technology (SST) program also seeks demonstrations of technical developments and capabilities of small spacecraft to serve as precursor missions (such as landing site investigation or in situ resource utilization (ISRU) prospecting) for human exploration, and as communications and navigation infrastructure for follow-on cislunar missions. SST CAPSTONE is an example mission.

Many technologies appropriate for this topic area are also relevant to NASA's lunar exploration goals. Small stages developed in this topic area would also be potential flight testbeds for cryogenic management systems, wireless avionics, or advance guidance systems and sensors. Sound rocket capabilities are being improved with options financed through this topic.

Small launch vehicles provide direct access for a small spacecraft to the destination or orbit of interest at a time of the small-spacecraft mission's choosing. In support of exploration, science, and technology demonstration missions, further expansion of these vehicles' reach beyond LEO is needed. To expand the risk-tolerant small-spacecraft approach to deep space missions, frequent and low-cost access to destinations of interest beyond Earth is required. Provision of support services by the transfer stage to the spacecraft post-deployment could enable more ambitious small-spacecraft missions.

In the longer term, technical capabilities of small spacecraft at Venus, Mars, or NEO destinations will be demonstrated by SST, and ultimately new kinds of transfer vehicles derived from these capabilities may be needed to propel them there.
Z8.10 Modular Systems for Cost-Effective Spacecraft Missions

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

Scope Title

Wireless Avionics Architectures and Wireless Sensing and Integrated Avionics

Scope Description

This subtopic scope solicits proposals to develop enabling concepts, components, and subsystems based on innovative avionics architectures for spacecraft. Of interest are wireless systems that demonstrate reliable data transfer across avionics components, subsystems, and interfaces to simplify system integration, reconfiguration, and testing. These can range from developmental and flight instrumentation systems used for qualification and diagnostics on large spacecraft to fully wireless avionics for small spacecraft. Solutions that enable new avionic architectures and provide capabilities that expand mission performance while decreasing the size, weight, and power consumption (SWaP) and cost of the resulting spacecraft are highly desirable. The goal of this effort is to mature wireless avionics technology that facilitates the reuse of components, subsystems, and software across multiple spacecraft and missions while reducing production and operating costs. Initial development and demonstration is anticipated to be performed using small spacecraft, but applicability to large spacecraft, lunar outposts, human-rated landers, and robotic elements is highly desirable.

Modularity is defined as utilizing a set of standardized parts or independent units to form a full avionics system, and flexibility allows adapting modular components across different configurations, missions, and design stages. For example, wireless subnets improve modularity by eliminating the physical data connections from each component, simplifying physical integration. The scope is intended to range from simple wireless sensors to complete avionics systems, including software incorporating functions compatible with common spacecraft components. This means
being able to integrate a given component or entire subsystem into flight hardware and software using object-oriented frameworks, allowing components or functions to be added to a new or existing spacecraft design without requiring significant changes to the other nonrelated components or subsystems.

This subtopic also solicits proposals to develop techniques, components, and systems that reduce or eliminate the dependency on wires, connectors, and penetrations for sensing and for the transmission of data and power across avionics subsystems, interfaces, and structures. Of interest are techniques that enable new applications through innovative methods such as the use of flexible materials and additive manufacturing. For example, the use of additive manufacturing and 3D printing to embed avionics components such as antennas, sensors, transmission lines, and interface functions into a spacecraft structure during the design and manufacturing process can increase efficiency while maintaining structural integrity. Similarly, the use of thin and flexible materials to construct passive wireless sensors enables sensing systems for structures such as parachutes and inflatable spacecraft without breaching the pressure interface. Systems that are applicable to small spacecraft (typically 6U/12U/24U CubeSats, including ESPA-class (Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter class)) but scalable to large vehicles can result in a significant reduction of risk for more complex and longer duration missions. Near-term missions include cislunar, lunar orbiting, lunar landed, and exploration precursor missions; low Earth orbit (LEO) “swarms” for Earth science and heliophysics; and disaggregated cooperative ensembles and sustained infrastructure for human exploration. New applications might include manned spacecraft inspection, repair, communications support, and related areas. Technology that supports onboard servicing, assembly, and manufacturing is specifically solicited. Proposals that provide reliable performance in extreme environments and that show a path to a flight demonstration are preferable.

The subtopic solicits developments in wireless avionics and wireless sensing for small spacecraft and may include technologies that:

1. Improve the reliability and applicability of wireless avionics for spacecraft with significant improvements in subsystem size, mass, and volume, particularly if the technology can simplify the spacecraft fabrication, test, and integration process.
2. Allow innovative architectures for wireless avionics featuring plug-and-play software supporting modular subsystems that can be easily incorporated into specific small-satellite missions.
3. Improve fault detection aboard spacecraft using wireless sensor systems to augment current wired sensors and which include the capability of adding sensors to address developmental and flight instrumentation use.
4. Use innovative techniques for embedding sensors and other avionics components into a spacecraft to reduce or eliminate large and heavy cables and connectors, or that enable data transfer inside and across rotating mechanisms and pressure interfaces or into remote locations where it is difficult or unfeasible to run cables or where cables are at risk of failure.
5. Use additive manufacturing of wireless components such as antennas, sensors, and processing elements to create new components that may be smaller and lighter than current products. These new components could be embedded into materials and structures that enable in situ structural health management, contributing to the development of smart structures and materials.
6. Include sensors and actuators that can be distributed among cooperative spacecraft to enable automated inspection of space assets or resource detection at the surface of the Moon, Mars, or other celestial bodies.
7. Development of wireless network and component technology that can enable time-critical control loops across spatially distributed elements can produce new avionics capability.

Key performance parameters (KPPs) would include improvements of at least a factor of 2 over existing technology in size, mass, and power consumption for sensors and associated components for a wireless instrumentation system. Improvements of sensor network throughput greater than five times the current 2-Mbps performance is desired, along with reduction of latency and incorporation of timing and position information.

Expected TRL or TRL Range at completion of the Project

3 to 6

Primary Technology Taxonomy

Level 1
Desired Deliverables of Phase I and Phase II

- Hardware
- Prototype
- Software
- Research
- Analysis

Desired Deliverables Description

Possible deliverables include benchtop hardware systems that demonstrate reliable wireless interconnectivity of two or more modules with a host flight central processing unit (CPU), or payload/developmental flight instrumentation (DFI) processor, inside a CubeSat or small-satellite form-factor bus. This system need not be flight ready, but it should be in a path to a flight demonstration that would serve as technology maturation and risk reduction activity for larger NASA missions such as Gateway and other Artemis projects.

Specific Phase I deliverables include:

- Methods of improving reliability of wireless avionics technology.
- Redundancy methods to broaden mission applicability.
- Improvements in tolerance to extreme environments, including radiation.
- Novel avionics architecture definition and demonstration.
- Software support for redundant modular avionics.
- Plug-and-play methods for handling dynamic changes to avionics configuration.
- Fault detection and recovery for wireless avionics.
- Improvements in spacecraft production.
- Improvements in spacecraft integration and test.
- Technologies that use additive manufacturing technology for embedded avionics systems that reduce cables, connectors, and penetrations and show a path to a full solution.
- Sensors and sensor systems based on current technology needs to develop point solutions that are applicable to NASA missions in near- to mid-range timeframes.

Phase II deliverables should build upon the work completed in Phase I to demonstrate the new technology at a higher Technology Readiness Level (TRL) with alignment to NASA mission needs:

- Demonstration showing the key innovations of the developed technology.
- Demonstration of specific new mission capabilities.
- Delivery of prototype hardware for NASA evaluation.

State of the Art and Critical Gaps

Development of small-satellites missions benefits from a growing number of users worldwide. This means there may be a large pool of commercial off-the-shelf components available for a specific mission (depending on the type and class of mission). A variety of command and data handling (C&DH) developments for CubeSats have resulted from in-house development, from new companies that specialize in CubeSat avionics, and from established companies who provide spacecraft avionics for the space industry in general. Presently there are a number of commercial vendors who offer highly integrated systems that contain the onboard computer, memory, electrical power system (EPS), and the ability to support a variety of input and output (I/O) for the CubeSat class of small spacecraft.
Wireless networks have been incorporated as crew support aboard the International Space Station (ISS). Wireless sensor networks have been flown as demonstrations. Dynamic self-configuring wireless networks have been evaluated in the laboratory. The American Institute of Aeronautics and Astronautics (AIAA) has defined the Space Plug-and-Play Architecture (SPA) standard, and flight demonstrations are planned.

The maturation of additive manufacturing and 3D printing technology are making embedded wireless sensors and avionics a possibility. Embedding transmission lines, antennas, connectors, and sensors onto a spacecraft structure turns that structure into a multifunctional system that reduces or eliminates bulky cables and connectors. Embedded passive wireless sensors can greatly increase sensing and telemetry capabilities, including providing low-cost techniques for vehicle health management in future missions. Moreover, flexible embedded passive sensors created with conductive and functional fabrics are enabling new opportunities for sensing in surfaces and systems where sensing has been traditionally absent, such as parachutes and inflatable structures.

Wireless power transmission is being used commercially for charging cell phones using resonant magnetic couplings. Passive sensors do not require an external power source. Power generation from light, vibration, radio-frequency (RF) energy, and other methods is needed to eliminate batteries and power connections for wireless sensor systems.

Relevance / Science Traceability

NASA and other space agencies are exploring the application of SmallSats for deep space missions. The availability of modular wireless data connectivity alleviates complexity in testing and integration of systems. Modular components allow easier reconfiguration and late additions to any design. This is a benefit conferred on any spacecraft of any size, with the larger systems benefiting from savings in mass due to a larger reduction in cable harnesses and connectors.

References:

7. NASA Trade Study: https://pdfs.semanticscholar.org/b7d6/e6d92ec78bb6b5ee4cfd5a7f613b9b4508b8.pdf?ga=2.244696965.1804159109.1563897519-1127952606.1563032260 [68]
spacecraft standards. Of particular interest are designs acquiescent to the Agency standards existing between grounding, thermal, software, and data transfer interfaces.

The adaptability introduced by an open and modular, interchangeable commercial-off-the-shelf (COTS) architecture furthers the ability to tailor current spacecraft designs for novel applications without requiring significant modifications to existing platforms. Also, of interest are advances in modules that minimize complexity in spacecraft manufacturing (such as deterring geometrical modifications by virtue of manufacturing). Advances in additive manufacturing may enable critical enhancements to the performance of small-spacecraft systems by embedding otherwise impractical internal features (such as through holes and cavities for electronics integration). Concepts that can support high specific power generation and management as well as thermal control are also of particular interest.

Systems that are applicable to small spacecraft (CubeSats up to ESPA class (Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter class) but scalable to large vehicles can result in a significant reduction of risk for more complex and longer duration missions. Near-term missions include:

- Cislunar, lunar orbiting, lunar landed, and exploration precursor.
- Low Earth Orbit (LEO) “swarms” for Earth science and heliophysics.
- Disaggregated cooperative ensembles and sustained infrastructure for human exploration.

New applications might include manned spacecraft inspection, repair, communications support, and related areas. Proposals that provide reliable performance in extreme environments and that show a path to a flight demonstration are preferable.

The subtopic solicits developments in open modular architectures for small spacecraft and may include technologies that:

1. Provide interchangeable hardware and software with standardized interfaces.
2. Enable spacecraft to be built up from plug-and-play components.
3. Improve the state of the art of open interfacing platforms suitable for small spacecraft, leveraging COTS wherever possible.
4. Leverage novel manufacturing-in-the-loop considerations for small-spacecraft design standardization.
5. Increase the reliability and durability of small-spacecraft hardware and software by integrating subsystem considerations directly into the design process at the architectural level.
6. Demonstrate expanded adaptivity for small spacecraft, allowing for platforms to be rapidly varied with respect to altering objectives and variable risk postures.
7. Exhibit advances in onboard power generation and management and/or improvements in thermal mitigation and dissipation for small spacecraft.

Expected TRL or TRL Range at completion of the Project:

3 to 6

Primary Technology Taxonomy:
Level 1: TX 02 Flight Computing and Avionics
Level 2: TX 02.1 Avionics Component Technologies

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software
Desired Deliverables Description:

Promising platform architectures that enable the standardization of COTS hardware and software could be demonstrated through benchtop setups validating numerous protocols and compliance with existing NASA design standards for small spacecraft. A demonstration of ease of hot-swapping would be ideal, demonstrating how rapidly such a system could be adapted for altered requirements with new instrumentation and subsystems.

The deliverables should address improvements for ease of integration of varied hardware and software, plug-and-play integration of small-spacecraft subsystems, increased assembly speed of small spacecraft, utilization of advanced manufacturing for ease of integration, automated error assessment for targeted repairability of subsystems, reduced small-spacecraft design complexity, and reduction of small-spacecraft development cost through standardized COTS.

Phase I Deliverable:

Trade study for and demonstration of how NASA small-spacecraft standards, such as thermal, grounding, and software/data normalizations, could be implemented into hot-swappable, modular architecture.

These architectures must be cognizant of:

- NASA thermal interface standards to demonstrate necessary conductivity and respective thermal isolation.
- NASA grounding interface standards to mitigate unwanted currents through single- or multiple-point grounding framework.
- NASA software and data interfacing standards, complying with Unified S-Band (USB) or Consultative Committee for Space Data Systems (CCSDS) standards.

Phase II Deliverable:

A benchtop hardware demonstration of open and modular architectures functioning at TRL 5 or above and using the Standards developed during Phase I. The components should take advantage of supply-chain-compliant, heritage-relevant COTS whenever possible.

State of the Art and Critical Gaps:

The current SOA leverages COTS and compiled standards for integrating small spacecraft into a functional system meeting varied mission requirements. A number of in-house developments within NASA have complemented progress in academia and private industry to develop the infrastructure required to expand and normalize the definition of small-spacecraft-compliant subsystems and instrumentation. An issue arises with the software and hardware architecture regulating the agreement of these subsystems with NASA standards. Commercial vendors offering plug-and-play components are often only compliant with a limited number of subsystems, and consequently there exists a need to address this with an open modular architecture to enable more rapid, compliant, and consequently cost-effective small spacecraft that meet NASA’s standards.

Relevance / Science Traceability:

NASA and other space agencies are exploring the application of SmallSats for deep space missions. Modular architectures would enable a hot-swap adaptivity to altering mission requirements and serve as low-cost, rapid solutions for emerging destinations as they arise. Modular components allow easier reconfiguration and late additions to any design. Small-spacecraft modularity can be analogous for larger systems as well by virtue of defining and standardizing interconnectivity of universal COTS systems, enabling new objectives to be realized with a wide variety of instrumentation with a wide scope of requirements.

References:
Cost-Effective Modular Batch-Producible Small Spacecraft

Scope Description

This subtopic scope requests proposals to address the need for industry collaboration to manufacture 30 to 100 small spacecraft for a wide variety of missions, addressing objectives ranging from heliophysics to constellation demonstrations and sensor web applications. The ability to fabricate relatively large "batches" of spacecraft will play an important role regarding the throughput required for addressing the needs of the subtopic mission objectives in a cost-effective manner. As an advent in tandem with small-spacecraft swarms, batch-producible spacecraft are an increasing need as larger spacecraft are replaced with many smaller spacecrafts, distributing sensing and collaboratively accomplishing objectives enabled novelty by variable topologies and network-based considerations.

Advances in batch producibility are in tandem with standardization of rapid manufacturing of small spacecraft by private industry and will likely take advantage of advances in throughput-favorable fabrication methods. The manufacturability of batch-producible small spacecraft would need to consider the required throughput of manufacturing as a factor intrinsic to the small-spacecraft design itself. Of particular interest are concepts that integrate reconfigurable subsystems (such as those for power generation) for increased manufacturing throughput as a virtue of reduced point-design. These systems must still remain compliant with existing NASA small-spacecraft protocols for thermal, electrical, communications, and redundancy considerations. However, batch-producible spacecraft should leverage design methodologies that would decrease the cost and increase the compatibility of these standardized requisites by virtue of the manufacturing process itself, exhibiting design-for-standardization through the engineering process.

Such a batch-producible set of small spacecraft should leverage cost-effective supply chain considerations wherever possible and should integrate commercial-off-the-shelf (COTS) components and instrumentation into the design of spacecraft architecture. The result of rapidly manufacturable batches of spacecraft should demonstrate a significant reduction in manufacturing costs for 30 to 100 buses, with quicker turnaround times than otherwise possible over a range of NASA-relevant projects.

Expected TRL or TRL Range at completion of the Project:

3 to 6

Primary Technology Taxonomy:
Level 1: TX 02 Flight Computing and Avionics
Level 2: TX 02.2 Avionics Systems and Subsystems

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware
- Software
**Desired Deliverables Description:**

**Phase I Deliverable:**

An overview and technical description of methods for batch producibility of small spacecraft within the range of 30 to 100 buses, demonstrating the integration of COTS as part of the framework. Successful demonstrations of this deliverable should demonstrate an increase in the competency of the following objectives:

- A standardized high-throughput manufacturing method to enable the fabrication of small spacecraft in batches of 30 to 100 buses (within the scope of CubeSats, up to and including ESPA-class spacecraft).
- A systematic decision tree that addresses fabrication turnaround-time considerations as a factor of spacecraft complexity.
- Demonstrated cost decreases for spacecraft batches with respect to the current state of the art (SOA).
- The integration and normalization of COTS relevant for batch production of small spacecraft as a function of supply chain availability and vendor capabilities.

**Phase II Deliverable:**

Integrating small-spacecraft standards into batch production and demonstrating an infrastructure that is modular, batch compliant, and cost effective. Successful demonstrations of this deliverable should demonstrate an increase in the competency of the following objectives:

- The integration of common NASA small-spacecraft standards (such as thermal, grounding, communications) directly into batch producibility.
- A method for rapid assembly of batch-produced small spacecraft that accounts for manufacturability directly into the architecture of common subsystems (such as power generation, communications, etc.).

**State of the Art and Critical Gaps:**

The current SOA of batch-produced small spacecraft relies heavily on the industry-demonstrated heritage of COTS for small satellites. These systems have limited throughput considerations and are currently inappropriate for meeting future mission requisites pertaining to small spacecraft requiring the fabrication and integration of 30 to 100 spacecraft at a time (such as those relevant to heliophysics missions, network demonstrations, and swarm considerations).

**Relevance / Science Traceability:**

Partnership with industry on batch production of spacecraft will be required for distributed missions including synthetic apertures, disaggregated science observations, rapidly established planetary communications architectures, constellations, and sensor web applications; planned heliophysics missions call for 30 to 100 spacecraft. Technology development missions would also benefit from low-cost and shorter lead-time standardized bus platforms.

**References:**


3. Cockrell, Jim. NASA Centers and Universities Collaborate Through SmallSat Technology Partnerships. 2018. [74]
http://msst.atl.calpoly.edu/~workshop/archive/2018/Spring/Day%201/Session%201/JimCockrell.pdf


Z8.13 Space Debris Prevention for Small Spacecraft

Lead Center: GRC

Participating Center(s): ARC

Scope Title

Onboard Devices for Deorbit and/or Disposal of Single Spacecraft

Scope Description

The rise in individual small spacecraft launches alongside increased deployment of small spacecraft swarms is greatly contributing to congestion in Low Earth Orbit (LEO). Between 2012 and 2019, the number of small spacecraft launches increased 5x to ~500 put into orbit in 2019. To date, this number continues to grow, with some companies planning/implementing swarms of several thousand, even tens of thousands, of small spacecraft. In recognition of the threat posed by space debris to Earth’s orbital environment and the greater space industry, orbital debris prevention has been incorporated in every U.S. National Space Policy since 1988, with the latest Space Policy (2020) providing the strongest language yet, outlining that “the United States shall … Limit the creation of new debris, consistent with mission requirements and cost effectiveness, during the procurement and operation of spacecraft, launch services, and conduct of tests and experiments in space” [Refs. 1, 2, 3]. Concern has grown as “the number of objects orbiting the Earth [has] grown substantially in recent years with well over 90% being dead objects (inoperative satellites, spent upper stages, and fragmentation debris)” [Ref. 4], and a number of studies from NASA and other national and international agencies and organizations have shown dire outcomes and possible “runaway debris situations” for “business-as-usual” scenarios in debris population growth predictions for the future [Ref. 5], as well as significant strain on the current space traffic management architectures to prevent such scenarios [Ref. 6]. Now there is significant concern that the situation will get worse with the ubiquitous emergence of small satellite (SmallSat) technologies and the planned deployment of swarms and constellations of thousands of satellites in LEO—many of which qualify as “SmallSats”—by multiple commercial companies, such as SpaceX, OneWeb, Theia, Boeing, Amazon Kuiper, Inmarsat, etc. Per Reference 4, “if all of these plans materialize, the population of operational satellites in LEO would jump by over a factor of ten—from ~1,000 today to over 16,000 within the next 10 to 20 years” and “has the potential to affect the space environment for generations and push any space traffic management system beyond its limits.” As a result, all spacecraft LEO operators could be faced with disruptive numbers of conjunction alerts and collisions between spacecraft and/or orbital debris, further exacerbating the situation.

While the challenges posed by space debris and the management of large constellations within that environment is a multidimensional problem with multifaceted solutions, this subtopic scope focuses on technical solutions for the deorbit and/or disposal aspects that relate to the safe end-of-life operations of SmallSat swarms and constellations.
The lifetime requirement for any spacecraft in LEO is 25 years post-mission, or 30 years after launch if unable to be stored in a graveyard orbit [Ref. 7]. With increased use of higher orbital regimes by small spacecraft and regulatory attention on long-term debris concerns, it is critical that the small spacecraft community responsibly manage deorbiting and disposal in a way that preserves both the orbital environment and efficiency of small missions. Development and demonstration of low size, weight, power, and cost (SWaP-C) deorbit capabilities that are compatible with common small spacecraft form factors is required to maintain the agility of Earth-orbiting small spacecraft missions while complying with regulatory activity. These low SWaP-C deorbit or disposal technologies are being solicited in this scope. In particular, deorbit/disposal technologies that enable higher orbits than currently possible are desired. Further, technologies that enable controlled deorbit/disposal are desired—that is, can actively be controlled throughout the disposal process to further protect against collisions and interferences with both active and inactive spacecraft and debris.

Clear key performance parameters should be given as a part of the offeror's solution. These performance parameters (e.g., SWaP-C) should be quantified, compared to state of the art (SOA), and put into context of a planned, proposed, or otherwise hypothetical mission to highlight the advantages of the offered technology over SOA and other proposed solutions.

**Expected TRL or TRL Range at completion of the Project**

2 to 5

**Primary Technology Taxonomy**

**Level 1**

TX 09 Entry, Descent, and Landing

**Level 2**

TX 09.X Other Entry, Descent, and Landing

**Desired Deliverables of Phase I and Phase II**

- Research
- Analysis
- Prototype
- Hardware
- Software

**Desired Deliverables Description**

In Phase I, a contextual study to further understand the feasibility of the proposed solution is desired. Ideally, Phase I would conclude with a basic proof-of-concept prototype (hardware or software as appropriate). Critical requirements and interfaces should be defined alongside refinements of the proposed key performance parameters in Phase I. The Phase I effort should provide evidence of the feasibility of key elements such as cost, assembly, integration, and operations. The concept should reach sufficient maturity to show strong feasibility for the defined mission environments and performance requirements. The prototype system design should reach sufficient maturity to define test objectives and map key performance parameters (mass, power, cost, etc.) from the prototype to the flight design. Hardware development during the Phase I effort should provide confidence in the design maturity and execution of the Phase II effort. Lastly, the Phase I effort should identify potential opportunities for mission infusion and initiate partnerships or cooperative agreements necessary for mission execution.

In Phase II, further development and technology maturation is desired. Ideally, Phase II would culminate with Technology Readiness Level (TRL) 5+ demonstration of the proposed solution. Both Phase I and Phase II should be approached with focus on infusion, ensuring solutions are being developed with the proper requirements, interfaces, performance parameters, partnerships, etc., such that they, through a Phase III award or otherwise, could be directly applied to real spacecraft and real missions.
State of the Art and Critical Gaps

The 2020 NASA State of the Art of Small Spacecraft Technology report [8], Section 14.0, Deorbit Systems, gives a comprehensive overview of the SOA for both passive and active deorbit systems. The report details drag systems, including tethers, the Exo-Brake, and others. Drag sails have been the primary deorbit technology to date. They have been developed, demonstrated, and even commercialized/sold for mission use. However, capability needs to continue to grow, especially for higher orbital application as well as for more controlled deorbit and disposal.

Relevance / Science Traceability

With increased use of higher orbital regimes by small spacecraft and regulatory attention on long-term debris concerns, it is critical that the small-spacecraft community responsibly manage deorbiting and disposal in a way that preserves both the orbital environment and the efficiency of small missions. Solutions are relevant to commercial space, national defense, and Earth science missions.

References

2. U.S. National Space Policy, 1988. [75]
7. NASA. Process for Limiting Orbital Debris. [77]

Scope Title

Autonomous Space Traffic Management Technologies for Small Spacecraft Swarms and Constellations

Scope Description

In recognition of the threat posed by space debris to Earth’s orbital environment and the greater space industry, orbital debris prevention has been incorporated in every U.S. National Space Policy since 1988, with the latest Space Policy (2020) providing the strongest language yet, outlining that “the United States shall … Limit the creation of new debris, consistent with mission requirements and cost effectiveness, during the procurement and operation of spacecraft, launch services, and conduct of tests and experiments in space” [Refs. 1, 2, 3]. Concern has grown as “the number of objects orbiting the Earth [has] grown substantially in recent years with well over 90% being dead objects (inoperative satellites, spent upper stages, and fragmentation debris)” [Ref. 4], and a number of studies from NASA and other national and international agencies and organizations have shown dire outcomes and possible “runaway debris situations” for “business-as-usual” scenarios in debris population growth predictions for the future [Ref. 5], as well as significant strain on the current Space Traffic Management architectures to prevent such scenarios [Ref. 6]. Now there is significant concern that the situation will get worse with the ubiquitous emergence of small satellite (SmallSat) technologies and the planned deployment of swarms and constellations of thousands of satellites in Low Earth Orbit (LEO)—many of which qualify as “SmallSats”—by multiple commercial companies, such as SpaceX, OneWeb, Theia, Boeing, Amazon Kuiper, Inmarsat, etc. Per Ref. 4, “if all of these plans materialize, the population of operational satellites in LEO would jump by over a factor of ten—from ~1,000 today to over 16,000 within the next 10 to 20 years” and “has the potential to affect the space environment for
generations and push any space traffic management system beyond its limits.” As a result, all spacecraft LEO operators could be faced with disruptive numbers of conjunction alerts and collisions between spacecraft and/or orbital debris, further exacerbating the situation.

While the challenges posed by space debris and the management of large constellations within that environment is a multidimensional problem with multifaceted solutions, this subtopic scope focuses on technical solutions for autonomous space traffic management aspects that relate to the safe operations of SmallSat swarms and constellations, with the aim of reducing the strain on current space traffic management architectures, particularly by removing the “human-in-the-loop” and replacing it with faster decision-making autonomous systems; improving the accuracy of conjunction alerts, particularly reducing the number of “false alarms”; and ultimately reducing the risk of collision and generation of orbital debris by the collision of spacecraft with other spacecraft or debris.

As part of this scope, the following technologies are being solicited:

- Low size, weight, power, and cost (SWaP-C) small spacecraft systems for cooperative identification and tracking: Development and demonstration of low SWaP-C and low-complexity identification and tracking aids for small spacecraft that can be scaled, produced, and readily standardized under the paradigm of small spacecraft ecosystems. With increased demands on existing space situational awareness capabilities, and with regulatory attention on the threat of spacecraft that are unidentified, misidentified, or too small to track, the small spacecraft community needs such technologies to allow the community to operate with lower risk to all spacecraft in orbit—without negatively impacting the efficiency of small missions—and to minimize the risk of space debris generation.

- Low SWaP-C spacecraft systems for autonomous reactive operations of small spacecraft swarms and constellations: Development and demonstration of low SWaP-C small spacecraft technologies, such as sensors and coupled maneuvering systems, that enable small spacecraft swarms and constellations to operate in formation, in close proximity to other objects (cooperative or uncooperative), or beyond where the capacity of human-in-the-loop control will be required to process input onboard and execute correct responses autonomously, ensuring the safety of both spacecraft and object.

- Supporting software modules that enable the above: Development and demonstration of software to be hosted aboard single spacecraft, across the spacecraft swarm/constellation, or on the ground, that enable the cooperative identification and tracking and/or autonomous reactive operations, and whose primary functions can be developed and demonstrated within the budget of standard NASA Phase I and II SBIR awards. This includes artificial intelligence/machine learning (AI/ML) techniques and applications that can enable autonomous orbit adjustment and other actions to mitigate the potential for in-orbit collisions. Also included are software applications and/or network applications that enable:
  1. Efficient information exchange between individual spacecraft.
  2. Minimal reliance on ground commanding.
  3. Efficient use of space-qualified computing architectures.
  4. High-precision swarm navigation and control.

- Supporting ground systems that enable the above: Development and demonstration of Ground Systems that enable the cooperative identification and tracking and/or autonomous reactive operations, and whose primary functions can be developed and demonstrated within the budget of standard NASA Phase I and II SBIR awards.

In the above descriptions, the terms “SmallSat” and “small spacecraft” are to be interpreted as interchangeable and apply to Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) class spacecraft and below, including CubeSats, with masses of 180 kg and less. Where applicable, technologies that apply to CubeSats are highly desirable, as that would favor greater adoption of the technology.

In all of the above, clear key performance parameters should be given as a part of the offeror’s solution. These performance parameters (e.g., SWaP-C) should be quantified, compared to state of the art, and put into context of a planned, proposed, or otherwise hypothetical mission. Technologies that, in addition to performing the requirements outlined above, can also be ported from LEO to deep space environments—enabling new science and
exploration SmallSat swarms/constellation-based missions—are highly desirable.

Expected TRL or TRL Range at completion of the Project

2 to 5

Primary Technology Taxonomy

Level 1
TX 17 Guidance, Navigation, and Control (GN&C)

Level 2
TX 17.2 Navigation Technologies

 Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype
- Hardware
- Software

 Desired Deliverables Description

In Phase I, a contextual study to further understand the feasibility of the proposed solution is desired. Ideally, Phase I would conclude with a basic proof-of-concept prototype (hardware or software as appropriate). Critical requirements and interfaces should be defined alongside refinements of the proposed key performance parameters in Phase I. The Phase I effort should provide evidence of the feasibility of key elements such as cost, assembly, integration, and operations. The concept should reach sufficient maturity to show strong feasibility for the defined mission environments and performance requirements. The prototype system design should reach sufficient maturity to define test objectives and map key performance parameters (mass, power, cost, etc.) from the prototype to the flight design. Hardware development during the Phase I effort should provide confidence in the design maturity and execution of the Phase II effort. Lastly, the Phase I effort should identify potential opportunities for mission infusion and initiate partnerships or cooperative agreements necessary for mission execution.

In Phase II, further development and technology maturation is desired. Ideally, Phase II would culminate with Technology Readiness Level (TRL) 5+ demonstration of the proposed solution. Both Phase I and Phase II should be approached with focus on infusion, ensuring solutions are being developed with the proper requirements, interfaces, performance parameters, partnerships, etc., such that they, through a Phase III award or otherwise, could be directly applied to real spacecraft and real missions.

State of the Art and Critical Gaps

Current space traffic management architectures typically have a significant involvement of “humans-in-the-loop” for the identification of conjunction threats, for making the decision on if and how to respond, and for implementation of the response. Currently the U.S. Air Force 18th Space Control Squadron provides conjunction advisories to virtually all space operators worldwide following measurements taken with its assets. The operators then assess and weigh the risks to their assets and the resources to be expended to mitigate those risks. This is a time-consuming process, typically on timescales that do not allow for rapid reaction to a rapidly evolving threat. It is further aggravated by the large uncertainties associated with the conjunctions, which can lead to many false alarms, resulting in an inability for operators to respond to all alerts, as it would consume too many resources, as well as “complacency that naturally occurs when the mission analysts are inundated with large numbers of alerts that turn out to be false alarms” [Ref. 4]. For instance, “under current tracking accuracies, the actual collision between Iridium-33 and Cosmos 2251 did not stand out from other conjunctions that week as being noticeably dangerous” and therefore was not acted upon, with the impact only identified after its occurrence.
To help address such situations, various stakeholders have been implementing solutions of their own, but these solutions are likely to run into limitations, particularly as more spacecraft are deployed and systems need to be scaled further and start interacting with each other:

- For example, to help protect its nonhuman spaceflight assets, NASA established its Conjunction Assessment and Risk Analysis (CARA) program, with operational interfaces with the 18th Space Control Squadron to receive close-approach information in support of NASA mission teams. As a whole, however, the system still features humans in the loop, and if further investments are not made, it may run into combined scalability and time-responsiveness issues as more commercial and/or noncooperative foreign assets deploy and/or pass through the operational orbits of NASA spacecraft. While regulatory solutions are part of the mix to help resolve the issues encountered, such as the Space Act Agreement between NASA and SpaceX to identify how each party will respond [Ref. 7], those solutions are slow to implement and have legislative limitations. Technical solutions will inevitably be necessary to address gaps posed by regulatory means.

- Deployers of SmallSat swarms and constellations are increasingly implementing software solutions for spacecraft to autonomously decide and implement collision-avoiding maneuvers. However, given the large capital and labor-intensive investment required to implement them, such systems may not be within the reach of all spacecraft operators, especially startup or single-spacecraft mission operators. Furthermore, with such technologies in their infancy, and with commercial operators racing to deploy and scale their spacecraft constellations to achieve market dominance, there is a very real risk that such systems may struggle to interface adequately with other autonomous and nonautonomous constellations, as was experienced by OneWeb and SpaceX [Ref. 8]. There may even be a risk of enhanced collision risk as each autonomous system independently takes evasive action that, unbeknownst to the other, increases the risk of collision, much like two persons unsuccessfully trying to avoid each other in a corridor.

Relevance / Science Traceability

- Low SWaP-C small spacecraft systems for cooperative identification and tracking: With increased demands on existing space situational awareness capabilities, and with regulatory attention on the threat of spacecraft that are unidentified, misidentified, or too small to track, the small spacecraft community needs low SWaP-C identification and tracking aids. Employing such methods would allow the community to operate with lower risk to all spacecraft in orbit without negatively impacting the efficiency of small missions. There is a clear need to develop and demonstrate low-cost and low-complexity identification and tracking aids that can be scaled, produced, and readily standardized under the paradigm of small spacecraft ecosystems.
  - Technologies used for identification and tracking aids in LEO may also have extensibility to the growing number of cislunar missions.

- Low SWaP-C spacecraft systems for autonomous reactive operations of small spacecraft swarms and constellations: Small spacecraft operating in formation, in close proximity to other objects, or beyond the capacity of human-in-the-loop control will be required to process input onboard and execute correct responses autonomously.
  - These sensor-driven operations will be enabling for safe proximity operations with spacecraft or small bodies as well as the detection and reaction to transient events for observation, such as would be required for sampling a plume from Enceladus. Furthermore, enabling multiple small spacecraft operating in coordinated orbital geometries or performing relative station-keeping can further expand human knowledge deeper into the universe by performing coordinated occultation, acting as virtual telescopes, and forming distributed apertures that would be prohibitively complex and expensive to launch into space as monolithic structures. Small spacecraft formation flight can also enable swarm gravimetry, synchronized observation of transient phenomena, and proximity operations for inspection of other assets.
References


Z10.01 Cryogenic Fluid Management

Lead Center: MSFC

Participating Center(s): JSC, MSFC

Scope Title

Cryogenic Fluid Management (CFM)

Scope Description

This subtopic seeks technologies related to cryogenic propellant (e.g., hydrogen, oxygen, methane) storage and transfer to support NASA’s space exploration goals. This includes a wide range of applications, scales, and environments consistent with future NASA missions. Such missions include but are not limited to upper stages, ascent and descent stages, refueling elements or aggregation stages, nuclear thermal propulsion, and in situ resource utilization. This subtopic solicits proposals in the following areas, in order of priority:

1. High-pressure-ratio compressor for on-orbit gas transfer: Design and develop concepts for a high-pressure-ratio compressor for supercritical xenon and helium, capable of increasing low-pressure fluid to 3,000 psia with continuous flow of up to 15 g/s, allowing for on-orbit transfer of gases for applications of refueling. The temperature range of the xenon is 17 to 40 °C. The compressor must be capable of surviving launch-load vibrations, be able to function accurately in microgravity and vacuum environment (10-5 torr), and be able to maintain gas cleanliness to Level A/10 for nonvolatile residue. For Phase I, the main deliverable should be a compressor design and performance analysis. For Phase II, the main deliverable should be a working engineering model of the compressor and the compressor itself.

2. Cryogenic flight-weight valves (minimum Cv >50, goal to Cv of ~100) for low-pressure (500 cycles with a goal of 5,000 cycles) to maximize the lifetime of the valve. Proposals can include metallic or nonmetallic sealing elements. Proposals should address the whole valve subsystem, including actuation and actuation mechanisms, with the goal of minimizing mass in Phase II. Phase I deliverable should be proof of concept of the valve with test data using liquid nitrogen, while the Phase II deliverable should be the valve.

3. Subgrid computational fluid dynamics (CFD) of the film condensation process for 1g and low gravity (lunar or martian) to be implemented into commercial industry standard CFD codes. The subgrid model should capture the formation and growth of the liquid layer as well as its movement along a wall boundary and should implement the volume of fluid (VOF) scheme. The condensation subgrid model should be validated against experimental data (with a target accuracy of 25%), with a preference for condensation data without a noncondensable. Emphasis should be placed on cryogenic fluid data, but noncryogenic data is
acceptable. Phase I should be focused on simplified geometries (vertical plates/walls), while Phase II should be focused on complicated geometries (e.g., full cylindrical tank). The subgrid model and implementation scheme should be the final deliverable.

4. Development of heat flux sensors capable of measuring heat fluxes between 0.1 and 5.0 W/m² for cryogenic applications. The sensors should have a target uncertainty of 2% full scale or less at temperatures as high as 300 K and at least as low as 77 K with a goal of 20 K. Proposers should target a demonstration of sensor operability in the 77-K temperature range in Phase I with a full demonstration of calibration and uncertainty in Phase II. Deliverable for Phase II should be the calibrated heat flux sensor.

Expected TRL or TRL Range at completion of the Project

2 to 4

Primary Technology Taxonomy

Level 1
TX 14 Thermal Management Systems

Level 2
TX 14.1 Cryogenic Systems

Desired Deliverables of Phase I and Phase II

Hardware Software Prototype

Desired Deliverables Description

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

State of the Art and Critical Gaps

CFM is a crosscutting technology suite that supports multiple forms of propulsion systems (nuclear and chemical), including storage, transfer, and gauging, as well as liquefaction of ISRU-produced propellants. The Space Technology Mission Directorate (STMD) has identified that CFM technologies are vital to NASA's exploration plans for multiple architectures, whether hydrogen/oxygen or methane/oxygen systems, including chemical propulsion and nuclear thermal propulsion. Several recent Phase II projects have resulted from CFM subtopics, most notably for cryocoolers, liquid acquisition devices, phase separators, broad area cooling, and composite tanks.

Relevance / Science Traceability

STMD strives to provide the technologies that are needed to enable exploration of the solar system, both manned and unmanned systems; CFM is a key technology to enable exploration. Whether liquid oxygen/liquid hydrogen or liquid oxygen/liquid methane is chosen by Artemis as the main in-space propulsion element to transport humans, CFM will be required to store propellant for up to 5 years in various orbital environments. Transfer will also be required, whether to engines or other tanks (e.g., depot/aggregation), to enable the use of cryogenic propellants that have been stored. In conjunction with ISRU, oxygen will have to be produced, liquefied, and stored; liquefaction and storage are both CFM functions for the surface of the Moon or Mars. ISRU and CFM liquefaction drastically reduces the amount of mass that has to be landed.

References

No references for this subtopic.
Z10.04 Materials, Processes, and Technologies for Advancing In-Space Electric Propulsion Thrusters

Lead Center: MSFC

Participating Center(s): JPL

Scope Title

High-Temperature, High-Voltage Electric Propulsion Harness Assembly

Scope Description

Electric propulsion (EP) for space applications has demonstrated tremendous benefit to a variety of NASA, military, and commercial missions. This subtopic seeks to address ongoing challenges with EP performance repeatability, hardware reliability, and total life-cycle cost. Critical NASA EP needs have been identified in the scope area detailed below. Proposals outside the described scope shall not be considered. Proposers are expected to show an understanding of the current state of the art (SOA) and quantitatively (not just qualitatively) describe anticipated improvements over relevant SOA materials, processes, and technologies that substantiate NASA investment.

In EP systems, power, commands, and telemetry are relayed between the power processing unit (PPU) and the thruster via dedicated electrical harness assemblies. These harnesses must support the voltage and current needs of the thruster, survive in-space conditions and the operational thermal environment, and not incur unacceptable line loss, radiated emissions, and mass and volume impacts to the spacecraft. Harnesses must also have sufficient flexibility and abrasion resistance, especially for thrusters that are integrated onto actuated gimbals. Individual EP technologies may have specific needs that must be addressed; for example, low-inductance harnesses are preferred in Hall-effect thrusters to reduce thruster discharge oscillations and to promote system stability.

Thermal management of EP systems is a persistent challenge and can be severe in both high-power (>10 kW) and high-power-density (e.g., compact subkilowatt) thrusters. This solicitation seeks advancements in cable and connector materials and designs to support harness assembly solutions addressing all of the following gridded ion and Hall-effect propulsion system needs:

- Voltages (after derating) up to 600-800 VDC (for Hall-effect thrusters) or up to 1.8-2.1 kVDC (for gridded ion thrusters).
- Operating temperatures of at least 350 °C, survival temperatures down to at least -60 °C, and the ability to survive at least 10,000 on-off thermal cycles.
- Direct currents (after derating) up to 10-15 A (for compact <1-kW systems) or up to 25-200 A (for >10-kW systems).
- Deratings consistent with NASA Technical Standard MSFC-STD-3012A (Appendix A) for connectors and wiring.
- Low outgassing materials consistent with the guideline (i.e., maximum total mass loss (TML) of 1% and maximum collected volatile condensable material (CVCM) deposition of 0.1%) in NASA Technical Standard MSFC-SPEC-1443B.
- Features (e.g., venting of connectors and backshells) to mitigate Paschen or corona discharges due to materials or trapped volume outgassing at operating temperatures.
- Features to support harness shielding and grounding.
- Available lengths, flexibility (e.g., bend radius), and abrasion resistance comparable to or better than SOA.

Expected TRL or TRL Range at completion of the Project

3 to 5

Primary Technology Taxonomy

Level 1

TX 01 Propulsion Systems
Level 2

TX 01.2 Electric Space Propulsion

Desired Deliverables of Phase I and Phase II

- Analysis
- Prototype
- Hardware

Desired Deliverables Description

Phase I:

1. Final report containing test data characterizing key properties that address the critical gaps as well as the design and test plan for an EP harness assembly solution to be implemented in Phase II.
2. Material samples that can be used for independent verification of claimed improvements over SOA.

Phase II:

1. Final report containing test data verifying key functional and environmental requirements of the EP harness assembly design, including a functional demonstration in an operating thruster environment (in which partnering with EP developers may be necessary).
2. Prototype harness assembly that can be used for independent verification of claimed improvements over SOA.

State of the Art and Critical Gaps

Recent NASA EP harnesses have utilized stranded, plated copper wiring with multilayer, crosslinked fluoropolymer (e.g., polytetrafluoroethylene (PTFE) and ethylene tetrafluoroethylene (ETFE)) insulation consistent with MIL-W-22759/SAE Standard AS22759D. Commercial off-the-shelf (COTS) wiring rated to 600 VDC and 1,000 VDC exists but is limited to temperatures below ~260 °C. Meanwhile, COTS electrical connectors (such as MIL-SPEC circular connectors) typically have even lower temperature limits.

Temperature derating requirements for electrical connectors mating to SOA EP thrusters have been challenging for recent NASA missions and have complicated mechanical retention and strain relief at the interface. Custom connector solutions or extensive component testing to relax derating requirements are possible approaches, but they are unattractive as increased development costs would be incurred for each mission. Harness material and design improvements that increase the maximum allowable harness temperature would improve the thermal margin for derating purposes on SOA thrusters and facilitate the development of thrusters with higher powers or power densities relative to SOA.

SOA EP harnesses frequently employ custom insulation wraps on COTS wiring in order to support high thruster operating voltages. Such wraps can be mechanically fragile and complicate harness handling and installation. Harness material and design improvements that increase the voltage rating are desirable to improve system reliability and to reduce life-cycle costs.

Relevance / Science Traceability

Both NASA’s Science Mission Directorate (SMD) and Human Exploration and Operations Mission Directorate (HEOMD) need spacecraft with demanding propulsive performance and greater flexibility for more ambitious missions requiring high duty cycles and extended operations under challenging environmental conditions. SMD spacecraft need the ability to rendezvous with, orbit, and conduct in situ exploration of planets, moons, and other small bodies (i.e., comets, asteroids, near-Earth objects, etc.) in the solar system; mission priorities are outlined in the decadal surveys for each of the SMD divisions.
For HEOMD, higher power EP is a key element in supporting sustained crewed exploration of cislunar space and Mars. This subtopic seeks innovations to meet future SMD and HEOMD propulsion requirements in EP systems related to such missions. The roadmap for such in-space propulsion technologies is covered under the 2020 NASA Technology Taxonomy [https://www.nasa.gov/offices/oct/taxonomy/index.html][82], with supporting information archived in the 2015 NASA Technology Roadmap TA-2 [https://www.nasa.gov/offices/oct/home/roadmaps/index.html][83].

References


Scope Title

Advanced Thermal Management for Hall-Effect Thrusters

Scope Description

Electric propulsion (EP) for space applications has demonstrated tremendous benefit to a variety of NASA, military, and commercial missions. This subtopic seeks to address ongoing challenges with EP performance repeatability, hardware reliability, and total life-cycle cost. Critical NASA EP needs have been identified in the scope area detailed below. Proposals outside the described scope shall not be considered. Proposers are expected to show an understanding of the current state of the art (SOA) and quantitatively (not just qualitatively) describe anticipated improvements over relevant SOA materials, processes, and technologies that substantiate NASA investment.

As Hall-effect thrusters are scaled up in power for next-generation missions with large payloads (including human crews), thermal management poses a major design challenge. Compact subkilowatt thrusters for small spacecraft also typically operate with high power density and face similar challenges. To protect critical components such as electromagnets, technological advances are needed to improve the efficiency with which heat can be radiated or conducted away from temperature-sensitive areas of the thruster.

NASA is soliciting proposals for high-emissivity coatings that are compatible with high thruster operating temperatures (300 to 400 °C) and remain compliant with the material outgassing guideline (i.e., maximum total mass loss (TML) of 1% and maximum collected volatile condensable material (CVCM) deposition of 0.1%) in NASA Technical Standard MSFC-SPEC-1443B. Development of discharge channels and anodes made from intrinsically high-emittance materials is also encouraged. Plasma-facing materials and coatings must be able to survive for >20,000 hr of thruster operation while maintaining their thermal performance.

Other approaches of interest include novel radiator geometries that can either be easily attached to existing thrusters or integrated into the design of existing thruster components. Heat pipes integrated into a standard Hall-effect thruster design are also of interest. The solutions must be compatible with expected maximum local
temperature in a high-power thruster at the implementation location (e.g., 400 to 600 °C in the vicinity of the inner magnet coil) as well as elevated saturation temperatures that do not produce excessive vessel pressure.

Novel radiator geometries, integral heat pipes, and/or channels for pumped fluid loops also open the design space to additively manufactured implementation of these features. Hiperco® is a typical material that these features could be additively manufactured from, but other magnetic materials may also be considered. Whatever solutions are presented, a reduction of at least 50 to 100 °C in peak inner coil temperatures is desired.

**Expected TRL or TRL Range at completion of the Project**

3 to 5

**Primary Technology Taxonomy**

**Level 1**

TX 01 Propulsion Systems

**Level 2**

TX 01.2 Electric Space Propulsion

**Desired Deliverables of Phase I and Phase II**

- Analysis
- Prototype
- Hardware

**Desired Deliverables Description**

**Phase I:**

1. Final report containing data from small-scale or coupon testing of the proposed heat rejection technology and a design and test plan for scaling up the technology to a Hall-effect thruster in Phase II.
2. If applicable, material samples that can be used for independent verification of claimed improvements over the SOA (e.g., this would apply to surface coatings).

**Phase II:**

1. Final report containing test data verifying thermal performance of the novel or improved heat rejection technology, demonstrated in an operating Hall-effect thruster environment (in which partnering with EP developers may be necessary).
2. If applicable, hardware prototypes delivered to NASA in order to enable testing of the new technology on additional laboratory thrusters (e.g., this would apply to bolt-on radiators, coatings, etc.).

**State of the Art and Critical Gaps**

High-emissivity coatings (such as black oxide) have been tested on high-power Hall-effect thruster components, but adhesion over >1,000 thermal cycles and during extended thruster operation remains challenging. Coatings exist that can radiate away heat efficiently while still having low absorptivity of radiated power from the background environment (Conversano et al. 2019). Exterior-facing thruster surfaces may be constructed from carbon to facilitate radiative heat loss (Reilly et al. 2016). The dominant heat load in the thruster arises from plasma impacting the discharge channel and anode (Reilly et al. 2016), so improving the ability of these surfaces to radiate could have significant benefits. A smaller heat load is generated within the magnetic coils, but the thermal
conductivities of the coil bobbins, ferromagnetic cores, and potting material are usually low, making the coils a problem area thermally. SOA thrusters are designed to maintain good thermal contact between internal components to maximize heat conduction from the interior to the exterior (Myers et al. 2016), but novel solutions such as heat pipes could dramatically improve heat transport efficiency. Radiators extending from the thruster body have been used for heat rejection in recent NASA Hall thruster designs (Myers et al. 2016, Conversano et al. 2019).

Relevance / Science Traceability

Both NASA's Science Mission Directorate (SMD) and Human Exploration and Operations Mission Directorate (HEOMD) need spacecraft with demanding propulsive performance and greater flexibility for more ambitious missions requiring high duty cycles and extended operations under challenging environmental conditions. SMD spacecraft need the ability to rendezvous with, orbit, and conduct in situ exploration of planets, moons, and other small bodies (i.e., comets, asteroids, near-Earth objects, etc.) in the solar system; mission priorities are outlined in the decadal surveys for each of the SMD divisions ([https://science.nasa.gov/about-us/science-strategy/decadal-surveys](https://science.nasa.gov/about-us/science-strategy/decadal-surveys) [81]). For HEOMD, higher-power EP is a key element in supporting sustained crewed exploration of cislunar space and Mars.

This subtopic seeks innovations to meet future SMD and HEOMD propulsion requirements in EP systems related to such missions. The roadmap for such in-space propulsion technologies is covered under the 2020 NASA Technology Taxonomy ([https://www.nasa.gov/offices/oct/taxonomy/index.html](https://www.nasa.gov/offices/oct/taxonomy/index.html) [82]), with supporting information archived in the 2015 NASA Technology Roadmap TA-2 ([https://www.nasa.gov/offices/oct/home/roadmaps/index.html](https://www.nasa.gov/offices/oct/home/roadmaps/index.html) [83]).

References


Scope Title

Cost-Effective Carbon-Based Electrodes for High-Power, High-Performance Gridded Ion Thrusters

Scope Description

Electric propulsion (EP) for space applications has demonstrated tremendous benefit to a variety of NASA, military, and commercial missions. This subtopic seeks to address ongoing challenges with EP performance repeatability, hardware reliability, and total life-cycle cost. Critical NASA EP needs have been identified in the scope area detailed below. Proposals outside the described scope shall not be considered. Proposers are expected to show an
understanding of the current state of the art (SOA) and quantitatively (not just qualitatively) describe anticipated improvements over relevant SOA materials, processes, and technologies that substantiate NASA investment.

Gridded ion thruster technology offers high efficiency, high specific-impulse capabilities, and has been used successfully to support NASA science missions as well as commercial Earth-orbiting applications. The primary life limiter for these devices is typically erosion of the accelerator electrode due to bombardment by charge-exchange ions. While NASA gridded ion thrusters have achieved the necessary lifetimes in the past by operating at derated current densities, there is interest in operation at higher thrust and power densities that would increase mission capture and allow for more compact thruster designs. Higher power and current densities result in increased erosion rates of the accelerator electrode, such that the refractory metals used on previous designs may no longer be sufficient to meet demanding lifetime requirements.

Carbon-based electrodes have shown promise by offering significantly higher erosion resistance compared to refractory metals. Innovative solutions are desired that would result in manufacturing processes for carbon-based electrodes that are cost-effective relative to prior efforts, making them competitive with SOA electrode manufacturing using refractory metals. These solutions must be capable of producing carbon-based electrodes with the following geometries, operating voltages, and thermal properties:

- Screen and accelerator electrode thicknesses of ~0.33 mm and ~0.50 to 0.75 mm, respectively.
- Screen and accelerator electrode open area fractions of ~70% and ~25%, respectively.
- Screen and accelerator aperture diameters of ~2 mm and ~1.25 mm, respectively.
- Gap between the screen and accelerator electrode of ~0.50 to 0.75 mm.
- A shallow spherical dome (i.e., dished) geometry for both screen and accelerator electrodes.

Note: Dome and flat geometries are both of interest to NASA. However, a dome geometry ensures sufficient electrode stiffness and first-mode natural frequency to withstand expected structural loading during launch as well as maintaining required electrode gaps and avoiding buckling due to compressive stresses caused by nonuniform temperature distributions along electrodes. Manufacturing solutions capable of producing only flat electrodes will also be considered but must demonstrate that structural loading during launch and potential buckling during operation will not be issues.

- Extensibility to beam extraction (i.e., perforated) diameters of 40 cm or larger.
- Tight tolerances on apertures’ locations (<0.1 mm) to facilitate proper alignment of apertures between screen and accelerator electrodes.
- Minimum voltage standoff capability between screen and accelerator electrodes of 2 kV.
- Peak operating temperatures of 450 °C.
- Coefficients of thermal expansion less than or equal to that of molybdenum (4.8x10-6 K-1).

Proposals are desired that offer solutions which are applicable for manufacturing of carbon-based screen and accelerator electrodes. However, proposals that focus only on carbon-based accelerator electrodes will be considered if such solutions are shown to be compatible with screen electrodes made with heritage refractory metals.

**Expected TRL or TRL Range at completion of the Project**

3 to 5

**Primary Technology Taxonomy**

**Level 1**

TX 01 Propulsion Systems

**Level 2**

TX 01.2 Electric Space Propulsion
Desired Deliverables of Phase I and Phase II

- Analysis
- Prototype
- Hardware

Desired Deliverables Description

Phase I:

1. A final report detailing the material properties and the manufacturing processes for the carbon-based electrodes, as well as an evaluation of the extensibility of the processes to sizes of interest (i.e., 40-cm perforated diameter or larger).
2. A scaled-down sample of each carbon-based electrode (either screen and accelerator or accelerator only, depending on the approach) representative of typical electrode thickness and open area fraction to be delivered to NASA for independent assessment and tests.

Phase II:

1. A final report detailing final manufacturing processes and an updated evaluation of the extensibility of these processes to sizes of interest (i.e., 40-cm perforated diameter or larger).
2. Carbon-based screen and accelerator electrodes (or accelerator electrode only, depending on the approach) at least 30 cm in diameter that can be hot-fire tested with a gridded ion thruster (in which partnering with EP developers may be necessary).

State of the Art and Critical Gaps

While extensive research and development of carbon-based electrodes have resulted in solutions that were technically adequate, the complexity and associated costs of manufacturing have been prohibitive toward widespread adoption into ion thruster technology. The material used for electrodes has historically been refractory metals, whose thermal and mechanical properties allow the electrodes to withstand the temperatures and launch loads they will experience while offering adequate erosion resistance. Fabrication using refractory metals such as molybdenum typically involves chemical etching to produce the apertures within the electrodes. Carbon-based solutions have been developed previously by several organizations and include carbon-carbon, amorphous graphite, and pyrolytic graphite (PG). Fabrication techniques for carbon-based electrodes have been rather varied and complex and have included methods such as chemical vapor deposition and carbonization. Apertures in carbon-based electrodes have been created using laser drilling, electric discharge machining (EDM), or machining. As such, innovative solutions are desired that would result in manufacturing processes for carbon-based electrodes that are less complex and/or more cost-effective than prior efforts.

Relevance / Science Traceability

Both NASA's Science Mission Directorate (SMD) and Human Exploration and Operations Mission Directorate (HEOMD) need spacecraft with demanding propulsive performance and greater flexibility for more ambitious missions requiring high duty cycles and extended operations under challenging environmental conditions. SMD spacecraft need the ability to rendezvous with, orbit, and conduct in situ exploration of planets, moons, and other small bodies (i.e., comets, asteroids, near-Earth objects, etc.) in the solar system; mission priorities are outlined in the decadal surveys for each of the SMD divisions ([https://science.nasa.gov/about-us/science-strategy/decadal-surveys](https://science.nasa.gov/about-us/science-strategy/decadal-surveys) [81]). For HEOMD, higher power EP is a key element in supporting sustained crewed exploration of cislunar space and Mars.

This subtopic seeks innovations to meet future SMD and HEOMD propulsion requirements in EP systems related to such missions. The roadmap for such in-space propulsion technologies is covered under the 2020 NASA Technology Taxonomy ([https://www.nasa.gov/offices/oct/taxonomy/index.html](https://www.nasa.gov/offices/oct/taxonomy/index.html) [82]), with supporting information...
archived in the 2015 NASA Technology Roadmap TA-2
(https://www.nasa.gov/offices/oct/home/roadmaps/index.html [83]).

References


Scope Title

High-Power Electric Propulsion Thrusters for Mars-Class Missions

Scope Description

Electric propulsion (EP) for space applications has demonstrated tremendous benefit to a variety of NASA, military, and commercial missions. This subtopic seeks to address ongoing challenges with EP performance repeatability, hardware reliability, total life-cycle cost, and future needs.

Critical NASA EP needs have been identified in the scope area detailed below. Proposals outside the described scope shall not be considered. Proposers are expected to show an understanding of the current state of the art (SOA) and quantitatively (not just qualitatively) describe anticipated improvements over relevant SOA materials, processes, and technologies that substantiate NASA investment.

Megawatt-class EP has been identified as a key NASA need for enabling sustained human Mars exploration missions. This solicitation seeks solutions that would advance the technical maturation of high-power EP thrusters. NASA is interested in thruster technologies that meet both of the following requirements:

1. Expected operability at ? 100 kW of electrical power, with scalability or clustering approaches capable of supporting ?1 MW of electrical power.
2. Present technology readiness level (TRL) of ? 4 at the thruster level per NASA NPR 7123.1C Appendix E, in which TRL 4 is defined in this solicitation’s context as a low-fidelity laboratory thruster with test performance demonstrating agreement with analytical predictions for a relevant environment.
To remain within the scope of SBIR awards, proposals addressing component-level or subcomponent-level innovations are desired with a clearly defined path toward thruster-level integration and ground demonstration. Proposals shall address the following:

- Justified compliance with the thruster-level power and TRL requirements listed above.
- Key performance parameters, both SOA and anticipated, relative to the baseline metrics in Table 1.3 of the National Academies’ “Space Nuclear Propulsion for Human Mars Exploration” 2021 report.
- Critical technical challenges identified to date associated with maturing the thruster technology (including interfacing with other elements of a complete EP subsystem) and how the proposed solution addresses one or more of the critical challenges.
- Anticipated compliance with the desired SBIR deliverables (Technological Details section, below).
- Anticipated compliance with the expected TRL range at completion of the project (Technological Details section, below).

Note: The expected TRL range at completion of the project addresses the TRL of the proposed component-level or subcomponent-level innovations. When integrated and demonstrated with a thruster during Phase II, the proposed innovations must support a thruster-level TRL ≥ 4.

**Expected TRL or TRL Range at completion of the Project**

3 to 4

**Primary Technology Taxonomy**

**Level 1**

TX 01 Propulsion Systems

**Level 2**

TX 01.2 Electric Space Propulsion

**Desired Deliverables of Phase I and Phase II**

- Analysis
- Prototype
- Hardware

**Desired Deliverables Description**

**Phase I**

1. Final report containing:
   - Design and test plan (to be implemented in Phase II) for thruster-level integration and demonstration of the proposed innovation.
   - Data from proof-of-concept or breadboard testing of the proposed innovation, along with comparisons to SOA and predicted performance.

**Phase II**

1. Final report containing test data verifying the performance of the proposed innovation, including a functional demonstration in an operating thruster environment.
State of the Art and Critical Gaps

Chapter 3 of the National Academies’ "Space Nuclear Propulsion for Human Mars Exploration" 2021 report provides an overview of SOA technologies and critical gaps for high-power EP thrusters.

Relevance / Science Traceability

Both NASA's Science Mission Directorate (SMD) and Human Exploration and Operations Mission Directorate (HEOMD) need spacecraft with demanding propulsive performance and greater flexibility for more ambitious missions requiring high duty cycles and extended operations under challenging environmental conditions. SMD spacecraft need the ability to rendezvous with, orbit, and conduct in situ exploration of planets, moons, and other small bodies (i.e., comets, asteroids, near-Earth objects, etc.) in the solar system; mission priorities are outlined in the decadal surveys for each of the SMD divisions (https://science.nasa.gov/about-us/science-strategy/decadal-surveys [81]). For HEOMD, higher-power EP is a key element in supporting sustained crewed exploration of cislunar space and Mars.

This subtopic seeks innovations to meet future SMD and HEOMD propulsion requirements in EP systems related to such missions. The roadmap for such in-space propulsion technologies is covered under the 2020 NASA Technology Taxonomy (https://www.nasa.gov/offices/oct/taxonomy/index.html [82]), with supporting information archived in the 2015 NASA Technology Roadmap TA-2 (https://www.nasa.gov/offices/oct/home/roadmaps/index.html [83]).

References


Z10.05 Rotating Detonation Rocket Engines (RDRE)

Lead Center: MSFC

Participating Center(s): GRC

Scope Title
Rotating Detonation Rocket Engine (RDRE) Injector Response, Recovery, and Operation Dynamics

Scope Description

RDRE injectors require further study and novel solutions to combat major challenges that this high-performance engine cycle experiences. Technology development efforts are needed to better understand how to reduce backflow potential of combustion products as the high-pressure detonation passes over the injector orifices. A high impulsive diodicity for injector elements represents one means by which this may be achieved. Recovery dynamics at various equivalent pressure-drop conditions may hold the key to minimizing deflagration losses. This is particularly the case for liquid/gas and liquid/liquid bipropellants. It is well known that recovery of propellants to reach the chamber at the same time and equivalently participate in the detonation process is where the majority of detonation benefits would come from. Finally, new element schemes that effectively stand off the detonation from the injector face as well as evenly distribute and mix propellant without losing unburnt propellant from the critical region are desired. Standing off the detonation from the injector face would reduce the overall pressure gradient.
that the injector orifices would experience and thus reduce backflow significantly. Each of these tasks is needed, among others, to reduce overall operating pressures to meet more reasonable liquid engine system requirements.

An ultra-high-performance detonation injector solution that attempts to resolve these challenges or address similar challenges is needed. Computational fluid dynamics modeling (CFD) and analysis in conjunction with cold-flow test, and finally hot-fire testing, would be highly desirable depending on the phase of the work. Solutions that resolve these challenges would afford NASA and the industry partner a feasible path forward to radically improving combustion device performances, enabling future mission architectures, including Moon to Mars.

This subtopic seeks innovative engineering solutions to the problem of injector response and detonation dynamics in the RDRE cycle with applicable propellants. Liquid/gas and liquid/liquid propellant phases are of primary interest, with particular interest in using cryogenic phase propellant. Methane, hydrogen, RP-1, hypergolics, and their subsequent phases are of primary interest to NASA. Gas/gas phase injection is not acceptable unless both liquid oxygen and fuel are in cryogenic states and both being used to regeneratively cool hardware.

**Expected TRL or TRL Range at completion of the Project**

2 to 5

**Primary Technology Taxonomy**

**Level 1**
TX 01 Propulsion Systems

**Level 2**
TX 01.4 Advanced Propulsion

**Desired Deliverables of Phase I and Phase II**

- Hardware
- Analysis
- Research
- Prototype

**Desired Deliverables Description**

Phase I is multifaceted and could include multiple development pathways. A feasibility study that demonstrates proof of concept for the given application is needed. This can be accomplished with CFD or other type of analysis that shows high diodicity injector schemes can be effectively employed in detonation engines. Further demonstration of manufacturing practicality of complex injector geometries will also be required. One way to do this would be to produce subscale injector orifices, potentially using additive manufacturing techniques. Conventional machining techniques could also be used to produce single-element flow specimens of various geometries. These orifices and specimens could then be subjected to a shock or simulated detonation. The injector’s response and recovery dynamics would then be measured. Visualization and measurement of backflow or backflow resistance would be very helpful in this regard. Cold-flow testing using water or air as propellant simulants would be the norm. New techniques for production, postprocessing, and operation of injector orifices would be ancillary but a major addition to the work as it would demonstrate reduction of cost and schedule for hardware development.

Phase I requires small-scale laboratory demonstration using cold-flow experiments and/or modeling efforts to show proof of concept. Proof of concept could include demonstration of elevated diodicity potential for specific injector element geometries over a baseline comparison case. Metrics by which diodicity can be assessed include geometries that produce diodicity of >1.4. However, there are schemes that could reach a diodicity of >10x factor. Efforts to understand propellant rates of recovery are also critical.

Phase II would entail cold-flow testing with simulated shock/detonation conditions in a laboratory setting and/or
heat sink/regenerative hot-fire testing that assesses injector response, recovery, and performances such as C*, thrust, and/or visual diagnostics of combustion emissions that allow for the deduction of combustion efficiency. Thrust measurements are desired as well.

State of the Art and Critical Gaps

Propulsion system performance advancement is virtually at a standstill. In fact, industry is now sacrificing combustion performance and specific impulse improvements for manufacturability. RDREs represent a potential for dramatic improvement in ease of manufacturing, combustion device specific-impulse performance, and advancing U.S. space access capability. High-efficiency propulsion system concepts such as the RDRE are being investigated across the United States, and interest has never been higher. Thus, this work seeks to radically improve and expand the design and test capability of RDREs toward making space access more feasible and cost effective.

Relevance / Science Traceability

The research requested through this solicitation is relevant to many current NASA projects and programs, particularly for future use with HLS (Human Landing System), SLS (Space Launch System), and the Moon to Mars agency architecture. There is also direct applicability to RDRE ARDVARC (Additive Rotating Detonation Variant Rocket Chamber), RAMFIRE (Reactive Additive Manufacturing for Fourth Industrial Revolution Exploration Systems), LLAMA (Long Life Additive Manufacturing Assembly, and ALPACA (Advanced Lander Performance Additive Chamber Assembly) programs at NASA Marshall Space Flight Center.

References

- D. Lim, “Experimental Studies of Liquid Injector Response and Wall Heat Flux in a Rotating Detonation Rocket Engine,” Purdue University Graduate School, 2019.

Scope Title

Methodologies for Improving Rotating Detonation Rocket Engine (RDRE) Exhaust Thrust Capturing (Nozzle Design Optimization) and Mitigation of Losses

Scope Description

Innovative methods by which RDRE exhaust products can be optimally captured to produce ideal thrust at minimum hardware mass are desired. The traditional RDRE nozzle typically involves the use of an aerospike-like plug nozzle in the center body and cowl or outer body nozzle. It is not fully understood how to optimally capture the thrust of an RDRE given that the exit flow has kinetic energy losses from the oscillatory exhaust. Methods by which these losses can be recovered would be of interest. Furthermore, methods by which the oscillatory outlet flow could be minimized would also be highly desirable.

In addition to the expansion section described above, novel methods for chamber and subsequent throat design are of interest. It is well known that an abrupt area contraction causes deleterious impacts to the detonation's stability and thus causes a decrease in detonator performance, which is thought to cause a decrease in global engine performance. Further investments into geometries that do not hinder detonation performance but also increase specific impulse are desired.

Expected TRL or TRL Range at completion of the Project
Primary Technology Taxonomy

Level 1
TX 01 Propulsion Systems

Level 2
TX 01.4 Advanced Propulsion

Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description

Phase I requires CFD modeling or equivalent analysis/experimental work that demonstrates loss minimization and thrust maximization in addition to attempts that reduce overall hardware mass and scale. The primary goal is to better understand how to design a coupled chamber and nozzle configuration for RDREs that will ideally produce thrust with minimized losses. Methodologies that investigate and assess how to best accomplish this end are a priority. One potential means by which this could be accomplished includes creation of a program that utilizes the method of characteristics to design a plug/outer nozzle configuration at specific design conditions.

Phase I requires modeling efforts to show proof of concept and a downselected geometry to manufacture and test. Proof of concept could include full CFD simulation or simpler analysis methodology over a baseline comparison case. The baseline could be a standard-practice straight annulus with plug nozzle designed using Bykovskii's relations [1,2]. Novel methods for reducing loss mechanisms will also need to be shown. These may include protruding channel geometries into the annulus that may act as stators.

Phase II would entail heat sink/regenerative hot-fire testing that assesses performances such as $C^*$, thrust, and/or visual diagnostics of combustion emissions that allow for the deduction of combustion efficiency.

State of the Art and Critical Gaps

Propulsion system performance advancement is virtually at a standstill. In fact, industry is now sacrificing combustion performance and specific impulse improvements for manufacturability. RDREs represent a potential for dramatic improvement in ease of manufacturing, combustion device specific-impulse performance, and advancing U.S. space access capability. High-efficiency propulsion system concepts such as the RDRE are being investigated across the United States, and interest has never been higher. Thus, this work seeks to radically improve and expand the design and test capability of RDREs toward making space access more feasible and cost effective.

Relevance / Science Traceability

The research requested through this solicitation is relevant to current NASA projects and programs, particularly for future use with HLS (Human Landing System), SLS (Space Launch System), and the Moon to Mars agency architecture. Advancement of liquid propulsion system specific impulse is also heavily dependent on nozzle design for the RDRE cycle.

References

Z12.01 Extraction of Oxygen, Metal, and Water from Lunar Regolith

Lead Center: JSC

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

**Scope Title**

Oxygen from Regolith

**Scope Description**

Lunar regolith is approximately 45% oxygen by mass. Most of the oxygen is bound in silicate minerals. Previous efforts have shown that it is possible to extract oxygen from regolith using various techniques. NASA is interested in developing novel oxygen extraction systems that can be proven to handle large amounts of lunar regolith throughput while minimizing consumables, mass, and energy. NASA is also interested in developing the supporting technologies that may enable or enhance the ability to extract oxygen from lunar regolith. Each of the following specific areas of technology interest may be proposed as individual efforts or combined.

- **Novel Silicate Reduction Methods:** Proposed concepts should describe a reduction method for highland anorthosite that avoids reduction of the regolith in the molten liquid state (i.e., gas/granular, liquid/granular, or vacuum/granular material processing). If reactants are utilized in the reduction process, and multiple reaction products are generated, all steps in regenerating the reactants and separating the products need to be considered. Proposed concepts must include a method to move regolith through the reaction zone (e.g., regolith inlet/outlet valves capable of passing abrasive granular material through the valve for hundreds of cycles). The target production rate for a pilot plant system is 1,000 kg of oxygen per year. The target production rate for a full-scale system is 10,000 kg of oxygen per year. Since access to continuous power is not initially planned, proposers will need to consider how to stop and restart their reduction method periodically throughout the year.
- **Noncontact High-Temperature Measurement:** Proposed concepts should be capable of determining temperatures up to 2,000 °C without contacting the material being measured (e.g., pyrometer). Compatibility with multiple oxygen extraction methods is desired. Instruments must be capable of operating inside of a vacuum chamber.
- **Regolith Feed/Removal Systems and Mineral Measurement for Oxygen Removal:** For oxygen extraction from regolith systems, it is anticipated that hardware will be required to transfer regolith from excavators to the reduction reactor and to transfer processed regolith from the reduction reactor to a holding hopper or the lunar surface. To better understand and control oxygen/metal extraction processes, NASA would like to examine the regolith material before and after the reduction process. Proposed concepts should describe a regolith feed/removal system that includes instrumentation to determine the amount of oxygen in the regolith upstream and downstream of an oxygen extraction zone. Measurements should be taken at a frequency that accounts for the regolith feed rate. The target regolith feed rate for a pilot plant system is 2.5
kg/hr. The target regolith feed rate for a full-scale system is 25 kg/hr. Compatibility with multiple oxygen extraction methods is desired. Instruments must be capable of operating inside of a vacuum chamber.

**Expected TRL or TRL Range at completion of the Project**

4 to 5

**Primary Technology Taxonomy**

**Level 1**
TX 07 Exploration Destination Systems

**Level 2**
TX 07.1 In-Situ Resource Utilization

**Desired Deliverables of Phase I and Phase II**

- Research
- Analysis
- Prototype
- Hardware

**Desired Deliverables Description**

Phase I efforts should provide a feasibility study and/or proof of concept. Phase II efforts should demonstrate the technology using lunar regolith simulant where applicable. Phase II efforts should be demonstrated no less than 1/10 of the pilot plant production rate where applicable and should describe how the process can be applied at the full-scale production rate.

**State of the Art and Critical Gaps**

Some oxygen-from-regolith methods have been demonstrated at relevant scales and are progressing toward TRL 6. Many other methods have been demonstrated at the bench scale, but current designs lack a means to move regolith in and out of the oxygen extraction zone. Many of these processes are used terrestrially, but industrial designs do not provide a means to keep gases from escaping to the vacuum of space.

**Relevance / Science Traceability**

STMD (Space Technology Mission Directorate) has identified the need for oxygen extraction from regolith. The alternative path, oxygen from lunar water, currently has much more visibility. However, we currently do not know enough about the concentration and accessibility of lunar water to begin mining it at a useful scale. Lunar water prospecting missions are required to properly assess the utilization potential of water on the lunar surface. Until more water prospecting data becomes available, NASA recognizes the need to make progress on the technology required to extract oxygen from dry lunar regolith.

**References**


Scope Title
Lunar Ice Mining

Scope Description
We now know that water ice exists on the poles of the Moon from data obtained from missions like the Lunar Prospector, Chandrayaan-1, Lunar Reconnaissance Orbiter (LRO), and the Lunar Crater Observation and Sensing Satellite (LCROSS). We know that water is present in permanently shadowed regions (PSRs), where temperatures are low enough to keep water in a solid form despite the lack of atmospheric pressure. Many efforts are now underway to develop technologies needed to extract and capture lunar water ice. However, many other volatiles may be co-located with the water ice that may have additional in situ resource utilization (ISRU) applications. NASA is interested in developing technologies to capture and utilize other volatiles that may be located in PSRs. NASA is also interested in developing the supporting technologies that may enhance efforts to excavate water ice. Each of the following specific areas of technology interest may be proposed as individual efforts or combined.

• Nonwater Volatile Capture: Proposed concepts should define a target volatile (e.g., H2S, NH3, SO2, C2H4, CO2, CH3OH, CH4) to be captured from lunar regolith and describe how it may be utilized in a way that reduces the cost of landing consumables on the lunar surface. Concepts need to operate in PSRs of the lunar poles (<100K), and collected products will be removed from the PSR and processed in a near-permanently lit location nearby. Concepts to minimize electrical power usage are highly encouraged.
• Regolith/Ice Crushing: Proposed concepts should be able to crush frozen regolith simulant with a water ice content of 90% by mass while minimizing temperature increase in the material. The target production rate for a pilot-plant-scale ice-crushing system is 10 kg of regolith per hour. The target production rate for a full-scale system is 100 kg of regolith per hour. Concepts should consider how volatiles released during crushing may be minimized or captured if a significant fraction are lost.

Expected TRL or TRL Range at completion of the Project
4 to 5

Primary Technology Taxonomy

Level 1
TX 07 Exploration Destination Systems

Level 2
Desired Deliverables of Phase I and Phase II

- Prototype
- Analysis
- Hardware

Desired Deliverables Description

Phase I efforts should provide a feasibility study and/or proof of concept. Phase II efforts should demonstrate the technology using lunar regolith simulant where applicable. Phase II efforts should be demonstrated no less than 1/10 of the pilot plant production rate where applicable and should describe how the process can be applied at the full-scale production rate.

State of the Art and Critical Gaps

Multiple efforts are now underway to extract, purify, and capture lunar water ice. However, little work has been performed on developing technologies to capture and utilize other useful volatiles that may be co-located within a PSR. Ice-crushing technology was developed at a small scale to support the Regolith and Environment Science and Oxygen and Lunar Volatiles Extraction (RESOLVE) project, but little work has been performed for larger scale applications.

Relevance / Science Traceability

NASA has referenced water ice as one of the reasons we have chosen the lunar poles as the location to establish a sustained human presence. The Space Technology Mission Directorate (STMD) has identified the need for water extraction technologies. The Science Mission Directorate (SMD) is currently funding the Volatiles Investigating Polar Exploration Rover (VIPER) mission to investigate lunar water ice.

References:

- Environment Science and Oxygen and Lunar Volatiles Extraction (RESOLVE), [https://ntrs.nasa.gov/citations/20150022136](https://ntrs.nasa.gov/citations/20150022136) [98]
- Volatiles Investigating Polar Exploration Rover (VIPER), [https://www.nasa.gov/viper](https://www.nasa.gov/viper) [99]

Scope Title

Size Sorting, Beneficiation, and Metal Production

Scope Description

Size sorting and beneficiation can be applied to ice mining and to oxygen extraction from regolith. Size sorting is a
necessary step in any in situ resource utilization (ISRU) process involving regolith to ensure that the regolith delivered to an ISRU plant does not include objects large enough to cause mechanical failures within the system. Beneficiation allows for improved efficiency of ISRU processes that involve heating regolith in order to acquire a specific resource. NASA is also interested in processes where the primary product is metal—specifically metals other than iron, since iron extraction from regolith is a fairly advanced technology. Each of the following specific areas of technology interest may be proposed as individual efforts or combined.

- **Size Sorting:** Proposed concepts should demonstrate a means to remove particles larger than 1 mm from a feedstock of lunar regolith simulant. The target production rate for a pilot-plant-scale system is 10 kg of regolith per hour. The target production rate for a full-scale system is 100 kg of regolith per hour.
- **Beneficiation of Water Ice:** Proposed concepts should describe a method for separating water ice from bulk regolith without causing the water ice to change phase. The described method should address how sublimation losses can be minimized. The target production rate for a pilot-plant-scale system is 10 kg of regolith per hour. The target production rate for a full-scale system is 100 kg of regolith per hour.
- **Mineral Beneficiation:** Proposed concepts should define a target mineral to be concentrated from lunar regolith feedstock and describe how it will be utilized in a way that reduces the cost of landing consumables on the lunar surface.
- **Metal Production:** Proposed concepts should define a target metal (e.g., aluminum) to be extracted from lunar regolith and describe how it will be utilized in a way that reduces the cost of landing consumables on the lunar surface. Proposed concepts must include a method to move regolith through the reaction zone (e.g., regolith inlet/outlet valves capable of passing abrasive granular material through the valve for hundreds of cycles.) Near-pure metals or metal alloys are acceptable. Properties of metals extracted for manufacturing should be considered and provided.

**Expected TRL or TRL Range at completion of the Project**

3 to 5

**Primary Technology Taxonomy**

**Level 1**

TX 07 Exploration Destination Systems

**Level 2**

TX 07.1 In-Situ Resource Utilization

**Desired Deliverables of Phase I and Phase II**

- Analysis
- Prototype
- Hardware

**Desired Deliverables Description**

Phase I efforts should provide a feasibility study and/or proof of concept. Phase II efforts should demonstrate the technology using lunar regolith simulant where applicable. Phase II efforts should be demonstrated at no less than 1/10 of the pilot plant production rate where applicable and should describe how the process can be applied at the full-scale production rate.

**State of the Art and Critical Gaps**

The Moon to Mars Oxygen and Steel Technology (MMOST) SBIR Phase II sequential project is currently implementing size sorting and beneficiation of minerals containing iron at a relevant scale and is also producing iron as the main product. There has been little advancement toward the production of other metals such as...
aluminum. The Aqua Factorem project funded through the NASA Innovative Advanced Concepts (NIAC) program represents the state of the art for ice beneficiation.

Relevance / Science Traceability

NASA has referenced water ice as one of the reasons we have chosen the lunar poles as the location to establish a sustained human presence. The Space Technology Mission Directorate (STMD) has identified the need for water extraction technologies. The Science Mission Directorate (SMD) is currently funding the Volatiles Investigating Polar Exploration Rover (VIPER) mission to investigate lunar water ice.

References

- Volatiles Investigating Polar Exploration Rover (VIPER). [https://www.nasa.gov/viper](https://www.nasa.gov/viper) [99]

Z13.01 Active and Passive Dust Mitigation Surfaces

Lead Center: JSC

Participating Center(s): JSC, LaRC

Scope Title

Advanced Technologies for Active Dust Mitigation

Scope Description

Proposals are sought that use unique methods that may require power, gases, mechanisms, vibrations, or other means necessary to keep vital surfaces clean under space conditions while not interfering with the form/fit/function of the surface they are acting upon. Self-cleaning surfaces that require minimal effort by astronauts are highly desired. Proposals that address removal of dust on passive (low surface energy) dust mitigation surfaces are also sought. Proposers are expected to show an in-depth understanding of the current state-of-the-art (SOA) and quantitatively describe improvements over relevant SOA technologies that substantiate investment in the new technology. Proposers must also quantitatively explain the operational benefit of the new technology from the perspective of improving or enabling mission potential. Some examples of active dust mitigation technologies include but are not limited to:

- **Brushing**: A self-cleaning brush to mechanically remove dust from surfaces. The brush can be mechanically operated using power or can be temperature activated, such as shape memory alloys.
- **Electrostatic removal**: Methods to use direct-current (DC) electric fields to remove dust from surfaces, either internal to the surface (embedded) or external using a removed high-voltage source.
Vacuum: Methods to remove particles from surfaces using suction of gases.
Jets: High-velocity gas jet that blows dust particles from surfaces.
Spinning surfaces: Surface rotates in a manner that does not allow collection of dust on it.
Vibrational surfaces: Vibrating surface bounces the particles off of the surface.
Electrodynamic removal: The surface contains embedded electrodes with varying high-voltage signals applied to lift and transport dust off of the surface.

Proposals are highly sought in which the active dust mitigation strategy could be combined with the SOA of passive dust mitigation technologies. For example, passive dust mitigation strategies include:

- Electrostatic discharge (ESD) coatings and films: Statically dissipative coatings are less likely to accumulate charge, and hence dust, in dry environments.
- Superhydrophobic coatings: Materials with a very high contact angle can lower the adhesion of water-based contaminants, not allowing the capillary forces to take hold.
- EVA- and robotic-compatible dustproof electrical, fluid, and gas connectors.
- Lotus leaf coating: Microscopic nanostructures used to limit the van der Waals force of adhesion.
- Peel-away coating: Removable surface coatings.
- Gradient surfaces that direct dust adhesion away from vital surfaces.

Strong proposals are those that identify the active dust removal strategy in coordination with other dust prevention and removal methods as listed above. Strong proposals will also include a brief description of an infusion plan for a flight demonstration using Phase II funding.

Expected TRL or TRL Range at completion of the Project
3 to 6

Primary Technology Taxonomy
Level 1
TX 12 Materials, Structures, Mechanical Systems, and Manufacturing
Level 2
TX 12.3 Mechanical Systems

Desired Deliverables of Phase I and Phase II
- Hardware
- Prototype

Desired Deliverables Description
At the end of the Phase I research period, it is expected that a material or technology will be identified and initial characterization results collected. Initial characterization should indicate whether further development of the technology would be scalable and should exhibit a dramatic reduction (>90% relative to full dust loading of a reference material surface such as an aerospace aluminum alloy or polymeric film surface such as Kapton® or Teflon®) in particulate adhesion for microparticles, specifically those described as lunar dust simulant, with diameters <50 µm. At the end of Phase II, it is expected that promising technologies will have been demonstrated
through relevant environmental test conditions. The materials or technology should be demonstrated to be scalable to quantities sufficient for application beyond laboratory research requirements, i.e., at kilogram or greater quantities for materials or a similar measure for a passive technology. Cost analysis for scaling to mission-requirements level, as will be elucidated through the course of this research, will also be required.

If a Phase II is awarded, further development of the technology shall be required, including a prototype delivered to NASA at the end of the 2-year project with a goal of achieving Technology Readiness Level (TRL) 6. A prototype of the new technology must be provided that shows the feasibility of the dust removal method. The technology must be demonstrated in a laboratory environment removing and/or keeping dust from adhering to a surface. The mass, power, volume, and potential costs associated with the implementation of this technology must be addressed. A well-developed infusion plan resulting in a flight demonstration must also be provided.

State of the Art and Critical Gaps

All new technologies for Active Dust Mitigation must include a full knowledge base of the SOA, and proposals that advance the current SOA are encouraged. For example, NASA has developed the Electrodynamic Dust Shield (EDS), which lifts and transports dust off of surfaces with embedded electrodes within a dielectric. A brief but not complete introduction to the technology can be found in the references provided.

The EDS can be incorporated into a variety of configurations addressing many of NASA’s needs. However, several potential improvements and technologies that can further the development of the EDS technology are also highly sought within this call. Some potential advances include:

- High dielectric breakdown strength for both glues/epoxies and the coating material: The efficiency of dust removal for the EDS is limited to the amount of voltage that can be applied to the electrodes. The electrical breakdown occurs across the 2D surface because of the dielectric strength limitation of the adhering material as well as the coating material.
- Flexible transparent surfaces with high current capabilities: The optically transparent version of the EDS uses indium tin oxide (ITO) as the main conductive medium for its electrode. Although the EDS is not a high-current DC device, the displacement current (I ~ dV/dt) can be quite high. Transparent electrode materials are sought that can replace ITO as the conductive medium that have higher current capabilities and lower overall resistivities. Another shortcoming of ITO is its range of flexibility. Many ITO coatings cannot be bent past a certain degree and are not compatible with numerous folds and bends.
- Electrical attachment: Most EDS systems have issues with the electrical connections between the high-voltage power supply (HVPS) and the electrodes. Any possibility of arcing and/or sparking as a result of slight differences between the wiring from one material configuration to another is exacerbated when powered with EDS waveforms. Proposals are highly sought that address this key issue for attaching high-voltage wires to electrodes embedded in an EDS circuit. EDS circuit electrodes are made using a variety of materials such as copper (wires or vapor deposited), ITO, silver paint wires, carbon nanotube (CNT), and graphene, to name a few. Likewise, these and other electrodes are usually resting on or embedded into a substrate such as glass, polyimide (Kapton®), clothing fibers, polyethylene terephthalate (PET), polytetrafluoroethylene (PTFE), polyamide (nylon), poly(methyl methacrylate) (PMMA, e.g., acrylic, LUCITE®, and other surfaces.
- Minimizing electromagnetic interference (EMI): Most EDS designs can generate electrical noise that would be disadvantageous if incorporated into a system. Methods to reduce electrical noise and EMI are highly sought.
- Safety: With all EDS systems, the use of high voltage requires safety measures for the astronaut and the equipment. Methods to improve the safety and reliability of the EDS in the case of arcing is highly sought.
- Smart EDS technology: As with all dust mitigation technologies, methods to include adaptive techniques are highly sought. The system should be able to check its environment to see if dust clearing is necessary and, if it is, apply power to the system until the cleanliness requirements are met for reliability and power minimization.

Other active systems also require maturation. Critical gaps in these areas include:
- Effective and scratch-resistant brushing techniques. Apollo astronauts used brushes that are largely ineffective for large surface areas and tend to scratch sensitive equipment, such as astronaut visors.
- Gaseous removal of dust on the lunar surface may contaminate other sensitive equipment. A better approach to gaseous or fluidized removal of dust is needed.
- Simple mechanical or vibrational dust mitigation implementations are required. As particles move, they also become highly electrostatically charged, further causing dust adhesion.

Relevance / Science Traceability

Adhesion of granular materials and the technologies that address mitigation through this subtopic will advance the state of knowledge of this difficult research subject. The interplay between the surface's energy, chemistry, and mechanical properties and the particle's surface is a fascinating but not well-understood science. This call will not only extend exploration missions on the lunar surface but will enable exploration missions that would not have been possible. For example, every mechanical seal was compromised on the Apollo missions over 3 days due to exposure to the dust. Research that elucidates this complex behavior toward lunar dust adhesion could be vital for realization of a sustained lunar presence, and although our understanding of the lunar environments has continued to improve, materials and technologies that arise from this research will expand our survival on dusty surfaces in space.

Ideally, a universal lunar simulant will be identified by NASA and should be used for performance verification of developed technologies. If no universal simulant is identified, the specific properties of the utilized particulate material should be identified and related to known properties of lunar dust.

References:

Texas, United States, 2009.

Scope Title
Advanced Technologies for Passive Dust Mitigation

Scope Description
This call seeks unique research proposals focused on passive approaches, i.e., those that do not require external stimulus, that will minimize the potential impact lunar dust will have on future exploration missions. These approaches may include novel materials and surfaces as well as technologies that require no external input (a self-activating system) while not interfering with the form/fit/function of the surface they are acting upon. Novel materials may include high-performance plastics, metals, ceramics, etc. Surfaces may be homogeneous or heterogeneous (i.e., nonisotropic surface properties resulting in directional dust adhesion control), and rough or smooth with topography imparted by any number of approaches, including, but not limited to: lithography, embossing, roll-to-roll processing, etc. Surfaces can incorporate strategies for mitigation of adhesion contributions from van der Waals interactions, electrostatic forces, and chemically reactive or mechanical interactions. Both the material and surface modification approach must be demonstrated to be scalable and exhibit a dramatic reduction (>90% relative to a reference material surface such as an aerospace aluminum alloy or polymeric film surface such as Kapton® or Teflon®) in particulate adhesion for microparticles, specifically those described as lunar dust simulant, with diameters <50 µm.

Strong proposals will seek to demonstrate the efficacy of lunar dust adhesion mitigation and the durability to retain these properties in a simulated environment. Strong proposals will include characterization of the solar reflectivity and infrared (IR) emissivity of the passive approach applied, if applicable. Strong proposals will also include a brief description of an infusion plan for a flight demonstration using Phase II funding.

Expected TRL or TRL Range at completion of the Project
3 to 6

Primary Technology Taxonomy
Level 1
TX 12 Materials, Structures, Mechanical Systems, and Manufacturing

Level 2
TX 12.1 Materials

Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype
- Hardware
Desired Deliverables Description

At the end of the Phase I research period, it is expected that a material or technology will be identified and initial characterization results collected. Initial characterization should indicate whether further development of the technology would be scalable and should exhibit a dramatic reduction (>90% relative to full dust loading of a reference material surface such as an aerospace aluminum alloy or polymeric film surface such as Kapton® or Teflon®) in particulate adhesion for microparticles, specifically those described as lunar dust simulant, with diameters <50 µm. At the end of Phase II, it is expected that promising technologies will have been demonstrated through relevant environmental test conditions. The materials or technology should be demonstrated to be scalable to quantities sufficient for application beyond laboratory research requirements, i.e., at kilogram or greater quantities for materials or a similar measure for a passive technology. Cost analysis for scaling to mission-requirements level, as will be elucidated through the course of this research, will also be required.

If a Phase II award is made, further development of the technology shall be required, including a prototype delivered to NASA at the end of the 2-year project with a goal of achieving Technology Readiness Level (TRL) 6. A prototype of the new technology must be provided that shows the feasibility of the dust removal method. The technology must be demonstrated to remove adhered dust or prevent dust adhesion in a laboratory environment simulating some aspects of lunar environmental conditions. Durability of the material surface toward lunar dust abrasion, thermal cycling, and other environmental considerations should also be addressed. The mass, power, volume, and potential costs associated with the implementation of this technology must be addressed. A well-developed infusion plan resulting in a flight demonstration must also be provided.

State of the Art and Critical Gaps

Although a myriad of materials and technologies exist for mitigation of surface contamination for a variety of terrestrial applications, requirements for mitigation of lunar dust adhesion indicate diminished efficacy of many materials. As an example, silicones are used ubiquitously to reduce adhesive interactions and can be effective for contamination prevention across a range of contaminants; however, these relatively soft materials would exhibit deleterious properties in a traditional manifestation arising from particulate embedding due to the sharp edges and hardness of the lunar dust. Likewise, hard traditional ceramic materials have been shown to be beneficial for terrestrial applications; however, triboelectrification of an insulating material would increase adhesion interactions with lunar dust. Beyond these specific lunar dust properties, magnetic interactions, chemical activity, and the velocity of the lunar dust, especially at the lunar terminator, all contribute to adhesion and therefore must be addressed for a material to be expected to perform well in this environment.

Critical technology gaps in passive dust adhesion mitigation include:

- Nanotechnology in permanently shadowed regions.
- Flexible materials with adhesion and abrasion resistance demonstrated across the thermal range of the lunar surface, -170 to 125 °C.
- Nonisotropic materials with directional dust adhesion control.
- Dust removal technologies integrated with passive dust mitigation materials.
- Materials and technologies for transition spaces from surface operations to habitat interior spaces.

Relevance / Science Traceability

Adhesion of granular materials and the technologies that address mitigation through this subtopic will advance the state of knowledge of this difficult research subject. The interplay between the surface’s energy, chemistry, and mechanical properties and the particle’s surface is a fascinating but not well-understood science. This call will not only extend exploration missions on the lunar surface but will enable exploration missions that would not have been possible. For example, every mechanical seal was compromised on the Apollo missions in the course 3 days due to exposure to the dust. Research that elucidates this complex behavior toward lunar dust adhesion could be vital for realization of a sustained lunar presence, and although our understanding of the lunar environments has continued to improve, materials and technologies that arise from this research will expand our survival on dusty
surfaces in space.

Ideally, a universal lunar simulant will be identified by NASA and should be used for performance verification of developed technologies. If no universal simulant is identified, the specific properties of the utilized particulate material should be identified and related to known properties of lunar dust.

References:

manifestation of the complex interaction of the lunar soil with multiple mechanical, electrical, and gravitational effects.

Mechanical systems will need to operate on the dusty surface of the Moon for months to years. These systems will be exposed to the harsh regolith dust and will have little to no maintenance. This scope seeks technologies that can function with or tolerate dust intrusion in the following areas:

- Actuators and power transfer components (motors, pistons, shape memory alloy, gear, belt, chain, steering, suspension, hinges, bearings, etc.).
- Fastening, joining, and securing components and hardware (structural connections, threaded fasteners, quick pins, latches, restraint systems).
- Sealing materials and techniques that can keep out regolith and operate in the harsh Moon/Mars environments.
- Dust-tolerant fluid and electrical connectors (quick disconnects, umbilicals, modular commodity interfaces).
- Moving components for dust protection (iris, hatch, covers, airlocks, closures, fabric/flexible protection).
- Tools and devices for exploration and in situ resource utilization (ISRU) (sample tools, dust cleaning, landing gear, pointing actuator).
- Material handling and transportation components (hoist, lift, pallet, pick and place, common transport interface, etc.).

Successful solutions will have the following performance characteristics:

- Operational for extended service of 10 to 100 months with limited or no maintenance.
- Linear and static joints will function and perform the designed actuation/motion/mate-demate cycles of 1,000 or higher.
- Linear and static joints will function with minimal solid film or without lubrication.
- Rotational joints will have operational lifetimes on the order of hundreds of thousands of cycles.
- All mechanisms will function throughout lunar temperature cycles between 127 °C (260 °F) and -173 °C (-280 °F).
- All mechanisms will function in the extreme cold of permanently shadowed regions (?238 °C).
- All mechanisms will function reliably with lunar regolith (simulant) coating the exposed mechanism surfaces.
- All mechanisms will function in the high vacuum lunar environment of 10^-9 Torr.
- All mechanisms and materials will function in the lunar electrostatic and radiation environment.

Expected TRL or TRL Range at completion of the Project

2 to 6

Primary Technology Taxonomy

Level 1

TX 07 Exploration Destination Systems

Level 2

TX 07.2 Mission Infrastructure, Sustainability, and Supportability

Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype
- Hardware
- Software
Desired Deliverables Description

Research should be conducted to demonstrate technical feasibility during Phase I and show a path toward Phase II demonstration, with delivery of a demonstration package for NASA testing in operational test environments at the completion of the Phase II contract.

Phase I Deliverables: Research, identify, and evaluate candidate technologies or concepts for dust-tolerant mechanisms. Simulations or laboratory-level demonstrations are desirable. Deliverables must include a report to document findings.

Phase II Deliverables: Emphasis should be placed on developing, prototyping, and demonstrating the technology under simulated operational conditions (regolith, thermal, vacuum). 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 is expected at the completion of the Phase II contract. The technology concept at the end of Phase II should be at a Technology Readiness Level (TRL) of 6 or higher.

State of the Art and Critical Gaps

Previous solutions used in the Apollo program did not address the current need of long-term usage. Terrestrial solutions often employ materials or methods that are incompatible with the lunar environment.

Critical Gaps:

- Seals at rotary and linear joints are very common for actuation in dusty environments. Most of these seals, however, use elastomers that would off-gas and become brittle in a lunar radiation environment and at lunar temperatures. Solutions are needed that employ advanced materials, metallic seals, or nontraditional techniques that can operate in the lunar environment for an extended period of time (months to years).
- Bearings that are tolerant of dust infiltration. Regolith getting past the protective seals and into bearings is a common failure point. Solutions are needed for bearings that are highly dust tolerant to reduce the risk of failures due to dust intrusion.
- Operations on the lunar surface will include assembly, construction, and extravehicular activity (EVA) tasks. These tasks will involve the mating/demating of various structural, electrical, and fluid connections. Dust on the surface of these joints will impede their proper function and lead to failures. Solutions are needed to protect these joints from dust contamination.
- Dust-protective enclosures, hatches, and moving covers are needed to protect delicate components. Materials and coatings are needed that eliminate or minimize the adherence of lunar dust to these surfaces. Solutions are needed for self-cleaning shapes, materials, and mechanisms that can clean/remove/reject regolith from vital moving parts of mechanisms as they operate.

Relevance / Science Traceability

Dust will be one of the biggest challenges for operation on the lunar surface for the Artemis program.

“I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think we can overcome other physiological or physical or mechanical problems except dust.” Gene Cernan, Apollo 17 Technical Debrief.

References

Technologies for Spacesuits in Extreme Surface Environments

Lead Center: JSC

Scope Title
Portable Life Support System (PLSS) Dust Protection

Scope Description
For spacesuits, challenges presented by lunar dust include damage from abrasion, the effects of dust’s electrostatic charge on the suit system, and dust intrusion to the suit system. Regarding the effects of dust intrusion, there is a need to protect components that must be exposed to, operate in, or operate after exposure to the lunar dust environment. There are multiple spacesuit components that require access to the environment for gas flow, both in nominal and off-nominal operations. Some of these components require specialized covers that prevent dust intrusion while at the same time allowing for sufficient gas flow. These components are:

1. PLSS Cover Vapor Vent Ports: The PLSS Cover has two ports to allow evaporated water from the Spacesuit Water Membrane Evaporator (SWME) and its backup, the Mini-Membrane Evaporator (Mini-ME), to vent to the surrounding vacuum. The operation of these components is dependent on a low backpressure, and each of the vent ports must have an effective flowthrough area of at least 7 in.\(^2\) to maintain the appropriate pressure for evaporation within the PLSS cover. The vents (two total, symmetrically located on each side of the PLSS cover) 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 in. on either side.

2. PLSS Vacuum Access Pigtail Umbilical: The Rapid Cycle Amine (RCA) is a component that resides in the Exploration Extravehicular Mobility Unit (xEMU) PLSS. The responsibility of the RCA unit is to remove carbon dioxide (CO\(_2\)) and water (H\(_2\)O) from the PLSS ventilation loop. The RCA unit functions in a swing-bed regenerative manner to adsorb CO\(_2\) and H\(_2\)O in one bed and desorb to vacuum in another bed. The PLSS Vacuum Access Pigtail Umbilical provides the vent path to vacuum for the RCA desorption cycle. This umbilical is 3 ft long with a diameter of 1.25 in. and is equipped with a free-flowing quick disconnect (QD) on the end. A specialized dust cover is needed for this umbilical to prevent dust intrusion. 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 vacuum environment. The ullage gas can be assumed to be 100% oxygen (O\(_2\)) at 2.15 psi. Without a specialized cover, this gas dissipates within about 2 sec. After the ullage gas has dissipated, the desorbed gas consists of CO\(_2\) and water (H\(_2\)O) with a mass flow of 325 to 360 g/min, depending on the bed loading and metabolic rate of the crewmember. Between 210 and 230 g/min of that flow is CO\(_2\). For efficient operation of the RCA, the rapid decompression of the vacuum line is essential, as is the subsequent diffusion of desorbed gas away from the absorber beds. The specialized dust cover must not impede either of these processes.

3. Purge Valves: The xEMU is equipped with two purge valves to perform pre-extravehicular activity (EVA) denitrogenation purge or to convert the closed-loop ventilation operation into an open-loop operation as a contingency life-support function during the termination of an EVA resultant from a system failure. The Display and Control Unit (DCU) Purge Valve is located on top of the DCU on the chest of the spacesuit, such that the crew can visually observe the valve as well as reach/activate it with either hand. This is the primary valve. A secondary valve, available in the event of a primary valve failure, is the Hard Upper Torso (HUT) Purge Valve, which is located over the crewmember’s right shoulder. This is a blind operation, accessible with only the right hand. Both valves will be exposed to the lunar dust environment and must be able to be activated and vent while operating in that environment. Both valves have a similar flow capability and function, providing an O\(_2\) flow rate of 1.55 to 1.69 lb/hr at 3.5 psi. Both valves include a two-motion activation that can be performed with EV-gloved hands: pinch and lift.

4. Positive Pressure Relief Valve (PPRV): The PPRV prevents overpressurization of the suit in the event of a failed open primary or secondary oxygen regulator. The xEMU has two PPRVs, both located on the HUT on the crewmember’s lower right side below the shoulder. The two valves do not function under nominal circumstances during EVA but depending on the vehicle pressure schedule and depress rate, could actuate during airlock depress. Current vehicle pressure schedules for human landing systems would make this unlikely with the current 8.6- to 8.8-psid cracking/reseat pressure. The full-open flow rate requirement for the PPRV is 7.49 lb/hr of dry O\(_2\) at 70 °F with suit internal pressure of 10.1 psia and vacuum as the external...
reference. The valve includes an inlet filter inside the suit and requires a venting protective cover on the outside of the suit that minimizes backpressure on the valve during venting operations.

5. Negative Pressure Relief Valve (NPRV): The NPRV prevents the suit from becoming too negatively pressurized during a rapid airlock repress such as that performed in the event of a suit emergency. Under this circumstance, the valve is designed to maintain the suit pressure at no more than a negative 0.5 psid. The requirement for the NPRV is 49 lb/hr of dry air at 70 °F, with the airlock pressure at 6.5 psia and a suit pressure at 6.0 psia. The NPRV is not used under nominal EVA operations but is exposed to the environment as it is located on the outside of the HUT, under the crewmember’s left shoulder. It must be capable of being exposed to dust with subsequent function if needed in this contingency.

6. Service and Cooling Connector (SCC): The SCC serves as the suit's main interface to vehicle services: O2, H2O, and power/data. The SCC is disconnected from the vehicle services umbilical at the beginning of an EVA and reconnected at its conclusion. While disconnected, the SCC must be protected from dust intrusion while operating in the dust environment. The protection must then be installed after disconnection and removed or inactivated during reconnection. The SCC includes two 3,000-psi O2 recharge QDs, three H2O QDs, and a 54-pin electrical connector ganged together in a single interface. The SCC presents a flat, outward-facing plane that is 2.5 by 4.0 in., located centrally on the DCU on the anterior of the suit.

Expected TRL or TRL Range at completion of the Project

3 to 4

Primary Technology Taxonomy

Level 1

TX 06 Human Health, Life Support, and Habitation Systems

Level 2

TX 06.2 Extravehicular Activity Systems

Desired Deliverables of Phase I and Phase II

- Analysis
- Prototype
- Hardware

Desired Deliverables Description

Phase I Deliverables: Reports demonstrating proof of concept, test data from proof-of-concept studies, and 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 conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, and 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

Good dust-mitigation technologies and strategies are nonexistent for the spacesuit.

Relevance / Science Traceability

This scope is included under the Space Technology Mission Directorate (STMD) for Dust Mitigation. The project customer for this scope is the Exploration Extravehicular Mobility Unit (xEMU) project, which is under the Human
Exploration and Operations Mission Directorate (HEOMD). Therefore, this scope has traceability to HEOMD as well.

References

Note to offeror:

- PLSS schematics and hardware drawings shall be provided if offeror is selected for award.
- Dust simulant characteristics shall be provided if offeror is selected for award.


Scope Title

Dust Removal Aids for Spacesuits

Scope Description

The Exploration Extravehicular Mobility Unit (xEMU) Environmental Protection Garment (EPG) is a multilayered softgoods (textile material) system. Its primary function is to protect the xEMU suit system from the extreme extravehicular activity (EVA) environment while enabling suit functionality. The EPG system itself must survive the environment and protect the suit from the environment while enabling xEMU functionality of its three subsystems—the pressure garment system (PGS), portable life support system (PLSS), and informatics system. The EPG shell fabric is the suit’s first line of defense as well as the source of regolith introduction back into lunar landers.

NASA is in search of cleaning aids for spacesuits. One part of a lunar dust mitigation solution involves cleaning off as much regolith dust as possible while still in the EVA environment. The more dust a crewmember can leave outside, the less intravehicular cleaning will be required, and less strain put on vehicle-level air filters. Projects currently underway are looking at numerous ways to improve suit cleaning beyond the capabilities used during Apollo. Examples include improved brush materials and geometry and a compressed gas system for forced dust removal.

Ortho-Fabric, the three-fiber shell fabric developed for the space shuttle suit outer layer, was designed for the shuttle airlock oxygen concentration of 30% at 10.2 psi (70.3 kPa) and for durability. While Ortho-Fabric does not support combustion in an exploration environment of 36% oxygen atmosphere at 8.2 psi, it is a woven fabric. The interstices of the weave (gaps between yarns) allow for some amount of lunar dust to penetrate, and therefore it is a poor barrier to dust. In addition, the GORE-TEX® expanded polytetrafluoroethylene (ePTFE) film is easily abraded by the dust. Although GORE-TEX® is a PTFE (Teflon®) and inert, it can accumulate a charge.

In short, NASA is without an adequate solution for removing lunar regolith from the outermost layer of the EPG system that covers the xEMU suit system. NASA is looking for innovative solutions for cleaning aids to address dust removal from the EPG and other external suit areas prone to dust contamination.

Expected TRL or TRL Range at completion of the Project

3 to 4

Primary Technology Taxonomy

Level 1

TX 06 Human Health, Life Support, and Habitation Systems

Level 2
Desired Deliverables of Phase I and Phase II

- Prototype

Desired Deliverables Description

Phase I Deliverables: Reports demonstrating proof of concept, test data from proof-of-concept studies, and 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 conditions. Hardware should be evaluated through parametric testing prior to shipment. Reports should include design drawings, safety evaluation, and 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 NASA.

State of the Art and Critical Gaps

Currently, Apollo-like brushes are being used for cleaning off dust on the spacesuits. Also, compressed gases are being assessed.

Relevance / Science Traceability

This technology will support the lunar mission where dust is a potential hazard to operating the spacesuit on the lunar surface safely.

This scope is included under the Space Technology Mission Directorate (STMD) for Dust Mitigation. The project customer for this scope is the Exploration Extravehicular Mobility Unit (xEMU) project, which is under the Human Exploration and Operations Mission Directorate (HEOMD). Therefore, this scope has traceability to HEOMD as well.

References

None

Z13.04 Lunar Dust Filtration and Monitoring

Lead Center: JSC

Participating Center(s): JSC, KSC

Scope Title

Lunar Dust Filtration and Monitoring

Scope Description

Advances in the removal, management, and monitoring of airborne particulates and external dust are sought to address the intrusion into and containment of lunar dust within the pressurized habitable volumes and compartments in crewed spacecraft systems. Specifically, advances in particle filtration and separation techniques,
barrier techniques, and monitoring instruments are integral to maintaining conditions conducive to crew health and safety as well as protecting spacecraft systems from dust-related fouling during crewed surface exploration missions.

Currently on the International Space Station (ISS), astronauts must vacuum protective screens covering filters weekly to remove larger particles and lint fibers, which are generated by their daily activities, particularly exercising. In the early, shorter Artemis missions, the crew will have to contend with very small amounts of typical spacecraft cabin aerosols and with large amounts of the new contaminant, lunar dust. Lunar dust particles will carry some level of charge which is not well understood or quantified at this time, and other cabin aerosols may be charged as well. Particles are irregularly shaped and jagged, with abrasive properties that can damage mechanisms and equipment.

In the long-range goal of establishing a sustainable human presence on the Moon in habitats, air quality in the larger living areas will be challenged by all the aerosols that come from longer term human occupancy and aerosols generated by the equipment and processes that keep the habitat operational. In this scenario, the time spent on cleaning should be minimal for the crew. Therefore, filtration and separation systems should be as maintenance free as possible, and potentially regenerable, to avoid the cost of flying spares and consumables. Based on the level of lunar dust contamination, even short missions (on the order of 30 days) may require some form of regeneration or autonomous maintenance to minimize or eliminate crew intervention. Specific needs on this front are particle-flow barriers, filtration media, and inertial cleaning prefilter devices that are self-cleaning and/or regenerable.

Another risk of suspended particulate matter (PM) in spacecraft is false smoke alarms. On ISS, the smoke detectors are disabled during vacuuming and other housekeeping activities for this reason. Ideally, this would not be the practice during extensive dust cleaning in the lander after extravehicular activities (EVAs), and creative solutions in particle monitors should address this issue.

PM monitoring technologies are sought to measure a wide range of particle concentrations that will exist in different stages of lunar missions. The lunar lander missions allow only minimal equipment within the small habitable volume but will have much higher concentrations of lunar dust. Therefore, miniaturized aerosol instruments should be capable of measurements in the range of tens of milligrams per cubic meter (mg/m$^3$) for particle sizes up to 20 µm and should be sensitive enough to verify small concentrations to prove that air cleaning systems are effective. Once cleaning has progressed, lunar dust mass concentrations may be very low, but large numbers of individual ultrafine particles may still be present. The Gateway outpost that will orbit the Moon will have some lunar dust contamination by way of the lander docking and exchanging air, as well as settled dust in the lander, which may be reentrained into Gateway air upon ascent, but overall, particle concentrations are expected to be much lower. The monitoring of this habitable space requires more sensitivity, with the ability to accurately measure down to 0.05 mg/m$^3$ for particles 10 µm and below.

Any monitoring technology is at risk of clogging from larger lunar dust particles or possibly even lint or other cabin aerosols. To avoid this, effective designs will have one or more precut features, such as size-selective inlets and screens, which should not require consumables or frequent maintenance and would potentially have self-cleaning features. Note that the ingestion of abrasive particles can cause damage to the internal components of a particulate monitor.

The performance of technologies should be evaluated through testing and/or analysis under relevant environmental conditions using aerosol reference instruments and relevant particle-size distributions of lunar dust simulants.

Measurement ranges for monitoring and permissible limits for filtration in lunar missions:

- Levels of suspended PM (cabin dust and lunar dust) must be maintained below 3 mg/m$^3$, and the respirable fraction of the total dust (smaller than 2.5 ?m in aerodynamic diameter) must be below 1 mg/m$^3$, per the standards in NASA-STD-3001 Vol. 2, Rev. B.
- More specifically:
  - During intermittent daily exposure periods that may persist up to 6 months in duration, lunar dust must be maintained below a time-weighted average of 0.3 mg/m$^3$ for particles less than 10 ?m.
  - For 7-day lander missions, lunar dust must be maintained below a time-weighted average of 1.6 mg/m$^3$ for particles less than 10 ?m.
Specific needs in each area of interest are given below.

**Bulk Particle Filtration and Separation Techniques:**

Techniques and methods are sought for compact, low-power, autonomous, regenerable bulk PM separation and collection. Techniques should be suitable for general spacecraft cabin air purification and removal of planetary or lunar (surface) dust in main cabin quarters and airlock compartments. The hardware developed needs to operate at reduced cabin pressures down to 56 kPa. The PM removal techniques and methods must accommodate high volumetric flow rates up to 3.4 m$^3$/min (for distributed ventilation architectures with multiple supply and return branches) and with pressure drop not to exceed 125 Pa. The system needs to meet requirements for both lunar dust and spacecraft cabin dust (derived from materials in the spacecraft, Environmental Control and Life Support System (ECLSS) processes, and biological matter and debris generated by the crew).

The proposed techniques and methods should provide the cleanliness levels stated above, either as a standalone unit or in conjunction with a high-efficiency filter stage. The overall filtration performance of the filtration system (which may include a high-efficiency stage) should be at minimum 99.97% collection efficiency for particles 0.3 µm in diameter (or HEPA efficiency standard). The filter and separation system also needs to provide microbial and fungal control as outlined in NASA-STD-3001 Vol. 2, Rev. B requirements. These standards must be maintained for a particulate generation rate of 0.31 mg/min per person and a surface dust intrusion rate of 50 g per EVA person (according to EVA-EXP-0070). The systems need to be capable of handling the total PM and planetary dust load over the broad size range of particles generated throughout the mission (up to hundreds of micrometers) and must operate in the surface environment for periods ranging from 2 weeks to 500 days or more. The filter and/or separation technology should provide sufficient capacity to collect and contain tens to hundreds of grams of lunar dust over its service life (which can include multiple regeneration cycles). If regenerable, the technology should provide an effective means of containing or preventing the release of the collected bulk PM during the regeneration process.

**Barrier Techniques:**

There is a need for PM management systems specifically designed to collect and remove lunar dust from airlocks, suit preparation compartments, or staging areas. These should provide a >99.5% effective barrier to surface dust transfer between different volumes or compartments. The barrier technique may include filtration, separation, and other mitigation techniques used within these smaller pressurized compartments, and/or techniques that prevent the transport or transfer of surface dust between compartments, to main cabin areas, or to orbiting habitats and crew transport vehicles.

**Monitoring Instrumentation:**

Instruments, or instrument technologies, that measure PM concentrations in particle size ranges specified in the cleanliness requirements (stated above) are desired. The instrument, or combination of instruments, will need to measure lunar dust and normal cabin dust in landers, airlocks, and habitable spaces at lunar gravity, as well as in the microgravity environment in the Gateway orbiter. Real-time measurement instruments must be compact and low power, require minimal maintenance, and be able to maintain calibration for 1 year. The instrument also needs to be compatible with 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 combined in one unit. PM sensors that measure size-segregated mass concentration (PM2.5 and PM10) over a wide range of mass concentrations and are capable of distinguishing between different material types (lunar dust, typical spacecraft cabin dust and smoke) are highly desirable.

In the long term, future integration of monitoring technologies with filtration or other cleaning technologies may drive the design and development of initially proposed technology solutions. Future autonomous vehicles are expected to use feedback loops for remediation of dirty air as well as monitoring filter and sensor health and performance.

**Expected TRL or TRL Range at completion of the Project**

2 to 4

**Primary Technology Taxonomy**
Level 1

TX 06 Human Health, Life Support, and Habitation Systems

Level 2

TX 06.1 Environmental Control & Life Support Systems (ECLSS) and Habitation Systems

Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype

Desired Deliverables Description

For Phase I, research, numerical modeling, and preliminary breadboard results in a report are feasible.

For Phase II, firms should deliver a working prototype and accompanying test data to NASA, demonstrating performance to specifications using lunar simulants and other relevant test aerosols.

State of the Art and Critical Gaps

The state of the art (SOA) for filtration relies on consumables, and there are few incentives for making regenerable filtration or prefilter barriers. Self-cleaning prefilter devices are not requirements for most commercial and residential filtration scenarios. The price for such systems is not justified when simple replacement filters are available. This solicitation specifies quantities of lunar dust loading in filters that far exceed the capacity of any commercially available filters.

The SOA for particulate monitoring includes miniaturized instruments, which may have very poor performance compared to reference-quality instruments. So-called "low-cost" sensors typically sacrifice accuracy for small-size and low-power needs and are only appropriate for environments that are relatively clean in comparison with the expected lunar dust contamination in the lander cabin after EVAs. In particular, it is difficult to accurately measure PM10 (particulate matter 10 µm and below) with commercially available miniaturized sensors. Instruments that are sensitive to single-digit mg/m$^3$ mass concentrations are typically not capable of measuring high concentrations. Size-selective inlets to instruments typically require cleaning and maintenance, and self-cleaning options are nonexistent. There is no commercially available instrument that can distinguish between aerosol types (dust, smoke).

Relevance / Science Traceability

Human Exploration and Operations Mission Directorate (HEOMD) and Life Support Systems (LSS) can use this technology. It is necessary for Artemis or any other dusty planetary destination.

References

Z14.01 Lunar Surface Excavation
Lead Center: ARC
Participating Center(s): GRC, JPL, LaRC

Scope Title
Lunar Surface Excavation

Scope Description

NASA is interested in developing excavation technologies to mine frozen volatiles resources by excavating the icy regolith in permanently shadowed regions (PSRs) and surrounding areas.

Currently, excavation robots that have been prototyped have been designed to excavate in dry regolith [1,2,3,4] to extract the oxygen contained in silicates and other minerals. Frozen volatiles, such as water, may act as a binder in the regolith, therefore possibly creating a very hard consolidated material. Existing excavation robots and implements have not been designed to excavate in this icy regolith mixed material.

In addition to icy regolith excavation capabilities, the excavation systems must be capable of operating in the extremely harsh lunar environment, including inside PSRs expected to be as cold as 40 Kelvin [5].

Excavation of lunar regolith is enabling for in situ resource utilization (ISRU), as the regolith will be the source of many feedstocks that can be used to make needed products in this domain.

This subtopic is focused on the following aspects of lunar regolith excavation:

- Excavation devices and sensors/feedback needed to better understand and eventually automate excavation processes for icy regolith excavation.
- Reliability and durability of regolith excavation hardware during excavation of hard/icy regolith containing frozen volatiles.

Proposals must address strategies and designs for both of these focus areas, with a strong emphasis on life-cycle reliability and durability.

For ISRU, excavation technologies are required to mine resources that will have been previously located and identified by resource prospecting methods. For oxygen extraction, the surface regolith may be mined, as the oxygen is ubiquitously present in the form of silicates, whereas volatile resources are thought to be beneath an insulating overburden that may be up to 1 m deep and beyond.

Recent missions to the Moon have identified a high potential for the existence of volatiles resources. The suite of Lunar Crater Observation and Sensing Satellite (LCROSS) and Lunar Reconnaissance Orbiter (LRO) instruments determined as much as 20% of the material kicked up by the LCROSS impact was volatiles, including methane, ammonia, hydrogen gas, carbon dioxide, and carbon monoxide. The water signature, considered a highly important and strategic lunar resources ore, was 5.6%. Mars mission data (Phoenix, Mars Reconnaissance Orbiter (MRO), etc.) have also shown that there are vast deposits of water ice in the martian subsurface, thus providing Mars-forward linkage for subsurface frozen regolith excavation technologies.

This subtopic is seeking proposals for prototype(s) designs, analysis, hardware, test data, and test reports of excavation devices and sensors related to lunar icy regolith excavation technologies capable of excavating icy regolith to depths of greater than 1 m. The required lifetime of the excavation devices shall be 5 years but may include robotic repair and maintenance.

The amount of regolith that is required to be mined corresponds to an ISRU system that can produce at least 15,000 kg of water over the duration of 225 days of actual operation in a calendar year. Assuming an approximately 3% water yield, it can be assumed that the requirement will be to deliver icy regolith to the ISRU...
water extraction plant at a rate of 100 kg/hr, without including the dry regolith overburden. Excavation system power needs shall be defined by the proposed designs, and it can be assumed that a NASA-provided electrical power plant and distribution system will be provided. It will supply 10-kW electrical power at 120 VDC, and it will provide continuous power regardless of lighting conditions. A relevant, realistic, and effective lunar concept of operations shall be part of the deliverables. Lessons learned, statistical data studies, and strategies from terrestrial excavation, site preparation, and mining operations are welcomed.

While the exact properties of the lunar regolith [6,7] with frozen volatiles are not yet clear, proposers are requested to research the existing literature and use terrestrial analogs to justify their designs and strategies.

Because the excavation systems will be operating in an extreme lunar environment, possibly inside a PSR, the reliability and durability of regolith excavation hardware will be of critical importance to mission success. This subtopic is also seeking studies and technologies that include strategies and designs to allow lunar icy regolith excavation systems to survive 5 years of continuous operation. Robotic maintenance strategies shall be defined and examined, and methods for robotic servicing shall be identified [8].

**Expected TRL or TRL Range at completion of the Project**

3 to 5

**Primary Technology Taxonomy**

**Level 1**

TX 07 Exploration Destination Systems

**Level 2**

TX 07.X Other Exploration Destination Systems

**Desired Deliverables of Phase I and Phase II**

- Research
- Analysis
- Prototype
- Hardware
- Software

**Desired Deliverables Description**

Phase I deliverables may be a conceptual design or development plan with analysis to show feasibility at relevant scales and/or a small demonstration of the concept or of a subsystem.

Phase II deliverables should be hardware demonstrations at a relevant scale. See Scope Description for additional information on Phase I and Phase II deliverables.

**State of the Art and Critical Gaps**

The state of the art consists of terrestrial prototypes at Technology Readiness Level (TRL) 3 or 4 that have been previously built and tested for SBIR/STTR, NASA Centennial Challenge, NASA competitions for universities, and in-house NASA technology development, such as the Regolith Advanced Surface Systems Operations Robot (RASSOR) 2.0 and the Advanced Planetary EXcavator (APEX).

**Relevance / Science Traceability**

The work desired applies to Technology Taxonomy (TX) Area 7: Exploration Destination Systems. It applies to the 2018 NASA Strategic Plan Strategic Goal 2: Extend Human Presence Deeper into Space and to the Moon for Sustainable Long-Term Exploration and Utilization. It also applies to the Plan’s Strategic Objective 3.1: Develop
and Transfer Revolutionary Technologies to Enable Exploration Capabilities for NASA and the Nation. It also applies to TX04: Robotic Systems, as the excavation equipment will need to operate without a human crew present during some periods.

References


Z14.02 Extraterrestrial Surface Construction

Lead Center: LaRC

Participating Center(s): KSC, LaRC

Scope Title

Extraterrestrial Surface Construction

Scope Description

Lunar and martian construction of infrastructure from extraterrestrial materials and materials beneficiated or produced from in situ resources has the potential to radically reduce the cost and increase the scale of ambitious future space exploration. Technologies that support development of infrastructure structural elements are sought. Innovative materials and processes technology advancements are required to enable rapid advancement of a lunar or martian village in a cost-effective manner.

Specific areas of technology development that are of interest include, but are not limited to, the following:

1. Construction technologies shall be based on the use of extraterrestrial materials and limit the need for any terrestrial materials. Development of lunar-construction-relevant materials and processes for infrastructure elements listed in point 2 below are highly encouraged.
Materials must have a defined application in a mission context. Proposers are asked to define any consumable materials that must be brought from Earth for construction.

2. Fabrication and assembly of pressurized and unpressurized structural systems, including (for example) landing/launch pads, roads, blast shields, and habitats.

- Both stationary and mobile fabrication/assembly systems shall be considered.
- Novel fabrication and assembly methodologies shall be considered.
  - Low-power methods and methods that benefit from the extraterrestrial surface environment are desired.

Technology development shall include design, analysis, fabrication, and testing of components, subsystems, and materials to enable full assessment and accountability of the technology product and fundamental findings with respect to their value toward reaching NASA’s goals. Existing design and nondestructive evaluation (NDE) techniques are expected to be used when applicable. A relevant commercially available extraterrestrial simulant that mimics the silicate and oxide minerals in regolith and/or the volatiles in the lunar permanently shadowed regions or martian surface and atmosphere is expected to be used for structure construction. Lunar materials, components, and systems that would be necessary for the proposed technology must be able to operate on the lunar surface (with thermal mitigations) in temperatures up to 110 °C (230 °F) during sunlit periods and as low as -170 °C (-274 °F) during periods of darkness. Martian materials, components, and systems must be able to operate on the martian surface in a CO₂-rich atmosphere (with thermal mitigations, if necessary) in temperatures up to 20 °C (70 °F) and as low as -153°C (-225 °F). Systems must also be able to operate for at least 1 year with a goal of 5 years without substantial maintenance in the dusty regolith environment. Proposers should assume that operations involving other systems (e.g., robotics) and future astronauts will be ongoing not more than tens of meters away from the local fabrication and construction activities (i.e., minimization of dust generation is expected).

**Expected TRL or TRL Range at completion of the Project**

3 to 5

**Primary Technology Taxonomy**

**Level 1**

TX 12 Materials, Structures, Mechanical Systems, and Manufacturing

**Level 2**

TX 12.X Other Manufacturing, Materials, and Structures

**Desired Deliverables of Phase I and Phase II**

- Research
- Analysis
- Prototype
- Hardware
- Software

**Desired Deliverables Description**

Phase I deliverables may be a conceptual design with analysis to show feasibility at relevant scales and/or a small demonstration of the concept.

Phase II deliverables should be hardware demonstrations at a relevant scale. See Scope Description for additional information on Phase I and Phase II deliverables.

**State of the Art and Critical Gaps**
Planetary surface construction is not a current capability. The state of the art is terrestrial-based construction technology, e.g., cement, wood, and steel forms and terrestrial additive construction.

Relevance / Science Traceability

The work desired applies to Technology Taxonomy (TX) Area 7: Exploration Destination Systems. It applies to 2018 NASA Strategic Plan Strategic Goal 2: Extend Human Presence Deeper into Space and to the Moon for Sustainable Long-Term Exploration and Utilization. It also applies to the Plan's Strategic Objective 3.1: Develop and Transfer Revolutionary Technologies to Enable Exploration Capabilities for NASA and the Nation.

References