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ID	Shortfall Title
1514	Atmospheric Metabolic Constituent Management for Habitation

Description

All habitat elements need carbon dioxide (CO_2) removal and oxygen (O_2) generation. The current ISS SOA systems provide basic functionality for adsorption of CO_2 and partial oxygen recovery (~47%). Issues with long-term reliability are being addressed but need validation with long-term integrated testing for extended endurance missions. Trace gas contamination can decrease system performance in integrated vehicle. Upgraded and new technologies are needed to reduce mass/power /volume/maintenance and improve oxygen recovery for long duration exploration missions. (Dependency: Launched food water content must be reduced to ~30% for the mass savings of increased oxygen recovery to be beneficial.) Technologies for high-pressure/purity oxygen generation for EVA recharge are needed for high frequency surface EVA missions. Technologies for providing high flow rate oxygen for days to treat potential medical conditions without exceeding cabin material oxygen flammability limits are needed for long duration missions. Monitoring of atmospheric metabolic constituents is addressed in the 'Environmental Monitoring for Habitation" shortfall. Improved system performance, improved reliability, and system enhancements to allow lower-level maintenance are beneficial to a reduction of departure mass and improved crew safety on long endurance missions where resupply is not feasible. System improvements and diagnostics assistance that reduces crew time are also beneficial.

Related Shortfalls

AHS-353: Recovering & Recycling O_2 from Metabolic CO_2
AHS-760: Oxygen Generation System improved reliability and decreased complexity
AHS-787: Oxygen Generation for low pressure cabin environments
AHS-878: High Pressure Oxygen for EVA tank resupply
AHS-1059: Highly reliable, closed-loop-forward CO_2 removal systems
AHS-1222: Medical O_2 Generation & Supply

Metrics

- CO_2 removal at <2.5 mmHg-enabling, <2.0 mmHg-enhancing demonstrated at 14.7 psia and at future surface habitat pressure
- Reduction in mass/kg O_2 produced
- >75% oxygen recovery from CO_2
- Capability to recharge EVA O_2 bottle
- Enriched medical oxygen (50-90% vol)

ID	Shortfall Title
1515	Atmospheric Non-Metabolic Constituent Management for Habitation

Description

Current methodologies for maintaining atmospheric non-metabolic constituents at prescribed levels are not going to meet the needs of future Moon and Mars missions. Current condensing heat exchangers currently require microbial mitigation dry outs and can catalytic produce undesired trace compounds. Nitrogen gas (N_2) for re-pressurization is provided in composite fiber overwrap vessels that have high equipment mass per gas mass. N_2 generation is an area of potential enhancement. This is significant penalty for high EVA missions where airlock losses can be significant. ISS trace contaminant adsorbers are obsolete and need replacement to support future missions. Lunar and Mars contaminant loads from regolith interactions with O_2 and H_2O may be needed. ISS HEPA filters are frequently cleaned, and their capacity may be quickly exceeded and may need frequent replacement on high EVA surface missions. Improved filter or pre-filter capacities for low cabin pressures (~4-9psia) systems in planetary surface airlocks and small habitats are needed. Many habitat elements need these functions to manage non-metabolic atmosphere constituents and will be dependent upon mission duration, EVA frequency, and gravity conditions. Monitoring of atmospheric non-metabolic constituents is addressed in the 'Environmental Monitoring for Habitation" shortfall. Improved system performance, improved reliability, and system enhancements to allow lower-level maintenance are beneficial to a reduction of departure mass and improved crew safety on long endurance missions where resupply is not feasible. System improvements and diagnostics assistance that reduces crew time are also beneficial.

Related Shortfalls

AHS-854: Robust Condensing Heat Exchanger
AHS-942: Nitrogen Resupply for Habitat Pressure Sustainability
AHS-1055: Adsorbents and Catalyst Media to address Trace Contaminant Control System Obsolescence
AHS-1117: Filtration for Lunar/Martian dust, cabin particulates, and smoke

Metrics

- Chemically inert condensing surfaces for condensate collection in ug, and low bacteria and fungi CFU
- > 1 kg N_2 / equipment mass (TBR)
- Demonstrate successful functioning after dormancy
- High collected particle mass/filter hardware volume
- Trace sorbents with high ammonia and dichloromethane (proxies) capacities

ID	Shortfall Title
1516	Water and Dormancy Management for Habitation

Description

All habitat elements need water, but how the functions are provided is dependent upon the element, mission duration, crew size, and gravitational force. ISS has never been uncrewed. Current ISS SOA does not have a proven way to enter and come out of dormancy, which leads to a significant microbial risk to the water systems. Iodine is used on ISS but must be removed prior to crew consumption creating microbial opportunities. Silver is only used for short mission stored water and can plate out of solution and not compatible with ISS Extravehicular Mobility Unit (EMU). Brine processing demonstrated to achieve ~98% overall recovery on ISS but mass reduction and odor control would benefit from improvement. Long duration surface habitat architectures need to address additional contaminants from surface dust and full body hygiene wastewater. Less reliance on Earth resupply consumables is needed for larger scale long duration planetary water systems. Improved system performance, improved reliability, and system enhancements to allow lower-level maintenance are beneficial to a reduction of departure mass and improved crew safety on long endurance missions where resupply is not feasible. System improvements and diagnostics assistance that reduces crew time are also beneficial.

Related Shortfalls

AHS-717: Brine Processing to recover water from urine brine
AHS-856: Potable Water Dispenser (PWD) design that supports sparing and dormancy concepts
AHS-867: Water Recovery Mitigation for Dormant Periods
AHS-984: Robust Advanced Water Recovery System
AHS-1005: Disinfection Solution that complies with the potable water microbial specification
AHS-1011: Water Recovery System for Surface Missions (Lunar and Mars)

Metrics

- High overall water recovery
- Ground sterilizable PWD
- Water system returns to operation without failure after more than one year of dormancy
- Biocide maintains very low CFU against 100 targeted microbes
- Low mass (consumables and equipment/kg water) water processing partial-g

ID	Shortfall Title
1517	Metabolic Waste Management for Habitation

Description

Missions longer than 1-2 days typically transition from short term body worn and handheld collection devices to a toilet to manage urine, feces, menses, and odor in a more hygienic manner and reduce overall mass. The ISS US Orbital Segment (USOS) primarily uses a Russian toilet system requiring high up-mass. Urine is precision dosed with hazardous liquid chemicals at toilet collection prior to delivery to water recovery system. Less hazardous chemicals and more reliable/lower mass hardware is beneficial to exploration. No resources are recovered from feces (~75% water). Feces biological activity generates noxious gases that must be contained or adsorbed. Odor control is only partially effective. US developed toilet is being evolved with additional pretreat dosing, fecal odor containment, and acoustic improvements to become operational. Future long duration micro-g missions would significantly benefit from reduced fecal consumables mass and improved long duration sustaining of rotary phase separation hardware. Surface missions need very low mass compact and hygienic commodes for initially small habitat volumes. Water recovery from feces is an enhancement that may be beneficial for long duration missions. Improved system performance, improved reliability, and system enhancements to allow lower-level maintenance are beneficial to a reduction of departure mass and improved crew safety on long endurance missions where resupply is not feasible. System improvements and diagnostics assistance that reduces crew time are also beneficial.

Related Shortfalls

AHS-807: Compact Low Logistics Commode for Exploration
AHS-365: Fecal Resource Recovery

Metrics

- Low mass of toilet for surface and microgravity
- Substantially reduce fecal containers mass/crew year
- Urine pretreat + dosing equipment <TBD kg/crew-year
- Successful recovery of TBD% of the water available in fecal matter

ID	Shortfall Title
1518	Logistics Tracking, Clothing, and Trash Management for Habitation

Description

Logistical mass is substantial and includes crew consumables, spare parts, packaging, and resulting trash. Maintaining sufficient ISS inventory accuracy and insight currently requires substantial allocations of crew time to track crew usage and relocation of items during a mission. Smaller and more distributed autonomous inventory tracking systems are need to reduce crew time and reduce ‘lost’ items. Accurate inventory accounting and localization provides a very useful data set to support crew and vehicle decision support and autonomy systems. Daily wear crew clothing does not meet ISS or reduced pressure flammability needs. Longer wear clothing to reduce launched mass is beneficial. Solvents are ~80% of cleaning wipe mass. Life support compatible cleaning solvents for maintenance and planetary protection goals are need to reduce mass. ISS trash is disposed of in departing pressurized logistics vehicles. ISS has experimented with very limited dry trash only jettison experiments. Wet trash (food packaging, wipes, clothing) microbial activity produces undesirable gas; water and contaminants are released when trash is moved to vehicle exterior. Trash stabilization to reduce airlock and vehicle exterior contamination for in-vehicle storage, in-space jettison, or surface disposal are needed. Improved system performance, improved reliablity, and system enhancements to allow lower-level maintenance are beneficial to a reduction of departure mass and improved crew safety on long endurance missions where resupply is not feasible. System improvements and diagnostics assistance that reduces crew time are also beneficial.

Related Shortfalls

AHS-355: Non-metabolic Solid Waste Processes
AHS-358: Resource Recovery & Repurposing from Trash
AHS-360: Low Mass, Low Volume Crew Clothing
AHS-366: Autonomous Logistics for Dormancy and Crew Readiness
AHS-825: Clothing for Enriched O_2 Atmospheres
AHS-983: Autonomous Inventory Tracking and Management for multiple element spacecraft
AHS-998: In-situ Integrated Disinfection Generation
AHS-1090: Surface Waste Disposal Container Venting
AHS-1145: In-flight Waste Mass Jettison

Metrics

- Stabilize trash to >TBD kg/m3 density and <0.6 water activity level
- Clothing systems mass <TBD and cleaning wipes mass <TBD kg/crew-day.
- Non-flammable clothing for 8.2 psia and 34% O_2
- Locate items to within TBD cm with localization mass of <TBD kg/outfitted module.
- Selectable solvent concentration and volume for disinfection wipes and item cleaning

ID	Shortfall Title
1519	Environmental Monitoring for Habitation

Description

ISS environmental monitoring has limited on-board monitoring capability for a small set of representative gases, chemicals, and recently initial DNA microbial identification. Detailed analysis relies on return of samples to Earth. Exploration distance and duration prevents continuation of the current monitoring approach of returning samples for detailed Earth analysis. Earth independent detailed analysis of a wide range of possible contaminants with sufficient calibration life to support Mars missions are beyond current capabilities. Closed loop life support in relatively small habitats with increasingly diverse materials can result in accumulation of both known and unexpected compounds. Instrument service life and calibration life are current challenges. Particles can be crew, vehicle material, or regolith sourced and cause frequent false fire alarms. Acoustic environment on ISS can exceed exposure limits but is not monitored with sufficient frequency to alert crew to don protection. Automated, distributed, low mass monitoring as well as acoustic improvements of acoustic sources (fans, pumps) and abatements are benifical. Detailed chemical compound and microbial species identification and quantification with long instrument calibration life is needed to support Mars transit missions (that may have three-year durations) and shorter lunar missions where it desirable to use the same systems over multiple missions.

Related Shortfalls

AHS-354: In-flight Water Quality Monitors for Quantification and Identification
AHS-763: In-flight Identification and Quantification of Microbes in Air, Water, and on Surfaces
AHS-791: On board monitors that measure particulates
AHS-1031: Major Constituent and Trace Contaminant Gas Monitoring for cabin air
AHS-1118: Acoustic Monitoring and Control

Metrics

- Automated microbial, speciation, viability analysis for air, water, and surface samples
- Particle mass concentration 0.1-10 micron diameter and distinguish between sources
- Detailed in-flight trace gas and water contaminant identification
- Prime mover cabin fans with duct born noise without abatement <TBD dB.
- Cleanable acoustic materials with >TBD dB transmission loss @125 Hz

ID	Shortfall Title
1520	Fire Safety for Habitation

Description

Large-scale (~2000 cm^2 material area) fire initiation, spread, monitoring, and cleanup has been limited in LEO and informed differences in microgravity drop tower tests (~5-10 cm^2). Lunar gravity fire material testing only performed in limited drop tower tests. The combination of partial gravity and elevated oxygen levels for lunar habitats poses material flammability, fire spread modeling, and detection/suppression layout knowledge shortfalls that need addressing. ISS Fire suppression uses water spray mist, carbon dioxide for Environmental Control and Life Support System (ECLSS) compatibility and some heritage halogen technology remains for special uses but is challenging post-fire cleanup. International Space Station (ISS) fire emergency response masks can be water filmed over after suppression and mask materials not compatible with high oxygen exploration cabins currently. Improved emergency response equipment and more realist crew training in representative cabin environment is needed.

Related Shortfalls

AHS-789: Material Flammability and Fire Propagation in low- and partial-gravity environments and at exploration atmospheres
AHS-808: Non-flammable materials, additives, and coatings
AHS-947: Fire Detection, Fire Suppression, and Post-Fire Monitoring and Clean-up
AHS-1035: Fire Safety Training
AHS-1143: Fire Emergency Breathing Mask

Metrics

- Test validated partial gravity flammability data to support NASA-STD-6001 Test 1 interpretation
- Fire suppression technology demonstrated against worst-case fire scenario for specific vehicles' pressure, oxygen, adjusted for gravity
- Emergency breathing mask cartridge performance with TBD% smoke/soot/water by vol @ TBD cm/s and <TBD Pa and <TBD°C rise at loaded capacity. Shelf-life of multiple years.

ID	Shortfall Title
1521	Crew Exercise and Sensorimotor Countermeasures

Description

There is a risk of loss of mission objectives, crew injury, or even loss of life if crew's ability to perform mission critical tasks (e.g.. surface EVA and vehicle egress/ingress) is not protected. ISS exercise protocols currently utilize multiple large mass devices to reduce deconditioning. Effective sensorimotor countermeasures are being researched but are not yet implemented. Approximately half of returning ISS crewmembers currently require substantial assistance in egressing Earth return vehicles with an unpressurized launch/entry suit. Novel countermeasures, assessment tools, and informatics tools are needed to protect physical performance capabilities and long-term health of cardiorespiratory, musculoskeletal, and neuromuscular (balance) systems during increasingly Earth-independent, resource-constrained, and long-duration exploration missions. Improved system performance, improved reliability, and system enhancements to allow lower-level maintenance are beneficial to a reduction of departure mass and improved crew safety on long endurance missions where resupply is not feasible. System improvements and diagnostics assistance that reduces crew time are also beneficial.

Related Shortfalls

AHS-724: Crew Health and Performance Countermeasure Informatics
AHS-771: Exercise Countermeasures
AHS-875: Exercise Vibration Isolation and Stabilization System
AHS-907: Bone Countermeasures
AHS-1075: Sensorimotor and Disorientation Countermeasures and Assessment Tools
AHS-1089: Cardiovascular Countermeasures

Metrics

- Hardware that is sufficient to meet 100% of the CHP standards for aerobic fitness, muscle strength, bone health, and sensorimotor health
- Informatics tool with 95% "User Acceptability" score
- 95% of crew initiated vibrational loading mitigated, as measured by loads and dynamics analysis
- Safe sensorimotor test (obstacle walk/turn within 25% of preflight performance) upon egress
- Safe 3.5 min stand test upon egress

ID	Shortfall Title
1522	Crew Health Countermeasures – Non-Exercise

Description

There is a risk to mission objectives if crew cannot perform at a high-level. The crew's long-term physical and behavioral health must be protected in increasing isolation (time delay) and duration in the deep space environment. In ISS long-duration missions (~6 months) early signs of Spaceflight Associated Neuro-ocular Syndrome (SANS) affects roughly 70% of crewmembers. Infectious and allergenic diseases frequently occur in-flight despite monitoring and existing protocols. Crew immune system efficacy decreases on ISS and there is limited long duration mission data (>6 months) to inform Mars missions. Behavioral health and performance countermeasures rely on real-time ground support, maintaining family connectivity, and personalized resupply. Novel countermeasures and assessment tools are needed to detect, monitor, and mitigate neuro-ocular changes, microbially-induced diseases, immune system disfunction, and behavioral adaptation & readiness during increasingly Earth-independent, resource-constrained, and long-duration exploration missions.

Related Shortfalls

AHS-896: Neuro-ocular Countermeasures
AHS-977: Microbially-Induced Disease Countermeasures
AHS-1114: Immune Countermeasures
AHS-1457: Behavioral Health and Performance Countermeasures

Metrics

- A countermeasure that can successfully prevent ocular structural changes or reverse them
- A measurable way to determine the impact of microorganisms and microbe-host interactions to allow countermeasure development
- Immune countermeasures with improved monitoring targets and protocols but metric TBD
- Tools that successfully support crew/family and crew/MCC connectedness, train for brain & behavioral health, maintain & repair relationships semi-autonomously

ID	Shortfall Title
1523	Earth Independent Human Operations within Habitation Elements

Description

Current space missions rely on near real time and large amount of ground support. Long-duration Earth-independent operations for crew missions beyond cis-lunar space will need new capabilities onboard to support the progressive reduction in ground support for time and safety critical operations requiring immediate response, specifically, detection of anomalous conditions (situation awareness), troubleshooting and diagnostics (decision support) and procedure generation and execution. Ground support will still be strongly leveraged for much of the mission, but short time-to-effect issues will benefit from independent crew assessments, decisions, and responses to mitigate or stabilize the situation until ground support can assist.

These technologies and tools include data integration and crew situational awareness, crew decision support, communication and mission management, high-fidelity human-in-the-loop analog simulation all converging on enabling onboard anomaly resolution for time critical system issues.

Related Shortfalls

AUTO-969: Streamline Sources of Information for Anomaly Resolution
AUTO-1009: Lack of capability to integrate planning resources into commanding tasks
LOGISTICS-1029: Payload Operations - Ground Independent Procedure Execution
AHS-1319: Integrated Earth-Independent Human Systems Simulation Technologies
AHS-1451: Asynchronous Distributed Operations Management Systems
AHS-1452: Situation Awareness Tools
AHS-1453: Decision Support Tools
AHS-1454: Human-Hardware Maintenance Interfaces and Tools
AHS-1455: Procedure Execution Support Tools

Metrics

- Successfully demonstrate simulation of time critical scenarios using mission relevant hardware and software
- Demonstrated ability for the crew to operate independently for a maximum of a 2–3-week communications black out period
- Where earth-dependent alternatives exist, reduce ground operator engagement and by a factor of 2x–5x.
- Simulation and analog capabilities with the minimum necessary fidelity and complexity to appropriately assess increasingly Earth-independent asynchronous distributed mission operations, especially for safety and time critical scenarios.

ID	Shortfall Title
1524	Crew Medical Care for Mars and Sustained Lunar

Description

Medical risk increases with exploration missions due to increased mission duration, increased isolation, increased cumulative radiation exposure, increased injury risk in planetary gravity, decreased access to resupply, and limited to no evacuation capability. Communication delays will need increased crew autonomy in the evaluation, decision support, and provision of medical care. Optimizing the medical system and increasing medical capabilities will protect crew health and performance which are paramount to mission success.

The medical system needs to include 1) medication safety and effectiveness, 2) in-flight medical decision support software, 3) integrated data architecture, 4) technologies to store, process, and analyze a variety of biological and non-biological samples, 5) diagnostic, treatment, and support tools that enable behavioral health and performance, 6) medical imaging, diagnostic, and treatment technologies necessary to effectively manage medical conditions, 7) integrated medical simulation capability, and 8) quantitative medical risk models and trade space analysis

Related Shortfalls

AHS-818: Safe and Effective Pharmaceuticals
AHS-853: Medical Decision Support Software & Informatics
AHS-881: CHP Integrated Data Architecture
AHS-937: In-situ Sample Storage, Processing & Analysis
AHS-989: Behavioral Health and Performance (BHP) Medical Capabilities
AHS-1046: Medical Imaging, Diagnostics, and Treatment Tech
AHS-1060: Integrated Medical Simulation Technologies
AHS-1178: Medical Risk Model and Trade Space Analysis Tools
AHS-1206: Medical Concepts of Operations, Level of Care

Metrics

- Established thermal, vacuum, radiation, & shelf-life performance of the exploration formulary
- Demonstrated EHR that is accessible and editable by both crew and ground teams
- Developed integrated data architecture across all crewmembers, vehicle systems, and mission phases
- Autonomous diagnostic tool, support modality, and psychotherapy intervention modality for BHP is developed
- Diagnostics, imaging, and treatment technologies in place to identify and treat 120 targeted medical conditions to prevent loss of crew and/or loss of mission
- Completion of a risk database containing evidence-based data for 120 key medical conditions

ID	Shortfall Title
1525	Food and Nutrition for Mars and Sustained Lunar

Description

Adequate food intake and nutrition is a critical countermeasure for maintaining crew health and performance. Food on ISS is frequently resupplied, so the shelf-life requirement is ~1-2 yrs. Resupply enables the system to include some fresh produce and crew preference items. Some nutrient content and quality factors may decrease in some foods depending on storage time and temperature, and pressure changes may risk package integrity. Mars missions may need food to have a 5-yr shelf life, with sufficient food variety to maintain long term system acceptability and intake that maintains health and performance. Food is the largest logistics mass for a Mars mission so determining the food quantity that benefits from cold storage to achieve a 5-yr shelf life, minimizing mass/power for cold stowage technologies, and defining the role of supplemental crop production to support crew health and performance are key shortfalls. Additionally, the ISS food system still contains ~46% water. As water and oxygen recovery technologies improve, reducing launched food water content to 30% is needed for overall integrated ECLSS-food mass savings. Food is a frequent interest area to reduce mission mass, but it is critical to understand the integrated health and performance risk/resource trades early to inform Mars element decisions.

Related Shortfalls

AHS-784: Food and Nutrition Impacts to Health and Performance
AHS-800: Safe, Acceptable, and Nutritious Food System
AHS-985: Food Intake Tracking
AHS-1013: Food Resources Requirements and Efficiency
AHS-1036: Refrigerated long term stowage chamber for food preservation in deep space (passive and active approaches)
AHS-1171: Low-Hydration Food for Exploration Missions

Metrics

- Data availability associating food intake to health and performance outcomes relevant to spaceflight
- Food system which 1) >90% of the food receives acceptable scores, 2) 100% of the nutritional requirements are established & met, and 3) food is demonstrated for at least 5 years
- Successful tracking of >95% of all crew food intake
- Food system that 1) fits within the resources of the mission profile/reduce resource use, 2) is operable and functionally acceptable for regular crew use, 3) is reliable (no risk of food loss/scarcity), 4) has an average launched water content of <30%

ID	Shortfall Title
1526	Radiation Monitoring and Modeling (Crew and Habitat)

Description

Space radiation environments for Lunar and Mars missions must be characterized to determine astronaut crew exposures; this information has vital influence on vehicle design and mission planning. Monitoring technologies characterize radiation fields seen by crew and sensitive electronics which will inform operations, impacts to crew health, and impacts to hardware. Current SOA radiation forecasting allows for relatively reliable prediction of incoming solar particle emission events, but provides poor predictions of duration, intensity, and the intensity-time profile of the entire event. Increased warning times (currently ~30 min) and accuracy of real-time operational forecasting is needed to inform mission operations of radiation hazards following development of the SPE event as well as the prediction of all clear periods. On-board, integrated space weather observation systems and Mars-centric observational (orbital, deep-space) assets supporting Earth-independent solar particle event monitoring are needed to enable human Mars missions off the Earth-Sun axis. New models, predictive algorithms, and possibly new measurements/observations will be beneficial to more accurately predict solar cycle modulation and the resulting intensity of Galactic Cosmic Radiation (GCR) environment beyond the current solar cycle.

Related Shortfalls

AHS-362: Solar Particle Events: Radiation models and forecasting
AHS-733: Advanced space radiation environment characterization systems: charged and neutral particle spectroscopy
AHS-735: Onboard Dosimetry Systems: Charged Particle Alert and Warning
AHS-883: Earth-independent Space Weather Forecast and Crew Alert Systems
AHS-915: GCR Radiation models and forecasting - Prediction of solar cycle modulation

Metrics

- Increase reliability of 24-hour SPE predications by a factor of ~2.5; Increase 7-day SPE time course of events (magnitude and duration) by a factor of ~5 after eruption
- Increase neutron detection capability to >100 MeV with uncertainty of <+/-TBD% with no more than a factor of 4 increase in instrument mass; stretch goal of measurements up to 1 GeV
- For cis-lunar & Mars >45 days operation without significant loss of data (less than 1 hr within 30 days)
- Demonstrate SPE forecasting capability using on-board systems and models fed by instruments on crewed vehicles equal to reliability of SOA operational models fed by data from scientific platforms with ground-based data processing
- Predict solar cycle duration within +/- 18 months for next solar cycle (>2030) and within +/- 24 m for subsequent cycle (2040's)

ID	Shortfall Title
1527	Radiation Countermeasures (Crew and Habitat)

Description

Radiation dose is mandated to be As Low As Reasonably Achievable (ALARA) within the design constraints of a mission. Solar Particle Event (SPE) shielding methods are relatively well understood. Lightweight, multifunctional SPE protection will be identified for each human mission element to optimize the combined shielding provided by the vehicle and the protection system, while minimizing both parasitic mass and impact on crew operations. Galactic Cosmic Radiation (GCR) is very difficult to mitigate. Passive shielding is mass prohibitive while active methods are very low maturity and utilize substantial vehicle mass and power. Effective GCR shielding strategies are needed to extend crew permissible mission durations to those envisioned for sustained lunar and Mars missions. With SOA shielding, crew will exceed lifetime radiation dose on a Mars mission. Biomarker panels are needed for in-flight monitoring of radiation-induced damage to serve as indicators of increased risk of immune and hematopoietic dysfunction, Central Nervous Systems (CNS) disorders, and early processes leading to the increased risk of cancer, CVD, and neurodegenerative conditions. Biomedical countermeasures are beneficial to mitigate the long-term health effects of exposure to space radiation during deep space exploration missions.

Related Shortfalls

AHS-364: Radiation shielding - Solar Particle Event (SPE)
AHS-725: Probabilistic Risk Models of Crew Health
AHS-1020: Biomedical Countermeasures to Mitigate Health Effects from Exposure to Space Radiation
AHS-1173: Radiation Shielding: Galactic Cosmic Radiation – Passive Technologies
AHS-1179: Radiation Shielding: Combined Galactic Cosmic Radiation (GCR) with protection from Solar Particle Events (SPEs) – Active Technologies
AHS-1307: Space Radiation Biomarker Technologies for In-flight Monitoring and Health Management

Metrics

- Ability to ensure crew SPE exposure does not exceed a 250 mSv effective dose limit
- Deliver operational long-term health models and develop capability to provide personalized risk estimates & provide methods to in-mission radiation risks
- Identification & validation of CM with known safety profile, mode of action, & efficacy
- Provide tools and technologies to optimize vehicle designs that reduce GCR crew exposures by % relative to free-space values at optimum average shield thicknesses between 10 to 30 g/cm2.
- Demonstrate that active technologies reduce GCR exposures by >50% relative to free space with reliability of at least TBD%
- Demonstrate sensitivity of biomarkers in crew with projected mission exposures >200 mSv with TBD% accuracy

ID	Shortfall Title
1528	Spacesuit Physiology

Description

Extravehicular Activity (EVA) will be the most physically and cognitively demanding task, with highest injury risk during lunar and Mars surface missions. Crews will perform far more EVA, with less rest than ever before. Many critical EVA support functions currently performed by humans and systems in ground-based Mission Control today must be performed by inflight crew, supported by new capabilities, due to communication latencies and/or drop-outs. Thousands of person-hours can go into planning and preparing for a single ISS EVA; improved planning capabilities (in-flight and ground) are very beneficial to enable high frequency exploration EVA. Suited injury occurred during Apollo, and during ISS training and ug EVAs. Understanding causes and modeling suit fit and human capabilities informs injury risk prevention during suit design, sizing adjustments, and possible mission conops. Decompression sickness (DCS) risk during planetary EVA is significantly greater than for microgravity EVAs; new risk assessment and mitigation capabilities are needed for planetary missions.

New technologies are needed to 1) provide EVA decision support, 2) provide crewmember state prediction, 3) provide injury prediction, monitoring, and mitigation, and 4) provide decompression stress prediction and mitigation.

Related Shortfalls

AHS-924: Suited Autonomous Health Monitoring and Decision Support
AHS-946: Suited Physiology and Performance
AHS-1051: Suited Fit and Injury
AHS-1104: Decompression Stress Prediction and Mitigation

Metrics

- Test verified decision support tools address 100% of identified hazards and risks (~37)
- All eight physical and cognitive parameters have been modeled and validated across the full range of anticipated operational EVA mission scenarios
- Characterize, mitigate, and monitor 100% of formally identified injury mechanisms (~27)
- All anticipated exploration pre-breath protocols and cabin/suit pressure environments for a mission have DCS risk prediction and mitigation capabilities been developed and validated

ID	Shortfall Title
1529	EVA and IVA Suit System Capabilities for Mars Missions

Description

New roles for humans performing EVAs, upgrades in EVA suits and tools are an essential part of achieving mission success. Habitation ingress/egress, life support, thermal control, waste management, in-suit nutrition, communication, mobility, and interaction with tools all need to be successfully integrated. While there are multiple options for Mars, mass reductions for Mars surface suits and systems are necessary for Mars partial gravity. Furthermore, there is unknown material degradation beyond LEO that future suits must account for. Human missions to Mars may require radical changes in the approach to EVA suit design. Lunar return, sustained lunar, and Mars surface Extravehicular Activity (EVA) will be the most demanding of EVA hardware in history due to the envisioned frequency and total number of EVAs within a mission. Improved EVA mobility between multiple elements requires additional suit functions while minimizing additional mass. Mars EVA includes new and unique challenges due to increased partial gravity twice that of the moon which will increase effective suit weight beyond what crewmembers can likely sustain. Improvements in materials to improve strength and decrease mass are highly desirable. Unlike the lunar EVAs, Mars EVA suits cannot utilize vacuum for mass efficient thermal insulation, heat rejection, and CO2 removal. New technology approaches are needed to allow EVAs within the low-pressure CO2 Mars atmosphere. Ionizing radiation impacts avionics and material selection. EVA tools for new lunar environments (including permanent shadowed regions, low lighting, and repeated use) and Mars planetary protection concerns exceed what was performed on Apollo EVAs. The SOA is the ISS EMU and Lunar xEMU and supporting vehicle mounted servicing equipment in development for use in LEO, cis-lunar, and the lunar surface. Heat rejection via water based sublimators or Spacesuit Water Membrane Evaporator (SWME) will have degraded performance under Mars conditions. Orion Crew Survival System (OCSS) is specifically designed and certified for Orion's Earth launch and return environments. Effective Mars EVA is needed to support a high science cadence.

Related Shortfalls

672: Long-life Thermal Control for Surface Suits Capable of Extreme access
823: Low-mass & Dust Tolerant Bearings for EVA Suit Design
850: EVA: Continuous CO_2 Removal for Mars Atmosphere (Non-vacuum)
898: Suited Transfer from Surface Asset to Lander (i.e. in event of a loss of an EVA suit function)
920: Mars Surface EVA Suit
927: EVA: Mass/Strength Optimized Composites
941: Material Degradation due to Radiation
956: Dust-tolerant/Exclusionary Interface Mechanism (PLSS)
981: EVA: Heat Rejection for Non-vacuum Applications
982: EVA: Mars Environnent Thermal Insulation
991: EVA: xEMU Quiescence, Reuse & Maintenance Interval
1062: Lunar Surface Environment Protection Garment (EPH) shell material system
1167: EVA Tools and Crew Mobility Aids for Sustained Lunar EVA and Mars EVA

Metrics

- Dependent on future integrated risk assessment trades, improved Mars spacesuit capable of supporting TBD lunar and Mars EVA strategy with acceptable TBD performance and TBD risk of adverse outcomes (TBR)

ID	Shortfall Title
1485	In-Space and On-Surface Manufacturing of Parts/Products from Surface and Terrestrial Feedstocks

Description

To support a thriving human presence and exploration throughout the solar system, in-space manufacturing is an essential next step as the space ecosystem undergoes rapid expansion. An on-demand and in-situ approach to manufacturing, maintenance, repair, and logistics will lead to the development of capable and affordable space architecture models. Both a sustained lunar presence and deep space exploration missions would benefit from the capability and flexibility to manufacture parts on demand due to long durations, limited resupply options, communication delays, and the inability to fully predict mission needs in the event of an unexpected failure. Currently, the capability to manufacture new products, spare parts, replacement units, or specialty tools in-situ does not exist beyond small demonstration components fabricated from polymers. Multi-materials printing, including but not limited to metals, electronics, and polymers is necessary to provide a manufacturing capability that can address needed spare parts and repair for Low Earth Orbit destinations, Gateway, lunar surface missions, and deep space exploration missions. This multifunctional manufacturing capability needs to be tailored to the space environment and may leverage this environment to produce high-quality products. Spare electronic parts include sensors, such as those used for Environmental Control and Life Support Systems (ECLSS), small electronic devices, and supporting components for energy and power applications. Metal and polymer parts include outfitting, structural components, basic tools, materials for daily crew use, and custom-designed parts for mission-critical needs.

Related Shortfalls

MANU-642, 952: On-demand manufacturing of metals, electronic components, recycling and reuse
MANU-643, 801: ISRU-derived materials for feedstocks (e.g.., Al, Si) – lunar and Martian
MANU-644: Lunar surface manufacturing and outfitting with metals, polymers, and composites
MANU-646, 722, 855: ISAM - welding in space, recycling and reuse
MANU-1341: Recycling and reuse of thermoplastics and metals for In Space Manufacturing
MANU-1342: Recycling of Orbital and Surface Debris from Active Debris Remediation for advanced manufacturing.
MANU-1343: Recycling/Reuse: On-surface Resource Utilization of Hardware, Trash, and ISRU Byproducts for surface manufacturing
MANU-1066: Manufacturing approaches to support habitat outfitting
MANU-1180: High performance materials tailored for in-space applications
MANU-1095: Ability to robotically construct lunar surface landing/launch pads and berms using in-situ regolith materials.

Metrics

- Metal feedstock options for 3D printing of spare parts on-demand.
- 20% of spare parts in space systems can be produced by ISM platforms and integrated into system
- Majority of systems designed for maintainability and accessibility to facilitate integration of spares produced on-demand rather than orbital replacement unit changeout.

ID	Shortfall Title
1486	In-Space and On-Surface NDE and Qualification of Components for Manufacturing, Assembly, and Construction

Description

This shortfall addresses the need to assess and qualify products that are manufactured, assembled, and constructed in space to ensure performance over the expected lifetime of the final component. This may be accomplished via in situ non-destructive evaluation (NDE), in situ modeling and simulation to predict the final part on the microstructure-performance paradigm, or a combination of both. Key challenges to close this shortfall include: a) NDE techniques suitable for use in the space environment; b) non-contact NDE techniques; c) low size, weight, and power NDE techniques; d) modeling and automated data processing to determine optimized inspection for autonomous in-space implementation and guide data-informed decisions, multiscale/multi-fidelity modeling of manufacturing processes, including thermophysical properties, solidification microstructures, mesoscale and macroscale properties, and component-level performance; e) integrated computational materials engineering (ICME) to build a digital twin of in-space manufacturing processes; f) application of simulations using onboard computing to predict part/process performance and to qualify joints/parts with minimal or no inspection; g) uncertainty quantification of joints/part properties and performance predictions; h) In-situ monitoring or inspection. NDE techniques will be required for all advanced processes developed for space manufacturing/construction, including but not limited to ISS, Gateway, a free flyer, depot, and future surface habitation. Without the parallel development of NDE techniques along with manufacturing process development, a sustainable architecture cannot be achieved. Anything produced in space needs to inspected to verify part quality before use; therefore, NDE needs to be adapted for in-space use.

Related Shortfalls

MANU-493: In-Space Joining of Structures and Materials [robotic assembly of]
MANU-1401: Autonomy and robotics for horizontal assembly [welding of]
MANU-646, MANU-722, MANU-855: In-Space Welding, bonding, mechanical joining - inability to join materials [laser beam welding]
MANU-651: Model-Based Technologies for Materials, Structures and Manufacturing
MANU-658: Accelerated Certification and Analysis Approaches
MANU-653: Space-Based Verification and Validation
AV-526: High Performance Spaceflight Computing (HPSC) Single Board Computer (SBC)

Metrics

- Modeling and simulation validation % error
- Detectable defects (size, morphology, composition, severity, etc..) via *in situ* NDE techniques, including real-time
- Uncertainty quantification (& reduction) of property & performance predictions of welds

ID	Shortfall Title
1487	In-Space and On-Surface Welding Technologies for Manufacturing, Assembly, and Construction

Description

Welding is a critical manufacturing technology used in more than 70% of finished goods on Earth. In-space welding (ISW) will be important to achieving NASA's goals for returning to the Moon and establishing a sustainable presence in space. These goals will be achieved in the form of infrastructure manufacturing, assembly, and repair. ISW is also a critically enabling technology for In-Space Servicing, Assembly, and Manufacturing (ISAM). This is especially true for large structures relevant to science and communications that cannot be contained within a single rocket fairing or would otherwise need complicated packaging and deployment mechanisms. Finally, the 2023 Biological and Physical Sciences (BPS) Decadal Survey specifically highlighted ISW as a focus area in need of further basic scientific understanding as the community aims to implement the technology in future NASA missions. This capability will also allow for the decoupling of launch design constraints from space structures by enabling the shipment of raw materials (wire, plates, and other feedstock) rather than finished components to space.

Related Shortfalls

MANU-493: In-Space Joining of Structures and Materials [robotic assembly of]
MANU-1401: Autonomy and robotics for horizontal assembly [welding of]
MANU-646, MANU-722, MANU-855: In-Space Welding, bonding, mechanical joining - inability to join materials [laser beam welding]
MANU-651: Model-Based Technologies for Materials, Structures and Manufacturing

Metrics

- Models guide manufacturing and processing in the microgravity environment
- Reliable and efficient in-space welding tools
- Models enable adjustment of process parameters for environment based on process signals and observations
- Available geometries and build rate of large-scale AM are suitable for Lunar structures

ID	Shortfall Title
1489	In-Space and On-Surface Manufacturing from Recycled and Reused Materials and Components

Description

NASA estimates that there is about 500,000 pounds of waste on the Moon left behind from previous missions. A technology driven recycle and reuse approach is necessary otherwise waste will continue to accumulate resulting in logistics problems, physical dangers, and an environmental disaster. Since launching materials from Earth is costly, the capability to recycle and reuse waste materials greatly simplifies logistics, reduces mission cost and risk, and minimizes the disturbance to local environments by reducing the need for long-term waste storage. This capability also meets the objective of developing sustainable architecture for exploration. Technologies that convert waste materials into feedstock for in-space manufacturing directly address these objectives by generating customizable, high-utility products from waste resources. Potential waste materials for this activity include but are not limited to logistics packaging, end-of-life structures, surface or orbital debris, and in-situ resource utilization (ISRU) products, where applicable. A waste management process that inventories, sorts, cleans, and separates materials into a relatively pure form is essential. Recycling technologies that convert materials into feedstocks for processes, such as joining and Additive Manufacturing (AM), and reuse technologies that are extensible to in-situ resource processing must be developed and will likely be material dependent. Similarly, in-space manufacturing methods, such as bound metal deposition, fused deposition modeling, and wire-fed AM, will need to be tailored to the available recycled or ISRU material feedstocks. Safety hazard reduction within the recycling process must be undertaken if the mission architecture would require use in a habitable environment. A robust and dependable recycling and reuse process coupled with in-space manufacturing would be beneficial for LEO destinations, Gateway, lunar surface missions, and long-duration space exploration missions.

SUPPORTS M2M Objective OP-12: Establish procedures and systems that will minimize the disturbance to the local environment, maximize the resources available to future explorers, and allow for reuse/recycling of material transported from Earth (and from the lunar surface in the case of Mars) to be used during exploration.

Related Shortfalls

MANU-642, MANU-952: On-demand manufacturing of metals, electronic components, recycling and reuse
MANU-643, MANU-801: ISRU-derived materials for feedstocks (e.g.., Al, Si) – lunar and Martian
MANU-644: Lunar surface manufacturing and outfitting with metals, polymers, and composites
MANU-646, MANU-722, MANU-855: ISAM - welding in space, recycling and reuse
MANU-1341: Recycling and reuse of thermoplastics and metals for In Space Manufacturing
MANU-1342: Recycling of Orbital and Surface Debris from Active Debris Remediation for advanced manufacturing.
MANU-1343: Recycling/Reuse: On-surface Resource Utilization of Hardware, Trash, and ISRU Byproducts for surface manufacturing
MANU-1066: Manufacturing approaches to support habitat outfitting
MANU-1180: High performance materials tailored for in-space applications
MANU-1095: Ability to robotically construct lunar surface landing/launch pads and berms using in-situ regolith materials.

Metrics

- Materials designed for reuse must meet application requirements such as flammability, toxicity, and off gassing.
- Materials designed for reuse must be recyclable at least five times with minimal degradation.
- Maximum instantaneous power required to repurpose the material must be less than 2kW.

ID	Shortfall Title
1490	Additive Manufacturing for New and High-Performance Materials

Description

It can take as long as 10–20 years to develop new aerospace materials together with compatible manufacturing processes and qualify them for use. However, new materials and some discarded experimental materials, coupled with new additive manufacturing processes, can be enabled and deployed much faster and at a fraction of the cost. This opens an entirely new range of possibilities for high performance components and infrastructure for both Earth-based and In-Space materials applications. These gains were previously not available or economical.

Advanced metal alloys are difficult to process using traditional manufacturing methods, and simplified processing of these alloys was previously thought to be impractical. Additive manufacturing has enabled game changing possibilities to develop and utilize new higher performance materials for extreme environments at reduced cost and lead times. Requirements for these Earth-based manufactured superalloys include 1) Burn-resistant (flammability), 2) Hydrogen-resistant, and 3) High-temperature (refractory). These new alloys are needed to enable low cost and higher performance launch vehicle and in-space advanced propulsion systems. To achieve the Lunar Infrastructure (LI)-4L and LI-8L Moon to Mars (M2M) objectives, these Earth-based lessons learned and developed processes will be leveraged to a wide range of in-situ materials (regolith based, carbon based for Mars atmosphere, and recycled materials). Advanced processes will be used to develop cost effective feedstock materials that have the correct chemical makeup and properties. They will then be used in the additive manufacturing of parts and infrastructure and the as-manufactured properties will be verified to meet requirements for operation in the extreme environments of space.

These real-world processing improvements will be combined with advances under the Integrated Computational Materials Engineering (ICME) shortfalls to develop custom materials and rapidly define processing parameters leading to quick-turnaround infusion into partner vehicles and propulsion systems. These new materials will meet partner needs for increased performance, reduced cost and schedule reductions and to prepare the way for in-situ derived material processing and manufacturing.

Related Shortfalls

MANU-648, MANU-781: Materials for extreme environments
MANU-649: New Process Development
MANU-1110: LOX Cooling of engine components
MANU-651: Model-based Technologies for Materials, Structures and Manufacturing
MANU-781: Hot Structures for Nuclear Thermal Propulsion (NTP)
MANU-1180: High Performance materials tailored for in-space applications

Metrics

- Cost
- Schedule
- Material performance (strength and temperature capabilities)
- Material availability

ID	Shortfall Title
1488	Additive Manufacturing for Propulsion

Description

Additive Manufacturing (AM) is enabling for a range of propulsion / in-space transportation solutions.

- Includes burn-resistant (flammability), hydrogen-resistant, refractory, and high temperature need to enable advanced propulsion systems and in-space systems (O2, etc..) towards
- AM material properties (database) of existing alloys to provide a baseline for new alloy design and support industry infusion
- Post processing for optimized performance (e.g.. heat transfer)
- Lower cost faster production of large nozzles
- Hot structures of Nuclear Thermal Propulsion
- Lightweight lower cost CFM Storage Tanks

If shortfall is not closed, industry unable to infuse results of NASA AM investments. Mars return architecture may not close with adequate margin.

Related Shortfalls

MANU-1303: Design Principles and Modeling is support of AM propulsion applications

Metrics

- Specific Impulse target, 340 Isp.
- System Level Thrust, 178 kN.

ID	Shortfall Title
1491	Additive Manufacturing of Large-Scale Components

Description

Human Lunar Return and Continuous Human Lunar Presence would benefit from large structures for propulsion components, vehicle components, tanks, towers, and habitation structures. In addition, scale is limited at which future parts can be built with high-complexity using Additive Manufacturing (AM) technologies. AM of large components enables components to be built from optimal and available materials in shorter schedules and often at lower cost with scale bridging from fine features to large, high-deposition rates for items such as Cryogenic Fluid Management (CFM) tanks. NASA must advance this area by working with industry to mature these technologies, lead the development for applicability to NASA's Moon to Mars (M2M) architectures, and stay relevant on advancing technologies.

To demonstrate advanced manufacturing and autonomous construction of large-scale components and infrastructure in support of continuous human lunar presence and a robust lunar economy, there are near-term activities that need to be started and accomplished. Evaluation of AM processes are needed to determine the optimum process for a given material, component being manufactured, and the environment where the build is taking place. Some of the AM processes including adaptive additive processes that utilize closed-loop process feedback algorithms that could be demonstrated in a terrestrial environment and then utilized for human lunar return or during sustained lunar evolution include Cold Spray, Laser Hot Wire, and Blown Powder Directed Energy Deposition (DED). Examples of development that can be accomplished is evaluating fine feature processing, evaluating large-scale technology at increasing scales, investigating novel lasers (multi-mode, blue, green) and integration of systems. This will result in significant advances in build time and material properties, characterization of process-microstructure-property relationships, surface finish development to improve performance, and component post processing. As AM process technologies evolve using new alloys and multi-materials and processes, additional design and programmatic advantages will be discovered.

Breakthroughs in materials and process modeling within the development of AM can significantly reduce risks and manufacturing time of large-scale components and infrastructure. This includes predicting and validating 1) 3-D microstructure from material characteristics, 2) machine process parameters for ODS alloys, 3) complex geometries, 4) stresses and microstructure for bi- and tri-metallic parts, 5) material characteristics for new alloys, and 6) optimization of parts and materials for additive processes.

Related Shortfalls

MANU-649: New Process Development
MANU-650, MANU-1097: Large Scale Freeform Applications
MANU-653, MANU-1092: Space-based Verification and Validation
MANU-1066: Manufacturing approaches to support habitat outfitting
MANU-988: Largescale Lightweight composite fuel storage tanks

Metrics

- Cost
- Schedule
- Material performance (strength and temperature capabilities)
- Material availability
- In-situ manufacturing

ID	Shortfall Title
1492	Materials and Process Modeling for In-Space and On-Surface Manufacturing

Description

The ability to turn raw and recycled components into finished and useable goods on the lunar surface will enhance sustainable living and working far from Earth (LIVE). Model-based methodologies that close this shortfall will have broad applicability to terrestrial manufacturing of propulsion systems, vehicles, habitats, and beyond. Physical processes that govern manufacturability of goods on the lunar surface and in cislunar space vary drastically from those on Earth due to extreme differences in temperature, pressure, and gravity. Earth-based manufacturing processes do not have the robustness to account for the confines of such austere environments as the lunar surface. Key manufacturing steps, such as welding and 3D metal printing, will be impacted by lunar conditions. These steps are complex nonlinear processes involving extreme temperature gradients and short time scales when changing between liquid, solid, gas, and plasma. Integrated Computational Materials Engineering (ICME) workflows, coupled with process and materials modeling approaches, have realized great success in recent years in accelerating Earth-based manufacturing processes such as welding, printing, forming, and materials extraction. This systems-based approach to designing products and manufacturing processes is positioned to capture the key physical differences between lunar and Earth conditions (e.g., effects of low-g on convection heat transfer in melt pools) by accelerating manufacturing, developing new materials, and reliably sustaining structures produced in situ on the moon. Modeling will increase the understanding of process variability under lunar conditions. Modeling will also enable forward-thinking, analytical approaches to enhance manufacturing in conditions that have never been encountered. There are several key challenges to close this shortfall, such as robust model-based workflows of lunar manufacturing in realistic lunar conditions including extraction, recycling, forming, joining, and printing. Software for ICME will require high-dimensional material input data that are not readily available for current engineering materials at lunar conditions and for lunar-derived materials. Extensibility of ICME workflows created for Earth-based manufacturing to lunar manufacturing will require input data, validation, and verification, along with uncertainty quantification.

Related Shortfalls

MANU-493: In-Space Joining of Structures and Materials
MANU-642, MANU-643, MANU-644, MANU-655, MANU-646: In-space manufacturing
MANU-649, MANU-650: New Process Development and large-scale freeform applications
MANU-651: Model-Based Technologies for Materials, Structures and Manufacturing
MANU-653: Space-Based Verification and Validation
MANU-658: Accelerated Certification and Analysis Approaches
MANU-722, MANU-855: In-Space Welding, bonding, mechanical joining - inability to join materials [laser beam welding]
MANU-1341: Recycling and reuse of thermoplastics and metals for In Space Manufacturing
MANU-1401: Autonomy and robotics for horizontal assembly

Metrics

- Manufacturing method compatibility and operability with austere lunar conditions through model demos
- Guide for lunar manufacturing documentary standards
- Earth-based lab and parabolic and suborbital flight experiments to calibrate physics models
- Error and Uncertainty quantification (& reduction)
- Lifecycle predictions of hab, pad, tower, and power systems manufactured in lunar conditions
- Critical flaw size for lunar-derived structures and tracking system including digital twins

ID	Shortfall Title
1493	Computational Materials-Informed Qualification and Certification for In-Space and On-Surface Manufacturing

Description

The ability to turn raw and recycled components into finished and useable goods on the lunar surface will enhance sustainable living and working far from Earth. Model-based methodologies that close this shortfall will have broad applicability to terrestrial manufacturing of propulsion systems, vehicles, habitats, and beyond. As with structural components manufactured on Earth, structural components made on the lunar surface or in cislunar space must undergo a rigorous Qualification and Certification (Q&C) process to demonstrate they will perform as intended. Traditional empirical methods used for Q&C of similar components made on Earth (e.g., development of extensive empirical databases) are impractical or impossible for components made on the lunar surface or in cislunar space. A new Computational Materials-informed paradigm offers the promise of meeting Q&C requirements while minimizing the reliance on expensive-to-obtain test data. This new paradigm builds on the maturation and integration simulation of material processing, microstructure and defect evolution, material properties and performance, along with appropriate levels of verification and validation (V&V) and uncertainty quantification (UQ). STMD can leverage a national effort, the Computational Materials for Qualification and Certification (CM4QC) Steering Group, that is addressing a similar challenge for the Q&C of additively manufactured aircraft components. The new Space Technology Research Institute, Institute for Model-based Qualification & Certification of Additive Manufacturing (IMQCAM), is a good example of an end-to-end digital twin approach.

Related Shortfalls

MANU-493: In-Space Joining of Structures and Materials
MANU-642, 643, 644, 655, 646: In-space manufacturing
MANU-647: Accelerate additive manufacturing certification
MANU-651: Model-Based Technologies for Materials, Structures and Manufacturing
MANU-653: Space-Based Verification and Validation
MANU-658: Accelerated Certification and Analysis Approaches
MANU-722,855: In-Space Welding, bonding, mechanical joining - inability to join materials
MANU-1096: Next Generation D&DT to Support Certification of Flight Hardware
MANU-1180: High performance materials tailored for in-space applications
MANU-1341, 1342, 1343: Recycling…for in-space/surface mfg

Metrics

- Propagation of uncertainty in processing simulation input parameters to uncertainty in performance simulation output parameters.
- Validation of the efficacy and decreased expense of Computational Materials-informed paradigm for Q&C using traditional (empirical) Q&C as a baseline.
- Standardization of a Computational Materials-informed paradigm for Q&C

ID	Shortfall Title
1494	Digital Transformation Technologies for Terrestrial, In-Space, On-Surface Manufacturing, and Operations

Description

While digital twins have become a powerful tool across numerous fields, their origin story is deeply rooted in the field of advanced manufacturing. And though artificial intelligence (AI) didn't originate solely from manufacturing, the industry undeniably played a significant role in fostering its application and growth. These powerful tools combine sophisticated models and data to inform critical decisions. Unlike traditional models, digital twins establish a dynamic connection between real systems and their virtual counterparts. Realizing the capabilities to manufacture, maintain, repair, or recycle products in space will depend on a new paradigm and accelerated adoption strategies to support Moon to Mars (M2M). Manufacturing in space presents unique challenges in verifying and validating the functionality and performance of products compared to Earth-based manufacturing. The ability to inspect and perform in-situ physical testing poses unique challenges in the space environment, and validating performance on Earth may not accurately predict how products will function. Digital twins and artificial intelligence for physics-based simulation, prediction, virtual testing, autonomous learning, big insights/limited data, and predictive maintenance offer a powerful approach to design, build, and test completely in a virtual world. They also accelerate advancement and overcome the limitations of verification and validation for in-space manufacturing, assembly, and construction. These technologies can be extended to many other M2M capabilities.

Related Shortfalls

MANU-493: In-Space Joining of Structures and Materials
MANU-642, MANU-643, MANU-644, MANU-655, MANU-646: In-space manufacturing
MANU-649, MANU-650: New Process Development and large-scale freeform applications
MANU-651: Model-Based Technologies for Materials, Structures and Manufacturing
MANU-653: Space-Based Verification and Validation
MANU-658: Accelerated Certification and Analysis Approaches
MANU-722, MANU-855: In-Space Welding, bonding, mechanical joining - inability to join materials [laser beam welding]
MANU-1341: Recycling and reuse of thermoplastics and metals for In Space Manufacturing
MANU-1401: Autonomy and robotics for horizontal assembly

Metrics

- Accuracy of predictions, % error
- Reduced costs
- Faster time-to-demonstrate
- Product properties and quality
- Scalability and Flexibility

ID	Shortfall Title:
1496	In-Space and On-Surface Manufacturing, Assembly, and Repair of Composite Structures

Description

NASA's vision to extend human exploration beyond Low Earth Orbit presents opportunities to deploy advanced manufacturing approaches that capitalize on emerging materials, structures, and operational concepts in the Moon to Mars (M2M) exploration architecture. Historically, mass estimates have grown dramatically as the spacecraft design evolves. This is especially relevant for architectural components intended for Mars where the cost per pound launched escalates by an order of magnitude relative to travel to and from the Moon, and two orders of magnitude relative to Low Earth Orbit. If only legacy materials, structural concepts, and manufacturing methods are considered, newer and more effective means of achieving required mass savings may be overlooked in favor of engineered solutions around current technology-shortfalls. This can lead to design inefficiencies and will not deliver the required mass savings and payloads.

The Artemis schedule allows time to mature key crosscutting technologies that can enable lightweight structural elements, especially the tailoring of these systems for in-space manufacturing, assembly, reconfiguration, and repair. In-space manufacturing circumvents the challenge of packaging large structures for launch, including design to survive launch loads. Designing structural components for in-space manufacturing or modification presents opportunities to explore lightweight material design and manufacturing concepts that include emerging-thermoplastic composites, emerging composite matrix resins, innovative nanomaterials, multifunctional reinforcements, and more damage-tolerant structures enabled by thin-ply composites.

This shortfall includes activities to develop novel approaches, materials, and methods for in-space manufacturing, assembly, reconfiguration, repair, and recycling and includes new materials, and development of appropriate certification and analysis approaches for long term service.

The Biological and Physical Sciences Research Decadal Survey calls for characterization of the effect of space environments on engineered polymers, establishing viability of materials for construction and repair in space and understanding how the space environment impacts the joining of materials, including welding.

Related Shortfalls

MANU-655: Joining Techniques for Thermoplastic Composites
MANU-656: Thermoplastic Composites for Space Applications
MANU-1146: Thermoplastic composite materials for unitized primary structures (ESDMD 3080)
MANU-558: Accelerated Certification and Analysis Approaches
SAT S&A-496: Integrated modeling and digital twin for space-based V&V
AMSC-955 : Structural Carbon Nanotubes (ESDMD 3077)
SAT S&A-1409: Structural Systems Designed to be Robotically Serviced and Manufactured In-space
SAT S&A-1471: Structural Systems Designed to be Robotically Outfitted (payload install, wiring, fluid, gas routing and connections)

Metrics

- Manufacturing/Assembly metrics
  - Power, difficulty, cost
- Manufacturing-approach enabled structural efficiency
  - Mass or specific strength/stiffness of specific elements
- Design and certification cost/time

ID	Shortfall Title:
1495	Advanced Manufacturing for Improved Dimensional Control of Large-Scale Space Structures

Description

A future where large telescopes enable the discovery of habitable exoplanets is envisioned in the current Astronomy and Astrophysics Decadal Plan. Structural components of these telescopes, such as mirror supports and backplanes, depend on dimensional stabilities that exceed those of the Hubble and James Webb telescopes by three orders of magnitude. Similarly, every space structure has critical dimensional requirements to meet its objectives. These dimensional requirements can be in the form of dimensional precision and accuracy, or dimensional stability, and these requirements become more challenging as the allowed maximum deviation is reduced or the size is increased. Thus, dimensional requirements can be categorized based on different classes of structures and applications, with defined performance metrics and manufacturing and analysis approaches for each class. The launch mass of space structures is a primary constraint, so manufacturing and structural design concepts that are optimized to provide the required functionality (e.g., strength, stiffness, dimensional stability, etc..) at minimum weight are desired.

This shortfall includes design considerations, materials, and manufacturing related to the dimensional requirements for all classes of structures that enable ultrahigh precision optics for science missions, as well as dimensional requirements for large-scale deployable flexible structures, such as solar arrays, with much looser dimensional metrics. The need for ultra-stable composite structures and adhesives is specifically called out several times in decadals as needed enabling technology for NASA science missions under consideration. The dimensional requirements for large-scale deployable structures address a major technology need and program risk for the Gateway Power and Propulsion Element and future solar sailing spacecraft: improved dimensional stability of deployable composite booms during manufacturing for solar array structures. These composite booms do not need high accuracy when deployed, but they are flexible and large enough to make the manufacturing problem very challenging.

Key challenges related to this shortfall include a) meeting the dimensional requirements for the range of requirement classes, b) the development of manufacturing innovations that can capitalize on high-stiffness/high-strength materials, hybrid material systems, and structural design concepts to yield extremely low dimensional change (e.g.., parts-per-billion (ppb)/°K level coefficients of thermal expansion—CTEs), and c) the development of consistent, precise manufacturing approaches for large-scale deployable structures.

Related Shortfalls

MANU-654: Dimensional Stability
MANU-1474: Large-Scale Deployable/High-Strain Composites
MANU-1180: High performance materials tailored for in-space applications
SAT S&A-453: Dimensionally Stable High Stiffness Structural Materials for In-Space Assembled Telescopes
SAT S&A-676: V&V of a precision assembled telescope using metrology
SAT S&A-495: V&V of in-space assembled modular structures using metrology

Metrics

- Structural accuracy and stability, different magnitudes for different classes of structure from low accuracy and stability for extremely large structures (30–100+ m) to ultrahigh accuracy and stability for large (5–10 m) and very large (10–50 m) telescopes and star shades.
- Specific science-mission metrics are: (1) effective coefficient of thermal expansion, (2) creep, and (3) tensile modulus.

ID	Shortfall Title
1575	Thermal and Vibrational Isolation for Ultra-stable Science Payloads

Description

Long exposure observations from spacecraft require a highly stable platform with precise line-of-sight pointing for a variety of missions. A particularly demanding example is the Habitable Worlds Observatory recommended by the Astrophysics 2020 Decadal Survey which requires unprecedented stability and pointing accuracy. Isolated and quiet payloads are necessary to achieve ultrastability (~ 10s of picometer) to enable the coronagraph system on Habitable Worlds reach the desired high level of contrast imaging.

Reduced vibration for high precision instrumentation on the new commercial LEO destination platform is also needed for fundamental physics experiments.

New solutions to isolate precision optical payloads from spacecraft vibration sources are needed. Concepts have been developed to provide a non-contact state (with only residual coupling from power and data cables and actuator effects) between an instrument and spacecraft while allowing for the necessary degree of rigid-body payload control to meet required telescope pointing and system line-of-sight agility. At least one needs to be demonstrated in flight.

Related Shortfalls

SS&A-453: Dimensionally Stable High Stiffness Structural Materials for In-Space Assembled Telescopes

MANU-1495: Advanced manufacturing for improved dimensional control of large-scale space structures

Metrics

- Vibration damping / isolation
- Thermal isolation
- Dimensional stability
- Large size

ID	Shortfall Title
1576	Micrometeoroid-Robust Protection of In-space Observatories

Description

The next great telescope will be the Habitable Worlds Observatory. It will be in orbit at Sun-Earth L2, as will most future Astrophysics missions since Earth orbit is becoming so crowded. L2 has more micrometeorites than expected, and their flux has not been well characterized. Prior telescopes had protective baffles integral to the telescope, but they were heavy.

Deployable shield technology is needed to protect from micrometeorite strikes for telescope optics of diameter 6 to 6.5 m without causing a cascading effect from shield damage.

Athermal (negative coefficients of thermal expansivity - CTE) materials would be helpful for dimensional stability.

Related Shortfalls

TBD

Metrics

- Low mass
- Protective capability
- Dimensional stability
- Large size

ID	Shortfall Title
767	Advanced designs for lightweight inflatable surface elements

Description

Inflatable softgoods structures can provide greatly enlarged living volumes for crews on extended exploration missions with minimal launch/landing mass and volume. Large inflatable surface elements include habitats and ISRU commodity storage tanks. Inflatable softgoods can also be used to provide small volume elements such as pressurized transfer tunnels, inflatable airlocks, suitport enclosures, flexible dust tolerant hangars, rover covers or garages, etc.

This shortfall includes the design, analysis, and test of these advanced inflatable designs. This technology can be utilized to provide needed systems for light weight habitable elements of a surface habitat and be delivered in a small launch/landing package.

Related Shortfalls

AMSC-750: Environmental protection materials for inflatable softgoods
AMSC-926: Structural health monitoring of inflatable softgoods
AMSC-951: Ultra-high strength materials for inflatable softgoods
AMSC-1007: Lifetime creep behavior of highly loaded inflatables
AMSC-1023: Inflatable air barrier durability through extreme environments
AMSC-1067: Packaging and deployment of inflatable softgoods
AMSC-1125: Hard structure integration with inflatable softgoods.
AMSC-1216: Advanced softgoods hatch development
AMSC-TBD: In-situ maintenance and repair of inflatables

Metrics

- Deployed volume per unit mass
- Packaging volume ratio

ID	Shortfall Title
1408	Advanced deployable load-bearing structures

Description

Future large space and lunar surface structures may benefit from the development of advanced lightweight deployable load-bearing structures. These structures will need to be lightweight but also stiff and with high-load carrying capability beyond the current state of the art for deployables. To this end, concepts such as origami-based designs, inflatable and rigidizable columns and trusses, and deployable trusses, might be good candidates for future applications. In addition, advance highly efficient packaging, deployment, retraction and modularity approaches should be sought.

This technical shortfall addresses capability needs for an alternate approach to render space structures expandable through the use of thin-walled composite structures that undergo large deformations during packaging and deployment. The composites are typically high-performance continuous carbon or glass fibers reinforced plastics. These thin-walled composite structures can be used to achieve compact packaging while achieving deployed strength, stability, mass efficiency, and reliability. However, there are many technological challenges that need to be addressed before these structures are widely adopted: material quality and consistency improvement, multi-scale modeling and failure mechanisms; standardization of dedicated test methods; certification approaches; long-term stowage effects (creep and relaxation) and environmental degradation at the material and structural level; large-scale manufacturing approaches including continuous methods of fabrication and assembly; cure-induced deformation predictive tools; multi-body deployment dynamics predictive tools; gravity off-loading testing methods for large-scale lightweight composite structures; and dynamic coupling of flexible composite appendages with spacecraft controls.

Related Shortfalls

PROP-700: Unique Platform PLP – Large Area Solar Array
MANU-1474: Large-Scale Deployable/High-strain Composite Structures
COMM-790: Tall (>30m) Inexpensive Self-Erecting Communication Towers

Metrics

- TBD

ID	Shortfall Title:
1304	Robust, High-Progress-Rate, and Long-Distance Autonomous Surface Mobility

Description

Technology advances to increase the speed, range, life, and autonomous capability of mobile surface robots are required to meet an array of future mission needs and "*demonstrate local, regional, and global surface transportation and mobility capabilities in support of continuous human lunar presence and a robust lunar economy*" (M2M Objective LI-06). Current surface mobility solutions rely heavily on human-in-the-loop, ground-based teleoperation insufficient for the human-scale operational cadence of the Artemis campaign. And robust and responsive autonomy during uncrewed periods is needed to maintain work throughput and relocate assets over significant distances and varied terrain. Likewise, science mission concepts such as Endurance-A (prioritized in the 2022 Planetary Science Decadal) require robust onboard decision making for real-time navigation with limited human oversight, while targeting extended traverses (over 2000 km) and speeds-made-good well beyond those achieved by prior surface mobility robots. Existing Mars rover state-of-the-art, with limited speed and onboard autonomous capabilities, is not sufficient for the robust, high-cadence, and increasingly Earth-independent operation of future exploration and science activities.

While ongoing terrestrial technology development provides a potential opportunity to adapt new capabilities to meet a subset of current needs, unique challenges exist for mobility in the lunar and Martian environments that limit direct infusion. Challenging environmental characteristics (e.g., harsh lighting effects, feature-sparse terrain) require new algorithmic approaches to autonomous mobility. Limited training data makes robust learning-based approaches difficult. Lunar-worthy perception sensors and onboard data processing are needed. And the design and integration of a broad class of autonomous navigation capabilities compatible with flight-worthy computing is critical for mission success.

Related Shortfalls

ROBO-660: Efficient Software for Onboard Localization, Hazard Detection, and Path Planning for Surface Mobility
ROBO-1630: Multi-Modal, 3D Terrain Sensing and Modeling with Semantic Interpretation
ROBO-777: Surface Navigation Sensors for Extreme Temperature, Radiation, and Dust Conditions
COMM-929: Rover Surface Navigation Systems and Sensor Development for Extreme Temperature, Radiation, and Dust
ROBO-1629: Onboard Terrain Embedding and Entrapment Prevention and Recovery Methods
ROBO-1317: Perception and Navigation Sensors for Extended Operation in the Lunar Environment and Lunar Lighting Conditions
ROBO-1628: Long-Range Rugged Drive Systems for the Lunar Environment
ROBO-1546: Robotic Mobile Manipulation for Autonomous Large-Scale Logistics, Payload Handling, and Surface Transport
ROBO-1641: Risk-Aware Autonomous Surface Navigation and Planning
ROBO-1642: Autonomous Navigation in Extreme Lighting
ROBO-1643: Real-Time Learning-Based Approaches to Autonomous Navigation with Limited Training Data

Metrics

- Traverse Speed and Distance
- Speed-Made-Good
- Number and Frequency of Operator Interventions
- Additional Metrics TBD

ID	Shortfall Title:
1538	General-Purpose Robotic Manipulation to Perform Human-Scale Logistics, Maintenance, Outfitting, and Utilization

Description

Agency objectives call for leveraging robotics to minimize crew time spent on overhead tasks like logistics, setup, and maintenance to maximize science and exploration return during crewed operations (Moon-to-Mars Objectives OP-9, SE-5, TH-9, TH-10). In addition to providing crew assistance, human-scale robotic manipulation allows for a broader set of infrastructure support and utilization tasks during uncrewed periods to enable long-term sustainability. Identified needs include logistics transfer and small-scale payload handling, equipment maintenance and tool use, the assembly and outfitting of equipment and infrastructure (including cable and connector manipulation), and the monitoring and utilization of science instrumentation and experiments. Lunar surface operations, Gateway, commercial destinations in low Earth orbit, and future Mars missions all benefit from versatile and robust robotic manipulation and caretaking, both IVA and EVA. The relevance of general-purpose robotic mobile manipulation extends to ISAM and autonomous science missions as well, while providing the critical ability to take physical corrective actions in off-nominal scenarios across all missions and applications.

Dexterous robotic manipulation must be capable of unrehearsed, unstructured tasks with limited human oversight or intervention. Resource efficient approaches to task, motion, and grasp planning must be integrated with space-worthy computing hardware. Advances in object detection, semantic segmentation, affordance recognition, and the coordination of mobility and manipulation are needed to provide the required levels of robustness and autonomous task throughput. Learning-based approaches hold promise but must overcome challenges associated with spaceflight application. And robotic hardware robust to the space environment yet still capable of human-scale unstructured tasks must be developed.

Related Shortfalls

SURFACE-1363: Robotic Caretakers
SURFACE-1617: Autonomous On-Surface Maintenance and Repair for Sustained Lunar Evolution
ROBO-1540: Intelligent Robots for the Servicing, Assembly, and Outfitting of In-Space Assets & Industrial-Scale Surface Infrastructure
ROBO-1425: Autonomous Unloading and Transferring of Cargo Using Intra-Vehicular Robotics (IVR)
ROBO-1631: Robotic Manipulation for Science and Utilization Onboard Commercial LEO Destinations
ROBO 892: Intra-Vehicular Robotics (IVR) for Payload and Science Utilization, Logistics, Maintenance, and Contingency Response
AMSC-1480: On-Surface Outfitting of Lunar Structures
SURFACE-1608 and -1609: Surface-Based Lunar Logistics Management
ROBO-686: Efficient Object Detection, Classification, and Pose Estimation
ROBO-1632: Affordance Recognition, Grasp Planning, and Execution for Autonomous Object and Interface Manipulation
AUTO-679: Task Planning and Execution Software for Autonomous Systems
AUTO-940: Fail-Operational Robotic Manipulation
ROBO-680: Robust Robotic Intelligence for High-Tempo Autonomous Operations in Dynamic Mission Conditions
ROBO-688: Adaptable Robotic End Effectors for Fine Grasping
AUTO-689: Machine Learning Platforms and Architectures for Space Exploration
ROBO-1308: High-Fidelity Testbeds and Facilities for IVA Robotic Manipulation and Mobility Development, Test, and Qualification

Metrics

- TBD

ID	Shortfall Title:
1546	Robotic Mobile Manipulation for Autonomous Large-Scale Logistics, Payload Handling, and Surface Transport

Description

Establishing and maintaining a sustained lunar presence calls for a broad autonomous logistics management capability with robots capable of performing critical supply-chain tasks associated with handling, maintaining, transporting, and distributing payloads, equipment, facilities, and a range of other resources at multiple scales, all independent of crew. Potential industrial-scale tasks include the transportation of large payloads, habitat modules, and high quantities of regolith to support Artemis basecamp setup, sustained operations, and a wide range of excavation, construction, manufacturing, and resource utilization activities (see M2M Objectives LI-4, LI-6, and LI-7). The relocation of large, multi-ton assets across the lunar surface expands science and exploration reach to new locations of interest, with robotic mobility providing a means to achieve this during both crewed and uncrewed periods. Inherently coupled with robotic mobility is the robust large-scale robotic manipulation required to manipulate equipment, interfaces, and the surrounding environment during task performance. Robotic payload offloading and relocation, for example, is a combined mobile manipulation task that plays a significant role in maximizing crew availability for broader science and exploration activities while sustaining surface operations during uncrewed periods.

Like general-purpose mobile manipulation at human-scales, large-scale robotic operations must be robust in unstructured environments and will require advances in sensing and autonomy in addition to novel hardware development suitable for task objectives. Improvements in power density, robust control of lightweight systems, the coordinated control of multiple agents, and the ability to exert significant forces at high rates in reduced gravity are all examples of technology needed to achieve higher force, larger scale, and longer duration work than previously achieved in space robotics.

Related Shortfalls

SURFACE-1608 and -1609: Surface-Based Lunar Logistics Management
ROBO-1644: Robotic Relocation of Large (Multi-Ton) Assets on the Lunar Surface
AMSC-385: Regolith and Resource Delivery System
AMSC-662: Robotic Regolith Manipulation and Site Preparation
ROBO-682: Robust Autonomous Mobility for Lunar Polar Volatile Extraction and Transport
ROBO-826: Payload Handling, Manipulation, and Transportation
ROBO-1027: Surface Aggregation
ROBO-1538: General-Purpose Robotic Manipulation to Perform Human-Scale Logistics, Maintenance, Outfitting, and Utilization
ROBO-1304: Robust, High-Progress-Rate, and Long-Distance Autonomous Surface Mobility
ROBO-1545: Robotic Actuation, Subsystem Components, and System Architectures for Long-Duration and Extreme Environment Operation
ROBO-1543: Multi-Agent Robotic Coordination and Interoperability for Cooperative Task Planning and Performance

Metrics

- TBD

ID	Shortfall Title:
1540	Intelligent Robots for the Servicing, Assembly, and Outfitting of In-Space Assets and Industrial-Scale Surface Infrastructure

Description

The ability to perform uncrewed servicing, assembly, and outfitting of both in-space assets and surface infrastructure is critical to expanding our science and exploration footprint across the solar system and sustaining long-duration operations on the lunar surface and other future destinations.

Unique robotic mobility and manipulation approaches are needed to address the scale of large servicing and assembly tasks both in space and on the lunar and Martian surfaces (e.g., traversing the full length of a tall communication tower during outfitting tasks; assembly of truss structures, radiators, or solar panels on large in-space assembled assets; the installation or replacement of instruments on high-value science assets; etc.). Advances in autonomous task planning and verification, especially in the presence of unplanned failures or unforeseen dynamics, are needed to provide robust performance in the absence of crew and reduce reliance on direct ground support. New end-effector tooling, sensors, and specialized control approaches suited for a broad range of infrastructure servicing and support activities are needed.

Coordinated control between robotic manipulators and their parent spacecraft bus during in-space operations must be matured to improve safety and reliability of dynamic operations while in contact with high-value assets. And both general-purpose and task-specific autonomous manipulation must be leveraged at multiple scales to establish and maintain comprehensive lunar surface operations, in-space servicing capabilities, a sustainable ecosystem, and a robust lunar economy.

Related Shortfalls

AMSC-617 and -1400: On-Surface Robotic Assembly of Structures
AMSC-618: Autonomy and Robotics for Vertical Assemblies
AMSC-662: Robotic Regolith Manipulation and Site Preparation
ECO-1480: On-Surface Outfitting of Lunar Structures
SSA-1412: Multi-Agent Autonomous Robotic Systems for Assembly and Construction
SSA-513: Robotic Assembly and Construction of Modular Structures for Sustained Space Infrastructure
SSA-520: Assembly of Nuclear Propulsion Vehicle Backbone Structure with Utility Connections
SSA-445: Future Great Observatory Servicing and Assembly Architecture and Agents
SSA-379: Upgrade or Install Instruments on Large Space Observatories
AP-1138 and -1224: In-Space & Surface Transfer of Propellants
ROBO-455: Extra-Vehicular Repositionable-Base Robotic Manipulators
ROBO-1283: Robotic Mobile Manipulation for Surface Infrastructure Assembly, Maintenance, and Logistics Management
ROBO-1538: General-Purpose Robotic Manipulation to Perform Human-Scale Logistics, Maintenance, Outfitting, and Utilization
ROBO-683: External Robotic and Autonomy Capabilities Suitable for the Extreme Space Environment
AUTO-679: Task Planning and Execution Software for Autonomous Systems

Metrics

- TBD

ID	Shortfall Title:
1545	Robotic Actuation, Subsystem Components, and System Architectures for Long-Duration and Extreme Environment Operation

Description

Robotic operation in the extreme environments of the Moon, Mars, and other destinations of interest across the solar system, is reliant on robust component technologies capable of surviving and operating in these challenging conditions. Additionally, a sustained presence on the Moon is only possible if surface systems can maintain performance over higher duty cycles and longer duration operations.

Unique environmental challenges in space include radiation, temperature extremes, harsh dust and abrasion, vacuum, and even exposure to corrosive chemicals at some science destinations. Terrestrial approaches to power-dense actuation, sensing, distributed avionics, and power storage that show promise in earth-based robotics are not guaranteed to transfer directly to spaceflight application without targeted development. Integrated protections against these environmental factors are needed to expand the life and viable operational environments of space robots. Additionally, capabilities beyond the existing terrestrial state-of-the-art in robotics are needed to meet the long-duration, expanded autonomy, and industrial-scale objectives of NASA's Moon-to-Mars program. The development and integration of novel power-dense actuation (including electric motors, gearing, and drive train components); high dynamic range sensors (perception, force/torque, etc.); long-lived, high-density onboard power storage and distribution, and computing and avionics architectures suitable for autonomous robots would dramatically improve mission reach.

Novel robotic system architectures must also be matured to provide modularity, repairability, and maintainability, recognizing that a sustained lunar presence cannot be achieved using prior single-mission robotic design paradigms or terrestrial approaches that leverage the availability of human operators for regular maintenance.

Related Shortfalls

THERMAL-1618: Survive and Operate Through the Lunar Night
AAS-447: Long-Life Avionics for Extreme Lunar Environments
PWR-1595: Energy Storage to Enable Robust and Long Duration Operations on Moon and Mars
THERMAL-593: Cold Tolerant Mechanisms
ROBO-1628: Long-Range Rugged Drive Systems for the Lunar Environment
ROBO-1340: Rover Wheels/Tires for Extended Duration Surface Missions in Extreme Lunar Environments
ROBO-687: Robotic Actuation for Extreme Cold Access
ROBO-911: Robotic Actuators, Sensors, and Interfaces
ROBO-684: Efficient Fault Tolerant Robotic Actuation
AMSC-995: Dust Tolerant Mechanisms and Sealing Surfaces
ROBO-773: Contamination Tolerant Tool-Changer for Use on Lunar and Other Off-Earth Missions
ROBO-683: External Robotic and Autonomy Capabilities Suitable for the Extreme Space Environment
AMSC-1345: Robotically Swappable Modular Subsystems
ROBO-1640: Robotic Architectures for Modularity, Repairability/Self-Repairability, and Maintainability by Both Crew and Robots
ROBO-1548: Sensing for Autonomous Robotic Operations in Challenging Environmental Conditions

Metrics

- TBD

ID	Shortfall Title:
1548	Sensing for Autonomous Robotic Operations in Challenging Environmental Conditions

Description

Robust and reliable sensing is a critical enabling component across all robotic capabilities and functions (e.g., inspection, manipulation, mobility, sampling, etc.). It is also needed independent of control paradigm, providing invaluable situational awareness to remote human tele-operators and enabling autonomous and semi-autonomous robotic operation. Perception sensing is of unique importance, but advances in contact/force sensing and other sensing modalities are also critical to enabling robust robotic operations.

The challenging environmental conditions of many mission destinations require advances in both sensor hardware and the software and algorithms that process data and model the environment and/or system state. Semantic classification and understanding of gathered data and resulting models is also needed to ensure robust task performance as robots autonomously interact with equipment, interfaces, and their environment. Immediate areas of need include robust perception in low or no lighting, and improved capabilities in high contrast and/or dynamic lighting conditions. This is particularly relevant in the vicinity of the lunar South Pole, as improved real-time sensing of terrain hazards, both geometric (e.g., slopes, rocks, and negative obstacles like craters) and non-geometric (e.g., unconsolidated regolith), will improve the safety and performance of robotic mobility (with near term implications for the Artemis campaign and science missions such as Endurance-A).

Space-qualified, low-size, -weight, and -power sensors are needed across all use cases (both robotic mobility and manipulation). Of particular interest are high dynamic range force sensors and active perception sensors that do not require artificial illumination (e.g., LiDAR) suitable for launch and operation in the harsh lunar environment. Terrestrial industry is actively developing new hardware technology, but targeted investment and development toward adaptation is needed to realize infusion to spaceflight applications.

Related Shortfalls

ROBO-1317: Perception and Navigation Sensors for Extended Operation in the Lunar Environment and Lunar Lighting Conditions
ACN-1318: Surface Navigation Systems for LTV and Crew for Extreme Temperature Radiation and Dust Conditions
ROBO-777: Surface Navigation Sensors for Extreme Temperature, Radiation, and Dust Conditions
ROBO-1630: Multi-Modal, 3D Terrain Sensing and Modeling with Semantic Interpretation
ROBO-931: Robot Contact Sensors
ROBO-959: Terrain and Hazard Relative 3D Point Cloud 6 DOF Pose
ROBO-979: Sub Newton and Tunable Robot Force Torque Sensors
EDL-317: High-Resolution, Continuous Lunar Maps for Precise Landing
ROBO-1545: Robotic Actuation, Subsystem Components, and System Architectures for Long-Duration and Extreme Environment Operation

Metrics

- TBD

ID 680

Shortfall Title:

Robust Robotic Intelligence for High-Tempo Autonomous Operations in Dynamic Mission Conditions

Description

To provide real-time support and perform time-critical tasks, robotic systems must be able to robustly handle faults, inadvertent task failures, and dynamic environmental conditions. Timely performance of physical corrective actions in off-nominal scenarios is a core component of uncrewed robotic maintenance and repair. Likewise, future flagship science missions with limited communication to ground operators will be required to rapidly respond in the presence of unpredictable failures, sub-system faults, or time-varying environmental conditions to meet critical data and sample collection windows.

The “fail-safe” paradigm of past mission architectures is counterintuitively less safe as mission scenarios become more dynamic. Future robotic systems must have broad situational and state awareness, the ability to rapidly make autonomous decisions, and inherent “fail-operational” or “fail-active” response capabilities to maintain safety and achieve mission success as architecture needs drive robotic operations toward greater levels of autonomy with limited real-time operator intervention. Onboard, self-reliant, and adaptive behaviors for rapid decision making and execution provide the dynamic capabilities needed to address short time-to-criticality scenarios.

Advances in fault detection, isolation, recovery, and response are needed. Novel approaches to leveraging machine learning based methods for high-tempo decision making and system, state, and environment modeling in the spaceflight context would provide significant benefit. And real-time, risk-aware planning and robust replanning in the presence of time-varying system degradations or unforeseen changes to task objectives would dramatically increase the safety, reliability, and sustained performance of robotic systems.

Related Shortfalls

TBD

Metrics

- TBD

ID	Shortfall Title:
1541	Intuitive and Efficient Human-Robot Interaction for Safe Teaming and Remote Supervisory Control

Description

Robust, reliable, safe, and efficient methods of human-robot interaction are required to achieve the *"integrated human and robotic systems with inter-relationships that* [will] *enable maximum science and exploration during* [future missions]" (see Moon-to-Mars Objectives TH-9 and TH-10). Collaborative operations performed by co-located human-robot teams and incidental interactions between crew and on-site autonomous/semi-autonomous robotic systems operating in parallel, both call for clear methods of communication and safe task coordination between agents. Efficient human-robot interaction is just as important during remote supervisory control of distributed robots. This could describe ground-based operators supervising one or many semi-autonomous robots in space, crew in orbit controlling robots on a surface, crew inside a surface habitat controlling remote robots external to the habitat, or any number of other permutations.

Development of tools, processes, autonomous approaches, and interfaces to effectively provide situational awareness to remote human operators and enable safe command and control across high-latency and bandwidth-limited networks is needed. Advances are needed to meet the challenging middle ground of real-time, semi-autonomous operation on the lunar surface and in cislunar space (which cannot rely on regular access to, or real-time communication with, ground operators as in LEO, but must progress beyond the slow operational cadences typical of Mars rover operations in order to achieve the human-scale pace required for regular sustained lunar operations). Technologies must also be extended for larger systems of remote robots and distributed human-robot teams, as well as increasing levels of onboard autonomy.

Related Shortfalls

ROBO-690: Efficient Remote Human-Robot Interaction
ROBO-1000: Supervisor Situational Awareness Modeling and Simulation
AUTO-679: Task Planning and Execution Software for Autonomous Systems
ROBO-1070: Crew-System/Robotic Interaction
ROBO-1633: Remote Supervisory Control in the Presence of Intermediate Time Delays and Communication Limitations
ROBO-1634: Remote Supervisory Control in the Presence of Deep Space Time Delays and Limited Communication
SURFACE-1363: Robotic Caretakers
ROBO-1182: Simultaneous Control of Multiple Robots
AUTO-1134: Autonomous Mission Operations Systems to Increase the Efficiencies of Payload Operations
AAS-529: Displays (Two-Dimensional Visual Electronic) for Deep Space Missions
AAS-1108: Consistent Crew Interfaces for Deep Space Missions
AAS-1420: Speech Recognition for Autonomous Crew Operations

Metrics

- TBD

ID
1336

Shortfall Title:

Robotic Mobility for Robust, Repeatable Access To and Through Extreme Terrain, Surface Topography, and Harsh Environmental Conditions

Description

Current space robotic mobility cannot provide access to many of the challenging environments and areas of unique interest that are critical to future science and exploration activities. The ability to scale steep crater walls and access sub-surface pits, caves, and other extreme topography enable a broad range of capabilities on both the moon and Mars. Sheer cliff faces and crater walls can offer valuable geological information if robots can effectively scale them for sampling or data collection. Sub-surface caves and lava tubes are, likewise, interesting science destinations, as well as potential habitat locations on the moon or Mars that provide protection from radiation or other harsh environmental hazards. Repeatable access to permanently shadowed regions, crater floors, and sub-surface areas also enables robust in situ resource characterization and collection.

Prior robotic missions have been limited to relatively benign terrain, and increasing the slopes, material properties, and other terrain hazards robotic surface mobility can handle will greatly increase safety, mission robustness, and the resulting science and exploration return realized during both crewed and uncrewed missions. Access over extreme terrain and topography is accompanied by the need to survive operation in harsh environmental conditions. Access to, and operation in, the extreme cold of permanently shadowed regions, for example, presents several technology challenges, but represents a key enabling capability for broad science and sustained exploration activities.

Robotic mobility for robust and repeatable extreme access is not limited to traditional surface rovers, as novel actuation or active suspension methods, reduced gravity hoppers and other above-surface mobility, legged systems, climbing or rappelling modalities, and various hybrid approaches could all prove useful to increasing science and exploration reach.

Related Shortfalls

TBD

Metrics

- TBD

ID	Shortfall Title:
1543	Multi-Agent Robotic Coordination and Interoperability for Cooperative Task Planning and Performance

Description

Heterogeneous multi-agent robotic teams are able to leverage the unique capabilities of individual robots to expand overall mission capabilities. Just as the pairing of the Ingenuity helicopter and the Perseverance rover on Mars introduced new possibilities for robotic scouting and sample collection, future science and exploration activities can benefit from new methods of leveraging multiple robotic systems for cooperative task performance. Applications include earth-independent distributed science measurements, large payload transport by fleets of smaller robots, and multi-robot in-space assembly of large structures. Greater autonomy is needed to coordinate multiple robots during joint operations and novel approaches to task allocation, planning, data sharing, and coordinated decision making are required.

Interoperability is a core recurring tenet of NASA's Moon-to-Mars Objectives, and the ability for disparate robotic systems to efficiently interact with each other and other surface systems is critical for sustained operations and establishing a robust lunar economy. Modular and extensible approaches to developing robotics and autonomy capabilities are needed to leverage reuse across applications and establish accepted interface standards between systems. And as the number of surface systems grows, autonomous operations will become more complex, requiring broader multi-agent system management and autonomous coordination for both earth-independent operations and efficient supervisory control of a large ecosystem of robots by small ground support teams.

Related Shortfalls

ROBO-1650: Cooperative Robotic Manipulation
ROBO-1651: Cooperative Robotic Mobility and Transport
ROBO-1648: Modular, Interoperable, and Extensible Robotics and Autonomy Flight Software Frameworks
AUTO-681: Architecture(s) and Frameworks for Autonomous Systems
ROBO-1649: Interoperability of Lunar Surface Robotic Systems
ROBO-1647: Autonomous Surface System Coordination
ROBO-1646: Multi-Agent Coordination for Distributed Science Measurements
ROBO-1645: Autonomous Task Allocation and Planning Across Heterogeneous Robotic Systems
SSA-1412: Multi-Agent Autonomous Robotic Systems for Assembly and Construction
SSA-445: Future Great Observatory Servicing and Assembly Architecture and Agents
SSA-1415: Hierarchical Autonomy
SSA-1416: Distributed Autonomy
SS-1378: Autonomous Maintenance Scheduling

Metrics

- TBD

ID	Shortfall Title:
1533	Autonomous Robotic Sample Identification, Classification, Collection, Manipulation, Verification, and Transport

Description

Significant priority is placed on in situ sample acquisition, handling, and return in the 2022 Planetary Science Decadal, with the report finding that "*priority missions need this technology area this decade*." Specific enabling technologies include autonomous sample selection and science targeting to increase earth-independence during periods of limited communication, onboard sample verification, robotic manipulation capable of collecting cryogenic samples in extreme environments, and integrated approaches to preserving sample integrity during return.

Instrumented drilling and intelligent fault handling are needed for robustness when interacting with samples and environments of unknown, varying, or particularly challenging material properties. Autonomous high-accuracy coordination of robotic mobility and manipulation is necessary for the reliable placement of science instruments and sampling tools in unstructured environments without the benefit of human-in-the-loop direction. The rate at which robots are able to independently identify and collect samples must also be increased to improve operational throughput over extended missions. And as sample operations extend to ever more challenging environments (e.g., permanently shadowed regions, thick ice, the Venusian atmosphere, sub-surface oceans, etc.) autonomous robotics must provide the means to accomplish identification, classification, and collection of these unique samples with high reliability.

Related Shortfalls

ROBO-1652: Robotic Manipulation for Cold/Cryo Sample Acquisition, Handling, and Return
AUTO-1653: Autonomous Sample Selection and Science Targeting
ROBO-1654: Onboard Robotic Sample Verification Technologies
ROBO-1655: Intelligent, Instrumented Drilling for Robust Autonomous Science Operations
PP-893: Containment of Unsterilized Martian Materials Being Studied in Mars Surface Laboratory or Being Returned to Earth for Advanced Study
AHS-937: In-situ Sample Storage, Processing & Analysis
LM-1188: Lunar Sample Transfer Capability into a Habitat

Metrics

- TBD

ID	Shortfall Title:
1547	Robotic Systems for Sub-Surface Access

Description

Significant scientific benefit can be gained from robust access to sub-surface regions, materials, and samples that cannot be readily inspected from the surface. Robust deep drilling beyond current capability levels is needed to reach these locations of interest and collect pristine/unmodified materials, while novel approaches to sub-surface instrument placement also greatly expand scientific reach. A key finding from the 2022 Planetary Science Decadal notes that *"2-10m drill technology is critical … to robustly sample pristine materials from subsurface layers of the widest variety of rock and ice materials on Mars, the Moon, and other bodies."* Furthermore, *"technology development to reach beyond 10 meters and access subsurface reservoirs and oceans would revolutionize our understanding of the interiors of terrestrial and icy/ocean worlds."*

Access through the thick icy crusts of Enceladus and other icy/ocean worlds would be a critical step in the search for life across the solar system. In addition to drilling and other deep sub-surface access techniques, sub-surface robotic mobility is a critical enabling technology for these investigations. Access through thick ice, followed by autonomous sub-surface ocean mobility allows for broader exploration, analysis, and sample collection activities. Technologies for sub-surface ocean mobility could also apply to future needs for transportation through other liquid mediums (e.g. Titan lakes).

Robotic mobility for sub-surface access through thick ice, sub-surface reservoir/ocean mobility, and deep sub-surface measurements and sample collection (via drilling or other novel means) must incorporate robust sensing, advances in control and actuation technologies, onboard intelligence, and planetary protection considerations to provide reliable, high-quality science return.

Related Shortfalls

TBD

Metrics

- TBD

ID	Shortfall Title:
1530	Aerial Robotic Mobility and Onboard Intelligence for Expanded Capabilities on Mars, Venus, and Titan

Description

Novel approaches to aerial mobility enable expanded scouting, scientific sampling, and support functions on Mars, while also providing an avenue for in-depth scientific discoveries throughout the atmospheres of Venus and Titan. This is a technology area of interest highlighted in the 2022 Planetary Science Decadal and includes advances in rotorcraft design and the maturation of variable-altitude balloons.

Technologies to enable long-distance and extended duration sorties are of immediate need, as are increased payload capacity and the integration of aerial mobility with sample manipulation and handling capabilities. The continuous nature of aerial flight also calls for even greater robustness and reliability across real-time autonomous navigation algorithms, planning, resource and health management, and fault recovery.

Note that this shortfall specifically addresses aerial/atmospheric robotic flight and mobility. Other means of above-surface mobility for other destinations (e.g., free-flying around small bodies, hopping across lunar surface terrain, etc.) are considered in related shortfalls 1336 and 1537.

Related Shortfalls

ROBO-1336: Robotic Mobility for Robust, Repeatable Access To and Through Extreme Terrain, Surface Topography, and Harsh Environmental Conditions

ROBO-1537: Free-Flying Systems for Robotic Inspection, Data Collection, and Servicing of In-Space Assets

Metrics

- TBD

ID	Shortfall Title:
1537	Free-Flying Systems for Robotic Inspection, Data Collection, and Servicing of In-Space Assets

Description

Free-flying robotic systems are needed to provide a rapid inspection and data collection capability in and around orbital habitats, satellites, and transit vehicles. Autonomous navigation, station keeping, and failure response paradigms must be developed for safe and effective operation in close proximity to crew and high-value spaceflight assets. This capability is especially important during long duration missions in deep space where available crew time for EVA or exterior vehicle access may be limited and situational awareness during contingency response carries even greater significance.

Small satellite inspectors deployed from high-value science assets would provide invaluable diagnostic data in the event of deployment failures or instances of performance degradation. The improved situational awareness provided by free-flying systems also improves in-space servicing and assembly operations and provides a means to rendezvous with and inspect uncontrolled or non-cooperative targets while keeping a parent vehicle at a safe distance. Unique benefits could be realized during science missions around small-bodies. And the combination of robotic free-flying with manipulation or other modes of 0g mobility (e.g.. climbing) could provide additional hybrid capabilities of value.

Critical to this technology is the development of low-cost systems that effectively incorporate robust collision avoidance, fault-tolerant navigation, and high-reliability hardware and software architectures for safe operation around high value assets.

Related Shortfalls

RPOC-373: Small Satellite RPOC with Close Free-Flying Inspection of a High-Value Asset

Metrics

- TBD

ID

1536

Shortfall Title:

Free-Flying Mobility Aids for Crew EVA

Description

Advances in free-flying robotic mobility are needed to support crew during microgravity EVA. Robustness over long duration use is critical to support extended missions with limited resupply, while increased autonomy and greater range will enable a wider array of safe EVA operations. The ability to remotely and/or autonomously rescue an incapacitated crew during EVA is a notable use case, with response and redundancy to a variety of contingency scenarios significantly enhanced by further advances in crewed microgravity mobility. Long-duration missions and the potential for significantly larger deep space transit vehicles or in-space assets that would be more complicated to traverse by traditional hand-over-hand climbing or robotic arm assisted relocations introduce unique challenges that are addressed by advances in free-flying mobility aids. The ability to rapidly respond with limited reliance on ground support or pre-planning for EVA activities also further opens the trade space for future architectural decisions.

Related Shortfalls

ROBO-1537: Free-Flying Systems for Robotic Inspection, Data Collection, and Servicing of In-Space Assets

PROP-1052: EVA/IVA Support Propulsion Development

AHS-1167: EVA Tools and Crew Mobility Aids for Sustained Lunar EVA and Mars EVA

RPOC-373: Small Satellite RPOC with Close Free-Flying Inspection of a High-Value Asset

Metrics

- TBD

ID
1539

Shortfall Title:

Intelligent Robotic Systems for Crew Health and Performance During Long-Duration Missions

Description

Current missions on ISS rely on high mass, power, and volume exercise equipment and significant crew time dedicated to exercise protocols to mitigate the effects of long-duration exposure to microgravity. The limited size of future vehicles and habitats requires more compact hardware solutions, and by enhancing new countermeasure devices with advanced robotic controls and increased sensing capabilities a more comprehensive approach to maintaining crew health can be provided. Robotic exercise systems must be compact, low mass, more power efficient, adaptable across crew members, robust with limited required maintenance, and provide for a range of exercise regimens. Advances in actuation, sensing, and onboard intelligence are needed to meet future needs. Likewise, robotic dynamometry and other diagnostic capabilities are needed for accurate in situ assessment of crew strength/performance and earth-independent prescription of exercise protocols. Human-safe control approaches for these interactive systems is paramount.

For long duration lunar missions, and especially extended Mars transits, the ability to provide remote medical care, both routine and contingency, is required. The terrestrial use of robotic medical systems and instruments has rapidly expanded in recent years, but these hardware and software approaches to remote care must be adapted for spaceflight use. Additionally, advances in spacesuit sensing and integrated powered augmentation to enhance crew performance and reduce injury risk following long-duration microgravity exposure would significantly expand the tasks crew can perform safely and effectively during extended missions.

Related Shortfalls

ROBO-1635: Compact Robotic Exercise Devices and Other Countermeasures to Maintain Crew Health During Long-Duration Missions
AHS-1521: Crew Exercise and Sensorimotor Countermeasures
AHS-1522: Crew Health Countermeasures – Non-Exercise
AHS-875: Exercise Vibration Isolation and Stabilization System
AHS-771: Exercise Countermeasures
ROBO-1636: Robotic Spacesuit Augmentation
ROBO-1637: Robotic Spacesuit Glove Augmentation
ROBO-1638: Compact Robotic Dynamometry and Diagnostic Systems for Monitoring Crew Health and Performance
AHS-1523: Earth Independent Human Operations within Habitat Elements
AHS-1524: Crew Medical Care for Mars and Sustained Lunar
ROBO-1639: Robotic Medical Devices for Remote Care
AHS-724: Crew Health and Performance Countermeasure Informatics
AHS-853: Operational Medical Decision Support Software and Informatics
AHS-989: Behavioral Health and Performance Medical Capabilities
AHS-1457: Behavioral Health and Performance Countermeasures

Metrics

- TBD

ID	Shortfall Title:
1534	Autonomous Robotics for Sustained In-Space Manufacturing Operations

Description

Terrestrial manufacturing relies heavily on robotics and automation to increase the efficiency and scale of operations. These sustained operations, however, are heavily subsidized by the presence of human operators and the ability on the ground to impose structure in the manufacturing setting (e.g., part fixtures, defined work cell geometry, etc.).

Sustained in-space manufacturing must be more robust to unstructured environments, with little to no reliance on human intervention. Autonomous production planning is important to achieve desired throughput, while sensing and entirely robotic evaluation and verification is needed to ensure the quality of manufactured products. Sustained operations without readily available human maintenance also call for broad process and performance monitoring, hardware suitable for long-duration operation, and robotic repair and replace capabilities as in other in-space applications (e.g., in-space servicing, infrastructure assembly and outfitting, habitat maintenance and utilization, etc.).

Significant synergy exists between manufacturing tasks and the underlying technology needs for robust autonomous robotic manipulation at multiple scales and autonomous logistics management. When applied to manufacturing, unique processes (such as welding, laser forming, recycling, composite manufacturing, and additive manufacturing) call for unique robotic tooling and the novel integration and coordination of multiple flight-worthy robots and autonomy architectures for both these specific use cases and the broader scaled capability enabling a sustained lunar and in-space economy.

Related Shortfalls

TBD

Metrics

- TBD

ID	Shortfall Title:
1531	Autonomous Guidance and Navigation for Deep Space Missions

Description

Autonomous transit with orbit insertion and orbit maintenance

Autonomous navigation required for deep space navigation and science that does not depend on communications with a ground station(s). Deployments of autonomous navigation in the past, and as currently envisioned for the future, are primarily for when ground navigation cannot meet requirements, which is true only for limited number of cases. Technology development, mostly in the areas of fault responses, onboard planning and sequencing, and interactions with other s/c subsystems is needed. Autonomous transit to the Moon with orbit insertion and orbit maintenance could be demonstrated initially with maturation to small bodies and planets as we look ahead to Mars-bound.

From ongoing SMD-sponsored ANDRAT Study: Autonomy technologies for efficient operations and cost-reduction are not likely to be adopted by any individual proposed mission because the burden of extensive test protocols and risk reduction activities coupled with the perceived requirement to maintain parallel human operators on high value missions would cause undue schedule and cost pressure on any single mission.

Related Shortfalls

ACN-1111: Accurate and safe landing navigation systems for environments with variable lighting conditions
ACN: 1462: Autonomous Navigation to Mars
ACN: 1465: Autonomous Navigation (AutoNav) System
AAS-527: High Performance Spaceflight Computing Software Tools
AAS-382: High Performance General Purpose Processors for Deep Space Missions
EDL-345: Dedicated high-performance computing for precise landing and hazard avoidance algorithms and sensor fusion
EDL-1242: Real-time mapping technologies for active terrain relative navigation (TRN) and hazard detection and avoidance during lunar descent
AUTO-679, AUTO-681, AUTO-689, AUTO-780, AUTO-889, AUTO-958, AUTO-1133, AUTO-1136, AUTO-1190, …

Metrics

- TBD

ID	Shortfall Title:
1544	Resilient Agency: Adaptable Intelligence and Robust Online Learning for Long-Duration and Dynamic Missions

Description

Resiliency is an ability to recover from or adjust easily to adversity or change. Resilient Agency extends this idea to the embodied intelligence and robotic platforms that bring this attribute to operational resiliency and/or improved performance over time and as the mission environment changes. This is especially relevant in environments in which humans cannot be in the loop or at sufficient distances that the temporal latency prevents communications. Building the trust and trustworthiness into these systems will require that we design in in-situ capabilities such as:

- Redundancy (at agent or sub-agent level)
- Realtime adjustments (to damage, attrition, repair, etc.)
- Learning/adaptation
- Diagnostics/Prognostics (digital twin, etc.)
- Self-healing agents and teams of agents
- …

and will be enabled via real-time adaptation and online (machine) learning. Machine decisions will be made with incomplete information, false information, etc. often in the face of time- and safety-critical situations. Further, decision made by a single agent that is part of a greater ecosystem means that decisions, performance, etc. will not be limited to local impact. Requiring machines to OODA (Observe --> Orient --> Decide --> Act) like humans do means asking machine intelligence to consider the impact of decisions not only on local performance but on neighboring agents and on the system of systems (the ecosystem) that will enable long-duration and dynamic missions.

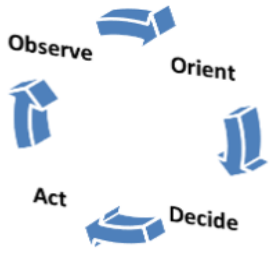
Related Shortfalls

AUTO-679: Task Planning and Execution Software for AS
AUTO-689: Machine Learning Platforms and Architectures for Space Exploration
AUTO-964: On-Board "thinking" autonomy
SS-1364: Autonomous, adaptable fault detection tools
SS-1362: Fault isolation and recovery capabilities
SSA-496: Integrated modeling and digital twin for space-based V&V
SSA-1414: Architectures and Framework for Economical and Scalable Autonomous Robotic Construction
AM-1491: Demonstrate Manufacture /Maintain /Repair /Recycle /Certify for M2M Architecture Elements with Digital Transformation Technologies (Digital Twin, AI, …)
AMSC-1402: High-fidelity models and simulations of lunar surface structures in a relevant environment (digital twin)

Metrics

OODA metrics

- Time to action
- Constraint violations
- …



ID

1542

Shortfall Title:

Metrics and Processes for Establishing Trust and Certifying the Trustworthiness of Autonomous Systems

Description

It is difficult to gain experience with and trust in operating a more autonomous system in a contested environment due to a lack of testing capability and procedures for deploying, shaking-down, and upgrading assets in adversarial environments. Needed capabilities include but are not limited to:

- Test and Evaluation (T&E)
- Verification and Validation (V&V)
- Distributed interoperable simulation platforms
- Proving grounds
- Interoperability Standards
- Benchmarks
- Cybersecurity
- Human-System Interaction
- Digital Twins (human, habitats, vehicles, ecosystem, etc.)

Additionally, the temporal paradigm shift from shorter human-centric sorties (measured in days or months) to autonomous and semi-autonomous missions to achieve the persistent and long-duration missions that are required for M2M adds requirements to test systems of systems over time including the entirely of the surface and/or in-space ecosystem in ways that we have not needed in the past.

Related Shortfalls

AAS-1403: Avionics Cybersecurity
AUTO-718: Autonomy Operation Standards
AUTO-723: Autonomy Testbeds and Testing Procedures
AUTO-873: Autonomy Coordination and Training
AUTO-891: Creation, scheduling and execution of activities by autonomous systems.
AUTO-916: Verifiable Autonomy
AUTO-980: Concepts of Operations for autonomous systems encompassing a hierarchical distributed functional architecture
AUTO-1106: Autonomy Testing Protocols
AUTO-1133: Methods and Hardware for Collecting Data to Enable Autonomy
AUTO-1199: Autonomy Verification and Validation Tools

Metrics

- TBD

ID	Shortfall Title:
1535	Autonomous Vehicle, System, Habitat, and Infrastructure Health Monitoring and Management

Description

Sustained operations of Gateway, Mars transit vehicles, human habitats, and the entire lunar infrastructure will require constant monitoring and, when necessary, management. This holds for crewed and uncrewed scenarios as well as dormancy periods. Monitoring will require the integration of environmental conditions (e.g., space weather), atmospheric conditions, interior climates (e.g., oxygen levels, particulates, etc.), the integrity of structures, any/all ongoing operations, etc. as well as the overall ecosystem including materials pipelines, construction schedules, etc. in which system and subsystem dependencies are defined.

In addition to monitoring, diagnostics to inform any actions to be taken by humans and/or machine are critical and must consider how degradation, change, or repair of any one system impacts and all systems in the ecosystem. Prognostics to inform maintenance cycles and predict when repairs will be needed to avoid shutdowns will also be crucial as avoiding failures is equally if not more important than addressing them. This enable fail-safe and fail-operational outcomes.

Related Shortfalls

AHS-XXXX: Crew Space Wx Monitoring
AHS-1118: Acoustic Monitoring & Control
LOGISTICS-791: On board monitors that measure particulates in the crew respiratory hazard range, survive dormancy, and work in low pressures.
AMSC-420: Health monitoring of lunar surface structures
AUTO-940: Fail operational robotic manipulation
ROBO-680: Robust Robotic Intelligence for High-Tempo Autonomous Operations in Dynamic Mission Conditions
ROBO-892: Intra-Vehicular Robotics (IVR) for Payload and Science Utilization, Logistics, Maintenance, and Contingency Response
AHS-366: Autonomous Logistics for Dormancy and Crew Readiness
AHS-1031: Major constituent and trace contaminant gas monitoring for cabin air
SS-1375: Solar wind/flare tracking and forecasting

Metrics

- TBD

ID	Shortfall Title:
1532	Autonomous Planning, Scheduling, and Decision-Support to Enable Sustained Earth-Independent Missions

Description

A sustained presence on the moon, and particularly long-duration missions to Mars, demand a greater need for crew independence from Earth-based mission control. Crewed missions beyond cis-lunar space will require new capabilities to address the realities of limited ground support.

Sustained and resilient Earth-independent operations call for technology that support human decision-making (i.e., helping the crew decide) rather than purely autonomous decision-making (i.e., letting the system decide) and must result in a robust on-board anomaly response capability that can be operated by crew members during rapidly-changing mission conditions.

Lower-level shortfalls identify specific development needs in vehicle systems, mission management capabilities, data integration infrastructure, crew interaction methodologies, and decision support.

Related Shortfalls

TBD

Metrics

- TBD

ID	Shortfall Title:
1625	Intelligent Multi-Agent Constellations for Cooperative Operations

Description

Autonomous cooperative multi-spacecraft system (i.e., constellation) for cost-effective interdependent and distributed measurement/operations). [ref: AS&R EFP]

Satellite formation flying (aka satellite clusters or constellations) has become increasingly viable due to advancements made in onboard intelligence and controls. Trailing satellite formations such as the "A-Train" have been on-orbit for decades and successfully return valuable earth science data but are not capable of reconfiguring their formation shape. For persistent satellite observations, we need to develop and demonstrate autonomous multi-agent cluster capabilities. These constellations enable persistent observations such as:

- Data-driven science observations (single- and/or multi-agent systems make onboard decisions on where to observe). This includes Tipping and Cueing small satellites in a constellation.
- Clusters intelligent assets will enable surface mapping (including resource identification), dynamic communication, grid management, and provide "structure" for other autonomous systems to use for navigation.
- Navigation Aid: agents can dynamically transition between/to any required pattern in real-time to provide as-needed structure in the environment (i.e., trajectory target).
- Data-driven Intelligence, surveillance, target acquisition, and reconnaissance (ISTR) will revolutionize the situational awareness for smarter decision-making in multiple domains.

and may also reduce the cost of any single asset/agent in a given constellation. Agents can exchange roles (e.g., leader/follower) and new agents can join a constellation at any point in time. This modularity accommodates attrition and enables fail-operational operations.

Related Shortfalls

SS-1438: Autonomy, Edge Computation, and Interoperable Networking for Small Spacecraft
AUTO-1478: Autonomous onboard conjunction assessment (CA) and collision avoidance (COLA)
ROBO-680: Robust Robotic Intelligence for High-Tempo Operations in Dynamic Mission Conditions

Metrics

- TBD

ID	Shortfall Title
1554	High Performance Onboard Computing to Enable Increasingly Complex Operations

Description

Advanced radiation tolerant onboard computing systems are needed both in space and on surfaces to offer increased processing performance, input/output (I/O) bandwidth, and data storage. Flexibility is also needed to adapt power, fault tolerance, processing bandwidth, and I/O bandwidth to mission needs. Future computing systems should support open system avionics architectures that provide interoperability between modules sourced from different vendors. These systems will enable increased autonomy for crewed and robotic science missions, as well as onboard data reduction where sensor bandwidth exceeds downlink bandwidth.

Related Shortfalls

AV-526: High Performance Spaceflight Computing (HPSC) Single Board Computer (SBC)
AV-382: High-Performance General-Purpose Processors for Deep Space Missions
AV-524: Advanced Spaceflight Memory – Volatile
AV-627: Advanced Spaceflight Memory – Non-Volatile
AV-525: Point-Of-Load (POL) Power Converters
AV-533: Coprocessors
AV-527: High Performance Spaceflight Computing Software Tools
AV-1403: Avionics Cybersecurity
AV-1065: Modular & Interoperable Avionics Arch
AV-TBD: Interoperable Avionics Modules
AV-616: Quantum Computing
AV-632: Low Power Embedded Computing Nodes

Metrics

- Processing Bandwidth
- I/O Bandwidth
- Memory Storage Capacity
- Power Dissipation
- Radiation Tolerance

ID	Shortfall Title
1551	Distributed Avionics to Enable Improved Performance and SWaP Efficiency

Description

Distributed avionics technologies are needed to allow the disaggregation of avionics functions within spacecraft or surface systems, thereby providing performance improvement, SWaP(size, weight, and power) reduction, and simplified integration and maintenance. Technologies are also needed to implement next generation wired and wireless avionic networks with high reliability with increased bandwidth for deep space missions. These networks must also accommodate traffic classes with varying levels of criticality.

Related Shortfalls

AV-632: Low Power Embedded Computing Nodes
AV-528: Radiation Tolerant High Bandwidth Interconnect
AV-449: High Bandwidth Deterministic Wireless Networks
AV-634: Next Generation Physical Layer Technologies for Deep Space Mission
AV-TBD: Distributed Avionics Architectures
AV-TBD: Simulation and analysis tools for mixed-criticality networks

Metrics

- Data Rate
- Determinism
- Latency
- Power Dissipation
- Radiation Tolerance

ID	Shortfall Title
1552	Extreme Environment Avionics

Description

Avionics are needed that can operate reliably in harsh lunar and planetary thermal, radiation, and dust environments. These environments will vary widely across crewed and science missions. Applications include lunar surface systems that can survive lunar night without heaters, sensor and actuators on spacecraft and surface systems that operate in environments without active thermal control, and high temperature electronics for Venus missions.

Related Shortfalls

AV-447: Extreme Environment Electronics for Science Missions
AV-1160: Extreme Environment Electronics for Crewed Missions
AV-539: Avionics Thermal Management for Extreme Environments
AV-1406: Dust Tolerant Avionics Connectors
SURFACE-1389: Cold and dust tolerant interface seals

Metrics

- Temperature Range
- Radiation Tolerance
- Lifetime
- Dust Tolerance

ID	Shortfall Title
1550	Crew Audio/Visual Interfaces for Long Duration Missions Beyond LEO

Description

Crew voice and audio systems are needed that can operate reliably for long duration missions beyond LEO. Crew interface needs span a variety of applications ranging from suits for EVA to crewed habitats to unpressurized rovers. Enhanced audio system capabilities are also needed, including speech recognition, to increase ease of use for crew.

Related Shortfalls

AV-529: Displays (Two-Dimensional Visual Electronic) for Deep Space Missions
AV-530: Graphics Processing for Deep Space Missions
AV-531: Heads Up Display (HUD) Optics for Exploration EVA
AV-532: Crew Voice and Audio Systems for Deep Space Missions
AV-1108: Consistent Crew Interfaces for Deep Space Missions
AV-1420: Speech Recognition for Autonomous Crew Operations
AV-1426: Projection Displays for Deep Space Missions
AV-1427: Resource Constrained Graphics Rendering
AV-1419: Deep Space Information Technology (IT) Infrastructure

Metrics

- Resolution
- Frame Rate
- Speech Intelligibility
- Radiation Tolerance

ID	Shortfall Title
1549	Advanced Data Acquisition Systems for Diverse Applications

Description

Data acquisition technology advances are needed to reduce the SWaP and cost and improving flexibility. Applications include low-cost data acquisition systems for small and cost-constrained missions to implement aerocapture sensing systems. Additionally, wireless sensing is needed to reduce harness mass/complexity, simplify integration and maintenance, and provide flexibility to modify instrumentation on-orbit for crewed missions. For robotic science missions, wireless sensing is needed for connectivity to deployed or rotating assemblies.

Related Shortfalls

AV-534: Low-Cost, Robust, High-Accuracy Data Acquisition Systems
AV-448: Wireless Sensor Networks
AV-536: Low-Cost Mixed Signal Application Specific Integrated Circuits (ASICs)

Metrics

- Resolution
- Sample Rate
- Radiation Tolerance
- Lifetime
- Cost

ID	Shortfall Title
1553	Foundational Technologies for Future Avionics Devices and Systems

Description

Foundational technology advances are needed to enable the next generation of onboard computing systems, avionics systems, sub-systems and components. Technologies are needed to design, fabricate, and package next generation radiation hardened microelectronics. Libraries and tools are needed to allow implementation of the next generation of space microelectronics on emerging semiconduction fabrication processes. Packaging advances are also needed to provide miniaturization and performance improvement for future space microelectronics. Additionally, testing technologies are needed to improve the efficiency and effectiveness of COTS device testing, enabling broader use of leading-edge COTS devices in future avionics systems. Technologies to enable future safety-critical avionics are needed, both at the component and architecture level.

Related Shortfalls

AV-450: Advanced Electronics Packaging
AV-535: Radiation Hardened By Design and Tools (RHBD) Libraries
AV-1407: Advanced Test Systems for COTS Microelectronics
AV-812: Avionics Modeling and Simulation for System Design and Evaluation
AV-TBD: Low-SWaP Fault Tolerance Architectures for Long Duration Missions
AV-TBD: Circuit Design Approaches for High-Integrity Devices

Metrics

- TBD

ID	Shortfall Title
1555	Next Generation Avionics Architectures

Description

Avionics architectures are needed with modularity and interoperability to enable systems to be developed using standard products from multiple vendors. Architectures are also needed that provide electrical and mechanical interfaces that enable robotic servicing. Additionally, technologies are needed to enable space cloud computing architectures where onboard computing tasks can be efficiently and reliably distributed across multiple spacecraft to surface systems, thereby providing high performance processing to resource constrained systems.

Related Shortfalls

AV-1065: Modular & Interoperable Avionics Arch
AV-1404: Serviceable Avionics
AV-1405: Space Cloud Computing

Metrics

- TBD

ID	Shortfall Title
1557	Position, Navigation, and Timing (PNT) for In-Orbit and Surface Applications

Description

Safe navigation for extended durations and distances on planetary surfaces requires an in-situ navigation and timing system. Ideally such a navigation and timing system will make use of several sub-systems including an orbiting constellation (e.g.. similar to GPS at Earth but likely also supporting communications and navigation) and surface relay terminals near hubs of exploration activity. Early operational versions of the orbiting constellation (s) providing navigation services will have technology shortfalls that, when filled, will yield a much more capable system as it matures. A key technology challenge is deployment/distribution of a suitable time scale that will require developing highly stable atomic clocks deployed in the orbital relays and on the lunar surface. Atomic clocks will serve as the central component for realizing the timescale and ensuring accurate radiometric tracking signals. A follow-on to the Deep Space Atomic Clock (DSAC) would yield a compact clock with sufficiently low-drift (two-orders of magnitude less than existing space clocks) for forming an accurate time scale. Another challenge is to develop a multi-band integrated receiver that can track various radio frequency signals available in the environment and form radiometric tracking data that could be used as part of an onboard navigation system (i.e., the Autonomous Navigation to Mars shortfall). Finally, certain missions at the Moon could also utilize weak-signal GNSS (from Earth) for navigation (an example would be for Gateway to aid with its 21-day autonomous navigation requirement); this will require developing sensitive GNSS receivers as well as pairing them with highly stable atomic clocks to obtain the required navigation accuracy.

Related Shortfalls

COMM-TBD: Next Generation Deep Space Atomic Clock
COMM-1318: Surface navigation systems for robotic and/or crewed surface vehicles and astronauts in extreme temperature and variable lighting conditions
COMM-1111: Accurate and safe landing navigation systems for environments with variable lighting conditions.
COMM-TBD: Lunar Navigation Satellite System (LNSS) + User Receivers
COMM-TBD: Weak Signal GNSS Receiver
COMM-TBD: Mars Navigation Satellite System (MNSS) + user receivers

Metrics:

- TBD

ID	Shortfall Title
1558	High-Rate Communications Across The Lunar Surface

Description

Eventually there will be a proliferation of devices on the lunar surface whose communication needs exceed the scheduling capacity of lunar orbital relays / direct-to-Earth (DTE) links or whose individual size, weight, and power (SWaP) constraints prohibit use of relay/DTE for Earthbound communication. High-rate surface links will be required to interface to these devices and mediate access of their on-demand communications needs to the more managed, long-haul links back to Earth. Use of standardized protocols is desired to maintain broad compatibility and interoperability between end users of these services and a diversity of commercial communication providers. The 3GPP cellular communication protocols are well suited to this need and will meet the requirements of both long range and short-range links for both low and high data rates and enable a transition from the IEEE 802.11 Wi-Fi protocols, reserved for high rate, short-range links. Key challenges are: a) characterizing the radiation tolerance of commercial off-the-shelf (COTS) system-on-chip (SOC) components which are increasingly difficult to replace due to their sophistication and power efficiency; b) architecting around COTS SOCs to yield overall system reliability sufficient for high-criticality applications; c) deploying sufficiently tall lunar towers to reap the benefits of long-range coverage in rugged lunar terrain; d) building models of the lunar RF propagation environment to inform coverage mapping and guide mission planning; e) developing operations and maintenance (O&M) interfaces to monitor and control lunar infrastructure remotely from Earth; f) scaling from constrained, initial lunar deployments to multi-cellular coverage with proper backhaul and roaming between different providers; g) seamlessly handling the transition between long-range (e.g.., 3GPP) and local (e.g.., Wi-Fi) services as availability and capability dictate without degrading the overall quality of service/experience.

Related Shortfalls

COMM-1281: 3rd Generation Partnership Project (3GPP) 4G / LTE Cellular Technology
COMM-TBD: 3rd Generation Partnership Project (3GPP) 5G Cellular Technology
COMM-1282: Radiation Hardened WiFi 6/6E Technology
COMM-790: Tall (>30m) Inexpensive Self-Erecting Communication Towers
COMM-TBD: Lunar Propagation Analysis and Modeling
AMSC-617: On-surface robotic assembly of vertical structures
AMSC-1408: Advanced deployable load-bearing structures

Metrics:

- TBD

ID	Shortfall Title
1559	Deep Space Autonomous Navigation

Description

A robust, fault tolerant autonomous navigation capability for deep space exploration and science missions is needed. An autonomous navigation capability should be able to accurately determine the trajectory of a spacecraft with minimal to no Earth-based ground navigation support as well as determine any trajectory correction maneuvers needed to maintain a desired flight path. The navigation system will be able to fuse a variety of sensor data to ensure accurate trajectory knowledge and can use that information to compute timely trajectory control maneuvers. This system should be extensible and scalable to cruise, approach, entry, orbit insertion and orbiting mission phases. Such a system, for example, is needed for crews going to and from Mars. Finally, the autonomous navigation system would need to be integrated into a system level autonomy executive for a fully capable level of autonomy.

Related Shortfalls

COMM-TBD: Autonomous Navigation to Mars
COMM-TBD: Next Generation Deep Space Atomic Clock
COMM-TBD: Mars Landing Navigation System
COMM-1111: Accurate and safe landing navigation systems for environments with variable lighting conditions.
COMM-TBD: Mars Navigation Satellite System (MNSS) + user receivers
COMM-TBD: Gimbaled Wide + Narrow Optical System
COMM-TBD: Pulsar X-Ray Navigation Receiver

Metrics:

- TBD

ID **Shortfall Title**

1560 High-Rate Deep Space Communications

Description

High-rate communications from the Moon and beyond is needed to enable future space exploration and science missions. For example, a robust communications infrastructure will be needed to support a sustained human presence on the Moon and its eventual industrialization. High data rate trunk lines between the Earth and the Moon are needed to reduce the number of individual links. The human exploration of Mars will also require high-rate communications between Earth and Mars. Return data rates to Earth, for example, are anticipated to be > 100 Mbps; forward data rates to Mars, based on experience from the International Space Station, are anticipated to be > 20 Mbps. Future deep space science missions also require higher data rates than possible with today's technology. Future deep space science missions will also require higher data rates than possible with today's technology. Key challenges include: (1) Low mass, large flight aperture antennas (RF) or telescopes (optical) for us in space; (2) High efficiency high power RF or optical amplifiers; (3) Low recurring cost, large effective area ground apertures for deep space communications.

Related Shortfalls

COMM-TBD: High-Rate Radio Frequency Communications To and From Mars

COMM-1321: High-Rate Optical Communications To and From Mars

Metrics:

- 1 Gbps from 1.5 Million Km
- 5 – 10 Gbps from the Moon
- 100 Mbps from Mars at maximum range (~2.7 AU)
- 20 Mbps to Mars at maximum range (~2.7 AU)

ID	Shortfall Title
879	In-space and On-surface, Long-duration Storage of Cryogenic Propellant

Description

The ability to store a cryogenic liquid with zero (or near zero) boil-off is a strategic capability that is not mature. The cryogenic fluid storage capability requires that a vehicle be designed to minimize heat input into the tank, then if required, provide active cooling systems to further reduce or eliminate the residual heat load. Additionally, as any heat gets into the system, there must be means for the control of the pressure of the system via venting or increasing the heat removal capability.

The soft cryo storage systems include SpaceX StarShip for Artemis HLS and Mars Transportation NEP(Nuclear Electric Propulsion)/Chem, SEP(Solar Electric Propulsion)/Chem and All Chem solutions. Hydrogen cryogenic storage systems include Blue Origin Artemis HLS and Transporter and the Mars Transportation NTP(Nuclear Thermal Propulsion) solution. Depots are also in development, but not manifested in the reference architecture.

Related Shortfalls

CFM-482: 90k Cryo Cooler
CFM-487: 20k Cryo Cooler
CFM-479: Tube-on-tank
CFM-475: Tube-on-shield
CFM-474: High Vac MLI
CFM-485: Soft Vac
CFM-TBD: Windsteam Insulation – CELSIUS Project
CFM-TBD: MOD Resistant Insulation
CFM-TBD: Load Bearing Insulation
CFM-471: Low Conductivity Structures
CFM-481: Cryo Thermal Coatings
CFM-TBD: Frangible / Active heat load reduction
CFM-479: Tube on Tank
CFM-475: Tube on shield
CFM-476, CFM-488: Vapor Cooling and Para to Ortho
CFM-491: Sun Shields
CFM-490, CFM-1144: Unsettled mass Gauging
CFM-489: Propellant Densification
CFM-478: Unsettled Venting
CFM-477: Forced Destratification
CFM-469: Autogenous Pressurization
CFM-462: Subsurface He Pressurization

Metrics

- % per day boiloff
- Stored propellant mass uncertainty

ID	Shortfall Title
792	In-space and On-surface Transfer of Cryogenic Fluids

Description

The ability to transfer a cryogenic liquid (usually propellant) from one tank to another is a strategic technology that is not mature. The issue is performing the transfer with minimal commodity loss and waste (unusable propellant in the supply tank). There are many aspects to transfer operations, such as Tank Pressurization, Liquid Acquisition, Line and Tank chilldown as well as cryo-couplers. Also having methods to extract the maximum possible commodity by using Liquid Acquisition devices or other methods/ techniques. This shortfall includes all of the elements required for efficient fluid transfer operations with acceptable risk tolerance. This includes modeling, testing to validate transfer models, cryo-couplers, etc..

Additional propellant resources (10-20%) are bookkept to guarantee mission success. Fueling large vehicles launched empty or partially filled will not be possible and refueling vehicles for reuse will not be possible if the shortfall is not closed. Lunar architecture is dependent as enabling technology. All Mars Transportation solutions currently under consideration are also dependent on these developments as enabling technology.

Related Shortfalls

CFM-461: Component Hardware for Transfer
CFM-465: Automated CryoCouplers
CFM-470: Cryo Flow Meters
CFM-464: LADs and Phase Separators
CFM-467: Transfer Operations
CFM-466: Tank Chilldown
CFM-463: Line Chilldown
CFM-469: Autogenous Pressurization
CFM-462: Subsurface He Pressurization
CFM-490: Unsettled mass Gauging

Metrics

- % Loss during transfer
- % residuals in supply tank
- Propellant transfer rate and duration

ID	Shortfall Title
755	Cross-Discipline Cryogenic Fluid Management Technologies

Description

Enabling the use of cryogenic fluids outside of primary propulsion is addressed in this shortfall. Examples are integrated RCS (reaction control system), reactant supply to fuel cell power generation, supply of oxygen to ECLSS, and autogenous pressurization. The ability to use propellant from the bulk tanks for RCS instead of a dedicated system that uses storables is an example of an efficiency gained through the uses of Cross Discipline Fluids. Also, the use of the bulk liquid to siphon off liquid to be heated to create gas is another example of more efficient commodity storage for the vehicle.

If not closed: CFM Technologies will be unable to support efficient architectures based on iRCS, fuel cell or ECLSS cryogenic fluid management. Note the reference architectures do not currently plan to use iRCS. However, Fuel Cells and ECLSS systems do plan to leverage cryogenic operating fluids.

Related Shortfalls

CFM-TBD: Fuel Cell Refueling
CFM-470: Cryo Flow Meters
CFM-463: Line Chilldown
CFM-469: Autogenous Pressurization
CFM-TBD: Commodity Transfer Pump
CFM-TBD: Integrated IRCS

Metrics

- TBD

ID	Shortfall Title
1194	Prediction Modeling of Cryogenic Fluid Dynamics and Operations

Description

Cryogenic Fluid Management implementation requires integrated systems with multiple technologies, complex interfaces and interdependencies. Technology development and system demonstrations, both ground and flight, include unique configurations, and also differ from future planned flight applications. Because of the range of technologies, fluids, configurations and scales, modeling is the only cost-effective method for predictive performance estimation. Model validation is required to improve predictive capabilities and inform future system's design optimization. The CFM technology domain has insufficient performance predictive capabilities and applicability limitations of validated models. Additionally, CFM requires practical computational costs for pervasive community use. CFM predictive modeling also enables development of autonomous controller logic models to be used both for Mars Transportation and surface operation cryogenic systems.

CFM predictive modeling is enabling for Mars Transportation where alternative propellant margins are too high for architecture closure.

Related Shortfalls

CFM-TBD: Instrumentation
CFM-TBD: Integrated System Demonstration
CFM-TBD: High Fidelity Modeling
CFM-TBD: High-to-Low Model Integration
CFM-TBD: Cryogenic Systems Control Models

Metrics

- Relative difference between CFD results and 1g test data for pressure time histories and for fluid and/or wall temperature time histories.
- The relative difference between CFD results and micro-g test data for pressure time histories and fluid and/or wall temperature time histories.
- Macro performance predictions (boil-off, line losses, residuals, vent cycles, operational validation, unsettled vs. settled operations, etc..)

ID	Shortfall Title
1226	Cryogenic Liquefaction

Description

This shortfall is in support of In-situ methods used to produce oxygen and/or hydrogen/methane on the surface. The working fluid needs to be liquefied for both storage and usage by various end users. This can be treated as an integrated ISRU implementation or can be separated.

This shortfall supports long-term sustainable architecture objectives.

Storage as a gas is feasible for non-propulsion applications (e.g., ECLSS) but storage density will be much lower. For propulsion applications, consumable fluids will have to be supplied to the surface (no ISRU).

Long duration cryogenic propellant storage also has potential to capture gas phase commodities and reliquefy regardless if ISRU sourced.

Related Shortfalls

CFM-468: Liquefaction Operations
CFM-479: Tube-on-Tank
CFM-482: 90k Cryo Cooler
CFM-487: 20k Cryo Cooler

Metrics

- Oxygen liquefaction rate
- Hydrogen liquefaction rate

ID	Shortfall Title
1561	Advanced Modeling and Test Capabilities to Characterize Dust Effects on Hardware

Description

Advancements in dust models are needed to better predict dust behavior, estimate loading conditions, and simulate dust mitigation techniques for exploration assets. More comprehensive models require particle adhesion, particle cohesion, particle transport, lunar dust particle characteristics, etc.. These models are essential because they attempt to mimic the environments in which the lunar systems must work.

Characterizing lunar dust over the variety of lunar landing locations is an essential knowledge shortfall foundational to understanding the environment. Updated measurements in the lab and from the surface serve as inputs to models and design guidance that hardware owners use to make design decisions.

Understanding the effects of lunar dust on various systems by properly testing is essential for designers to prepare for lunar operations.

Related Shortfalls

AMSC-793: Dust transfer between vehicles/elements
AMSC-779: Dust particle charge & chemical composition dependence on adhesion/cohesion of dust
AMSC-863: Characteristics of the finest fraction of lunar dust as it varies by location
ISRU-836: Lunar Dirty Thermal Vacuum Large Test chambers
AMSC-1045: Effects of dust deposition on systems, including thermal, optical, & mechanical
EDL&PL-321: Validated Prediction of Plume Surface Interaction (PSI) for Vehicles Landing on the Moon
LOGISTICS-1176: Models/Measurements for Transport of Contaminants in Mars Atmosphere
ISRU-TBD: Extraterrestrial surface environmental simulators, test facilities, and test sites

Metrics

- Quantify dust transfer, accumulation, and adherence using models
- Quantify dust accumulation using sensor data from the surface
- Quantity performance degradation of various systems from dust accumulation from ground testing or surface operations

ID	Shortfall Title
844	Passive Dust Mitigation Technologies for Diverse Applications

Description

Passive dust mitigation technologies prevent or minimize dust accumulation and adherence on surfaces. Dust may have accumulated as a result of interactions of systems or subsystems exposed to dusty surfaces either directly or indirectly as a result of missions to the Moon, Mars and/or small bodies.

Passive dust mitigation is defined as mitigation measures that require no human intervention (or power) to operate properly.

Passive surface technologies can include surface coatings and topography modification. Surface treatments include limiting chemical, mechanical, or electrostatic adhesion.

Passive dust mitigation also encompasses solutions for crew cabin filtration, as well as monitoring, both internally and externally.

Related Shortfalls

THERMAL-521: Dust Tolerant Thermal Systems
LOGISTICS-1117: Filtration for Lunar/Martian dust, cabin particulates, and smoke
LOGISTICS-906: Lunar EVA Suit Dust Mitigation
LOGISTICS-791: On board monitors that measure particulates in crew respiratory hazard range, survive dormancy, and work in low pressures
THERMAL-514: Thermal Control Coatings
MANU-648: Materials for extreme environments
AMSC-767: Advanced designs for softgoods surface elements
LOGISTICS-1062: Lunar Surface Environmental Protection Garment (EPG) Shell Material System
LOGISTICS-1326: Logistics Transfer Port
ISRU-556: Mars atmosphere dust filtration
ISRU-443: Mars atmosphere collection and pressurization for ISRU
EDL&PL-342: Navigation and guidance technologies that provide precise knowledge and maneuver planning for lunar missions
AMSC-424: V&V: Environmental effects on System

Metrics

- Varies system to system
- Advance TRL of passive dust mitigation solutions
- Successful demonstration of technologies in relevant environment through laboratory and/or lunar surface demonstrations

ID	Shortfall Title
1047	Active Dust Mitigation Technologies for Diverse Applications

Description

Active dust mitigation technologies remove accumulated dust from surfaces or prevent dust particulate from adhering. Dust may have accumulated as a result of interactions of systems or subsystems exposed to dusty surfaces either directly or indirectly as a result of missions to the Moon, Mars and/or small bodies.

Active dust mitigation is defined as mitigation measures that require human intervention (or power) to operate properly.

Active dust mitigation technologies can include electrostatic removal, electrodynamic removal, magnetic removal, liquid removal, and vibrational removal.   Examples solutions include the electrodynamic dust shield, vacuums, compressed gas, electron beam ionization, brushing, etc..

Solutions that combine active and passive mitigation are considered active mitigation.

Related Shortfalls

LOGISTICS-906: Lunar EVA Suit Dust Mitigation
THERMAL-521: Dust Tolerant Thermal Systems

Metrics

- Varies system to system
- Advance TRL of active dust mitigation solutions
- Successful demonstration of technologies in relevant environment through laboratory and/or lunar surface demonstrations

ID	Shortfall Title
1568	Entry Modeling and Simulation for EDL Missions

Description

This shortfall is for validated modeling and simulation (M&S) capabilities and tools to enable Phase A-E analysis in support of the selection, design, development and operation of missions at all scales to all planetary destinations, including commercial missions with an Earth entry segment. Most entry missions, particularly to other planetary destinations, are inherently Test-as-You-Fly exceptions because there are no ground test facilities that can adequately reproduce all aspects of the flight environment. Consequently, such missions are critically dependent on modeling and simulation capability for all phases of mission design.

Sub-shortfalls capture key discipline and multi-discipline level modeling deficiencies for each destination of relevance. While the component disciplines are generally the same for all EDL missions, the detailed models tend to be destination, and mission, dependent.

The component disciplines captured by this shortfall are:

- Aerodynamics
- Aerothermodynamics
- Thermal Protection Systems (TPS) Modeling
- Guidance, Navigation and Control (GN&C)
- Atmospheric modeling

Validating these discipline-level and coupled models requires testing in specialized facilities, such as shock tubes, wind tunnels, ballistic ranges, spin tunnels, arc jets, and other heating/loading facilities, just to name a few. In addition, the need for high-end computing capabilities and models devised to run on advanced computing architectures, are included in this shortfall.

Related Shortfalls

EDL&PL-295: TPS Modeling & Optimization for Human Mars Exploration
EDL&PL-296: TPS Modeling & Optimization for Robotic Missions
EDL&PL-316: Validated Modeling for In-Flight Separation and Recontact
EDL&PL-319: Atmospheric Model Development
EDL&PL-324: Validated Aerothermodynamic Prediction for Human Mars EDL
EDL&PL-325: Validated Aerothermodynamic Prediction for Robotic Missions
EDL&PL-326: Validated Aerothermodynamic Prediction for EDL at Earth
EDL&PL-327: Validated Static and Dynamic Aerodynamics Prediction from Supersonic to low Subsonic Speeds
EDL&PL-328: Validated Wake Models, Including RCS Thruster Effects
EDL&PL-329: Multi-disciplinary / Coupled EDL Performance Models
EDL&PL-330: High-End Computing Capability for EDL Modeling
EDL&PL-348: Entry GNC Modeling to Enable Precision Landing at Mars
EDL&PL-349: Entry GNC Modeling for Planetary EDL
EDL&PL-351: High-Mass, High-Velocity Earth Entry GNC
EDL&PL-411: Supersonic Dynamics Test Facility
EDL&PL-412: Planetary Aerothermodynamics Test Facility
EDL&PL-1440: Validated Thermostructural Modeling for TPS Integrated onto Aeroshell Structure

Metrics

- M&S validation status and quantified uncertainty levels for each mission class

ID	Shortfall Title
1569	High-Mass Mars Entry and Descent Systems

Description

The Mars Viking-heritage entry, descent and landing systems that have been employed for Mars robotic science missions to date will not scale to human Mars mission masses. Blunt-body aeroshells are constrained by the diameter of the launch vehicle shroud, and Viking-certified supersonic parachutes are inadequate for safe, precise landing of large payloads. Prior systems studies have demonstrated, that, due to the tenuous atmosphere at Mars, only SRP (Supersonic Retro-Propulsion) will meet the requirements for supersonic descent. The system will need to effectively stage from hypersonic entry to an SRP assisted descent, while meeting requirements for an eventual precision landing.

Because we cannot perform a relevant end-to-end flight test for Mars EDL, vehicle systems are certified through high-fidelity simulations. This end-to-end flight mechanics simulation capability is comprised of environmental models and system models validated through component ground and/or flight testing. Unique facilities, access to flight-relevant environments, and high-end computing are foundational capabilities that will enable development and certification of the human-scale Mars vehicles. While not a shortfall per se, investment in flight mechanics modeling and associated systems analysis / concept studies are a critical part of the shortfall closure process. The simulation environments and processes that have been employed since Mars Pathfinder begin with vehicle concepts and continue through day-of-landing operational use. In the near term, these simulations can support system/architecture studies to perform a basic assessment of general classes of entry and descent architectures relevant to human Mars missions. The architecture space may span blunt-body deployable (such as hypersonic inflatable aerodynamic decelerators, HIADs) to mid L/D and other emerging concepts.

Related Shortfalls

EDL&PL-298: Ground Development and Scale-Up of Inflatable Decelerators
EDL&PL-299: Flight Test Validation of Integrated High-Mass Mars Entry and Descent Architectures
EDL&PL-306: Control Technologies for Exploration Class Inflatable Decelerator
EDL&PL-406: Exploration Class Mid L/D System
EDL&PL-312: Supersonic Retropropulsion (SRP) Engines
EDL&PL-322: Supersonic Retropropulsion (SRP) Modeling & Simulation
EDL&PL-344: Supersonic Retropropulsion (SRP) Guidance, Navigation and Control Algorithms
EDL&PL-TBD: High Speed Propulsion Tunnel
EDL&PL-TBD: Supersonic Retropropulsion (SRP) Flight Testing

Metrics

- Entry system mass
- Landing precision

ID	Shortfall Title
1572	Performance-Optimized Low-Cost Aeroshells for EDL Missions

Description

Ablative and reusable TPS (thermal protection system) concepts, performance optimized and scalable aeroshell structures, in-situ health monitoring capability, and associated reliability assessments "on the shelf" to meet the needs of exploration missions (both human and robotic) and the emerging commercial sector. This shortfall includes approaches to reduce the cost and time to certify new materials for mission use, as well as ground-based testing improvements to enhance the value of high enthalpy testing as a critical element of the overall Aeroshell validation/verification story.

Related Shortfalls

EDL&PL-297: Efficient Backshell TPS
EDL&PL-300: Efficient Heatshield TPS
EDL&PL-302: High-Mass, High-Velocity Earth Entry Thermal Protection Systems
EDL&PL-303: Mass-Efficient Large Aeroshell Structures
EDL&PL-323: Aeroshell/TPS Reliability Prediction
EDL&PL-338: Aeroshell/TPS Integrated System Health Monitoring
EDL&PL-407: Multi-Use Ablative TPS
EDL&PL-408: High Enthalpy TPS Test Facility for Crewed Mars Entry
EDL&PL-413: Efficient Reusable TPS
EDL&PL-414: Cost Efficient TPS Certification
EDL&PL-1442: Instrumentation and Facility Characterization for High Speed / High Enthalpy Ground Test Facilities

Metrics

- TBD

ID	Shortfall Title
1564	Aeroshell In-Situ Flight Performance Data During EDL

Description

Develop and fly instrumentation to collect in-situ engineering performance data from planetary and Earth entry aeroshells, with a focus on validating EDL performance models including aerothermodynamics, TPS (thermal protection system) material and structural response, aerodynamics, and flight dynamics.

Given that planetary entry is almost always a "Test as You Fly" exception for any mission class, the collection of quality validation data from every planetary entry is the only way to ensure that the state of the art of planetary entry modeling continues to evolve with validated predictions and quantified uncertainties.

Related Shortfalls

EDL&PL-335: EDL Flight Vehicle (Aeroshell) Flight Performance Data for Human Mars Entry and Earth Return
EDL&PL-336: EDL Flight Vehicle (Aeroshell) Flight Performance Data for Robotic Missions
EDL&PL-337: Low-Cost EDL Flight Instrumentation Data Acquisition System

Metrics

- Determination of vehicle aerodynamics, aerothermodynamics, TPS response
- Instrumentation system cost

ID	Shortfall Title
1563	Aerocapture for Spacecraft Deceleration and Orbit Insertion

Description

Aerocapture is a “propellantless” way to insert a spacecraft into orbit, by using atmospheric drag during a single atmospheric pass to decelerate the spacecraft and achieve the desired apoapsis and orbital inclination. Modeling capabilities exist to study aerocapture concepts for science missions (orbital or landing), but model validation via relevant system demonstrations is essential to establish scalability and readiness for infusion into future Ice Giant and/or Mars missions. Key sub-disciplines include TPS (mass efficiency is desired due to large heat loads and the direct trade between aeroshell vs propellent mass), aerosciences (to predict aerodynamic heating and body forces during transit), and GNC (algorithms and control strategies to enable accurate atmosphere exit for a range of concepts from ballistic to mid L/D).

Related Shortfalls

EDL&PL-304: Ice Giant Aerocapture
EDL&PL-305: End to End Flight Validation of Aerocapture
EDL&PL-346: Small Spacecraft Aerocapture

Metrics

- TBD

ID	Shortfall Title
1567	Entry Capabilities for Small-Scale and Commercial Spacecraft

Description

Small spacecraft (from 1U to ~180 kg) are now ubiquitous in Earth orbit, but their use on interplanetary missions is still in its infancy. Enabling small spacecraft to efficiently and cost-effectively perform aerocapture, entry, descent, and/or landing is a key next step. This shortfall encompasses EDL concepts and technologies that are compatible with rideshare opportunities and deliver payloads meaningful for science return. Deployable hypersonic decelerators, passive control methods, robust guidance approaches, and efficient landing attenuation methods are some of the key envisioned capabilities.

There is a rising market for commercial Earth return capabilities, from small to large scale, enabling launch stage reuse, satellite servicing, debris mitigation, delivery of goods manufactured in space, scientific sample return, and many other emerging needs. New design paradigms and constituent subsystem approaches may provide advantages that support marketable vehicles (as opposed to one-of-a-kind NASA missions). Minimizing cost yet maximizing robust performance over a range of payloads will be key aspects of these new systems.

Related Shortfalls

EDL&PL-163: High-Reliability Earth Entry Vehicles for Robotic Missions
EDL&PL-307: Small Spacecraft EDL
EDL&PL-308: Small Entry Vehicle Test Platform
EDL&PL-309: Low Cost On-Demand Payload Return
EDL&PL-344: Small Spacecraft Propellentless Deorbit Devices

Metrics

- Entry system mass for payload delivered
- Packaging volume
- Complexity
- Cost
- Robustness to uncertainties

ID	Shortfall Title
1574	Validated Performance Models for Planetary Parachutes

Description

Despite decades of use, parachutes remain an unpredictable, risky component of many entry, descent and landing (EDL) missions. Whether it is the return of humans from the International Space Station, or the landing of a large rover on Mars, parachute systems are a costly focus of system development. The goal with this shortfall is to make parachutes a more predicable EDL tool. With modern computing capabilities, understand, predict, model and test planetary parachutes for supersonic, subsonic and cluster applications. Develop new instrumentation concepts to capture needed validation data from planned tests as well as during mission EDL.

Related Shortfalls

EDL&PL-310: Supersonic Parachute Systems and Modeling
EDL&PL-311: Subsonic Parachute Systems and Modeling
EDL&PL-334: Flight Instrumentation to Acquire Parachute Performance Data

Metrics

- TBD

ID	Shortfall Title
1565	Assessment and Validation Capabilities for Integrated Precision Landing Systems

Description

Maturation and validation of precision landing (PL) capabilities for infusion into an integrated EDL guidance, navigation and control (GN&C) subsystem requires a combination of simulation, lab/field, and flight tests -- listed in order of increased cost, fidelity, space mission relevance, and mission risk reduction. EDL in general cannot be validated with a typical "test as you fly" approach because of the complexity and cost of flight testing complete EDL systems. Precision landing capabilities consist of sensors and algorithms to enable a vehicle to determine its surface-relative location and orientation actively during EDL, as well as the location of safe landing sites, which in turn enables the PL system to intelligently plan maneuvers to accomplish a safe and precise touchdown. Assessment and validation require PL-capabilities evaluation as active components in a vehicle GN&C subsystem because the measurements and maneuvers have a cause and effect on each other. Simulations provide a first step in algorithms validation within an integrated system but with sensor models. Lab and field testing of sensors provides relevant data for algorithms processing but without mission-relevant dynamic stimuli. Flight testing provides the closest mission-analog for active testing of an integrated PL system prior to implementation within mission flight systems.

Related Shortfalls

EDL&PL-1479: High-Fidelity EDL&PL Integrated Simulations with PLHA Algorithms, Sensor Models and Terrain Model
EDL&PL-TBD: Low-Cost Dynamic HWIL Platforms for Frequent Tests of Integrated PLHA Sensors, Flight Software and Analog Terrain
EDL&PL-347: High-Altitude Closed-Loop Precision Landing and Hazard Avoidance Flight Test Platform
EDL&PL-308: Small Entry Vehicle Test Platform

Metrics

- Performance validation of integrated PL system to within TBD % error between simulation and test
- Demonstration of closed-loop GNC capabilities in simulation and test
- Establishment of a unique EDL&PL-relevant test capability not available via other test platforms

ID	Shortfall Title
1571	Navigation Sensors for Precision Landing

Description

High accuracy and precise sensing is critical for enabling precision navigation to land within 10's of meters of targeted surface locations. Multiple mission scenarios for landing at the Moon, Mars and elsewhere require sensors capable of long-range measurements, sensing in low-to-no light conditions, and sensing in diverse EDL environments. Future multi-function sensors combining multiple measurement types are also of priority to advance integrated capabilities and reduce PL-system size/mass/power.

Related Shortfalls

EDL&PL-TBD: Active Surface-Relative Navigation Sensors for Crewed and Robotic Lunar Descent and PL
EDL&PL-TBD: Navigation Sensors Evolved for Crewed and Robotic Mars EDL Scenarios
EDL&PL-339: Integrated, Multi-Function PLHA Sensor(s) for Crewed Lunar & Mars Missions
EDL&PL-340: Integrated, Multi-Function PLHA Sensor(s) for the Environments of Robotic Science Missions
EDL&PL-TBD: Wind Velocity Sensing for Increased Mars-Entry Navigation Precision

Metrics

- Sensor accuracy and precision inline with PL-navigation requirements for lunar/Mars/science-relevant mission environments
- Performance validated within anticipated EDL environments (aero/thermal/dust/PSI) to ensure technology readiness for mission infusion
- Development of dissemination/commercialization plan to ensure availability to NASA and commercial missions

ID	Shortfall Title
1573	Terrain Mapping Capabilities for Precision Landing and Hazard Avoidance

Description

Precision landing and hazard avoidance (PLHA) algorithms require topologically-consistent terrain maps for computing navigation information relative to the landing site and for assessing the hazardousness of potential landing sites for safe vehicle touchdown. Generation of the maps onboard or offboard is dependent on 1) the capabilities of orbital assets to generate maps at mission-specific resolutions, 2) the terrain illumination conditions during EDL allowing passive (e.g., camera) sensors vs necessitating active (e.g.., lidar) sensors, and 3) the lander touchdown-hazard tolerances and the map resolution required to determine landing-site safety. Existing sensors for real-time and onboard mapping during EDL do not yet achieve all performance targets relevant to NASA robotic science and human exploration missions and associated environments that require surface-relative localization or hazard detection in low-to-no light conditions. Existing orbital reconnaissance maps leveraged for surface-relative localization systems and mission surface planning also require improvements to remove seams, discontinuities, seams, and anomalies.

Related Shortfalls

EDL&PL-317: High-resolution, continuous Lunar maps for precise landing
EDL&PL-318: High-resolution, continuous Mars maps for precise landing
EDL&PL-314: Real-time mapping sensors for active TRN and hazard detection relevant to Icy moon EDL environments
EDL&PL-343: Real-time mapping sensors for active TRN and hazard detection during lunar descent scenarios
EDL&PL-410: Real-time mapping sensors for active TRN and hazard detection evolved for Mars-relevant EDL scenarios

Metrics

- Validation of map quality (shortfalls, discontinuity, warpage) to be within architecture-specific requirements for use in PLHA
- Validation of mapping sensors to generate maps within application-specific tolerances
- Performance validated within anticipated EDL environments (aero/thermal/dust/PSI) to ensure technology readiness for mission infusion
- Development of dissemination/commercialization plan to ensure availability to NASA and commercial missions

ID	Shortfall Title
1562	Advanced Algorithms and Computing for Precision Landing

Description

Precision landing capabilities require advanced onboard algorithms and processor capabilities for the real-time fusion of large quantities of sensor data to obtain EDL navigation knowledge, detection of small surface hazards, and guidance maneuver planning to precisely touch down at a safe location near targeted surface sites. Navigation algorithms capable of performing data fusion and surface relative localization with active and passive sensor data are necessary for EDL over surfaces with low-to-no illumination and for landings where there are limited or no pre-existing reconnaissance images. Guidance algorithms capable of providing physically-achievable maneuvers are required for PL and hazard-avoidance diverts to ensure vehicle thrust commands do not exceed physical limits, the maneuvers do not send the vehicle into the ground, and to ensure PL optical sensors remain pointed at critical targets during EDL translation. Hazard detection algorithms must provide landing site characterization in real time during EDL and ensure to a high probability that the identified sites are indeed safe for landing.

Related Shortfalls

EDL&PL-342: Navigation algorithms for lunar-relevant PL sensors and descent scenarios

EDL&PL-TBD: Guidance Algorithms using convex optimization lunar PL and hazard diverts

EDL&PL-350: Navigation algorithms evolved for Mars-relevant PL sensors and descent scenarios

EDL&PL-TBD: Guidance algorithms for Mars-relevant entry conditions, large descent diverts, and hazard avoidance

EDL&PL-345: High-performance computing for PLHA GNC algorithms and sensor fusion

EDL&PL-341: Robust Terminal Descent GN&C for Low-Visibility Conditions Induced by PSI Effects

EDL&PL-TBD: Computationally-Efficient Algorithms for Hazard Detection and Safe Landing-Site Identification

Metrics

- Demonstration of combined GN&HD-algorithm and flight-processing performance inline with available or upcoming (HPSC) flight processors
- Validation of navigation filter logic for enabling PL to within 50m or any mission-specific relevant requirements
- Validation of guidance algorithm resilience (solution guarantees and physical constraint satisfaction) for mission-specific use cases
- Development of dissemination/commercialization plan to ensure availability to NASA and commercial missions
- Release software to NASA SRS or make available to ITAR-compliant US companies

ID	Shortfall Title
1566	Characterization of Plume Surface Interaction

Description

Plume Surface Interaction (PSI) occurs during the final phase of propulsive landing and creates risk to both the lander itself and pre-existing surface assets in the vicinity of the touchdown site. Characterization of PSI is critical to understanding the physics of the event and to design and implement mitigation approaches for Moon, Mars and other planetary destinations. The shortfall focuses on developing strategies to ensure successful EDL and PLHA in plume-induced ground environments.

Predictions of PSI are reliant on Computational Fluid Dynamics (CFD) models due to an inability to scale ground test data and lacking Lunar or Martian landing data. Current CFD models for PSI have not demonstrated or validated predictions of cratering or ejecta with sufficient fidelity for a multi-constituent granular phase representative of Lunar regolith or Martian soil. Reduced computational expense of PSI simulations is required for practical use in configurations where symmetry cannot be applied.

Consequently, this shortfall encompasses improving computational models, validating those models with ground test data, and developing and using flight instrumentation to obtain in-situ data during future Lunar and Mars landing missions. Finally, validated models require integration into high-fidelity flight mechanics simulations, and GNC approaches must be developed that are robust to degraded visibility conditions induced by PSI.

Related Shortfalls

EDL&PL-321: Validated Prediction of PSI for Vehicles Landing on the Moon
EDL&PL-331: Validated Prediction of PSI for Vehicles Landing on Mars
EDL&PL-332: Validated Prediction of PSI for Robotic Landers to Prioritized Science Destinations
EDL&PL-333: Flight Instrumentation to Acquire PSI Performance Data for Model Validation
EDL&PL-341: Robust Terminal Descent GN&C for Low-Visibility Conditions Induced by PSI Effects
EDL&PL-409: Dedicated "Dirty" PSI Test Facility
EDL&PL-TBD: PSI modeling and integration into high-fidelity EDL simulations

Metrics

- Predict PSI surface erosion & crater width/depth within % of ground test & flight data for Lunar and Martian relevant environments
- Predict PSI ejecta energy flux within % of ground test & flight data for Lunar and Martian relevant environments

ID	Shortfall Title
1570	Lander Capabilities for Soft Touchdown

Description

Touchdown is the final critical step in landing on any solar system body, and landing system architectures are driven by EDL terminal velocities, vehicle structure and mass considerations, as well as knowledge of the surface topology. Precision landing capabilities to minimize velocities prior to touchdown facilitate reduction in landing system mass and complexity for solar bodies with well-known surface topology. Destinations with frequently changing, or unknown, surface topologies require additional conservatism or unique approaches to EDL and landing system architecture.

Related Shortfalls

EDL&PL-313: Mass-Efficient Landing Attenuation Systems
EDL&PL-405: Touchdown System for Icy Moons

Metrics

- Size/Mass/Cost trade between existing approaches and potential savings to determine readiness for further development/infusion
- Performance of simulations models and prototype testing to demonstrate readiness for infusion and larger-scale development/test

ID	Shortfall Title
369	Excavation of granular (surface) regolith for ISRU commodities production

Description

ISRU production of commodities and construction feedstock will require the excavation and delivery of 100,000's metric tons of regolith material per year to support initial commercial production levels. SoA (state-of-the-art) is the lander-mounted Surveyor or Phoenix scoop < 0.01 metric tons Thus, development of larger scale excavation and delivery systems may be needed to meet potential ISRU production needs.

Related Shortfalls

AMSC-389: Dust tolerant sensors for regolith collection and excavation force measurement
AMSC-390: Low-mass robotic platforms for mining and regolith manipulation
ISRU-403: Instruments to measure Geotechnical regolith properties
ISRU-404: Instruments to determine local regolith mineral/chemical composition
THERMAL-521: Dust tolerant thermal *control* systems
AMSC-661: Automated wireless recharging
AMSC-1292: Autonomy for high-throughput excavation operations
AMSC-1345: Robotically swappable modular components
AMSC-1395: Rugged autonomous robotic platforms for mining and regolith manipulation
AMSC-1396: Long-duration lunar system survival and reliability
AMSC-995: Dust Tolerant Components
ROBO-TBD: Robust, High-Rate, and Long-Distance Autonomous Surface Mobility

Metrics

- Amount of granular regolith excavated
- Total distance traveled
- Excavation rate

ID	Shortfall Title
384	Excavation of hard/compacted/icy material

Description

ISRU production of commodities (e.g.., water oxygen, rocket propellant, etc..) will require the excavation and delivery of 1,000’s metric tons of icy regolith material per year to support commercial production levels. Therefore, initial demonstrations of this capability should be scalable. SoA (state-of-the-art) is lunar core drilling. It is expected that 1000 metric tons of icy regolith will yield on the order of 50 metric tons of water.

Related Shortfalls

AMSC-389: Dust tolerant sensors for regolith collection and excavation force measurement
AMSC-390: Low-mass robotic platforms for mining and regolith manipulation
ISRU-439: Detection of subsurface ice at less than 10's m scale
ISRU-441: Long-duration resource evaluation in the extreme PSR environment
THERMAL-521: Dust tolerant thermal *control* systems
AMSC-661: Automated wireless recharging
AMSC-1292: Autonomy for high-throughput excavation operations
AMSC-1345: Robotically swappable modular components
AMSC-1395: Rugged autonomous robotic platforms for mining and regolith manipulation
AMSC-1396: Long-duration lunar system survival and reliability
ROBO-TBD: Robust, High-Rate, and Long-Distance Autonomous Surface Mobility

Metrics

- Amount of icy regolith excavated
- Total distance traveled
- Excavation rate

ID	Shortfall Title
385	Regolith and resource delivery system

Description

Results from preliminary ISRU architecture studies indicate that the delivery/transportation systems will be required to deliver regolith from the excavation site to the ISRU processing facility. Similarly, delivery vehicles will be required to move ISRU process waste to a dump site, and to move beneficiated/processed materials to their final use location. These delivery systems may be required to travel distances of 1500 km per year and repeatedly traffic over the same unprepared path, required to operate in the harsh lunar environment, survive multiple lunar nights, and last 5+ years. This is a high-level shortfall that identifies the capability development and demonstration requirements that lead to an initial industrial scale capability. Demonstration opportunities for delivery/transportation systems will be established as ISRU pilot plants are demonstrated.

Related Shortfalls

AMSC-390: Low-mass robotic platforms for mining and regolith manipulation
THERMAL-521: Dust tolerant thermal *control* systems
AMSC-661: Automated wireless recharging
AMSC-1292: Autonomy for high-throughput excavation operations
AMSC-1345: Robotically swappable modular components
AMSC-1395: Rugged autonomous robotic platforms for mining and regolith manipulation
AMSC-1396: Long-duration lunar system survival and reliability
AMSC-995: Dust Tolerant Components
ROBO-TBD: Robust, High-Rate, and Long-Distance Autonomous Surface Mobility

Metrics

- Amount of regolith delivered
- Total distance traveled
- Repeated trafficking (# of trips)
- Delivery rate

ID	Shortfall Title
662	Robotic regolith manipulation and site preparation

Description

Gathering and moving large quantities of regolith on the lunar surface will be necessary for site preparation prior to any major construction activity. Site preparation will require clearing rocks, cut and fill, bulldozing, regolith size sorting, grading, leveling, compaction, and surface stabilization operations. Additionally, bulk regolith manipulation can be used to construct simple and low-cost infrastructure elements such as berms for landing plume containment around launch/landing pads and FSP radiation shielding, as well as placement of regolith overburden to provide radiation and micrometeoroid protection for shelters and habitats.

A robotic platform with sufficient traction and novel implements are needed to provide these functions. Designs should consider modularity to enable reconfigurability and repairability. Demonstration opportunities for regolith manipulation and site preparation will be established as ISRU pilot plants and on-surface construction are demonstrated.

Related Shortfalls

AMSC-389: Dust tolerant sensors for regolith collection and excavation force measurement
AMSC-390: Low-mass robotic platforms for mining and regolith manipulation
AMSC-391: Sensors & Systems for geotechnical & topographical characterization
AMSC-394 – 398: Various site prep implements
THERMAL-521: Dust tolerant thermal *control* systems
AMSC-661: Automated wireless recharging
AMSC-1292: Autonomy for high-throughput excavation operations
AMSC-1345: Robotically swappable modular components
AMSC-1395: Rugged autonomous robotic platforms for mining and regolith manipulation
AMSC-1396: Long-duration lunar system survival and reliability
AMSC-995: Dust Tolerant Components
ROBO-TBD: Robust, High-Rate, and Long-Distance Autonomous Surface Mobility

Metrics

- Site preparation area
- Surface grading & flatness
- Compaction density and depth

ID	Shortfall Title
617	On-surface robotic assembly of vertical structures

Description

The assembly of vertical structures such as tall towers, walls, shelters, and habitats are key infrastructure elements needed on the moon and Mars to support a sustained lunar presence. Assembled tall towers can efficiently and cost effectively support solar power generation (nearly full year power availability at modest heights ~50-100m above surface), communication, inspection, observation, and navigation systems. Other simple vertical structures might include walls, cranes, environmental shields, and scaffolding for construction. More complex structures include unpressurized shelters to protect surface assets and crew, and pressurized volumes for habitation.

These vertical structures can be constructed via autonomous robotic assembly using combinations of standard structural elements such as trusses, beams, and panels...these elements can be either Earth-sourced or ISRU-derived.

Systems for autonomous robotic assembly (element manipulation and joining), inspection, repair, and site preparation will all be necessary to complete the on-surface structural assembly process.

Applications:

- Towers, cranes & scaffolding
- Walls and environmental shields
- Unpressurized Shelters
- Habitable volumes
- ISRU commodity storage

Related Shortfalls

AMSC-420: Heath monitoring of lunar surface structures
SAT S&A-495: In-situ inspection and certification
AMSC-618: Autonomy and robotics for vertical assembly
AMSC-619: Joints and joining methods for structural assembly
AMSC-631: ISRU-based structural elements for assembly
AMSC-635: Foundation anchors for surface assembly and construction
AMSC-636: Structural elements for assembly
AMSC-TBD: In-situ structural repair
SAT S&A-1412: Multi-agent Autonomous Robotic Systems for Assembly and Construction
MANU-1487: In-Space and On-Surface Joining/Welding Technologies for Manufacturing, Assembly, and Construction
COMM-790: Tall (>30m) Inexpensive Self-Erecting Communication Towers

Metrics

- Height of assembled structure
- Supported payload
- Structural efficiency
- Use of lunar sourced materials

ID	Shortfall Title
1400	On-surface robotic assembly of horizontal structures

Description

Many different types of infrastructure will be required for establishing a permanent lunar presence including roads, landing pads, shelters, and habitats. Much of the horizontal infrastructure (specifically, roads, landing pads, and dust-free zones) can be constructed via autonomous robotic assembly using standard structural elements such as panels (Earth-sourced metallic or composite), and bricks/pavers (regolith-based elements). Initial materials could be shipped from Earth however, technologies should be pursued to develop these structural elements from ISRU. Systems for autonomous robotic assembly (element placement and joining), inspection, repair, and site preparation will all be necessary to enable the on-surface assembly of horizontal structures.

Applications:

- Roads
- Launch/landing pads
- Dust-free zones
- Foundations

Related Shortfalls

AMSC-420: Heath monitoring of lunar surface structures
SAT S&A-495: In-situ inspection and certification
AMSC-619: Joints and joining methods for structural assembly
AMSC-631: ISRU-based structural elements for surface assembly
AMSC-635: Foundation anchors for surface assembly and construction
AMSC-636: Structural elements for assembly
AMSC-673: Regolith paver joining and repair
AMSC-1294: ISRU-based paver/brick production
AMSC-1401: Autonomy and robotics for horizontal assembly
AMSC-TBD: In-situ structural repair
SAT S&A-1412: Multi-agent Autonomous Robotic Systems for Assembly and Construction
MANU-1487: In-Space and On-Surface Joining/Welding Technologies for Manufacturing, Assembly, and Construction

Metrics

- Span of construction (e.g.., walls and shields)
- Volume and floor space (e.g.., shelters and habs)
- Structural efficiency
- Use of lunar sourced materials (%)

ID	Shortfall Title
425	On-Surface In-situ Construction of Vertical Structures

Description

The construction of vertical structures such as walls, shelters, and habitats are key infrastructure elements needed on the moon and Mars to support a sustained lunar presence. Simple vertical structures might include walls, environmental shields. More complex structures include unpressurized shelters to protect surface assets and crew, and pressurized volumes for habitation. Vertical ISRU-based construction requires beads or layers of material stacked such that the resulting structure has appropriate inter-layer adhesion and sufficient strength to meet the needs of the overall structure being produced. Significant challenges exist related to the deposition of the material in a low-pressure environment, in-situ inspection and material characterization, power, and scale-up to large structural applications.

Applications:

- Unpressurized Shelters
- Walls and environmental shields
- Habitable volumes

Related Shortfalls

AMSC-416: Deposition of materials in low-pressure environment
AMSC-420: Heath monitoring of lunar surface structures
AMSC-421: In-situ process inspection and certification
AMSC-422: As-built materials characterization
AMSC-423: materials characterization & degradation
AMSC-427: ISRU-derived Materials to Usable Construction Feedstock
AMSC-429: Autonomy and robotics for vertical construction
AMSC-434: Material/feedstock handling
AMSC-635: Foundation anchors for surface assembly and construction
AMSC-TBD: In-situ structural maintenance & repair

Metrics

- Height of constructed structure
- ISRU based material composition (%)
- Feedstock mass

ID	Shortfall Title
666	On-Surface In-situ Construction of Horizontal Structures

Description

Establishing horizontal structures such as launch/landing pads (LLP), roads, and dust-free zones can be achieved using ISRU-based in-situ construction techniques. This construction capability will build upon the development and demonstration of smaller-scale ISRU-based structural elements such as pavers and bricks by utilizing similar materials and processes linked to a mobile platform for large area printing. Significant challenges exist related to the deposition of the material in a low-pressure environment, in-situ inspection and material characterization, power consumption, and scale-up to large structural applications.

Applications:

- Roads
- Launch/landing pads
- Dust-free zones
- Foundations

Related Shortfalls

AMSC-416: Deposition of materials in low-pressure environment
AMSC-420: Heath monitoring of lunar surface structures
AMSC-421: In-situ process inspection and certification
AMSC-422: As-built materials characterization
AMSC-423: materials characterization & degradation
AMSC-427: ISRU-derived Materials to Usable Construction Feedstock
AMSC-429: Autonomy and robotics for vertical construction
AMSC-434: Material/feedstock handling
AMSC-635: Foundation anchors for surface assembly and construction
AMSC-TBD: In-situ structural maintenance & repair
AMSC-674: Road Construction
AMSC-1293: LLP Construction

Metrics

- Surface constructed structure
- ISRU based material composition (%)
- Feedstock mass
- Power consumption
- Construction rate

ID	Shortfall Title
1480	On-surface Outfitting of Lunar Structures

Description

Outfitting is a complex process by which a structure is transformed into a useable system by in-situ installation of subsystems, e.g.., distributed power and data systems and cables, sensor packages, fluid and gas transfer, ECLSS, hatches and penetrations, interior furnishings. A wide array of technologies are needed to robotically install, connect, inspect, and repair these systems and support the construction of various structural concepts such as Power and communications towers, LLPs, shelters, and habitats.

Applications (Outfitting needs):

- Unpressurized Shelters (Power, Data, Fluids)
- Power and Communications Infrastructure (Power & Data)
- Launch/Landing Facilities (Power, Data, Fluids)
- Pressurized Volumes/Habitats (Power, Data, Fluids, ECLSS)
- ISRU Processing facilities (Power, Data, Fluids)

Related Shortfalls

AMSC-663: Autonomy and Robotics for outfitting
AMSC-995: Dust Tolerant Components
MANU-1066: Manufacturing approaches to support habitat outfitting
AMSC-623: Design and integration of electrical harnesses
AMSC-624: Connection of secondary electrical systems (sensors, comm & nav packages, etc..)
AMSC-630: Outfitting of tower with power generation package & comm & nav systems
AMSC-TBD: Inspection and repair of electrical harnesses
AMSC-675: Outfitting for fluid transfer and refueling
AMSC-TBD: Inspection and repair of fluid transfer systems
AMSC-TBD: Outfitting of ECLSS
LOGISTICS-1214: Habitat outfitting approaches for inflatable habitat structures and/or vertically constructed habitats

Metrics

- Capacity & Coverage
- Connectivity dimension (1D, 2D, 3D)
- Complexity and part count
- Mass efficiency

ID	Shortfall Title
1577	Perform resource reconnaissance to locate and characterize resources and estimate reserves

Description

While resources on both Moon and Mars have been identified they have not been mapped or characterized to the extent needed to locate a reserve. ISRU “reserves” are deposits of resources that are sufficient to meet the use case over a sustained period. To accomplish this, resource deposits must be understood in terms of the spatial and depth distribution (at meter resolution), the form and concentration, and the physical and environmental properties of the resource. Resource reconnaissance necessarily includes orbital and surface measurements as well as the associated geostatistical and resource favorability models that correlate those measurements. In order to locate a reserve, the resource favorable areas must also be accessible within the constraints of the use case and architecture. To create reserve estimates, resource favorable maps must be overlaid with terrain, lighting, and other environmental data. These fully integrated “reserve” maps are part of this shortfall, as the instruments and measurement methods to obtain the orbital and surface data sets.

Related Shortfalls

ISRU-403: Instruments to measure Geotechnical regolith properties in extreme lunar environment
ISRU-404: Instruments to determine local regolith mineral/chemical composition
ISRU-439: Detection of subsurface ice at less than 10's m scale
ISRU-440: Instruments to characterize energy release profile of volatilizes in regolith
ISRU-441: Long-duration resource evaluation in the Lunar PSR environment
ISRU-442: Predictive Water Favorability Model
ISRU-549: Mars Resource Mapping and Reconnaissance
ISRU-776: Lunar Resource Mapping and Reconnaissance

Metrics

- Resource identification at exploration scales (depth, spatial)
- Area Coverage of resource favorability models/maps (with quantified uncertainty)

ID	Shortfall Title
1578	Extraction and separation of water from extraterrestrial surface material

Description

Water is a critical resource for exploration, both in its raw form and processed into hydrogen and oxygen. Accessing locally sourced water bolsters life support and makes it possible to produce propellants, both oxygen and fuel, in-situ. Water has been identified in the regolith on both the Moon and Mars. This includes water as ice in the permanently shadowed region (PSR) of the lunar poles and in the Martian subsurface. Martian regolith also contains hydrated minerals that may also be a source of water. Water extraction technology is dependent on the location and form of this water (for example mining a subsurface glacier vs hydrated mineral extraction from surface material). Techniques to mine or acquire the water, and potentially other volatiles, so they are not volatilized (lost) to the environment in the process is a challenge, as is hardware operations in harsh water-bearing environments (lunar PSRs, Martian subsurface). This shortfall addresses the acquisition of the water (e.g., excavation of icy regolith, water extraction), the capture or retention of that water, and the separation of water from other volatile species (e.g., purification). The technologies must be applicable to commercial scales (tons of product per year).

- Processing the extracted water into a ISRU commodity (e.g.. propellants, purified water for life support) is covered under another shortfall.
- Extracting other volatile (non-water) species is addressed in a separate shortfall.

Related Shortfalls

ISRU-550: Mars surface material processing for water
ISRU-551: Mars subsurface ice acquisition and processing for water
ISRU-558: Size sorting of granular regolith over long duration operations for ISRU.
ISRU-559: Mineral separation/beneficiation methods for long term ISRU operations
ISRU-560: Hardware for crushing hard/icy regolith w/ minimal resource loss
ISRU-561: Sensors for real-time monitoring of resource status for ISRU processing operations
ISRU-562: Regolith transfer hardware for long duration ISRU operations
ISRU-563: Sensors for evaluating regolith flow during transfer
ISRU-567: In-situ resource extraction & collection in Lunar PSRs
ISRU-568: Lunar volatile extraction in reactors/enclosures in PSRs
ISRU-569: Regolith tolerant valves for low temperature - lunar PSRs
ISRU-575: Sensors to monitor ISRU process gases
ISRU-580: ISRU water cleanup and water quality measurement
ISRU-581: ISRU System modeling
ISRU-583: Lunar Water System Integration and Testing
ISRU-1334: Mars ISRU System Level Integration and Testing
AMSC-384: Excavation of hard regolith/ice material
AMSC-385: Regolith and resource delivery system
AMSC 386: Mechanisms and mobility components for long-duration operations with abrasive regolith in lunar environmental conditions

Metrics

- Production rate of water
- Energy/Power draw normalized to production rate
- System up-mass/volume
- Maintainability (e.g.. Life cycle/wear, years of operation, required terrestrial consumables)

ID	Shortfall Title
1579	Extraction and separation of non-water volatile resources from Lunar regolith

Description

A variety of volatile resources are bound to the lunar regolith both in the cold traps (such as permanently shadowed craters) and as implanted solar wind gases. While water is a volatile, this shortfall specifically addresses other species that may be of interest. Within the cold traps LCROSS detected a variety hydrogen, nitrogen, and/or carbon bearing species whereas solar wind volatiles can include carbon, nitrogen, hydrogen, and helium. These could be processed into consumables for life support, nutrients for plant growth, propellants, etc.. Some of these volatiles may be liberated in the process of other ISRU activities, such as water extraction, but would require additional separation and processing steps to isolate them and/or generate the desired product. The technologies must be applicable to commercial scales (potentially tons of product per year).

- Water is also a volatile, but it is addressed specifically in a separate shortfall.

Related Shortfalls

ISRU-558: Size sorting of granular regolith over long duration operations for ISRU.
ISRU-559: Mineral separation/beneficiation methods for long term ISRU operations
ISRU-560: Hardware for crushing hard/icy regolith with minimal resource loss
ISRU-561: Sensors for real-time monitoring of resource status for ISRU processing operations
ISRU-562: Regolith transfer hardware for long duration ISRU operations
ISRU-563: Sensors for evaluating regolith flow during transfer
ISRU-567: In-situ resource extraction & collection in Lunar PSRs
ISRU-568: Lunar volatile extraction in reactors/enclosures in PSRs
ISRU-569: Regolith tolerant valves for low temperature - lunar PSRs
ISRU-575: Sensors to monitor ISRU process gases
ISRU-576: Separation & Collection of secondary volatile species
ISRU-581: ISRU System modeling
ISRU-583: Lunar Water System Integration and Testing
AMSC-384: Excavation of hard regolith/ice material
AMSC-385: Regolith and resource delivery system
AMSC 386: Mechanisms and mobility components for long-duration operations with abrasive regolith in lunar environmental conditions

Metrics

- Production rate
- Energy/Power draw normalized to production rate
- System up-mass/volume
- Maintainability (e.g. Life cycle/wear, years of operation, required terrestrial consumables)

ID	Shortfall Title
1580	Extraction and separation of oxygen from extraterrestrial minerals

Description

Resources are bound within the mineral components of extraterrestrial surface materials (e.g., regolith, rock). On the lunar surface for example, oxygen makes up around 40% of the regolith, bound in mineral oxides. While mineral composition can vary across the planetary surface, some resources (like the oxygen) are ubiquitous, thus very accessible to a variety of exploration architectures. The energy to release oxygen from the minerals is high and typically requires high temperatures and/or chemical reactants for extraction. These extraction systems necessarily include material handling systems (excavation/delivery, size sorting, etc.), the extraction reactor, gas handling and separation processes that are regenerative, and sensors to understand reaction process/efficiencies. The harsh environment that these systems must operate (temperature, regolith induced wear) and the long-term operation required of these systems (years) are significant, and unique, technology challenges for ISRU. The technologies must be applicable to commercial scales (tons of product per year).
The focus of this shortfall is currently the Moon. While Mars regolith also contains mineral oxides, the main target for oxygen on Mars is the carbon dioxide in the atmosphere.

- This shortfall addresses oxygen from surface minerals. Oxygen from water is addressed in separate shortfall.
- Metal/metalloids are often a byproduct oxygen extraction system but are addressed in a separate shortfall.
- While this shortfall includes some oxygen separation/purification, the requirements are dependent on the use case. A separate shortfall addresses processing of the products into consumables.

Related Shortfalls

ISRU-558: Size sorting of granular regolith over long duration operations for ISRU.
ISRU-559: Mineral separation/beneficiation methods for long term ISRU …
ISRU-560: Hardware for crushing hard/icy regolith with minimal resource loss
ISRU-561: Sensors for real-time monitoring of resource status for ISRU …
ISRU-562: Regolith transfer hardware for long duration ISRU operations
ISRU-563: Sensors for evaluating regolith flow during transfer
ISRU 564: Oxygen Extraction from lunar regolith
ISRU-565. Regolith tolerant valves for high temperatures
ISRU-575: Sensors to monitor ISRU process gases
ISRU-578. CO/CO2 Separation and Recycling
ISRU-581: ISRU System modeling
ISRU-582: Lunar O2 System Integration and Testing
ISRU-729: Solar Thermal Power for ISRU
ISRU-1280: Regenerative contaminant removal systems for ISRU Product/Reagent
AMSC-369:Excavation of granular (surface) regolith material for ISRU …
AMSC-385: Regolith and resource delivery system
AMSC 386: Mechanisms and mobility components for long-duration operations …
AMSC-426: In-situ Analysis of Input Material

Metrics

- Production rate of oxygen
- Energy/Power draw normalized to production rate
- System up-mass/volume
- Maintainability (e.g., Life cycle/wear, years of operation, required terrestrial consumables)

ID	Shortfall Title
1581	Extraction and separation of extraterrestrial atmospheric resources and gaseous products/reactants

Description

Gaseous resources include extraterrestrial atmospheres as well as gaseous products and reactants from surface elements including regolith ISRU systems, ullage propulsion gases, and habitation assets. The primary near-term interest is the Mars atmosphere where the Carbon Dioxide can be converted to Oxygen. Other Mars atmospheric constituents such as Nitrogen can also be of use. This shortfall addresses the acquisition and initial processing of the resource. For the Mars environment this includes acquiring the CO_2 from the atmosphere (which may require pressurization), filtering contaminants (e.g., dust), separating other constituents using regenerative technologies, and extracting the Oxygen from the CO_2. The technologies must withstand the unique environments of ISRU including high temperatures and potentially 'dirty' gas streams (e.g.. dust, contaminants) over long term operation (years) with limited maintenance. The technologies must be applicable to commercial scales (tons of product per year).

- Note that the Mars Oxygen ISRU Experiment, MOXIE, onboard the Mars Perseverance rover has demonstrated CO_2 to O_2 conversion at subscale in 2021, but additional scalability challenges must be addressed for commercial applications.

Related Shortfalls

ISRU-443: Mars atmosphere collection and pressurization for ISRU
ISRU-554: Mars atmosphere carbon dioxide separation
ISRU-555: Mars atmosphere nitrogen/argon separation and collection
ISRU-556: Mars atmosphere dust filtration
ISRU-570: Carbon Dioxide Conversion to Oxygen
ISRU-575: Sensors to monitor ISRU process gases
ISRU-578. CO/CO_2 Separation and Recycling
ISRU-581: ISRU System modeling
ISRU-1280: Regenerative contaminant removal systems for ISRU Product/Reagent Gas Streams
ISRU-1334: Mars ISRU System Level Integration and Testing

Metrics

- Production rate
- Energy/Power draw normalized to production rate
- System up-mass/volume
- Maintainability (e.g.. Life cycle/wear, years of operation, required terrestrial consumables)

ID	Shortfall Title
1582	Extraction and separation of metals/metalloids from extraterrestrial minerals

Description

Resources contained in the mineral components of extraterrestrial surface materials are a key for ISRU. While regolith composition can vary across the planetary surface, some resources are ubiquitous, thus very accessible to a variety of exploration architectures. The products of interest in the near term are oxygen and various metals/metalloids for manufacturing feedstock (aluminum, silicon, etc.). While metal is often a byproduct oxygen extraction systems, additional processing is required. The energy to release mineral-bound resources is high and typically requires high temperatures and/or chemical reactants for extraction. Often processing of molten material is required for metal/metalloid extraction. Since minerals at different locations have different metal content, processes will need to be tailored for the mineral and metal/metalloid of interest (e.g. lunar polar regolith is poor in iron & titanium). These extraction systems necessarily include surface material (e.g., regolith, rock) handling systems (excavation/delivery, size sorting, etc.), the extraction reactor, gas handling and separation processes that are regenerative, and sensors to understand reaction process/efficiencies. The harsh environment that these systems must operate (temperature, regolith induced wear) and the long-term operation required of these systems (years) are significant, and unique, technology challenges for these ISRU systems. The technologies must be applicable to commercial scales (tons of product per year).

- Refining and feedstock production processes to convert raw metal/metalloid into a useable form is addressed in a separate shortfall
- Oxygen is often a byproduct of metal/metalloid extraction systems but is addressed in a separate shortfall.

Related Shortfalls

ISRU-558: Size sorting of granular regolith over long duration operations for ISRU.
ISRU-559: Mineral separation/beneficiation methods for long term ISRU operations
ISRU-560: Hardware for crushing hard/icy regolith with minimal resource loss
ISRU-561: Sensors for real-time monitoring of resource status for ISRU processing.
ISRU-562: Regolith transfer hardware for long duration ISRU operations
ISRU-563: Sensors for evaluating regolith flow during transfer
ISRU 566: Metal extraction from Regolith
ISRU-565. Regolith tolerant valves for high temperatures
ISRU-575: Sensors to monitor ISRU process gases
ISRU-578. CO/CO2 Separation and Recycling
ISRU-581: ISRU System modeling
ISRU-582: Lunar O2 System Integration and Testing
ISRU-729: Solar Thermal Power for ISRU
ISRU-1280: Regenerative contaminant removal systems for ISRU Product
AMSC-369:Excavation of granular (surface) regolith material for ISRU consumables
AMSC-385: Regolith and resource delivery system
AMSC 386: Mechanisms and mobility components for long-duration operations…
AMSC-434: Basic transportation of loose regolith within an AM system for …
AMSC-426: In-situ Analysis of Input Material

Metrics

- Production rate
- Energy/Power draw normalized to production rate
- System up-mass/volume
- Maintainability (e.g.. Life cycle/wear, years of operation, required terrestrial consumables)

ID	Shortfall Title
1583	Produce propellants and mission consumables from extracted in-situ resources

Description

Once resources are extracted from the extraterrestrial source, additional processing maybe required to convert them into the consumable or commodity of interest. For example, water, once extracted and purified, could be used as is, or it can be converted into oxygen and hydrogen for propulsion. Other volatiles or reaction products such as nitrogen, carbon, etc. can be processed into other consumables for life support, plant growth, etc. Carbon sources from life support systems and extraterrestrial resources can be combined with hydrogen and other collected gases to produce hydrocarbon fuels, plastics, and nutrients. This shortfall addresses the technologies needed to do this additional refining and can include electrolysis, gas separation systems, and reactors. These technologies must withstand the unique environments of ISRU including extreme temperatures and potentially 'dirty' product streams (regolith dust, chemical contaminants) for long term operation (years) with limited maintenance. The technologies must be applicable to commercial scales (tons of product per year).

- This shortfall addresses consumables but does not address manufacturing feedstock production and refining, which is in another shortfall.

Related Shortfalls

ISRU-571: Methane production with ISRU
ISRU-572: Long Duration Water Electrolysis
ISRU-577: Regenerative gas dryers to remove water before liquefaction
ISRU-579: H2/CH4 Separation and Recycling
ISRU-581: ISRU System modeling
ISRU-582: Lunar O2 System Integration and Testing
ISRU-583: Lunar Water System Integration and Testing
ISRU-589. ISRU from Waste materials
ISRU-1333. ISRU for Novel Products
ISRU-1334: Mars ISRU System Level Integration and Testing
CFM-879: Cryogenic Propellant Storage)
CFM-1226: In Situ Cryogenic Fluid Liquefaction

Metrics

- Production rate/processing rate
- Energy/Power draw normalized to production rate
- System up-mass/volume
- Maintainability (e.g.. Life cycle/wear, years of operation, required terrestrial consumables)

ID	Shortfall Title
1584	Produce manufacturing and construction feedstock from extracted in-situ resources

Description

Extraction of metals from regolith can be used to support surface construction and manufacturing efforts. However, the raw resource will need to be refined into a form that is usable for manufacturing systems. Bulk regolith itself is also a viable construction material. Production of binders from waste materials and/or product streams (e.g.. hydrocarbons, plastics) can be accomplished with ISRU processes. Raw resources extracted from surface minerals (e.g.. Metals) will require purification and refining to meet application needs. It must also be processed into a useable form (e.g.. wire, ingots, bars) to generate a manufacturing feedstock. Since the feedstock and the manufacturing & construction technique are closely related, close coordination is required with Manufacturing & Construction. Raw bulk regolith may also require modification and/or processing for use a construction material (berms, structures, etc..). So, in addition to refining and feedstock production, this shortfall also addressed bulk regolith collection and handling considerations as well as the production of granular material (regolith) binders from ISRU resources (waste hydrocarbons, plastics, etc..) for construction use. The technologies must be applicable to commercial scales (tons of product per year).

- Note that metal extraction from the regolith minerals is covered in a different shortfall.

Related Shortfalls

ISRU-558: Size sorting of granular regolith over long duration operations for ISRU.
ISRU-560: Hardware for crushing hard/icy regolith with minimal resource loss
ISRU-561: Sensors for real-time monitoring of resource status for ISRU processing..
ISRU-562: Regolith transfer hardware for long duration ISRU operations
ISRU-563: Sensors for evaluating regolith flow during transfer
ISRU-589. ISRU from Waste materials
ISRU-1333. ISRU for Novel Products
AMSC-385: Regolith and resource delivery system
AMSC 386: Mechanisms and mobility components for long-duration operations
AMSC-434: Basic transportation of loose regolith within an AM system for deposition
AMSC-426: In-situ Analysis of Input Material
AMSC-432: Extrusion of molten materials (regolith or metal / regolith blend)
AMSC-667: Extrusion of Polymer/Regolith-based material for in-situ additive …
AMSC-428: Development of ISRU-based 'concrete' reinforcement materials.
AMSC-433: Extrusion of cementitious (binder plus regolith as aggregate) materials.
AMSC-430: Laser Sintering of Regolith
AMSC-431: Microwave Sintering of Regolith
AMSC-427: ISRU-derived Materials to Usable Construction Feedstock
MANU- 801: Inability to produce manufacturing feedstocks in situ from lunar or …

Metrics

- Production/processing rate
- Energy/Power draw normalized to production rate
- System up-mass/volume
- Maintainability (e.g.. Life cycle/wear, years of operation, required terrestrial consumables)

ID	Shortfall Title
581	ISRU System Modeling

Description

ISRU systems involve many components/subsystems; interface conditions between these are key to design of viable system hardware. Components/subsystems are often modeled with physics-based models and empirical test data to facilitate hardware scaling, con-ops planning, and optimization. These models must be pulled together into a full ISRU system model to enable scaling studies, concept of operations, and optimization at the system level; as well as getting system level mass/power predictions for mission architecture planning. Flexible, widely available platforms are needed that allow for subsystems to be input as modules and swapped to evaluate different technology options in trade studies. These trade studies are critical to architecture definition activities. Validating the models with integrated system tests (subsystems and end to end) is also a key aspect of this shortfall.

Related Shortfalls

ISRU-582: Lunar O2 Int & test
ISRU-583: Lunar water Int & test
ISRU-1334: Mars Int & Test

Metrics

- Modularity: Number and level of component/system modules
- Parametric Optimization capabilities
- Useability/availability of software

ID	Shortfall Title
1585	Extraterrestrial surface environmental simulators, test facilities, and test sites

Description

Flight hardware development, and the preceding technology development efforts, require appropriate test platforms to validate design. These test platforms are required to simulate some or many aspects of the relevant extraterrestrial environments including temperature, pressure, dust/regolith, solar simulation, electrical charging, etc. No one simulator exists that accomplish all conditions. While test facilities exist at NASA, and partner entities, not all environmental conditions are addressed in the combinations required for a given system. Critically, as we move forward to a long-term sustainable commercial infrastructure on the Moon and beyond, the demand for these test platforms (and their abilities) will increase. This shortfall is broad to cover a variety of needs but includes test facilities (e.g.. environmental chambers), analog test/field sites, proving grounds, and virtual test environments. Also included here is the production and management of regolith simulant materials (including dust and bulk regolith simulants), which are required to test hardware that interacts directly with the surface.

Related Shortfalls

ISRU-582: Lunar O2 Int & test
ISRU-583: Lunar water Int & test
ISRU-1334: Mars Int & Test
ISRU-836: Lunar Dirty Thermal Vacuum Large Test chambers
AMSC-1045: Effects of dust deposition on systems, including thermal, optical, & mechanical
AMSC-TBD: Advanced Modeling and Test Capabilities to Characterize Dust Effects on Hardware

Metrics

- Hardware size accommodation
- Parameters simulated vs parameters needed for test
- Availability/accessibility

ID	Shortfall Title
361	Surface Mating Mechanisms

Description

Vehicle/module mating systems are required for surface operations where two or more vehicles are mated together. Depending on the application, these surface mating mechanisms may need to be 1) be sufficiently lightweight and dust tolerant; 2) mate systems aligned by wheeled rovers and systems installed via EVA or EVR; 3) include required fluid coupling interfaces to accommodate sustainable refueling of cryogenic and storable fluids and high-pressure gases; 4) include data, power, thermal, mechanical support interfaces; 5) include versions applicable to lunar and Mars surface operations; 6) include crew passage variations, and smaller optimized variations for non-crew passage applications such as robotic refueling, refurbishment, logistics, ISRU, etc.; and 7) include design and interfaces for incorporation of pre-fabricated docking systems, pressurized hatches, and other interfaces into large scale regolith-based surface construction habitats. These various interfaces would allow pressurized rovers or mobile habitats to dock with each other and regolith-based surface habitats, enable crew transfer between elements without the need for EVA, and direct interfacing to robotic rovers for charging, data transfer, fluid transfer, etc.

Related Shortfalls

RPOC-500, RPOC-506, RPOC-849: Surface Mating/Attachment and Pressurized Transfer of Crew and Cargo
AMSC-995: Dust Tolerant Components
RPOC-1508: International Surface Mating Interface Standard and Specification
SAT S&A-1499, SAT S&A-1507: Resource Transfer Umbilicals for power/data and fluid
SAT S&A-849: Docking System Seals That Are Tolerant to Space Environments, Mission Duration
AMSC-1047: Surface Dust Mitigation via Active Technologies
RPOC-TBD: Surface proximity operations/rendezvous navigation sensors and targets
AMSC-TBD: Verification of interoperability
AMSC-TBD: Mechanical/electro-mechanical Actuation (NEW?)
AMSC-1067: Packaging and deployment of inflatable softgoods

Metrics

- Interoperable compatibility
- Life/Cycles
- Passageway size/shape
- Mass
- Power
- Reliability
- Maintainability

ID	Shortfall Title
379	Upgrade or Install Instruments on Large Space Observatories

Description

Upgrading or installing new instruments on-orbit enables a significant opportunity for transformational science and programmatic launch agility for large space observatories. Revolutionary instruments with larger detectors and new measurement techniques propel our understanding with landmark discoveries. Since its 1990 launch, the Hubble Space Telescope (HST), largely due to five servicing missions to repair and add functionality, has changed our fundamental understanding of the universe and has been the most productive science mission in the history of NASA. HST serves as the mission archetype for servicing Habitable Worlds Observatory (HWO). This shortfall targets observatories where several instruments are aligned with a single telescope as opposed to independent instruments hosted on a persistent platform (e.g.., ISS). Related shortfalls capture instrument interfaces, installation accommodations, and robotic technologies necessary to expand the HST- and ISS-derived capabilities to achieve routine and autonomous robotic operations at potential Sun-Earth L2 observatory.

Related Shortfalls

SAT S&A-692: Contamination concerns associated with servicing scientific observatories
SAT S&A-377: Precision instrument latches for Great Observatories
ROBO-455: Extra-vehicular repositionable-base robotic manipulators
SAT S&A-375: Affordable on-demand unpressurized cargo module delivery to in-space assets
SAT S&A-694: Thermal safekeeping approach for unpowered on-orbit or on-surface installation
SAT S&A-691: Modular and scalable thermal design for on-orbit Instrument Installation
AV-449: High Bandwidth Deterministic Wireless Networks

Metrics

- Science return
- Programmatic launch agility
- Structural parasitic mass

ID	Shortfall Title
1506	In-Space & Surface Transfer of High-Pressure Gases

Description

Planned lunar and Mars exploration require automated transfer of inert high-pressure pneumatic fluids, which includes both automated in-space and Lunar/Mars surface operations. This shortfall captures the required activities to enable efficient pneumatic fluid transfer with acceptable risk posture, which includes modeling, testing (to validate models), connectors and actuators, etc. Key challenges related to couplings include; a) reliable automation and fault tolerance for human-rated systems; b) very-low-release-fluid, dust-tolerant couplings to minimize contamination or degradation of client spacecraft or observatory systems and hazards to human crew; c) robot-friendly closeout and mating accommodations; d) couplers and pneumatic fluid systems for spacecraft w/o docking systems; and e) fluid metering and leak detection.

In-space applications generally applicable to many users include propulsion system high-pressure gas replenishment to support refueling of pressure regulated systems or blowdown systems where existing pressurant has been vented.

Related Shortfalls

SAT S&A-374: Storable Propellant Mass Accounting
ECO-517: Pressurant accommodation and ullage control during in-space fluid transfer
SAT S&A-370: Venting of PMD Tanks in Microgravity
SAT S&A-371: Efficient Pneumatic Compressor/Pump for In-Space Gas Transfer
SAT S&A-857: Flight-Qualified Pneumatic (N and He) Compressors
AHS-357: High pressure oxygen for EVA tank resupply and medical response
LOGISTICS-878: High pressure oxygen for EVA tank resupply
LOGISTICS-972: Nitrogen Resupply for Habitat Pressure Sustainability

Metrics

- Modeling and simulation validation % error
- Efficient compressor % efficiency
- Mass accounting % accuracy

ID	Shortfall Title
1138	In-Space Transfer of Electric Propulsion Propellant

Description

Both Solar Electric and Nuclear Electric Propulsion (SEP and NEP) transportation systems require, in-space xenon transfer, with a reference NEP architecture requiring up to 100 t (TBR) of transfer in cis-lunar space. Architectures require near-zero-loss xenon transfer with large volumes supported by repeated, autonomous transfers of multiple (TBR) metric tons. To meet potential desired timelines and transfer volume, high-rate transfer (i.e., average flow rate up to 15 g/s) may be needed.

Related Shortfalls

SAT S&A-371: Efficient Pneumatic Compressor/Pump for In-Space Gas Transfer
SAT S&A-372: In-space Xenon Transfer Technologies

Metrics

- Propellant Transfer Rate
- Modeling and simulation validation % error

ID	Shortfall Title
512	Cooperative interfaces, aids, and standards

Description

Standard interfaces to allow interaction between ISAM systems and servicing or assembly agents must be specified to support interoperability between systems. Without such standards and prepared interfaces, each mission would require non-recurring engineering of both spacecraft components and robotic end-effectors or tools. Incorporating prepared cooperative interfaces for ISAM will enable more capable and robust missions, including inspection, relocation, refueling and fluid transfer, repair, replacement, upgrade, and simplified integration ISAM capabilities into space assets.

Related Shortfalls

SAT S&A-1270: Capture and grapple interfaces, aids, and standards
SAT S&A-1497: Rendezvous and proximity operations interfaces, aids, and standards
SAT S&A-1507: Fluid transfer interfaces, aids, and standards
SAT S&A-1498: Closeout interfaces, aids, and standards
SAT S&A-1499: Power and data interfaces, aids, and standards
SAT S&A-1500: Repair interfaces, aids, and standards
SAT S&A-1456: Scalable electro-mechanical latches for Instrument Installation on Great Observatories
SURFACE-1380: Interfaces designed for robotic manipulator access
ROBO-871: Robot Friendly MLI Closeout Techniques

Metrics

- Existence of interface standard
- Existence of designs that use interface standard
- Standard demonstrated in flight

ID	Shortfall Title
376	Modular design for in-space installation

Description

ISAM can enable modular spacecraft design, where the spacecraft's subsystems are decomposed into swappable modules that connect with known interfaces. Types of modules include structural, power, data, insulation, shielding, fluid transfer, opto-mechanical, thermal, attitude determination and control systems, and propulsion. Incorporating this design paradigm into spacecraft development still requires development of the modular building blocks, the ecosystem of interfaces between them, and the operational shift in spacecraft development and testing. Development of standard modules and interfaces between them will allow for modular spacecraft design and in-space assembly. Modular design enables the replacement of obsolete instruments on a large observatory, as has been demonstrated on the Hubble Space Telescope (HST). Modular design also could accelerate ground development and testing, and it prioritizes early definition of subsystem interfaces, which could simplify and accelerate subsystem development. Modular design increases the opportunity to validate interfaces for assemblies that are too large in scale to "test as you fly" or even assemble on the ground. Incorporating modular design interfaces also increases the programmatic flexibility for when components are delivered and integrated and how anomalies are resolved.

Related Shortfalls

PWR-1103: Common modular building blocks for energy storage with improved performance relative to SOA.
AV-1065: Modular and Interoperable Avionics Architecture
PWR-872: Modular battery charger and management system
AMSC-623: Design of Electrical Harness for in-situ installation
SAT S&A-512: ISAM cooperative interfaces, aids, and standards

Metrics

- Parasitic Mass and Volume
- Number of robot motions required to install module
- Number of single-point failures
- Number of module types
- Adaptability
- Reuse/Reconfigurability

ID	Shortfall Title
513	Robotic Assembly and Construction of Modular Systems for Sustained In-Space Infrastructure

Description

Robotic assembly and construction represent a new paradigm of operating in space—for both orbital and surface operations. This capability enables future mission designers to flexibly create and evolve systems that are larger than previously possible, repair and upgrade systems robotically, and leverage support capabilities (ISRU, material logistics, robotic agents, and more) to reduce cost and help create an economical, scalable, and sustained presence in space. Structures can be designed to offer varying benefit depending on mission needs: high precision, high strength, reconfigurability, or other capabilities. Quantitative metrics like size, reliability, and precision are application-dependent, and systems need not be large to benefit from the ability to evolve and maintain itself over time.

Related Shortfalls

SAT S&A-1409: Structural Systems Designed to be Robotically Serviced and Manufactured In-space
SAT S&A-1471: Structural Systems Designed to be Robotically Outfitted (payload install, wiring, fluid, gas routing and connections)
SAT S&A-1412: Multi-agent Autonomous Robotic Systems for Assembly and Construction
SAT S&A-456: High precision modular structures
SAT S&A-1414: Architectures and Framework for Economical and Scalable Autonomous Robotic Construction
SAT S&A-1411: Autonomous Robotic Structure Maintenance and Repair System
THERMAL-1212: Lightweight, High Temperature Radiators for NEP
THERMAL-1475: Reversible, high temperature fluid interface

Metrics

- Size of assembled structure
- Assembly throughput
- Cost per part
- Assembly reliability

ID	Shortfall Title
1483	Enable commercially-provided Rendezvous, Proximity Operations, and Capture (RPOC) products and services

Description

ISAM-enabled missions involve the aggregation of materials and manipulators in space, which require rendezvous, proximity operations, and capture (RPOC) capability. Current RPOC systems are large, expensive, and usually limited to a single use case or client. Advancements in RPOC are required to accelerate industry's development of lower-cost RPOC hardware and software packages that can be used in multiple use cases. Some near-term examples of ISAM capabilities enabled by these advancements include inspection, payload delivery, relocation, repair, upgrade, and disposal.

While it is possible to perform inspections and payload deliveries with today's state of the art technology, doing so requires expensive vehicles, bulky appendages, and/or astronaut EVAs, which are cost prohibitive and risky. Leveraging small satellites for RPOC applications like inspection and cargo delivery reduces the cost to provide this capability to missions that may not be possible under cost constraints.

Related Shortfalls

RPOC-373: Small Satellite RPOC with close free-flying inspection of a high-value asset
RPOC-452: Small Satellite RPO Propulsion Capability
SAT S&A-375: Affordable on-demand unpressurized cargo module delivery to in-space assets
RPOC-637: Small Satellite Docking
RPOC-1501: Capture of legacy spacecraft
SMALLSAT-1432: Rendezvous, Proximity Operations, and Debris Remediation using Small Spacecraft

Metrics

- Approval Process for RPOC
- Cost
- COTS-Enabling GNC sensing performance for ISAM
- Response Time and frequency of delivery
- Destination
- COTS-Enabling Propulsion fault tolerance
- COTS-Enabling Propulsion Performance
- COTS-Enabling ISAM interfaces

ID	Shortfall Title
498	Broad and dependable supply chain for space-qualified robotic hardware, electronics, and associated software

Description

This shortfall addresses the need for a broader, more diverse supply chain for space-qualified robotic hardware that enables everything from standardized to customized robotic systems. A healthy supply chain for space-qualified robotic hardware, software, sensors, and interfaces will reduce robotic development time and cost, enabling the use of more affordable servicing and assembly robotics. The abundant availability of robotic systems for use in space applications would encourage the design of robotic capabilities in missions and architectures during the early design phase, and therefore promote an ecosystem of ISAM-ready clients and operations.

Related Shortfalls

AMSC-429: Lacking COTS robotics for process tooling manipulation
ROBO-455: Extra-vehicular repositionable-base robotic manipulators
ROBO-683: External Robotic and Autonomy Capabilities Suitable for the Extreme Space Environment
ROBO-684: Efficient Fault Tolerant Robotic Actuation
ROBO-1283: Robotic Mobile Manipulation for Surface Infrastructure Assembly, Maintenance, and Logistics Management

Metrics

- Sufficient Domestic Suppliers
- Lead time for procurement
- Cost

ID	Shortfall Title
1262	**Remediation of Small Debris**

Description

There may be up to 1 million pieces of debris that are 1-10cm diameter. Nearly 100 million pieces of debris with 1-10mm diameter may be present. Solutions for tracking and removal of small debris must be able to address a substantial fraction of such debris on a timescale that is relevant to spacecraft operators.

For debris smaller than 10 cm diameter, existing space situational awareness capabilities cannot track the debris well enough for satellite operators to mitigate risk by performing conjunction assessments. Some proposed capabilities for removing small debris, such as the use of ground- or space-based lasers, only need to track the debris for a few minutes—just long enough to nudge the debris into the atmosphere. While it is a simpler challenge than tracking for conjunction assessment, the ability to track small debris well enough for removal has not been demonstrated. To achieve tracking or removal of small debris at scale, capabilities must be as low-cost and as highly scalable as possible. Thus, breakthrough solutions to these capability shortfalls and others are required.

Related Shortfalls

INSTR-1472: Small orbital debris and MMOD Detection Systems
COMM-1279: Orbit determination and tumble rate sensing for orbital debris
SAT S&A-1331: Space and ground-based laser systems for tracking, nudging, and removing orbital debris
SAT S&A-1503: Laser-Matter Interactions for orbital debris remediation
SAT S&A-1504: Adaptive Optics for Beam Control through Atmosphere at Low Elevation Angles
SAT S&A-1505: High Energy Rep-Rated Laser Designs for orbital debris remediation
SURFACE-1379: Debris early warning system
SURFACE-1352: Surface-based instrumentation for full field debris characterization

Metrics

- Risk reduction value
- Cost of remediation
- Total items remediated

ID	Shortfall Title
1476	Remediation of Large Debris

Description

Debris remediation services are those that move, remove, or reuse extant debris to reduce the risks associated with it. It is desired that innovative systems that can perform remediation services would be scalable to bulk remediation services, potentially by remediating risk from different types of debris and/or remediating multiple debris items per mission. Potential methods include physical capture and disposal (via uncontrolled or controlled atmospheric entry), relocation (including via non-contact methods, and small relocations for just-in-time collision avoidance – likely the most cost-effective method), and reuse or recycling.

Orbital debris created by objects such as abandoned vehicle stages, non-functional satellites, and fragments of launched materials impedes our ability to use space by increasing the cost of space operations (maneuvering around debris), threatening the safety of astronauts and satellites, limiting the ability to launch spacecraft, and potentially rendering entire orbits unusable for a generation or more.

Related Shortfalls

SAT S&A-1331: Space and ground-based laser systems for tracking, nudging, and removing orbital debris
SAT S&A-1503: Laser-Matter Interactions for orbital debris remediation
SAT S&A-1504: Adaptive Optics for Beam Control through Atmosphere at Low Elevation Angles
SAT S&A-1505: High Energy Rep-Rated Laser Designs for orbital debris remediation
RPOC-538: Capture of large space debris
SAT S&A-512: ISAM cooperative interfaces, aids, and standards
RPOC-1501: Capture of legacy spacecraft
SAT S&A-1332: Controlled reentry via reusable debris remediation spacecraft
SAT S&A-1330: In-space attachable debris removal actuators
EDL-444: Small Spacecraft Propellentless Deorbit Devices
RPOC-1447: RPO with uncontrolled object
SMALLSAT-1432: Rendezvous, Proximity Operations, and Debris Remediation using Small Spacecraft
COMM-1279: Orbit determination and tumble rate sensing for orbital debris
SAT S&A-1502: Characterization of large debris geometry, materials, structural integrity, and passivation status.
PROP-611: Solar Electric Propulsion – High-DV ESPA-Class Spacecraft
MANU-1342: Recycling of Orbital and Surface Debris from Active Debris Remediation for advanced manufacturing

Metrics

- Risk reduction value; Cost of remediation; Total items remediated

ID	Shortfall Title
1477	Mitigation of New Orbital Debris Generation

Description

Technologies and methods that reduce the generation of new debris include advanced MMOD shielding, anti-fragmentation, improved post-mission disposal capabilities, reductions in intentional debris generation, and autonomous collision avoidance. From the White House Orbit Debris R&D Implementation plan: "Debris mitigation is defined as designing to prevent or limit the creation of new debris. It encompasses measures taken before an individual object becomes classified as debris. It includes any hardware or software configurations that would be implemented into the design of launch vehicles, satellites, or space missions and mission profiles that have the intention or outcome of minimizing the generation of debris in orbit. Add-on devices for trackability and on-board propulsion for spacecraft maneuverability, insofar as those technologies help prevent the creation of new debris, are also considered under this pillar."

The plan prioritizes the following as efforts for NASA: "minimizing the probability of accidental explosion of operational and defunct batteries, propulsion systems, and other subsystems/components with histories of explosions" (Section 1.2.2); "software to generate feasible close approach mitigation and maneuver instructions consistent with the physics-based and operational constraints of spacecraft and operators—and do so autonomously (section 1.4.1); capabilities to detect such strikes on-orbit (section 1.9.1, if CBA indicates there is value in this); "research to improve hypervelocity impact capabilities and develop new protection techniques and new shielding methodologies, such as developing new multifunctional shields using nanostructures or self-healing materials" (section 1.10.1); new technologies such as drag enhancement devices and automated disposal systems (1.11.1); affordable, available sensor technologies for micro/CubeSats to reduce tracking errors and increase accuracy of collision prediction (1.11.2).

Related Shortfalls

EDL-444: Small Spacecraft Propellentless Deorbit Devices
AMSC-750: Environmental protection materials for inflatable softgoods
AMSC-1098: Combined MMOD, Thermal and Radiation Shielding Weight Optimization
AMSC-926: Integrated structural health monitoring of inflatable softgoods
AUTO-1478**:** Autonomous onboard conjunction assessment (CA) and collision avoidance (COLA)
SMALL-1438: Autonomy, Edge Computation, and Interoperable Networking for Small Spacecraft

Metrics

- Post-mission disposal compliance rate; survivable MMOD size;

ID	Shortfall Title
1596	High Power Energy Generation on Moon and Mars Surfaces

Description

Fission surface power systems can enable robust operations on the Moon and Mars providing a high reliability sun-independent (i.e. provides power with sunshine or while in shadow) multi-kWe-scale power source. To support future high temperature reactors, sensors are needed for (1) rugged, accurate thermocouples for high temperature measurement in high radiation, (2) direct, accurate pressure measurements, (3) mass flow rate, (4) neutron flux measurement at high temperatures, and (5) In-situ corrosion monitoring.

Existing solar array systems do not provide sufficient durability or scale to support full scale ISRU production in the Lunar Pole thermal, dust , and radiation environment. Current technology for deployment of towers and reflectors is not optimized to gather sunlight low on the horizon as at the Lunar poles. Mission architects must know what capability will be available to them to start full-scale ISRU production operations.

Related Shortfalls

PWR - 502: Fission Surface Power
PWR - 1218: High temperature sensors for fission power systems
PWR - 504: Photovoltaic Arrays up to 50 kWe Increments
ASMC- 617: On-surface robotic assembly of vertical structures
ASMC- 1480: On-surface Outfitting of Lunar Structures

Metrics

- 40 kWe class system for Fission Surface Power
- 50 kWe class system for photovoltaic systems

ID	Shortfall Title
1597	Power for Non-Solar-Illuminated Small Systems

Description

Small rovers, science landers, and resource prospecting systems would benefit from 50-100 We up to multi-100 We, sun-independent power sources. These missions may span from short duration to multiyear timelines. There is a near term need for this product to provide key strategic capability for Artemis ISRU development in the understanding of the distribution of water ice in the permanently shadowed regions of the Lunar South Pole. Longer term needs are to provide power to distributed sensor payloads for long duration science investigations. Static and dynamic radioisotope systems (DRPS) include an interest in development and testing of power conversion technologies that utilize alternative isotopes to plutonium.

Related Shortfalls

PWR - 509: Radioisotope Heat/Power Source in 500 We Increment

THERMAL - 522: Freeze tolerant thermal components

PWR - 510: Low temperature batteries

Metrics

- Beginning of life power ranging from 50 – 500 We utilizing traditional and alternative fuel sources

ID	Shortfall Title
1595	Energy Storage to Enable Robust and Long Duration Operations on Moon and Mars

Description

Energy storage is a primary driver in the design of most science and exploration missions. These systems range from small scale lunar rovers and landers to ISRU and habitat systems for the Moon and Mars. This shortfall addresses a variety of energy storage needs to meet these mission demands.

- Industrial scale ISRU production facilities and crewed outposts will require large-scale, long life, maintenance-free energy storage.
- Mobility energy storage for scientific exploration and ISRU operations in PSRs require battery operations at low temperatures. Improvements in performance, reliability, and specific energy might result from advanced chemistries, novel packaging, and/or improved thermal management.
- Mission requirements vary but high specific energy batteries that have been designed to operate in, and survive, the lunar surface environment would benefit multiple applications. New technologies and/or modifications of existing commercial systems are considered.
- Space-rated energy storage systems that are modular may allow for repairs to be within a mission. Common modular building blocks for energy storage with improved performance relative to SOA are needed.
- The reliability of a modular system may be maintained by a corresponding modular battery charger. COTS Battery Management Systems do not match the radiation, safety redundancy, and modularity requirements needed.
- Common energy storage modules for multiple vehicles, EVA suits, and tools, along with associated standards that can be used by multiple organizations will help to minimize spares and development costs. Improvements to energy density, tolerance to extreme environments, long life and reliability benefit multiple applications.
- Space-rated Modular Smart Charger systems can allow predictive diagnosis of batteries to allow longer missions and life extensions.

Related Shortfalls

PWR - 505: Long Life Static Energy Storge up to 1 MWhe Increment
PWR - 510: Low Temperature Secondary Battery Modules up to 50 kWhe Increment
PWR - 745: Energy Storage for Planetary Surfaces
PWR - 872: Modular battery charger and management system
PWR - 895: Modular Battery: Energy density of low cycle life energy storage
PWR - 1103: Common modular building blocks for energy storage with improved performance relative to SOA.
PWR - 1192: Smart Charger (Predictive Diagnosis)

Metrics

- Specific energy (>200 Whr/kg) operating in the lunar environment
- Operation below 235 K

ID	Shortfall Title
1591	Power Management Systems for Long Duration Lunar and Martian Missions

Description

Power management systems provide monitoring, control, and regulation to ensure sufficient power is available at all stages reliably throughout a mission. State of the art electronics do not provide sufficient durability to support long duration operations in the Lunar and Martian thermal, dust, and radiation environments and are not maintainable in those environment.

Power management subsystems built from common, interchangeable building blocks that can be used across multiple vehicles and surface elements would optimize spares and reduce maintenance impacts for long duration in-space operations. Components must be replaceable at the card or board level; dust compatibility is necessary for applications where replacement would occur in the lunar or Martian dust environment.

Noncontact voltage and current sensors are needed to allow power system monitoring without the failure modes introduced with in-line sensors.

Related Shortfalls

PWR - 460: Reliable, Rad-Hard Power Electronic Power Converters
PWR - 732: Maintainable power management subsystems built from common, interchangeable circuit boards and back planes
PWR - 816: High reliability, radiation-tolerant space power management systems
PWR - 821: Noncontact sensors for power monitoring

Metrics

- % efficiency
- Long life and reliability (N+ redundancy)
- Power conversion devices specific power
- Life operation

ID	Shortfall Title
1592	High Power, Long Distance Energy Transmission Across Distributed Surface Assets

Description

High energy power generation is expected to be stationary (or with limited mobility/relocatability), requiring an ability to transmit power over large distances to a variety of users. This shortfall seeks to address those needs both for general use and specific use cases. These needs include:

- Operation of full-scale static assets (ISRU/outpost) require that power be transmitted up to 10s of km-distances across the surface from generation assets
- Superconducting cables of 10 kW capacity and 5 km length for use in permanently shadowed regions (PSR)
- Non-contact voltage and current sensors are needed to allow power system monitoring without the failure modes introduced with in-line sensors
- Scientific exploration and ISRU ice mining operations in PSR benefit from power transmitted from insolated regions to mobile assets in the PSR interior
- Electrically insulated transmission cable, spooling, and load connection systems that can be unrolled and deliver power point-to-point with 0.99 reliability at 1000 V (source and load) and at 10 kWe scale in the Lunar dust, MMOD, and thermal environments (both insolated and PSR), losing no more than 3% per km and at maximized delivered power per unit of cable system mass
- Wireless power transfer includes surface to surface and orbit to surface applications

Related Shortfalls

PWR - 503: Transmission Cable Systems up to 10 kWe Increment, AC and DC at > 1 kV
PWR - 508: Wireless Power Transmission up to 10 kWe Increment
PWR - 821: Noncontact sensors for power monitoring
PWR - 1158: Surface Power Transfer Cables /Connectors/Dust Compliant
PWR - 1394: Cabled Power Transmission in Permanently Shadowed Regions

Metrics

- Wireless: losing no more than 80% source-to-load over 5 km
- Wired: > 10kWe transmission at > 10 km with less than 3% loss

ID	Shortfall Title
1390	Power and Data Transfer in Dusty Environments

Description

Lunar and Mars surfaces present challenges of dust migrating into and interacting with electrical connections. These connectors range in size and voltage (up to 10kWe at < 200 VDC) and may include additional data transfer systems such as fiber optics. Connections may be made robotically or through crew assisted means. This shortfall includes physical connections as well as closely coupled wireless connectors.

Related Shortfalls

PWR - 732: Maintainable Power Management Subsystems Built From Common, Interchangeable Circuit Boards and Back Planes
PWR - 1158: Surface Power Transfer Cables/Connectors/Dust Compliant
PWR - 1394: Cabled Power Transmission in Permanently Shadowed Regions
AMSC - 995: Dust Tolerant Components
AV - 1406: Dust Tolerant Avionics Connectors
SURFACE - 1389: Cold and dust tolerant interface seals

Metrics

- Wireless SOA systems currently at 100W levels
- Dust tolerant connectors demonstrated in lab at 120 VDC and 1 kW levels

ID	Shortfall Title
1593	Lunar Surface Power Generation from ISRU Derived Resources

Description

Extended exploration and operations on the lunar surface will benefit from in-situ resource utilization (ISRU) derived power components. These range from energy generation and storage to power transmission systems. These may be developed fully from ISRU produced materials and/or may include minor component supplemented materials. Technologies and components include:

- Power transmission conductors and cabling
- Photovoltaic cells, blankets, and array structures
- Flow batteries with anolyte and catholyte ISRU derived components

Related Shortfalls

PWR - 1391: Long distance power cables from Lunar regolith minerals
PWR - 1392: Large scale solar power generation via photovoltaic blankets produced from Lunar regolith minerals
PWR - 1393: Large scale secondary chemical energy storage produced from Lunar regolith minerals
MANU - 1485: In-Space and On-Surface Manufacturing of Parts/Products from On-Surface and Terrestrial Feedstocks (Spares, Repairs, New Parts)
MANU - TBD: Produce Manufacturing and Construction Feedstock from Extracted In-Situ Resources

Metrics

- MW power across 100's km distances
- MW photovoltaic energy generation
- GWh storage capacity

ID	Shortfall Title
1594	Martian Surface Power Generation from ISRU Derived Resources

Description

Liquid oxygen / liquid methane fuel cells may become the power generation component of an ISRU-based economy on Mars. Primary power from liquid oxygen / liquid methane reactant storage may be a mass-optimal solution for certain Mars mobility assets and Landers. Developing high reliability, high power scalable systems will be required to meet this need.

Related Shortfalls

PWR – 511: CH_4/O_2 Primary Fuel Cell Power up to 10 kWe Increment

ISRU - 571: Methane Production with ISRU

ISRU - 570: Carbon Dioxide Conversion to Oxygen

Metrics

- To date, solid oxide fuel cells have been tested at 1 kWe-scale breadboard configurations

ID	Shortfall Title
1224	In-Space & Surface Transfer of Earth Storable Propellants

Description

Planned lunar and Mars exploration benefits from automated propellant transfer of hypergolic propellants, including both automated in-space and Lunar/Mars surface operations. This shortfall captures the required activities to enable efficient propellant transfer with acceptable risk posture, which includes propellant transfer modeling, testing to validate propellant transfer, connectors and actuators, etc.. Key challenges related to couplings include; a) material compatibility (especially oxidizer) and seal life issues to accommodate multiple on-orbit refuelings (w/ exposure of the seals); b) reliable automation and fault tolerance for human-rated systems; c) very-low-spill, dust-tolerant couplings to minimize contamination or degradation of client spacecraft or observatory systems and hazards to human crew; d) robot-friendly closeout and mating accommodations; e) couplers and fueling systems for spacecraft w/o docking systems; and f) fluid metering and leak detection.

Related Shortfalls

ROBO-374: Storable Propellant Mass Accounting
ECO-517: Pressurant accommodation and ullage control during in-space fluid transfer
SAT S&A-370: Venting of PMD Tanks in Microgravity
SURFACE-TBD: Surface-based fluid management for near/mid-term missions

Metrics

- Modeling and simulation validation % error
- Phase separator % propellant loss
- Propellant tank diaphragm material compatibility and reversible operability
- Mass accounting % accuracy

ID	Shortfall Title
1221	Mars Ascent Vehicle Propulsion

Description

A High gear ratio propulsion system is required to safely return crew and system(s) to Earth from Mars. Mars Ascent Stage performance has significant ripple impact throughout the architecture. Failure to achieve the Mars Ascent Stage performance objectives would likely impose additional risk and performance shortfalls on EDL systems.

If shortfall is not closed, Mars return architecture may not close with adequate margin.

This shortfall is largely an engineering development shortfall if using traditional propulsion system approaches. The RDRE is an alternative approach that requires technology development for the MAV application with higher performance.

Related Shortfalls

PROP-TBD: Large Pump-fed storage (NTO/MMH)
PROP-594: Cryogenic Propulsion - Reusable Liquid Rocket Engine (LRE) System
PROP-756: Supersonic Retropropulsion Engines
PROP-321: Supersonic Retropropulsion (SRP) Deep Throttle Engines
PROP-648: Materials for extreme environments

Metrics

- Specific Impulse target
- System Level Thrust

ID	Shortfall Title
544	Solar Electric Propulsion to Support Orbital Platforms

Description

The Advanced Electric Propulsion System (AEPS) Solar Electric Propulsion (SEP) capability is baselined for the Power and Propulsion Element (PPE) of the Gateway. This shortfall focuses on the maturation of a 12.5kWe magnetically shielded human rated Hall Effect Thruster to support the ~50kWe PPE system.

AEPS technology is necessary for Gateway platform functionality and operations. If the shortfall is not closed and a flight qualified AEPS is not delivered, the Artemis architecture leveraging Gateway is fundamentally non-viable.

Related Shortfalls

None

Metrics

- Power
- Thrust
- Specific Impulse
- Throughput
- Mass

ID	Shortfall Title
610	Solar Electric Propulsion - High Specific Impulse

Description

This shortfall is for higher performance electric propulsion solutions at commercially and Science Mission Directorate (SMD) relevant power levels (e.g.. ~3-10kWe per string)

Multiple NASA SMD Flagship missions have increased performance through the use of solar electric propulsion with higher specific impulse than SOA Hall Effect Thrusters; design reference missions include the Titan Saturn System Mission, Uranus Flagship Orbiter, Neptune Orbiter, Cryogenic Comet Sample Return, etc...

Commercial applications benefit from the ability to operate at higher thrust for orbit transfer / raising, but higher specific impulse during station keeping.

This shortfall could be closed through the full qualification of NASA Evolutionary Xenon Thruster (NEXT) over the full throttle range (partial throttle range demonstration on DART) or a High Voltage (i.e. High specific impulse) Hall Effect Thruster variant.

Related Shortfalls

None

Metrics

- Power
- Thrust
- Specific Impulse
- Total Impulse

ID	Shortfall Title
611	Sub-kW and kW Class Electric Propulsion Systems

Description

Fully flight qualified, high-throughput, radiation-tolerant, magnetically-shielded, sub-kW or kW-Class Xe Hall Effect Thruster Electric Propulsion string enabling high-ΔV ESPA-class deep space missions or Orbital Maneuvering Vehicles.

The technology is cost enabling for a range of commercial, DoD and science missions of interest. Target is for >2km/s of Delta-V for spacecraft equal or smaller than ESPA Grande opportunities.

Related Shortfalls

PROP-1430: Novel, Versatile, and Cost-Effective Propulsion Systems and Maneuverability for Small Spacecraft

Metrics

- Power
- Throughput
- Specific Impulse
- Efficiency

ID	Shortfall Title
612	In-Space Diagnostics for Electric Propulsion

Description

Plasma Diagnostic Package (PDP) for inflight characterization of AEPS 12.5 kWe thruster plume and spacecraft interactions during Gateway/PPE operations. Measurement/Sensor Suite includes the following:

[1] Ion Flux / Faraday Probe (A/m2);
[2] Ion Energy / Retarding Potential Analyzer (eV);
[3] Plasma Potential / Langmuir Probe (V);
[4] Plasma Density / Langmuir Probe (#/m3);
[5] Electron Temperature / Langmuir Probe (eV);
[6] Surface Erosion / Erosion Sensor or Photometer (mm/kh);
[7] Material Redeposition / Photometer or Quartz Crystal Microbalance (mm/khr);
[8] Discharge Current Oscillations / Pearson Coil (A);
[9] Plasma Plume Oscillations / High-Speed Faraday Probe (A/m2).

There is an acknowledged lack of capabilities to ground test high power electric propulsion in a relevant environment. In-Space diagnostics are critical for risk reduction and characterization of in-space performance.

Related Shortfalls

None

Metrics

- Mass
- Power Consumption – Peak and Continuous

ID	Shortfall Title
703	Rotating Detonation Rocket Engine (RDRE)

Description

Advanced pressure gain detonation combustion concepts to provide transformational CP performance for launch, in-space, and lander systems. The enhanced performance and mass/volume reductions associated with the technology can greatly increase deliverable payload.

Increased lander payload mass and reduced engine system volume requirements over conventional constant pressure rocket technology.

If the shortfall is not closed, the primary impact will be a forced reliance on conventional constant pressure rocket engines with significant increases in engine system mass & volume requirements leading to notable reduction in payload mass capability. The degree of impact to the lander element of the architecture is a dramatic reduction in deliverable payload and mission margin.

Unavailability of the technology and forced reliance on current state-of-art constant pressure rocket engines would dramatically reduce mission margin and potentially increase the number of cargo pre-deployment landings.

Related Shortfalls

PROP-TBD: In-Situ RDRE Environment Diagnostics
PROP-TBD: RDRE injector parameters and detonation dynamics design sensitivity
PROP-TBD: Time Resolved RDE Measurements
PROP-TBD: Combined Thermal-Structural Environments Modeling
PROP-TBD: Modeling and Computational Methods for Reduced RDRE CFD Computational Costs
PROP-TBD: Wave-tracking Adaptive Mesh Refinement
PROP-TBD: CFD-based RDRE Geometric Optimization
PROP-TBD: Liquid Spray Characterization in Detonation Environment
PROP-TBD: Condensed Phase Detonability
PROP-TBD: Conjugate Heat Transfer Modeling
PROP-TBD: RDRE Nozzle Flow Modeling
PROP-648: Materials for extreme environments

Metrics

- Chamber Length Reduction
- Specific Impulse vs. SOA

ID	Shortfall Title
696	Enable Storable Propulsion Systems in Low Temperature Environments

Description

Baseline TALOS (Thruster Advancement for Low Temperature Operations in Space) - Development of Cold-Tolerant, Hypergolic, Bi-Propellant, MON-25/MMH *Pulse-Mode* Propulsion Systems to Enable Extreme Environment Surface Access. Currently working MON-25/MMH thruster capability of effectively throttling through applying a large range of thruster pulse modulation. Propulsion system qualification, propellant characterization and REFPROP equations of state are required. Direct support for CLPS landers to lunar surface.

Extensible TALOS (Thruster Advancement for Low Temperature Operations in Space) - Deep Space Variant, High-Throughput TALOS Propulsion Systems to Enable Extreme Environment Deep Space Access and Landings.

Related Shortfalls

None

Metrics

- Nominal Thrust
- Reduced Propellant Thermal Control Requirements
- Propulsion System Mass Reduction
- Propulsion System Volume Reductio
- Propulsion System Cost Reduction

ID	Shortfall Title
700	Solar Sails for Propellant-less Propulsion

Description

Mature solar sail technologies to provide essentially unlimited spacecraft ΔV as an enabler of unique platform propellant-less propulsion capabilities. Solar sail thrust is proportional to area, larger sails are need for responsive transport in the solar system and station keeping for a pole sitter about the earth.

Related Shortfalls

PROP-TBD: Photon Sail reflective Membrane Size
PROP-TBD: Photon Sail Deployment and Support System
PROP-TBD: Photon Sail Attitude Control and Momentum Control
PROP-TBD: Photon Sail Ancillary Embedded Technology
PROP-1474: Large-Scale Deployable/High-Strain Composite Structures
PROP-1458: Propellant-less or Regenerating Propulsion Systems
PROP-444: Small Spacecraft Propellentless Deorbit Devices
PROP-1330: Active Debris De-orbit or Removal Actuators

Metrics

- Deployable Sail Membrane Area
- Spacecraft Thrust/Mass Ratio

ID	Shortfall Title
701	Green Propellant Propulsion Systems

Description

A need exists for a high performing, in-space storable, low-toxicity alternative to hypergolic propellants. Although several "lower toxicity" propellants have been ground tested and in specific cases flown (e.g.., GPIM, Lunar Flashlight, PRISMA) no 'one size fits all' alternative or drop-in replacement for hypergolic propellants exists. Candidate green propellants which have some technical maturation but not quite high enough TRL to be applicable for all missions use cases/classes exist including:

- Liquid monopropellants (e.g., the ionic liquids ASCENT produced in the US and LMP -103S produced by the EU) and Green Hydrazine
- These are viable with limited flight pedigree for small satellites in the < 22 N thrust classes but lack substantial development in the medium and large thrust range (110 N - 440 N)
  - Potential for expanse into the > 22 N thrust classes exists but more tech maturation is needed
- Green bi-propellants which have the potential for larger thruster classes, but more technology maturation is needed to grow this as viable/reliable for science & exploration missions

Tech maturation in green propulsion also needs to focus on successful demo of low-toxicity ground handling (e.g.., spacecraft fueling and transportation of propellants), higher propellant throughput, lower power requirements/cheaper/more reliable catalyst mat'l for mono-prop green thrusters, overall reliability of prop system components (valves, material compatibility, etc..)

Rapid growth of propulsion capabilities in small spacecraft is dependent upon moving away from traditional propellants. US supply limitations and potential international (e.g.., EU REACH agreement) restrictions threaten future in-space transportation capabilities or larger systems. Extreme environments/missions require new propellants and materials As an example, ASCENT's in-space liquid storability, combining this capability with larger thruster classes makes it a viable candidate for a future Mars Ascent Vehicle.

Related Shortfalls

PROP-TBD: Material development for "green" monopropellant thrusters
PROP-TBD: Efficient monopropellant heater development/thermal management
PROP-TBD: Address DOT requirement for transportation/handling
PROP-TBD: Unknown scalability of prop thrust/through-put for wider range of mission/use cases
PROP-TBD: Green bi-prop systems for higher thrust/efficiency and larger spacecraft
PROP-TBD: Propellant production cost/availability and disposal
PROP-TBD: Availability of propellant data to unlimited distribution
MANU-648: Materials for extreme environments

Metrics

- Short Term Thrust (3-5 year)
- Mid Term Thrust (5-7 year)
- Long term (7-10 year)
- Lifetimes Improvement
- Reduction in Ground Cost
- Propellant through-put

ID	Shortfall Title
707	Transformational Advanced Energetic Propulsion (AEP)

Description

Transformational in-space transportation capabilities for rapid and efficient solar system wide access and extremely ambitious interstellar missions requires the establishment of novel propulsion technologies incorporating Advanced Energetic Propulsion (AEP) processes & concepts including advanced nuclear fission & fusion technologies. Closing this shortfall will require significant base R&T investments over a broad reaching low-TRL technology portfolio including Multi-MW Low-Alpha NEP (Nuclear Electric Propulsion), Advanced Thermal Fission, Directed Energy (Direct & In-Direct Drive Modes), Low-Alpha Fusion, and Breakthrough Physics Research. The key initial challenge is to demonstrate fundamental proof-of-concept and scaling viability in simplified ground-based laboratory experiments. These successful ground demonstrations would provide a defendable and rational basis for follow-on mid-TRL technology development & maturation activities aimed at eventual space flight demonstrations.

Includes Multi-MW Low-Alpha NEP, Advanced Thermal Fission, Directed Energy (Direct & In-Direct Drive), Low-Alpha Fusion, and Breakthrough Physics. Dramatic reductions in trip time and crew exposure to space environment effects

Related Shortfall

PROP-TBD: High-Temperature Fission Fuels/Reactors
PROP-TBD: High-T/W, High-Isp NTP System
PROP-TBD: Low-Alpha, Multi-MW NEP System
PROP-695: Low-Alpha, High-Power EP String
PROP-TBD: Low-Alpha, High-Temp Energy Conversion
PROP-TBD: Low-Alpha, High-Temp Heat Rejection
PROP-TBD: Low-Alpha, High-Power PMAD
PROP-TBD: Low-Alpha Fusion Propulsion System
PROP-TBD: Low-Alpha Directed Energy Propulsion
PROP-706: STP Sun Diver Interstellar Probe
PROP-610: Low-Alpha, High-Power SEP

Metrics

- S/C Thrust-to-Mass Ratio and/or Characteristic Acceleration
- Specific Impulse
- Propulsion System Specific Mass

ID	Shortfall Title
1511	Advanced Computational Fluid Dynamics Tools / Capabilities

Description

Computational Fluid Dynamics (CFD) Tools and Capabilities require advancement to meet the needs of future missions for analysis to support design, assessment of risk, and uncertainty reduction. Increased reliance on simulation requires CFD tools to make efficient use of modern and emerging computational hardware, such as heterogenous and GPU systems, for complex systems of governing equations including real fluids, multiphase flows, and chemical reactions involving many reactions and species.

CFD models for simulating combustion in liquid fueled rocket engines lack the ability to model subcritical fluid mixing and reactions which are critical to analysis of Rotating Detonation Rocket Engines (RDREs) and hypergolic fuel engines. Existing approaches for reducing the complexity and computational expense of the combustion reaction model, such as flamelets, have not been demonstrated for hypergolic liquid-liquid reactions and are not capable of simulating transient combustion dynamics during engine startup, shutdown, or RDRE operation.

Related Shortfalls

TBD

Metrics

- TBD

ID	Shortfall Title
1512	Modern Solid Motor Design and Analysis Tools / Capabilities

Description

Solid motor design and analysis tools and capabilities require modernization to reduce design and analysis cycle times, efficiently optimize application-specific designs and provide performance predictions.

The significant potential of additively manufactured solid propellant can be leveraged if we have analysis tools that can model complex new grain geometries and variable propellant properties.

Coupled thermal, structural, and fluid dynamic behaviors, which cannot be accurately modeled with legacy tools, drive numerous important phenomena in solid rocket motors including deformed grain ballistics, ignition, burnout, coning, erosive burning, and scarfed, valved, and angled nozzles. There exists an urgent need for solid propulsion tools that make use of modern Computer-Aided Engineering tools like CAD and mesh formats which enable streamlined interoperability among numerous engineering disciplines.

In addition to enabling greater interface efficiencies and analysis fidelity, a cohesive computer aided engineering tool suite enables systems engineering functions like rapid design cycles, system-level optimization, and model-based systems engineering.

Related Shortfalls

PROP-TBD: 3D-Printed Solid Fuel Propellant Grains
PROP-TBD: Coupled Multidisciplinary Analysis tools for Solid Rocket Motor Design
PROP-TBD: Rapid Vehicle Design and Sizing Tools for Solid Rocket Motor Propulsion System Design
PROP-1303: Advanced Manufacturing Governing Design Principles
PROP-1152: Additive Manufacturing Certification
PROP-1431: Responsive Access to Space for Small Spacecraft and Payloads

Metrics

- Design Cycle Time
- Enables 3D-printed propellant grain design
- Accessible design tool for mission architects

ID	Shortfall Title
1052	EVA/IVA Support Propulsion Development

Description

Currently have performance limitations on IVA/EVA operations given existing technology design/packaging/materials. Improving performance and lowering cost of the IVA/EVA Support System would lower barriers to operational deployment for EVA activities, vehicle inspection/safety monitoring, and observation of vehicle operations (docking/deployment, etc..).

Related Shortfalls

AHS-1167: EVA Tools and Crew Mobility Aids for Sustained Lunar EVA and Mars EVA
PROP-701: Green Propellant Propulsion

Metrics

- Improve specific impulse through use of non-toxic alternatives to remain IVA/EVA compatible
- Reduced cost per flight propulsion system.

ID	Shortfall Title
1513	Advanced Solid Propulsion Systems

Description

Capability shortfall includes higher performance propellant formulations, vacuum qualification of propellants for extreme environments, propellant aging, propellant radiation exposure, propellant/liner material obsolescence, risk reduction and anomaly resolution. Also included are motor design optimization and advanced manufacturing of insulators, actuators, motor structures, nozzle technology, etc..

Target applications include in-space and planetary propulsion elements to support deep space descent stages (e.g.. Europa Lander), planetary ascent stages and various maneuvering applications like stage spin-up/despin (e.g.. Mars Ascent Vehicle), tumble/retro motors. Target applications also include Earth Launch and Crew Safety applications like SLS BOLE (Booster Obsolescence and Life Extension), Orion LAS (Launch Abort System), Commercial Crew, etc.. Target applications also include gas generator applications for attitude control and controlled landing.

Related Shortfalls

PROP-TBD: Aluminum-Lithium Fuel for Solid Rocket Motors
PROP-TBD: Metalized HTPB Binder for Solid Rocket Motors
PROP-TBD: Coated Boron Fuel for Solid Rocket Motors
PROP-1430 Propulsion for Small Spacecraft
PROP-1221: Mars Ascent Vehicle Propulsion
PROP-1431: Responsive Access to Space for Small PROP-Spacecraft and Payloads
PROP-1180: High Performance Materials Tailored for In-Space Applications
PROP-1101: Carbon-Carbon Rocket Engine Nozzles

Metrics

- Specific Impulse
- Mass Savings
- Volume Reduction
- Long term aging

ID	Shortfall Title
709	Nuclear Electric Propulsion for Human Exploration

Description

Integrated Multi-MW HALEU NEP system employing a fission reactor-based heat source combined with a thermal-to-electric energy conversion scheme to drive an electric propulsion system. Supports NEP/Chem reference mission by providing efficient cruise ΔV for crewed/cargo Mars transportation system.

CTE 1: Reactor and Coolant Subsystem (RXS)
CTE 2: Power Conversion Subsystem (PCS)
CTE 3: Power Management & Distribution (PMAD) Subsystem
CTE 4: Electric Propulsion Subsystem (EPS)
CTE 5: Primary Heat Rejection Subsystem (PHRS)

Related Shortfalls

PROP-TBD: Reactor and Coolant Subsystem (RXS)
PROP-TBD: Power Conversion Subsystem (PCS)
PROP-TBD: Power Management & Distribution (PMAD) Subsystem
PROP-TBD: Electric Propulsion Subsystem (EPS)
PROP-TBD: Primary Heat Rejection Subsystem (PHRS) (High temperature heat rejection for nuclear applications)
PROP-695: Multi-MW NEP
PROP-372: In-space Xenon Transfer Technologies

Metrics

- Power
- Reactor Temperature
- Radiator Temperature
- Radiator Area
- PMAD Efficiency
- Total System Alpha

ID	Shortfall Title
702	Nuclear Thermal Propulsion for Human Exploration

Description

High-thrust (25-klbf), high-Isp (900 sec) HALEU Nuclear Thermal Propulsion (NTP) engine system to provide crewed Mars transportation system gravity well ΔV. This is parallel approach to the NEP/CP Reference Mission. The current SOA for thermal rockets is chemical combustion solutions. LOx/LH2 is the highest specific impulse combustion solution, and LOx/LCH4 is under development for system level advantaged; limited to ~1/2 the specific impulse performance of NTP.

Related Shortfalls

PROP-TBD: Fuel > 2750k

Metrics

- Thrust
- Specific Impulse
- Thrust-to-weight
- Run Duration
- Restarts

ID	Shortfall Title
705	Low Power Nuclear Electric Propulsion

Description

Low-to-moderate power 1-40 kWe NEP systems employing a nuclear based heat source combined with a thermal-to-electric energy conversion scheme to drive an electric propulsion system. Nuclear-based heat source potentially derived from adjacent developments for Fission Surface Power (FSP), Dynamic-RPS, or Lattice Confinement Fusion (LCF).

Related Shortfalls

PROP-611: High DeltaV kW Class EP
PROP-TBD: Power shortfalls

Metrics

Power
Power system alpha
Thruster throughput

ID	Shortfall Title
1626	Advanced Sensor Components: Imaging

Description

Advances in scientific knowledge are often based on advances in instrument technology.

A common need for imagers, spectrometers, and LIDARs is high-performance focal plane arrays that can operate at sufficiently high temperatures to eliminate the use of cryocoolers and their power consumption and vibration, and multiplexed readout electronics, and on-board image processing.

For Earth science, detectors are needed in multiple wavelength ranges that span UV, optical, IR, and microwave, including sensitive single photon detectors.

For Planetary science, detectors are need over multiple ranges that span from RF, microwave, optical, UV, EUV, and x-ray for multiple remote sensing applications, including solar-blind UV detection.

For Astrophysics, efficient, ultrasensitive photon detectors , are needed in the many wavelength bands: UV/O/IR, mid-IR, far-IR, millimeter/submillimeter, and microwave.

Related Shortfalls

INSTR-TBD: Focal Plane Arrays (FPAs)
INSTR-TBD: Multiplexed Read-out electronics
INSTR-TBD: On-board Image Processing

Metrics

- Sensitivity
- Resolution – spectral, energy
- Number of detector elements
- Lower SWaP (size, weight, and power) for same level of performance
- Dynamic range
- Wavelength coverage
- Rad-hardness
- Operating temperature (eliminate need for cyrocoolers)
- Low detector noise and low readout noise
- Low deadtime
- Quantum efficiency
- Stability in time

ID	Shortfall Title
1627	Advanced Sensor Components for Heliophysics and Lunar-Based Astronomy

Description

Heliophysics needs smaller particle and field sensors to support their transition to systems of distributed spacecraft for multi-point solar observations. Remote sensing of coronal magnetic fields is a high priority, followed by remote sensing of neutral winds in the upper atmosphere. Sensors which can potentially support all heliophysics sensor priorities include Ly-alpha sensors (Hanle effect) for remote sensing of coronal magnetic fields and lidar, NO sensors, and THZ images for remote sensing of neutral winds in the upper atmosphere.

For astronomy, low-Frequency (30-90 MHz) radio lunar telescope technology is needed to detect the red-shifted 21-cm HI line (rest frequency at 1420 MHz), known as the epoch of reionization or "the Cosmic Dawn" of the universe.
Other lunar-based observatories.

A description of Astrophysics science objectives, needs, shortfalls, and technical details are found at: Astrophysics Projects Division (nasa.gov)

A description of Heliophysics science objectives, needs, shortfalls, and technical details are found at: 2023 HEliophysics Strategic Technology Office (HESTO) shortfall and Trend Analysis (zenodo.org)

Related Shortfalls

INSTR-TBD: Field & Particles Detectors
INSTR-TBD: Remote Sensing Detectors for the Sun and Upper Earth Atmosphere
INSTR-TBD: Radio Lunar Telescope Technology

Metrics

- Sensitivity
- Resolution – spectral, energy
- Number of detector elements
- Lower SWAP for same level of performance
- Dynamic range
- Wavelength coverage
- Rad-hardness
- Operating temperature (eliminate need for cyrocoolers)
- Low detector noise and low readout noise
- Low deadtime
- Quantum efficiency
- Stability in time

ID	Shortfall Title
1598	Quantum Sensors That Use Photons

Description

Transform NASA missions that detect light by exploiting untapped and newly discovered quantum phenomena, such as quantum entanglement & quantum squeezing, to achieve orders of magnitude improvements in sensitivity and resolution; to observe or measure what previously could not be done.

Single photon detectors (e.g.., TES, KIDs, SNSPDs, SQUIDs, bolometers) can enhance sensitivity for Earth & planetary science, astronomy, fundamental physics & biological research, and deep space laser communication. They can provide the basis of transformational instruments such as a single-photon 3D mapping lidar, an improvement over conventional lidars that need thousands of transmitted photons to detect a scattered return, and because the photon returns are time-tagged to the picosecond they render 3D info, like vertical vegetation structure, glacier features, or return a 3D image in a river of dark, sediment-laden water. Larger single photon detector arrays, with energy resolution & wavelength coverage, expanded dynamic range, rad-hardness, would allow telescopes to characterize exoplanets, conduct large-scale surveys of galaxies, discover properties of dark matter, explore Planck physics at the smallest dimensions.

Quantum entanglement (e.g.., illuminating with correlated photon pairs) using single photon detectors can offer further improvements in sensitivity and resolution, especially in noisy, lossy environments. Quantum squeezing is a technique(s) of improving sensitivity and resolution by manipulating, to your advantage, the Heisenberg Uncertainty principle (which quantifies highest precision available to any measurement).

Super-Sensitivity refers to going below the Standard Quantum Limit & down to the Heisenberg Limit for ultimate sensitivity. Super-resolution refers to going below the diffraction limit. These breakthroughs are possible using quantum entanglement and quantum squeezing. The greatest success story is NSF's Laser Interferometer Gravitational Wave Observatory which detected the first gravitational wave, a ripple in spacetime produced by a black hole merger. Expect other new & successful instruments.

Related Shortfalls

INSTR-TBD: Single photon detectors and arrays
INSTR-TBD: Quantum Entanglement
INSTR-TBD: Quantum Squeezing
INSTR-TBD: Super-Sensitivity & Super-Resolution
INSTR-TBD: New Kinds of Quantum Sensors

Metrics

- Sensitivity & Super-sensitivity
- Resolution & Super-resolution
- Detector array format,
- Lower SWAP for same level of performance
- Dynamic range
- Wavelength coverage
- Rad-hardness

ID	Shortfall Title
1599	Quantum Sensors That Use Atoms, Ions, and Spins

Description

Transform NASA science missions by achieving orders of magnitude improvements in sensitivity & resolution by using individual or clouds of atoms, ions, and spins, and/or exploiting quantum entanglement & quantum squeezing.

Atomic clocks for space need to be more accurate & stable (10-18 or better), accordingly better optical comb frequency readouts, lower SWAP, & become space-qualified. Two orders of magnitude more precise than DSAC. These research-grade clocks could enable a test of General Relativity (time dilation effects); detect dark matter & distinguish among particle candidates. Quantum entanglement experiments could reveal how gravity & quantum mechanics mesh. Precision navigation & timing.

Atom interferometers can measure mass, acceleration, gravity, & gradients, with different requirements/designs for sensitivity. Earth Science Decadal has named mapping the Earth's gravity field as critical. An atom-interferometer-based time-variable gravity gradiometer offers better spatial and temporal resolution from a single spacecraft compared to the two-spacecraft approach considered for ESD's Gravity Recovery and Climate Follow-on (GRACE-FO). It could measure a planet's mass distribution (geodesy) and how it changes in time - on Earth, ice sheet melting, ocean currents, sea level rise, ground water aquifer depletion.

Quantum magnetometers have potential to enable autonomous navigation in GPS-deprived environments; possibly eliminate need for long booms currently used to shield magnetic field measurements from spacecraft electromagnetic interference.

Rydberg sensors have potential as quantum radars measuring forest canopy, cryosphere.

Related Shortfalls

INSTR-TBD: Atomic Clocks (Time, Frequency)
INSTR-TBD: Atom Interferometers (Mass, Acceleration, Gravity, Gravity Gradient)
INSTR-TBD: Quantum Magnetometer (Magnetic Field)
INSTR-TBD: Rydberg Sensors (Electric Field)
INSTR-TBD: New Kinds of Quantum Sensors

Metrics

- Sensitivity
- Resolution
- Stability
- SWaP
- Rad-hardness

ID	Shortfall Title
1600	Enable Paradigm for System Science to Include Interactions Between Subsystems

Description

Develop new approaches and technologies to stimulate creation of space missions that emphasize investigating the interconnections and cross-influences of disparate parts of larger physical systems. Earth science missions currently tend to be theme-centric. Examples: (1) Instead of focusing on the cryosphere, expand mission to address impact of the changing ice sheets on clouds/weather, oceanography/ocean currents, biodiversity, and greater climate. (2) Improve odds of unambiguous detection of extant life on Mars through many more measurements on (an always limited) sample, including overall geochemical/geophysical context. (3) Expand a space weather mission to include concurrent couplings between the Sun, solar wind, magnetosphere, ionosphere.

At the top level, the vision requires larger numbers of simultaneous, diverse remote sensing & in situ measurements on multiple time and spatial scales. Planetary/Astrobiology Decadal (2023) calls for a more holistic approach to instrument/observation-architectures in which whole is greater than sum of parts. Earth scientists call for observations that are more persistent; for longer life, multi-function instruments; lower costs, lower SWaP(size, weight, and power); more efficient use of data storage & data processing resources.

Instruments should be more multi-function, collaborative, agile, capable of adaptive sensing. To resolve a knowledge shortfall, there is a need for a workshop to determine how measurements should be grouped across subsystems for real-time adaptive sensing decision making and for scientific impact. Adaptive sensing must be guided by models, some of which will tap AI-methods for mining incoming data to predict the immediate future, enabling decision making about adaptive sensing modes.

To save spacecraft resources instruments should have high levels of multi-functionality, capable of morphing and shape-shifting – tapping photonic integrated circuits that are beginning to be programmable and nano-optics/transform optics, for example, that are creating novel, even dynamically controllable optical elements that manipulating light in previously unimaginable ways.

Related Shortfalls

INSTR-TBD: Workshop to determine impactful cross-subsystem measurements and combinations of measurements (Earth and/or Planetary/Astrobiology)
INSTR-TBD: Extreme multifunction instruments, components, common/shared elements
INSTR-TBD: Absolute Self-Calibration techniques
INSTR-TBD: Adaptive Sensing Models - real-time process integrators for guiding adaptive sensing. AI to predict/anticipate future developments ("forward modeling").
INSTR-TBD: Reductions in Instrument Size, Weight, Power, Volume, Cost.

Metrics

- More types of data combined to produce new information (greater "awareness")
- Increase in data volume that can be handled; storage & processing efficiency.
- Reduction in SWAP, cost.
- "Data in" compared to "knowledge out". (TBD)

ID	Shortfall Title
1601	Enable Observation of Whole Top-to-Bottom Dynamic Ecosystems

Description

Enable the observation of a whole, top-to-bottom whole ecosystem (including flora, fauna, micro-organisms etc..) with a capability to identify & monitor constituent species & individual organisms on multiple temporal & spatial scales, noting interactions between them and with their environment. Particularly challenging environments include dark ocean depths, hidden areas under forest canopies, under soil, obscured habitats, caves/crevasses, cryosphere. Example applications: Earth conservation/biodiversity; agricultural plant health & food security; search for life on Mars and water worlds; monitoring the changing microbiome of isolated astronaut habitats.

Current state of the Art: Physically tagging animals; limited numbers of ground observation stations; photo-traps. Marine observations focus mostly on ocean photic & coastal zones rather than deep pelagic zones; limited numbers of expeditions and/or sampling buoys.

Technology needs: Environmental monitors/sensors for trace constituents (chemical, biological), remote & in situ sensors, nature-/field biology life detection that expands beyond human sensory modes to include sensing nearby nervous systems (electric field); acoustic & low-light signaling; chemical scent; tactile/pressure sensing. Machine learning/AI for processing data and recommending new sensing targets for future sensors. Information-storage efficient neuromorphic cameras or instruments that turn on only for events. Non-line-of-sight (NLOS) techniques for imaging, detection, videography for recording subjects and events. Integration of multi-platform observations. Holistic sensing in which the whole is greater than the sum of the parts. Sensing/detector architectures that minimize data storage. Instruments that tap field-biology approaches and new sensory modes might be helpful for detecting on extant microbial life on other planets, for the cases where life is very different from life on Earth.

Related Shortfalls

INSTR-TBD: Environmental Monitors/Sensors
INSTR-TBD: Remote and In Situ sensors
INSTR-TBD: Nature-inspired/field biology life detection
INSTR-TBD: Neuromorphic cameras & instruments
INSTR-TBD: Non-line-of-sight detection, imaging, videography
INSTR-TBD: Multi-platform holistic & distributed sensing networks/integration. (In situ, remote ground, air, space)
INSTR-TBD: Sensing architectures for efficient data storage/use

Metrics

- Information products of whole observation system greater than sum of its parts. Potential reduced data processing time.
- Reduced number of ecosystem “blind spots”
- Number of species/classes observed
- Number of potential observed interactions between life forms with each other and with the environment

ID	Shortfall Title
1602	**3D/3D+ Imaging and Tomography of Complex Features and Dynamical Processes**

Description

Sense and visualize phenomena/features on Earth, other planets, and other worlds in 3D, time, and/or other physical parameters (dimensions) of interest –e.g.., composition, physical/geological/chemical/biological data. Develop space medicine tools for astronauts living far from Earth. Application examples: Image changing Earth/planetary terrains at presently inaccessible spatiotemporal scales; tomography of interior of asteroids; imaging or tomography of storm cloud time-development or cloud microphysics; natural hazards warning/monitoring; Earth ecosystem (e.g.., forest) status & evolution; ocean floor study; ice sheet melt & changing ocean sea level & currents.

Technology challenges include:

- 3D/3D+ Cloud Tomographic Imaging;
- Ka-band ultra-high frequency bandwidth Synthetic Aperture Radar (SAR) for high spatial resolution of planetary/asteroid surfaces
- Active/passive multi-angle UV/visible/IR polarimeters deployed to space (e.g.., flown on PACE but expand approach to microwave.) Tomography algorithms using AI/ML to exploit PACE data.
- Multi-frequency microwave Doppler radar with polarization (e.g.., storm applications)
- Advanced Structure-from-Motion-Multi-View-Stereo photogrammetry) for topography, new apps
- Single photon 3D+ mapping lidars
- Quantum lidars (using quantum entanglement) (e.g.., polarization-entangled cloud/aerosol lidar)
- Quantum Illumination (entanglement-enhanced holography, microscopy, et al.)
- Synthetic aperture imaging lidar (SAIL)
- Descent imaging lidar for landings & science
- Compact x-ray computed tomography (XCT): imaging on planetary surfaces; AI-enhanced medical imaging
- Compact Nuclear Magnetic Resonance (NMR) sensing for bio-molecular characterization/ distribution.
- Key Components (e.g.., Large aperture, multi-frequency radar antennas (S to W-bands); UV/visible/IR polarimeters on chips)

Related Shortfalls

INSTR-TBD: 3D/3D+ cloud tomographic imaging
INSTR-TBD: Ka-band Ultra-high Frequency Bandwidth SAR
INSTR-TBD: Microwave Active/Passive Multi-angle UV/visible/IR polarimeters
INSTR-TBD: Tomography algorithms
INSTR-TBD: Multi-frequency Microwave Doppler radar with polarization
INSTR-TBD: Advanced Structure-from-Motion Multi-View Stereo Photogrammetry
INSTR-TBD: Single photon 3D+ mapping lidar
INSTR-TBD: Quantum-illumination Enhanced Instruments
INSTR-TBD: Quantum Lidars
INSTR-TBD: Synthetic Aperture Imaging Lidar (SAIL)
INSTR-TBD: Descent Imaging Lidar
INSTR-TBD: Compact X-ray Computed Tomography; AI/ML
INSTR-TBD: Compact NMR
INSTR-TBD: Key Components

Metrics

- Spatial resolution
- Frames/second; Processing speed
- Size of point cloud

ID	Shortfall Title
1603	Situational Awareness Sensors and Tools for Astronauts

Description

Solar Particle Events (SPEs) remain difficult to forecast & "now"-cast, and they continue to pose a risk to astronauts, especially if caught away from a shelter on the lunar surface. They occur when Solar Energetic Particles are emitted from the Sun and are accelerated o high energies during a solar flare or in interplanetary space by a Coronal Mass Ejection (CME). Unlike the much more predictable Galactic Cosmic Radiation (GCR) which is slowly modulated by the Sun's 11-year solar cycle, SPEs occur episodically and exhibit high variability in terms of intensity, duration, composition, and energy spectra. Their occurrence varies from several per week when the Sun is "active" to fewer than one per month when the Sun is quiet, following an 11-year cycle generally consisting of 4 inactive years (solar minimum) and seven active years (solar maximum). In 2019, state-of-the-art probability of detection for a 20 minutes "now-cast was only 40%, with a false alarm rate of almost 60%. Even with recent use of machine learning, success rate has not improved by a lot. More kinds of data are needed. Plans are underway to fly solar imagers at Sun-Earth L4 and L5 Lagrange points. Development of AI and other new modeling tools are needs to continue.

A high priority technology challenge is to develop the first remote sensor of the solar corona & observe how it gives rise to solar wind. The solar wind carries CMEs away from the Sun, accelerating SPEs. This is the top ask from SMD/Heliophysics.

There are two other important sensors that have been especially challenging: a nitric oxide (NO) remote sensor for upper atmospheric/ionospheric neutral winds & a THz imager of ionospheric electron density. This region of the Earth's atmosphere can provide space weather insights because it is the lower conducting boundary of a global electrodynamic circuit connecting the ionosphere-magnetosphere-solar wind and the aurora drive high winds here. Measurements of the Earth's upper atmosphere are challenging because it is too high for balloons and too low for a spacecraft to do in situ measurements, requiring new kinds of remote sensors.

Related Shortfalls

INSTR-TBD: Solar corona remote sensor (using Hanle effect)
INSTR-TBD: Nitric oxide sensor
INSTR-TBD: Terahertz (THz) imager of ionospheric electron density
INSTR-TBD: AI Tools for SPE Forecasting
INSTR-TBD: Lunar Space Environment Sensors/Sensor System

Metrics

- Timeliness and time window for SPE forecasts/early warning
- SPE probability of advanced detection
- Low false alarm rate
- Accuracy micrometeoroid & debris track vectors
- Micrometeoroid & orbital debris size-/velocity-threshold for detection

ID	Shortfall Title
1604	Find, Study Habitable Zone Earth-like Exoplanets and Search for Biosignatures

Description

ASTRO2020 Decadal Science Strategy has identified the top priority astronomy and astrophysics goal: find, characterize, study in detail, and search for signatures of life on extrasolar planets in the habitable zones of their parent stars. This calls for a large aperture infrared/optical/ultraviolet space telescope that has a high contrast coronagraph capable of blocking the light from the bright parent plant to reveal the faint planet ("direct detection"). It will also carry a sensitive, high-throughput, broadband spectrograph to study (the potentially life-altered) atmospheres of these worlds to look for biomarkers (e.g.., water, oxygen, methane, carbon dioxide, and many other possibilities). Some concepts call for a large 6-meter IR/Optical/UV space telescope, a larger Great Observatory, and/or a starshade, which is a free-flying 60-meter deployable structure for starlight suppression external from the telescope, as an alternative or addition to the internal coronagraph starlight suppression approach.

Over the past two decades, various other techniques discovered thousands of exoplanets (most extremely different from any found in our solar system) and revealed that 30% of stars in the Milky Way have Earth-like worlds in their habitable zones. However, the transit method (observes mass of planet moving across stellar disk), radial velocity method (observes "wobble" of parent star as planet orbits around it, and gravitational microlensing () either rely of rare occurrences that do not allow observational revisit for detailed study, or they specialize on zones too close or too far from the parent sun to be habitable zone. Direct detection can be used by the largest of ground-based observatories, but it can only directly image young (still glowing) giants which do not require the high contrast that directly imaging an exoEarth.

Key challenges include high contrast coronagraph (contrast improvements, stability, efficiency), detectors (large format, high resolution FPAs; large format efficient, low dark rate photon counting detectors for far-UV to near-UV), UV detector sensitivity improvements; Mirrors & Optics (high angular resolution UV-Vis-NIR mirrors, filters); Coatings (High reflectivity, broadband FUV-to-NIR); Starshade (deployment, stability, starlight suppression).

Related Shortfalls

INSTR-TBD: High contrast coronagraph
INSTR-TBD: Detectors
INSTR-TBD: Mirrors and Optics
INSTR-TBD: Coatings
INSTR-TBD: Starshade

Metrics

- Optical contrast (exoplanet host star brightness) 10-10
- Inner/Outer Working Angle (field-of-view, field-of-regard) – how close/far from star
- UV/Optical/NIR bandwidth
- Pointing stability (low jitter)
- Low loss, high throughput, low stray light, low aberration and low obscuration

ID	Shortfall Title
1605	Peer Back Farther in Time to the Early Universe

Description

Develop far-Infrared (FIR) space telescope technologies to enable a new, cosmic-dust-penetrating view into the early Universe. Enable a new understanding of: the history of energy release in galaxies; the formation of stars; the growth of black holes at the center of young galaxies; the rise of the first heavy elements from primordial gas, formation of planetary systems and habitable planets.

Technology challenges include Large Aperture Deployable Antenna (for Far-IR/THz/sub-mm astronomy for frequencies over 100 GHz); Advanced Cryocooler Technologies (high performance sub-Kelvin cooler); FIR Detector Arrays and Cryogenic readouts (large format, low noise & ultra-low noise Far-IR direct detectors; heterodyne FIR detector systems; improving calibration of Far-IR heterodyne measurements); Advanced FIR Instrumentation (high resolution direct detection FIR spectrometer; High-throughput, large format object selection technologies for multi-object and integral field spectroscopy); Far-IR imaging Interferometer for high-resolution spectroscopy; FIR spatio-spectral Interferometry (tomographic spectral line mapping); Large Cryogenic Optics for mid-IR to Far-IR.

Related Shortfalls

INSTR-TBD: Large Aperture Deployable Antenna
INSTR-TBD: Advanced Cryocooler Technologies
INSTR-TBD: FIR Detector Arrays & Cryogenic Readouts
INSTR-TBD: Advanced FIR Instrumentation
INSTR-TBD: Large Cryogenic Optics (mid-IR to FIR)

Metrics

- Low frequencies not achieved before
- Sensitivity, low dark current

ID	Shortfall Title
1606	Observe Some of the Most Energetic Phenomena in the Universe

Description

Develop space x-ray telescope technologies to enable the study of the origin and growth of the first supermassive black holes; co-evolution of black holes, galaxies, and cosmic structure; physics of accretion, particle acceleration (such as GeV galactic cosmic rays), active galactic nuclei, quasars, and the inter-galactic medium.

Technology challenges include:

- Detectors (Broadband X-ray detectors; Fast, low noise megapixel imaging arrays with moderate spectral resolution; Large, fast, high spectral resolution, small-pixel X-ray focal plane arrays, Rapid readout electronics for X-ray detectors);
- X-ray Optics (High-resolution,, large-area X-ray optics)
- X-ray Coatings: (Low-stress, high stability X-ray reflective coatings)
- X-ray Optical Elements (Large-wavelength-blocking filters for X-ray microcalorimeters; High-efficiency X-ray grating arrays for high-resolution spectroscopy)
- X-ray Instrumentation (Advances in X-ray polarimeter sensitivity; Very-wide-field focusing instrument for time domain X-ray astronomy)
- Precision Timing for space-based astrophysics

Related Shortfalls

INSTR-TBD: X-ray Detectors & Readouts
INSTR-TBD: X-ray Optics
INSTR-TBD: X-ray Coatings
INSTR-TBD: X-ray Optical Elements
INSTR-TBD: X-ray Instrumentation
INSTR-TBD: Precision Timing

Metrics

- Angular and spatial resolution
- Effective aperture
- Energy range
- Spectral resolution
- Bandpass

ID	Shortfall Title
1607	Detect New Astronomical Messenger - Gravitational Waves

Description

For millennia, light has been the messenger that has enabled us to "see" & learn about the Universe, but that changed in 2015, when ground-based LIGO (Laser Interferometer Gravity wave Observatory) detected the first gravitational wave, ushering in a new era in which we can "hear" invisible (non-electromagnetic) objects and events in the Universe. The signal was produced by two small merging black holes from which emanating ripples in space time.

The first space-based gravitational wave (GW) observatory is ESA-led, NASA-partnered LISA (Laser Interferometer Space Antenna) to launch in early 2030's. It will consist of three spacecraft whose relative positioning will shift slightly with the passage of a gravitational wave (a ripple in space-time). The spacecraft will carry inertially stabilized test masses whose relative positions are measured via laser beams with a precision of less than a diameter of a helium nucleus over a million miles distance.

Japanese-led space-based GW observatory, launching also in the 2030s will detect deci-Hertz GWs, compared to LISA (milli-Hertz). The US is leading a space-based GW observatory to follow LISA.

Technology challenges include:

- Ultra-stable Structures & Control (Complex ultra-stable structures; Disturbance reduction; Micro-newton structures, stable telescopes);
- Gravitational Wave Metrology (Gravitational reference sensor; High power, high stability laser; Laser phase measurement chain for measuring deci-hertz gravitational waves

Related Shortfalls

INSTR-TBD: Ultra-stable Structures & Control
INSTR-TBD: Gravitational Wave Metrology

Metrics

- Frequency band
- Sensitivity
- Stability
- Disturbance isolation

ID	Shortfall Title
1430	Small Spacecraft Propulsion

Description

Deep space and advanced near-Earth missions envisioned for multiple classes of small spacecraft require additional ΔV over the multiyear life of a mission to orbit raise, maneuver, and inject systems into high energy trajectories. Reliably manufacturable onboard propulsion systems than can impart more ΔV are needed for both nanosatellites (CubeSat) and microsatellites (large CubeSat / small ESPA (EELV Secondary Payload Adapter) class. Such systems can be paired with other deep-space and nontraditional-orbit access approaches, including ESPA class or larger Orbital Maneuvering Vehicles, to close mission designs.

To enable significantly increased propulsive capability in nanosatellites, systems are required that have a high impulse per unit of spacecraft and high total impulse, while remaining low power per unit of spacecraft. For use beyond LEO, systems must be tolerant to the deep space radiation and harsh thermal environments for multiple years. High-density propellant may be needed to achieve the required performance within volume limitations. Microsatellite-scale systems have less size, weight, and power constraints, but need increased thrust to accomplish missions within a reasonable timeframe. Microsatellite-scale systems can also be used for precision attitude control of larger systems, such as space telescopes.

Included in this shortfall are technologies to modify the drag profile of a spacecraft or small planetary probe such that de-orbit, orbit maintenance, or re-entry is achievable. This aspect can enable small spacecraft utilization for a multitude of missions both within Earth's atmosphere and in atmospheres of locations such as Mars or the Jovian planets.

Performance attributes of ideal propulsion technologies include:

- Low SWaP-C (size, weight, and power – cost) when compared to current state-of-the-art
- Capable of operation in a deep space environment (either by inherent tolerance or by novel redundancy schema)
- High thrust and/or high efficiency
- High reliability
- Scalable manufacturability (infusible into constellation design)

Examples of applicable systems include:

- Chemical Propulsion
- Electrical Propulsion
- Solar Sails & Tethers
- Atmospheric Deceleration / Aerocapture Systems

Related Shortfalls

SMALLSAT-TBD: Nanosatellite Propulsion (CubeSat scale)
SMALLSAT-TBD: Microsatellite Propulsion (large CubeSat / small ESPA-class scale)
SMALLSAT-1459: High-reliability Propulsion System Components and Subsystems
SMALLSAT-TBD: Propulsion-based ACS (including Micro-Thrusters)
SMALLSAT-TBD: Novel Propellent (including Dual-mode and "Green" Propellants)
EDL-444: Small Spacecraft Propellantless Deorbit Devices
PROP-700: Solar Sails
PROP-701: Green Propellant Propulsion Systems
RPOC-452: Small Satellite RPO Propulsion Capability
EDL&PL-346: Small Spacecraft Aerocapture
SMALLSAT-TBD: Propellant Management and Feed Systems for Small Spacecraft (including Small Spinning Spacecraft)
SMALLSAT-1436: Efficient and Safe Higher Power Systems for Small Spacecraft

Metrics

- System-level ΔV capability
  - 2.5 km/s ΔV for Cislunar applications
  - 2.5 – 5 km/s ΔV for Lunar, Martian, Venusian & Asteroid Belt applications
- Propulsion system lifetime throughput / total Impulse, minimum / specific impulse range, specific mass / power
- Propulsion system cost and time to integration
- Solar sail areal density and lightness factor
- SWaP-C of solar sail momentum control systems and solar sail booms
- Extension of solar sail support system operational / survival thermal limits (to <0.4 AU)

ID	Shortfall Title
1431	Access Beyond LEO for Small Spacecraft

Description

This shortfall addresses the need for vehicles, platforms, and technologies that enable access to non-traditional orbits, including destinations beyond LEO such as Cislunar space, Lagrange points, Martian space, Venusian space, and additional deep space locations. Access refers to greater availability to orbital environments for technology and science using hosted platforms and/or vehicle systems which provide physical accommodations, power, data, and appropriate environmental control for relevant payloads. Examples of technologies which contribute toward closing this shortfall include:

- Orbital Maneuvering Vehicles (OMVs) and/or small launch interplanetary transfer stages to achieve multiple orbits on a single mission and/or reach cislunar and deep space destinations not otherwise reachable through rideshare launches. OMVs should also provide position, navigation, and timing (PNT) services and communications relay to enable payload hosting for deep space missions.
- Modular small spacecraft systems and subsystems which, when combined, can function to meet a variety of different mission or system objectives with a low SWaP-C (size, weight, and power – cost). Similarly, basic bus platforms which can be configured to meet a variety of mission roles without extensive engineering effort to meet a varying set of basic mission requirements. This "plug-and-play" capability could dramatically shift the paradigm of small spacecraft utilization. Achieving modularity would also facilitate batch production, additive manufacturability, and machine-learning optimized system design.
- Novel small spacecraft form factors (such as flat pack) or mechanisms that enable new mission configurations or new cost-effective utilization of small spacecraft.
- Improved launch and handling safety of traditional spacecraft subsystems that enable their usage for small spacecraft missions. Reductions of risks such as hazardous gas discharge, fire, and explosion through redundancy and/or elimination of root cause for batteries and propulsion systems could impact the state-of-the-art by enabling their usage on lower cost missions, even if the overall performance is less than the true state-of-the-art for the respective technology area.

Related Shortfalls

SMALLSAT-TBD: Multi-orbit Access for Hosted Payloads, Including OMVs
SMALLSAT-TBD: Rideshare Platforms for Cislunar and Mars
SMALLSAT-TBD: Modular Small Spacecraft Systems, Platforms, and Interfaces, Including Batch-Producible Systems
PROP-610: Solar Electric Propulsion - High Specific Impulse

Metrics

- >10 km/s ΔV systems/platforms for Heliophysics and deeper space applications, including space weather sensor deployments
- Range and breadth of accommodable interface requirements
- Range and breadth of accessible space environments
- Elimination of license and/or regulatory requirements involved with integration of a spacecraft solution

ID	Shortfall Title
1434	Communication Technology and Capabilities for Small Spacecraft

Description

Small spacecraft missions beyond Earth require compact and low power, but high bandwidth transceivers for use on the Moon, Mars, the rest of the inner planets, around asteroids or other small bodies, and at other deep space destinations. Additionally, this shortfall will require novel solutions that reduce reliance on existing ground-based communication services that can hinder utilization of distributed small spacecraft for autonomous observation and missions beyond Earth. These hindrances include lengthy licensing applications and congested frequency bands.

Future missions require systems that are lower SWaP-C, can operate in multiple frequency bands (S, X, and Ka-Band) or optical, and can reach higher uplink and downlink speeds with ground stations. Each method of spacecraft communication will have unique metrics for improvement to state-of-the-art, with divergence between radio frequency communication systems vs. optical communication systems. Improvements to performance and SWaP-C could be met with novel antennas, transceivers, and/or in advancements to supporting technology such as solid-state power amplifiers and/or ground-based terminals.

Related Shortfalls

SMALLSAT-TBD: Capability, SWaP-C, and Accessibility Improvements to Optical Communications for Small Spacecraft, Including Ground-Based Systems
SMALLSAT-TBD: SWaP-C Improvements to Secure Communication Systems for Small Spacecraft
SMALLSAT-TBD: Novel Communication Systems (including Quantum Communication Systems)
COMM-TBD: Low recurring cost ground terminal for deep space receiver

Metrics

- Uplink/Downlink rates
- Pointing requirements
- SWaP-C of communication systems and reduction of operational costs
- Communication availability / ubiquity
- Link security
- Communication system reliability

ID	Shortfall Title
1432	Rendezvous, Proximity Operations, and Debris Remediation using Small Spacecraft

Description

This shortfall addresses the need for sensors, networking, autonomous operations capabilities, and vehicle systems that can enable small spacecraft to conduct proximity operations both in close range to target objects (including natural targets such as asteroids / other small bodies and high value assets such as operational satellites / human occupied space platforms) as well as to other small spacecraft as part of distributed operations or formation flight. Examples of technologies which close this shortfall would include sensors which provide precise ranging between small spacecraft as well as to target objects and/or provide awareness of the space environment, algorithms which enable autonomous flight operations using sensor data, and decision-making capabilities.

Included in this shortfall is management of orbital traffic, conjunction alerts, and orbital debris monitoring. Small spacecraft smaller than 1U have become more capable yet remain a challenge for tracking. Large scale rideshare missions, with multiple spacecraft deployed within a short duration in a single orbital plane, also pose a challenge for tracking and identification because individual spacecraft can often not be resolved. Technologies to address this could include passive aids, active identification systems, and other features which enable tracking and ID from ground and/or space-based assets.

Technologies which enable the safe de-orbit (whether by return to Earth surface or otherwise by disposal) of small spacecraft in any operational orbit environment is within the scope of this shortfall. Safe disposal / end of mission requirements are becoming more stringent to curb the increasing orbital traffic management challenge. Technologies which allow small spacecraft to return to Earth for return of samples, hardware, or complete vehicle reuse are included within this scope, as they specifically address the issue of deorbit or disposal by returning the orbital hardware to Earth, and as such no longer posing a debris or orbital traffic management concern. Technologies for deorbit, disposal, and/or return can be passive (deceleration devices, tethers, and associated technologies to enable their implementation) or active (i.e. propulsion systems). Technologies for removal of existing debris are also within the scope of this shortfall.

Related Shortfalls

SMALLSAT-TBD: Orbital Debris Management Techniques and Technology, including Active Debris Remediation with Small Spacecraft
SMALLSAT-TBD: Space Situational Awareness (SSA) and Traffic Coordination Systems
SMALLSAT-TBD: Fail-safe Small Spacecraft Systems for Passive Passivation
RPOC-373: Small Satellite RPOC with close free-flying inspection of a high-value asset
RPOC-1537: Free-Flying Systems for Robotic Inspection, Data Collection, and Servicing of In-Space Assets
RPOC-1542: Metrics and Processes for Establishing Trust and Certifying the Trustworthiness of Autonomous Systems
SMALLSAT-TBD: Safe-trajectory Design for Small Spacecraft
RPOC-637: Small Satellite Docking
COMM-1279: Orbit determination and tumble rate sensing for orbital debris
SAT S&A-512: Cooperative interfaces, aids, and standards
TBD: Small Orbital Debris Sensors for Detection & Tracking
INSTR-TBD: Reductions in Instrument Size, Weight, Power, Volume, Cost.

Metrics

- Redundant abort capability for proximity operations
- Independent tracking of spacecraft in proximity
- Discernable attributes of observed objects

ID	Shortfall Title
1433	Position, Navigation, and Timing for Small Spacecraft

Description

Continued small spacecraft use in deep space requires highly accurate position knowledge and precision timing that does not depend on GPS or other Earth-centric aids. Future small spacecraft missions will need to autonomously determine and transmit relative and absolute orbital states as well as maintain and exchange precise timing. These capabilities are required for small spacecraft to act as infrastructure for other missions, for distributed missions comprised of small spacecraft, and for standalone small spacecraft missions beyond Earth. Access to Earth network ranging may not be available for multiple concurrent missions, missions with multiple elements, or be limited by radio capabilities for smaller missions.

Navigation technologies and techniques may include inertial navigation combined with enhanced visual navigation capabilities, X-ray emissions, and laser range finding. These systems must be compatible with the inherent size, weight, power, and cost constraints of small spacecraft platforms. Onboard image and data processing is required to allow for autonomous navigation. 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. Improvements in 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 references sources are not available or feasible.

Related Shortfalls

SMALLSAT-TBD: SWaP-C Improvements to Integrated Clock/Radio Systems for Small Spacecraft
SMALLSAT-TBD: Novel PNT Solutions (including Quantum Sensing Technologies)
SMALLSAT-TBD: Small Spacecraft Compatible Absolute Navigation Systems
COMM-TBD: Next Generation Deep Space Atomic Clock
COMM-TBD: Atomic Clocks and Optical Frequency Combs (time, frequency)
AS-TBD: Sensors and sw for perception, inertial, and physical interaction in unknown/extreme environments
AS-TBD: Autonomous Systems: Deep Space Navigation

Metrics

- SWaP-C of combined clock and radio systems
- Environmental robustness of PNT components
- Accuracy of time keeping
- Use cases of timing solutions
- Position estimate accuracy
- Duration of independent operation prior to calibration signal

ID	Shortfall Title
1437	Dynamic and Capable Thermal Control for Small Spacecraft

Description

Given the small densely packed CubeSat form factor, as advancements in power systems enable significantly increased power generation, improved thermal control and waste heat rejection will become increasingly critical. Thermal control capabilities that will enable small spacecraft to go further and accomplish more include:

- Novel form factors, materials, and coatings that improve tunability of thermal surfaces
- Multimodal components for operational and survival small spacecraft configurations, including dynamic radiators and thermal switches
- Dynamic radiators and thermal switches that can adjust their thermal properties for specific mission phases or locations
- Components with higher operational and survival temperature ranges than current state-of-the-art. These systems must also be tolerant to the deep space radiation and thermal environments during missions anticipated to last multiple years.

Related Shortfalls

SMALLSAT-TBD: Lower Mass/Volume, High Heat Rejection Systems
SMALLSAT-TBD: Lower Mass/Power Thermal Switches
THERMAL-1132: Variable heat rejection
THERMAL-484: Advanced Radiators – Deployable
THERMAL-761: Two-phase active thermal control systems with reduced mass
THERMAL-604: Advanced Active Cooling for Electronics and Avionics
THERMAL-605: Integrated Structural/Thermal Elements
AV-539: Avionics Thermal Management for Extreme Environments

Metrics

- Thermal surface tunable range and properties
- Improvement to heat rejection capability per unit mass and/or unit power
- Adjustable conductivity range of thermal switches
- Operational and survival temperature range of spacecraft components

ID	Shortfall Title
1436	Efficient and Safe Higher Power Systems for Small Spacecraft

Description

Small spacecraft platforms impose area and volume constraints on deployable power generation systems and power storage systems. Future missions require more power for electric thrusters, active sensors, and communications systems, while simultaneously expanding into more challenging environments further from Earth and for longer duration missions. In the near term, additional power is needed for electric thrusters. Solar arrays intended for use at Mars and other similar distance destinations for sensors, communications, and other applications will need additional beginning of life (BOL) power, additional specific power generation, and additional stow rates. Outer planet missions require capabilities significantly beyond the current state-of-the-art including solar cells with unprecedented specific power generation paired with large flexible solar arrays based on solar sail or roll out designs, or small nuclear power sources.

Improvements to power storage systems will also benefit future missions by enabling longer duration missions and missions with longer eclipse periods. As power usage grows, the need to store additional power safely and reliably will also grow. For small spacecraft, power storage compatible with small launch vehicles and rideshare launches will also be of high importance. All these systems must also be tolerant to the deep space radiation and thermal environment during missions anticipated to last multiple years.

Related Shortfalls

SMALLSAT-TBD: Commercially Viable Radioisotope Power Sources
SMALLSAT-TBD: Efficient and Low SWaP-C Solar Array Deployment Mechanisms
SMALLSAT-TBD: Integrated Power Systems (Efficiency Packing Factors, Combining Communication and/or Thermal Systems)
PWR-TBD: Power for Non-Solar-Illuminated Small Systems
PWR-509: Radioisotope Heat/Power Source in 500 We Increment
PWR-510: Low temperature batteries
AMSC-1408: Advanced deployable load-bearing structures
AV-1551: Distributed Avionics to Enable Improved Performance and SWaP Efficiency
AV-1552: Extreme Environment Avionics
SMALLSAT-1459: High-reliability Propulsion System Components and Subsystems

Metrics

- Power density (power per volume, area, and/or mass)
- Power system efficiency
- Power generation (improvements to both BOL and EOL)
- Extendable volume range of deployable systems
- Power storage metrics, including total lifetime cycles, safe depth-of-discharge
- Reduction of RI regulatory overhead

ID	Shortfall Title
1438	Autonomy, Edge Computation, and Interoperable Networking for Small Spacecraft

Description

Increasing numbers of small spacecraft and small spacecraft constellations require an improvement in the ability to perform autonomous operations in order to: reduce demand on limited ground network assets; enable rapid, on-board responses to time sensitive scenarios (i.e. conjunction response or a dynamic observation event); and enable multiple small spacecraft to operate as a single distributed system to perform advanced observations applicable to space and earth science without ground stations in the loop.

Advancements to autonomy in small spacecraft will allow for distributed systems, more robust situational awareness, improvements to fault detection and recovery, more intelligent data collection, and can address some communications limitations. Machine-learning (ML) algorithms, radiation-tolerant computational hardware, and methods to reduce or optimize the need for human interaction of spacecraft decision making are all relevant technologies.

Related Shortfalls

AV-TBD: High Performance Onboard Computing to Enable Increasingly Complex Operations
AV-TBD: Extreme Environment Avionics
AV-TBD: Distributed Avionics to Enable Improved Performance and SWaP Efficiency
AV-TBD: Advanced Data Acquisition Systems for Diverse Applications
AS-780: Spacecraft Anomaly Dataset
AS-689: Machine Learning Platforms and Architectures for Space Exploration
AS-TBD: Autonomous Systems: Resilient Agency
AS-TBD: Autonomous Systems: Deep Space Navigation
AS-TBD: Autonomous Systems: Continuous (Multi-Agent) Ecosystem Operations
COMM-1559: Deep Space Autonomous Navigation
SMALLSAT-TBD: Machine-learning Algorithms for Fault Detection, Isolation, and Recovery of Small Spacecraft Systems

Metrics

- Improvement to radiation tolerance metrics for subsystems and components usable with small spacecraft SWaP-C
- Computational load of ML and edge computation algorithms
- Processing performance capability and reliability
- Network availability

ID	Shortfall Title
1608	Surface-based lunar logistics management for near/mid-term missions

Description

New technologies are needed to minimize crew manual labor through efficient tools to offload, position, and deliver large and small payloads arriving to the surface. Developments should be extensible toward fully autonomous systems to handle incoming payloads. In some cases, docking/berthing/transfer ports are required. Once offloaded, technologies to enable tracking of logistics items as they move across the surface will be needed.

Related Shortfalls

SURFACE-1359: Payload maneuvering tools for offloading, positioning, and delivery
ROBO-826: Payload handling, manipulation, and transport
LOGISTICS-1326: Logistics transfer port
LOGISTICS-1441: Large payload/logistics transfer into pressurized volume
RPOC-361: Surface berthing and docking mechanisms
SURFACE-1352: Autonomous tracking tools for surface assets
SURFACE-1356: Surface-borne resource tracking and visualization

Metrics

- Mass and volume of maneuverable payload
- Crew time required to maneuver payload
- Position location accuracy of mobile pa

ID	Shortfall Title
1609	Surface-based lunar logistics management for sustained lunar evolution

Description

For a sustained lunar presence, robust logistics management technologies will be desired to improve tracking of assets, provide servicing and outfitting of mobility assets, and provide autonomous payload mobility. The ability to track items will need to evolve to accommodate an increase in items and to locate items with a higher accuracy.

Related Shortfalls

SURFACE-1358: Mobility outfitting and servicing station
SURFACE-1352: Autonomous tracking tools for surface assets
SURFACE-1359: Payload maneuvering tools for offloading, positioning, and delivery
ROBO-826: Payload handling, manipulation, and transport

Metrics

- TBD

ID	Shortfall Title
1610	Surface-based food management for sustained lunar evolution

Description

New food production and management technologies are desired to enable long duration crewed surface missions. On-surface production of food will reduce up-mass and provide data for missions planned further from Earth.

Related Shortfalls

SURFACE-1370: In-situ food quality sampling
LOGISTICS-985: Food intake tracking
SURFACE-TBD: Surface-based green house
SURFACE-1371: Commodity consumption monitoring and prediction to insure on-demand availability
LOGISTICS-1171: Low-hydration food for exploration missions

Metrics

- TBD

ID	Shortfall Title
1611	Surface-based end-of-life equipment management

Description

As an increased number of landers reach the lunar surface, the number of parts potentially available for reuse/recycling will also increase. A method of tracking these parts and matching them potential use cases will minimize waste and reduce up-mass requirements for future missions. Algorithms to enable maximum reuse/recycling of waste/trash/scavenged parts, while minimizing disposal will be desired along with autonomous disposition for recycling, on-surface disposal, return-to Earth disposal, or in-flight jettison.

Related Shortfalls

SURFACE-1385: Supervisory waste/trash management tools
SURFACE-1355: Autonomous inventory management algorithms for part sourcing decision making
SURFACE-1354: Scavenging database to inventory abandoned assets for potential reuse/recycling
MANU-1341: Recycling and reuse of thermoplastics and metals for in space manufacturing
ISRU-589: ISRU from waste materials

Metrics

- TBD

ID	Shortfall Title
1612	Surface-based fluid management for near/mid-term missions

Description

New technologies are needed to minimize crew manual labor through efficient tools to enable fluid transfers on a surface. Seals need to be very low leak in a cold and dusty environment. Robotically operated (extensible to autonomously operated) umbilicals are desired to enable fluid transfers between mated elements. Mobile fluid transfer capabilities are desired to transfer fluids between unmated elements separated by distance. Tools to enable in-situ interface integrity between assets mated for fluid transfer and reduced mass and volume leak detectors are also desired.

Related Shortfalls

SURFACE-1389: Cold and dust tolerant interface seals to enable surface transfers
SURFACE-1367: Reduced mass and volume vacuum-capable leak detectors
SURFACE-1381: In-situ interface integrity verification
SURFACE-1372: Mobile commodity transfer capabilities
SURFACE-TBD: Robotically operated surface umbilicals to enable fluid transfers (including data and power)
CFM-879: Long duration storage of cryogenic propellant in space on a surface
CFM-792: In-space and surface transfer of cryogenic propellant
PROP-1224: In-space and surface transfer of hypergolic propellant
SAT S&A-1506: In-space and surface transfer of high-pressure gases

Metrics

- TBD

ID	Shortfall Title
1613	Surface-based fluid management for sustained lunar evolution

Description

For a sustained lunar presence, robust fluid management technologies will be desired to ensure on-demand availability of critical fluids. Capabilities to autonomously mate/de-mate, control flow, identify leaks, and recover commodities will be desired. In addition, consumption monitoring along with production and delivery tracking will be desired to ensure on-demand availability. For fluids with purity requirements, the ability to verify standards in-situ is vital.

Related Shortfalls

SURFACE-1344: Autonomously operated surface umbilicals to enable fluid transfers (including data and power)
SURFACE-1368: Autonomous commodity recovery
SURFACE-1386: Autonomous surface-based cryogenic flow control
SURFACE-1366: Algorithms for autonomous leak evaluation and disposition
SURFACE-1369: In-situ fluid purity sampling
SURFACE-1371: Commodity consumption monitoring and prediction to insure on-demand availability
SURFACE-TBD: Scavenging database to inventory residual gases from abandoned assets for potential reuse/recycling
CFM-879: Long duration storage of cryogenic propellant in space on a surface
CFM-792: In-space and surface transfer of cryogenic propellant
PROP-1224: In-space and surface transfer of hypergolic propellant
SAT S&A-1506: In-space and surface transfer of high-pressure gases

Metrics

- TBD

ID	Shortfall Title
1614	Surface-based planning and scheduling technologies for sustained lunar evolution

Description

A long duration surface presence will exceed the complexity of all prior human missions, including the ISS. In-situ modeling and decision-making technologies that can plan surface operations to achieve a complex set of evolving mission goals will be desired to ensure efficiency, safety, and mission success.

Related Shortfalls

SURFACE-1374: Decision making algorithms for robotic task prioritization
SURFACE-1376: Master planning models
SURFACE-1378: Autonomous maintenance scheduling
SURFACE-1365: Data fusion tools to merge complex and disparate data for real-time autonomous decision making

Metrics

- TBD

ID	Shortfall Title
1615	Common tools for on-surface maintenance and repair for reduced crew interaction

Description

Crew time will be at a premium during surface missions therefore it is strongly desired to reduce the time crew spends on maintenance tasks. Development of new maintenance and repair technologies that are interoperable and multi-use will simplify operations, thus reducing crew time required for those activities. Simplifying repair and maintenance operations across a complex network of surface assets will also reduce launch mass of repair systems and increase the reliability and efficiency of surface operations.

Related Shortfalls

SURFACE-1382: Interoperability adaptors
SURFACE-1380: Interfaces designed for robotic manipulator access
SURFACE-1383: Multi-use, mobile, self-alignment tool
SURFACE-1357: Common repair toolkits
SURFACE-1364: Reconfigurable sensor systems

Metrics

- TBD

ID	Shortfall Title
1616	Dissipation of electrical charge on surface assets

Description

Equipment on the lunar surface will accumulate a static charge due to lunar surface potentials, which are dictated by local lighting and plasma conditions. Additional charging will be incurred by mobile equipment due to the triboelectric effect. Tribo-charging can be mitigated by sunlight but represents a larger concern in shadowed regions. Lunar regolith has low electrical conductivity, and as such does not provide a sufficient path to dissipate electrical charge that has built up on equipment. Earth-like grounding systems will not provide electrical grounding to lunar hardware. New technologies and concepts are required to maintain electrical systems and provide crew safety.

Related Shortfalls

SURFACE-1349: Electrical grounding on the lunar surface
SURFACE-TBD: Tools for removal of electrical charge

Metrics

- TBD

ID	Shortfall Title
1617	Autonomous on-surface maintenance and repair for sustained lunar evolution

Description

A sustained human presence on the lunar surface will require infrastructure, which will require maintenance and repair to achieve reliable, available systems. To minimize crew time required for maintenance and repair, autonomous capabilities must be developed. Autonomous prognostics, fault detection, isolation, and recovery systems, along with robotic methods of repair and routine maintenance, would significantly reduce crew burden and increase system reliability.

Related Shortfalls

SURFACE-1360: Autonomous, adaptable fault detection tools
SURFACE-1361: Prognostics algorithms, including extreme environment factors
SURFACE-1388: Reduced maintenance of surface-based hardware/components through intelligent devices
SURFACE-1362: Fault isolation and recovery capabilities
SURFACE-1363: Robotic care-takers
SURFACE-1384: Autonomous robotic seal replacement
MANU-1489: In-Space and On-Surface Manufacturing of Parts/Products from Surface and Terrestrial Feedstocks

Metrics

- TBD

ID	Shortfall Title
1618	Survive and operate through the lunar night

Description

Assets on the surface of the moon will be subjected to wide environmental sink temperature variations (on the order of 35 K to 400 K) and large variations in induced heat loads (on the order to 5 W to 10 kW). The ability to survive and operate through these extreme variations is required to enable long-duration surface operations. New power, thermal management, and actuation technologies are required and will need to work together to accomplish this goal for science experiments, mobility assets, habitats, and more.

Related Shortfalls

THERMAL-483, THERMAL-472, THERMAL-1132: Variable heat rejection
THERMAL-522: Freeze tolerant thermal components
PWR-510: Low temperature batteries
PWR-509: Radioisotope power/heat sources
AV-539, 447, 1160: Avionics thermal management for extreme environments
AMSC-393, ROBO-1346, 687, THERMAL-593: Cold tolerant mechanisms

Metrics

- Asset survival time in days
- Asset operability during unlighted conditions

ID	Shortfall Title
1619	High temperature heat rejection for nuclear applications

Description

Nuclear technologies (such as fission surface power and nuclear electric propulsion) can be optimized by rejecting waste heat at high temperatures (on the order of 500 K). New thermal control coatings designed to optimize optical properties while maintaining adherence to the substrate are required. In addition, waste heat transport should be optimized, and lightweight radiators need to be developed. For those systems operating on the lunar or Martian surface, dust-tolerance/mitigation is also desired.

Related Shortfalls

THERMAL-948: Nuclear waste heat transport
THERMAL-484, THERMAL-499: Advanced radiators
THERMAL-514: Thermal control coatings
THERMAL-521: Dust tolerant thermal systems
THERMAL-519: Advanced heat pipes
THERMAL-1475: Reversible, high temperature fluid interface

Metrics

- TBD

ID	Shortfall Title
1620	Conditioned stowage to maintain science and/or nutritional integrity

Description

Many types of utilization samples will require conditioned stowage at a range of temperatures, including cryogenic temperatures. Current capabilities exist to transport small volumes at moderate temperatures for short durations. However, samples will require conditioned storage from collection through Earth return to maintain their integrity for science investigations. For long duration, Earth-independent missions, different elements of the food system may need to be stowed at ambient, refrigerated, or freezing temperatures for a prolonged periods to maintain nutrients and overall acceptability. Biological samples may need to be refrigerated. There are both active and passive approaches to address these needs. For use cases requiring transit, low SWaP (size, weight and power) will also be critically important.

Related Shortfalls

LOGISTICS-1119: Cryogenic sample return
THERMAL-TBD: Cold sample return
LOGISTICS-1036: Refrigerated long term stowage chamber for food preservation in deep space
LOGISTICS-800: Safe, acceptable, and nutritious food systems
CFM-482: High capacity/high efficiency cryocoolers 90 K
THERMAL-1022: Phase change materials with increased energy storage

Metrics

- TBD

ID	Shortfall Title
1621	Cryogenic cooling for science instrumentation

Description

Cryogenically cold temperatures, approximately 4-5 Kelvin, must be achieved with ultra-low vibration to enable high sensitivity detectors. Traditional cryo-coolers require a compressor, which induces vibrations above the allowable threshold. To combat this, science missions with high sensitivity detectors often fly large tanks of cryogenic helium, which boils off over time. Novel, ultra-low vibration cryogenic coolers or helium boiloff reduction technologies could significantly reduce the mass required for these missions, while simultaneously extending mission life.

Related Shortfalls

THERMAL-TBD: Ultra-low vibration cryo-cooler for temperatures below 4 Kelvin

THERMAL-TBD: Integrated refrigeration for liquid helium preservation/recovery

CFM-461: Valves, actuators, and components

CFM-486: Structural heat load reduction

Metrics

- Vibration limits
- Mass reduction

ID	Shortfall Title
1622	Novel thermal technologies to improve environmental control of habitats

Description

Single-phase (liquid) heat transfer fluids have been successfully used in a variety of active thermal control systems for human and robotic spacecraft. Human spacecraft have historically used thermal control fluids in either one-fluid (Apollo) or two-fluid (Shuttle, ISS, Orion) architecture configurations. Two-fluid systems have typically been driven by the need to minimize the risk of crew exposure to hazardous fluids within the vehicle, and simultaneously providing design robustness to varying heat loads and thermal environments external to the vehicle. While these two-fluid systems increase mission flexibility and decrease risk to crew, they require additional system mass to accommodate support hardware associated with having multiple fluid loops. In addition, traditional heat transfer fluids have relatively small operational ranges. Emerging fluid technologies may enable designer fluids capable of maintaining high efficiency operation through the wide temperature swings expected due to extreme surface environments. Two-phase active systems may provide similar benefits. Recent advancements in materials have shown feasibility of potential solid-state cooling solutions. Advancements in these, and other areas may reduce overall thermal management system mass, improve performance, and in some cases, eliminate hazards to crew.

Related Shortfalls

THERMAL-537: Designer heat transfer fluids
THERMAL-TBD: Solid-state cooling (elastocaloric, barocaloric)
THERMAL-761: Two-phase active thermal control systems with reduced mass
THERMAL-471: Variable heat rejection
THERMAL-521: Dust tolerant thermal systems
LOGISTICS-854: Robust condensing heat exchanger

Metrics

- TBD

ID	Shortfall Title
672	Long-life thermal control for surface suits capable of extreme access

Description

Improved space suits are desired to enable sustainable crew surface operations. Thermal control of these suits will need to accommodate unique surface environments not relevant in low Earth orbit. Specific challenges include maintenance of suit fabric optical properties in a dusty environment, heat conduction through boot contact with the lunar surface, variable heat rejection needs due to ambient temperature variations, and quantity of consumables required for extended suited excursions. A system level design approach is needed. Active and passive thermal systems must work together to achieve adequate results. Technologies for consideration in the system design may include advanced heat exchangers, dust tolerant fabrics, designer heat transfer fluids, and more.

Related Shortfalls

THERMAL-523: Advanced heat exchangers
THERMAL-521: Dust tolerant thermal systems
THERMAL-537: Designer heat transfer fluids
THERMAL-TBD: Closed-loop thermal control
LOGISTICS-1062: Lunar surface environmental protection garment shell material systems
LOGISTIC-982: Mars EVA suit environment thermal insulation
LOGISTICS-981: Heat rejection for Mars EVA suit in on-vacuum applications
LOGISTICS-906: Lunar EVA suit dust mitigation

Metrics

- TBD

ID	Shortfall Title
1623	Advanced thermal modeling capabilities

Description

Integrated multi-physics modeling techniques are desired to enable more efficient thermal management system designs. Examples include concurrent thermal/structural analysis; integrated surface environment and thermal management system analysis; high-fidelity, reduced run time, two-phase flow modeling; etc..

Related Shortfalls

THERMAL-613: Advanced modeling techniques
THERMAL-782: Lunar & Martian thermal data and modeling tools
THERMAL-TBD: Topology optimization algorithms
CFM-1194: Cryogenic fluid management predictive and validation modeling
CFM-492: Medium (nodal) and high (Computational Fluid Dynamics(CFD)) fidelity systems modeling

Metrics

- TBD

ID	Shortfall Title
1624	Advanced thermal management technologies for diverse applications

Description

Enhanced thermal management technologies can have sweeping impacts on a variety of space missions. The related shortfalls list specific areas where advancements can have the broadest impacts. For example, state of the art radiators require a large mass per unit surface area to adequately reject heat throughout various mission phases. Radiators often require very large surface areas and dominate system mass. Up-mass and volumetric limits can result in mission constraints. New manufacturing techniques have emerged allowing for integration of thermal systems with structural elements. Advancements in this area will reduce system mass and may fundamentally alter approaches to thermal management systems. High thermal conductivity heat pipes will reduce thermal management system mass and increase spacecraft heat rejection capabilities. High efficiency, reduced mass heat exchangers (increased UA and decreased pressure drop) will result in improved performance. As electronics systems become more powerful, it is necessary to improve cooling capabilities to maintain optimal performance with minimal mass, like high efficiency (increased UA and decreased pressure drop) coldplates. Thermal Control Coatings (TCC) are used in a variety of applications and require improved optical properties at both beginning and end of life. SoA white-paint radiator coatings degrade significantly over time and through exposure to high energy particles expected during transits through the Van Allen belt. TCCs in surface applications will degrade through dust accumulation. Thermal Management Systems exposed to wide temperature variations in extreme environments would greatly benefit from the ability to withstand freeze thaw cycles of working fluids. SoA systems fracture/rupture upon freezing, which could result in loss of mission. Existing freeze prevention methods degrade system performance.

Related Shortfalls

THERMAL-605: Integrated structural/thermal elements
THERMAL-519: Advanced heat pipes
THERMAL-523: Advanced heat exchangers
THERMAL-604: Advanced active cooling for electronics and avionics
THERMAL-484, 499: Advanced radiators
THERMAL-514: Thermal control coatings
THERMAL-522: Freeze tolerant thermal components
THERMAL-521: Dust tolerant thermal systems

Metrics

- TBD

ID	Shortfall Title
1586	Enhanced Access to Orbital and Suborbital Space for Flight Demonstration and Test

Description

This shortfall addresses a need for technologies that enable operation of suborbital and orbital payloads and vehicles. Access refers to testing in space, space-like or near-space environments which feature microgravity conditions; environmental exposure; and entry, descent, and landing (EDL) test profiles. Examples of technologies which contribute toward closing this shortfall include:

- Access to higher altitude and longer duration flights for both suborbital and orbital vehicles and high-altitude balloons - enabling longer duration exposure as well as access to re-entry environments critical for EDL technologies.
- Accommodations on rocket stages as part of launch vehicle flight profiles, enabling both regular access to space for hosted payloads, as well as re-entry and/or return capabilities for compatible launch vehicles and stages.
- An accessible hosted orbital platform market capable of providing stated services for multiple orbits in a variety of orbital environments.
- Longer duration microgravity flight test profiles.
- Greater availability and profile envelopes of rocket powered landing vehicles in support of EDL objectives.
- Point-to-point suborbital flight profiles.
- Hypersonic test platforms.
- Technologies which enable the cost-effective and dynamic hosting of payloads on flight vehicles (suborbital, orbital, and planetary lander). Payload hosting includes the provisions of communications, power, and structural accommodations to meet the interface requirements of an attached sensor or instrument. Technologies that enable payloads to be as vehicle-independent as possible would facilitate rapid integration, enable early payload development without vehicle-interface knowledge, and unlock the ability to quickly conduct flight tests on multiple different platforms.

Related Shortfalls

<u>SMALLSAT-TBD:</u> Longer Duration Exposure to Space Environments
<u>SMALLSAT-TBD:</u> Increased Cadence of Access to Space Environments
<u>SMALLSAT-TBD:</u> Scalable early-stage interface systems for suborbital testing
<u>SMALLSAT-TBD:</u> Specialized Interface for Payloads and Sensors
<u>SMALLSAT-TBD:</u> Human-tended Microgravity Research Equipment and Capabilities
<u>EDL-TBD:</u> Small Spacecraft and Commercial Entry Capabilities
<u>EDL&PL-309:</u> Low Cost On-Demand Payload Return

Metrics

- Duration of exposure to relevant space environment
- Launch cadence of test platforms
- Range and breadth of accommodable interface requirements
- Range and breadth of accessible test environments

ID	Shortfall Title
1587	Wildfire Integrated Effect Chain

Description

The United States and other parts world of the are facing a wildland fire crisis resulting from many decades of fire suppression, climate change, and human populations moving closer to historically fire prone areas. This wildland fire crisis needs a new management paradigm that takes full advantage of the best available science, technology, and capabilities to overcome current barriers to more efficient and effective wildland fire management. Science and technology are fundamental to anticipating and managing the new reality of extreme fires in a warming world. Indeed, recent U.S. government reports, such as the Wildland Fire Mitigation and Management Commission report, identify a holistic approach to addressing the wildfire crisis by creating communities and landscapes that are resilient to wildfire. Various government entities such as USFS, Cal Fire, DOI, DHS, NOAA, and industry are all working on sub systems of the needed Effect Chain. Improved technology and the integration of that technology is highlighted as key to solving that wildland fire crisis.

Related recommendations include (i) improving the prediction of fire in the wildland and built environment interface through data aggregation and science-based decision support services and (ii) enabling the provision of real-time, science-based, and data- rich scientific and technical analytic services, decision support, and predictive services to inform land and fuels management, community risk reduction, and fire management and response. Shortfalls span Earth observation, modelling/prediction, and integration into a common system are currently impede adoption in wildland fire management.

By building systems architecture, integration opportunities using application protocol interfaces, we will reduce the risk of heterogeneous systems evolving. Therefore, one-NASA approach will facilitate the federal government to build an end-to-end architecture that will allow entire effects chain from prediction, modeling, in-time assessments, detection, tracking, suppression, and recovery as well as related decisions using systems engineering approach which will begin with architecture.

Related Shortfalls

OTHER-TBD: Facilitating machine learning and artificial intelligence to create new data products needed for wildland fire management and for management of the constellation of observing platforms.
OTHER-TBD: Data fusion, enabling the seamless exchange of information between spaceborne, airborne, and in situ assets.
SENSORS-TBD: Enhanced capabilities of existing science instruments needed for monitoring pre- fire, active-fire, and post-fire environments.
SENSORS-TBD: Instruments with reduced mass and power for accommodation by next-generation small spacecraft and aerial platforms (e.g.., HALE).
SENSORS-TBD: Enabling unprecedented measurements from multiple vantage points through model-directed, coordinated observations using autonomous tasking.
OTHER-TBD: Addressing computational challenges for modeling and for data acquisition, fusion, and processing in a real-time environment.

Metrics

- Time to fire detection and input to predictive models
- Detection fidelity
- IT system NWCG standards inclusion

ID	Shortfall Title
1588	Protect Earth from Destructive Natural Impacts (Planetary Defense)

Description

Protecting Earth from impacts of the naturally occurring Near-Earth Objects (NEOs – asteroids and comets whose orbits about the Sun bring them into Earth vicinity) is vital for human welfare. Planetary defense has 3 key aspects: (1) Detection and characterization, (2) Impact threat assessment, and (3) Mitigation. The first steps in assessing and mitigating a potential impact threat is the ability to discover previously unknown asteroids and comets which could approach Earth, accurately determine their orbital state to predict their potential of Earth impact in the future and characterize their size and composition. If an impact threat is detected, its potential effect on Earth needs to be assessed. The object's size, composition, speed, and atmosphere incidence angle affect the extent to which the object will ablate and/or break up during atmospheric entry and what effects will reach Earth's surface. Fragments that reach the lower atmosphere and/or Earth's surface can cause destructive atmosphere shock waves, thermal effects, cratering and ejecta or tsunamis, and other widespread damage. Modeling and predicting these effects requires a multi-disciplinary approach including atmospheric and oceanic prediction, disaster assessment, and other diverse fields. Once a significant impact potential is confirmed, mitigation strategies can be applied to the body. The Double Asteroid Redirection Test (DART) demonstrated that an asteroid's trajectory can be affected by the kinetic impact of a spacecraft; however, effectiveness of mitigation techniques are dependent on the size, composition and time to impact of Earth. Effectiveness of a mitigation mission requires more accurate characterization of the impacting body via either longer range sensing technology or rapid deployment of spacecraft for in-situ investigation of the object. Alternative mitigation techniques which may be more effective for a given object composition or time available before impact will need demonstration of propulsion, large mass push or pull technologies, sensing, and autonomy technologies beyond the current state-of-the-art.

Related Shortfalls

SENSORS-TBD: Detection and characterization of Near-Earth Objects
EDL-TBD: Ablation and breakup modeling
OTHER-TBD: Damage and threat assessment modeling
OTHER-TBD: Near Earth Object mitigation

Metrics

- Detection range for a given size, e.g. detection of 100-meter size asteroid
- Range for collection of composition measurements (of 100-meter sized asteroid)
- Time for space mission development and deployment to the threat object
- Time required for application of effective mitigation and at what distance from Earth, i.e. time to deflect object from Earth impacting trajectory

ID	Shortfall Title
1589	Space Situational Awareness

Description

Increasing numbers of spacecraft operators and spacecraft constellations has led to a significant increase in on-orbit objects (active, passive, and debris). Increased space situational awareness, identification, tracking, conjunction prediction, and maneuver coordination will become critical to an expanded LEO economy as well as USG and NASA activities in near earth locations.

New systems of sensors to identify, track, characterize, and provide high resolution ephemeris will facilitate an increased awareness of the orbital environment. Rapid identification and tracking enables operators to quickly commission their systems after deployments from rideshare missions allowing them to quickly integrate into space traffic management solutions.

Future Space traffic management solutions will be a critical component to SSA; focusing on enabling fair and effective solutions for identifying probable collisions characterized by risk profile, enabling maneuvering responsibility, and conjunction deconfliction.

Related Shortfalls

shortfall #: And title

Metrics

- TBD

ID	Shortfall Title
1590	Planetary Protection

Description

Planetary Protection is the practice of protecting solar system bodies from contamination by Earth life and protecting Earth from possible life forms that may be returned from other solar system bodies. NASA promotes the responsible exploration of the solar system by implementing and developing efforts that protect the science, explored environments and Earth.

Current robotic spacecraft are assembled in various levels of clean facilities, cleaned to prevent contaminants, and sterilized using heat. Once humans enter exploration systems, preventing contamination at our exploration destinations becomes much more complex. Bioburden management, sample handling, and sensing/monitoring will be key components of effective planetary protection measures. In-situ technologies that can minimize crew effort and operational complexity to keep contamination prevention realistic and cost-effective will be an effective part of a successful scientific exploration campaign.

Related Shortfalls

TBD

Metrics

- Cost
- Effectiveness