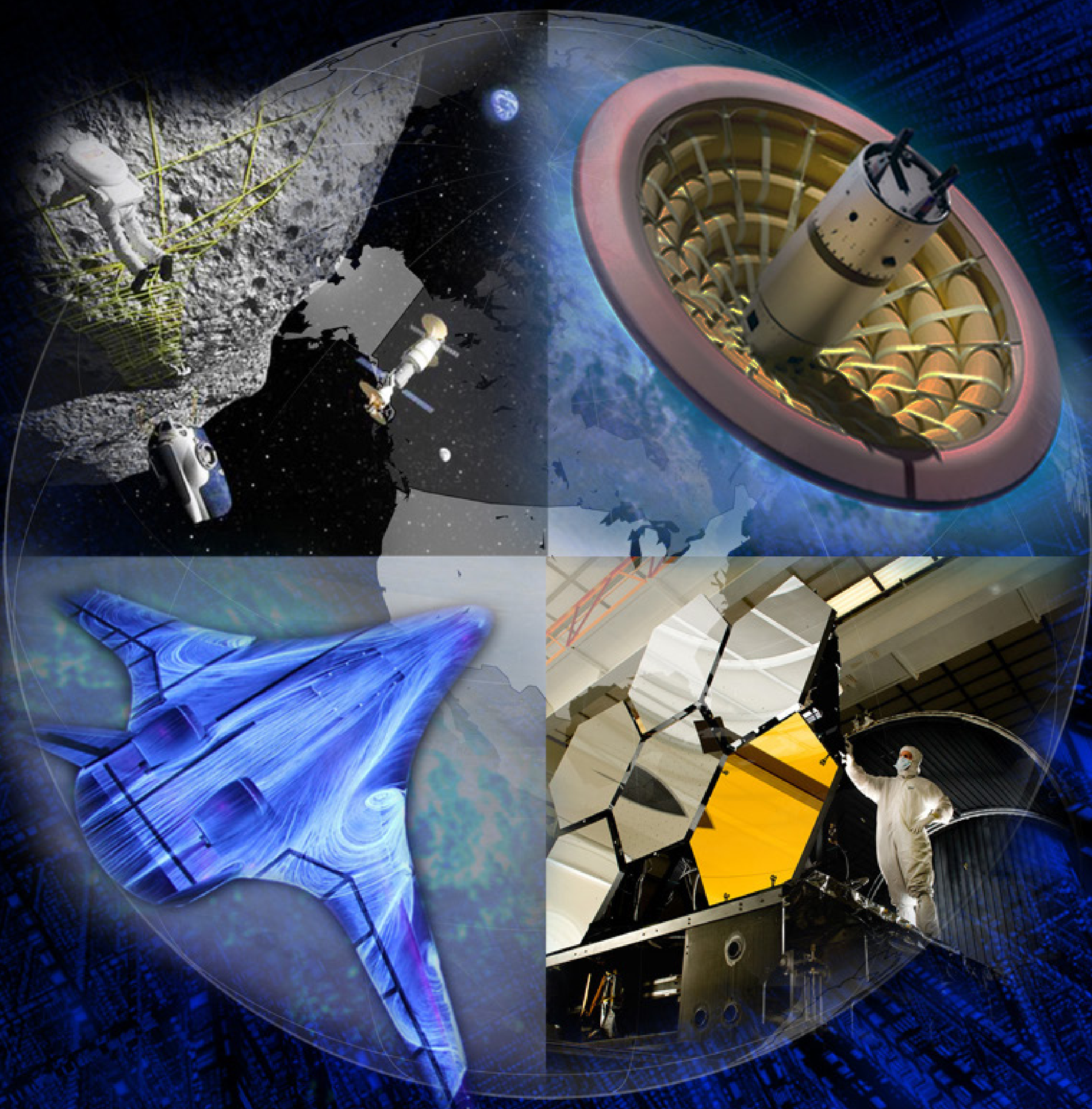
National Aeronautics and Space Administration

# NASA Technology Roadmaps
## TA 7: Human Exploration Destination Systems



May 2015 Draft

## *Foreword*

NASA is leading the way with a balanced program of space exploration, aeronautics, and science research. Success in executing NASA's ambitious aeronautics activities and space missions requires solutions to difficult technical challenges that build on proven capabilities and require the development of new capabilities. These new capabilities arise from the development of novel cutting-edge technologies.

The promising new technology candidates that will help NASA achieve our extraordinary missions are identified in our Technology Roadmaps. The roadmaps are a set of documents that consider a wide range of needed technology candidates and development pathways for the next 20 years. The roadmaps are a foundational element of the Strategic Technology Investment Plan (STIP), an actionable plan that lays out the strategy for developing those technologies essential to the pursuit of NASA's mission and achievement of National goals. The STIP provides prioritization of the technology candidates within the roadmaps and guiding principles for technology investment. The recommendations provided by the National Research Council heavily influence NASA's technology prioritization.

NASA's technology investments are tracked and analyzed in TechPort, a web-based software system that serves as NASA's integrated technology data source and decision support tool. Together, the roadmaps, the STIP, and TechPort provide NASA the ability to manage the technology portfolio in a new way, aligning mission directorate technology investments to minimize duplication, and lower cost while providing critical capabilities that support missions, commercial industry, and longer-term National needs.

The 2015 NASA Technology Roadmaps are comprised of 16 sections: The Introduction, Crosscutting Technologies, and Index; and 15 distinct Technology Area (TA) roadmaps. Crosscutting technology areas, such as, but not limited to, avionics, autonomy, information technology, radiation, and space weather span across multiple sections. The introduction provides a description of the crosscutting technologies, and a list of the technology candidates in each section.

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# Executive Summary

This is Technology Area (TA) 7: Human Exploration Destination Systems, one of the 16 sections of the 2015 NASA Technology Roadmaps. The Roadmaps are a set of documents that consider a wide range of needed technologies and development pathways for the next 20 years (2015-2035). The roadmaps focus on "applied research" and "development" activities.

TA 7 Human Exploration Destination Systems, covers the broad range of technology candidates associated with enabling successful human activities in space, from missions operations to in-situ resource utilization (ISRU). The TA 7 Human Exploration Destination Systems Technology Area Breakdown Structure (TABS) consist of six Level 2 technology focus areas. They include: 7.1 In-Situ Resource Utilization; 7.2 Sustainability and Supportability; 7.3 Human Mobility Systems; 7.4 Habitat Systems; 7.5 Mission Operations and Safety; and 7.6 Cross-Cutting Systems. The technological goals and challenges that will be required to safely and cost effectively enable human exploration missions of discovery for our nation, the planet, and for the benefit of all humankind are documented.

## *Goals*

All TA 7 goals relate to sustaining human presence in space, which will require existing systems and vehicles to become more independent, incorporate intelligent autonomous operations, and take advantage of the local resources. Advances must be made in finding, extracting, and processing in-situ resources. The reliability of all mission systems—especially habitation components—must be improved, and all systems must be easier to maintain or repair. Human crews must have more time available for performing core mission activities and spend less time maintaining systems or managing logistics. Crews must also be less reliant on ground operations support and must conduct more training during the mission. Additionally, planetary protection techniques must be developed and refined to protect crews and Earth while preventing contamination. The same is true for mobility systems to efficiently transport humans to exploration areas of interest, as well as integrate effectively with other vehicles systems.

**Table 1. Summary of Level 2 TAs**

| 7.0 Human Exploration Destination Systems | Goals: | Sustain human presence in space and provide more time for performing core mission activities, while reducing reliance on Earth. |
|---|---|---|
| 7.1 In-Situ Resource Utilization | Sub-Goals: | Leverage in-situ resources to dramatically reduce launch mass and cost of human exploration missions. |
| 7.2 Sustainability and Supportability | Sub-Goals: | Establish a self-sufficient, sustainable, and affordable long-duration human space exploration program. |
| 7.3 Human Mobility Systems | Sub-Goals: | Enable humans to safely and efficiently perform work or scientific activities outside their primary spacecraft. |
| 7.4 Habitat Systems | Sub-Goals: | Develop an autonomously operating spacecraft that promotes crew health and well-being while reducing required crew maintenance and servicing and optimizing resource utilization. |
| 7.5 Mission Operations and Safety | Sub-Goals: | Manage space missions from the point of launch through the end of the mission for long-duration missions and over long time delays. |
| 7.6 Cross-Cutting Systems | Sub-Goals: | Manage particulate contamination transported by operations, lander plume ejecta, and larger-scale construction and assembly technologies. |

## *Benefits*

The capabilities and technology candidates defined in TA 7 will collectively improve NASA's ability to conduct affordable and sustainable human mission operations beyond Earth while opening up commercialization opportunities in low-Earth orbit (LEO) for industrial development, academia, and entertainment space industries. Benefits include:

- Use of in-situ resources that enable and enhance robotic and human missions beyond the traditional mission architectures and launch vehicle capabilities by allowing more payload mass to be dedicated to science or crew.
- Improvements in tools for maintenance, self-repair, food systems, and logistics management that reduce crew workload and enhance crew safety.
- Mobility systems that enable in-space and planetary exploration such as atmospheric flyers, surface roving, in-space taxis, and extravehicular activity (EVA) or extravehicular robotics (EVR) mobility enable productive science missions and extend human activities.
- Advances in systems that enable "intelligent" habitats and evolvable habitat systems, which will reduce transportation mass and volume, and improve crew comfort, safety, and productivity.
- Mission operations enhancements that lower the cost of future missions and reduce the impact of time delays for remote destinations through improved crew autonomy and increased reliability.
- Planetary protection technology candidates that ensure the safety of the exploration crew and sample handling personnel.
- Particulate prevention and mitigation technology candidates that significantly extend the life and performance of surface hardware and improve health of crew.
- In-space construction and assembly capabilities that reduce constraints resulting from launch vehicle limitations and increase the flexibility and utility of in-space and surface vehicles and structures.

# Technology Area 7

## Human Exploration Destination Systems 1 of 5

# Enabling Technology Candidates Mapped to the Technology Need Date

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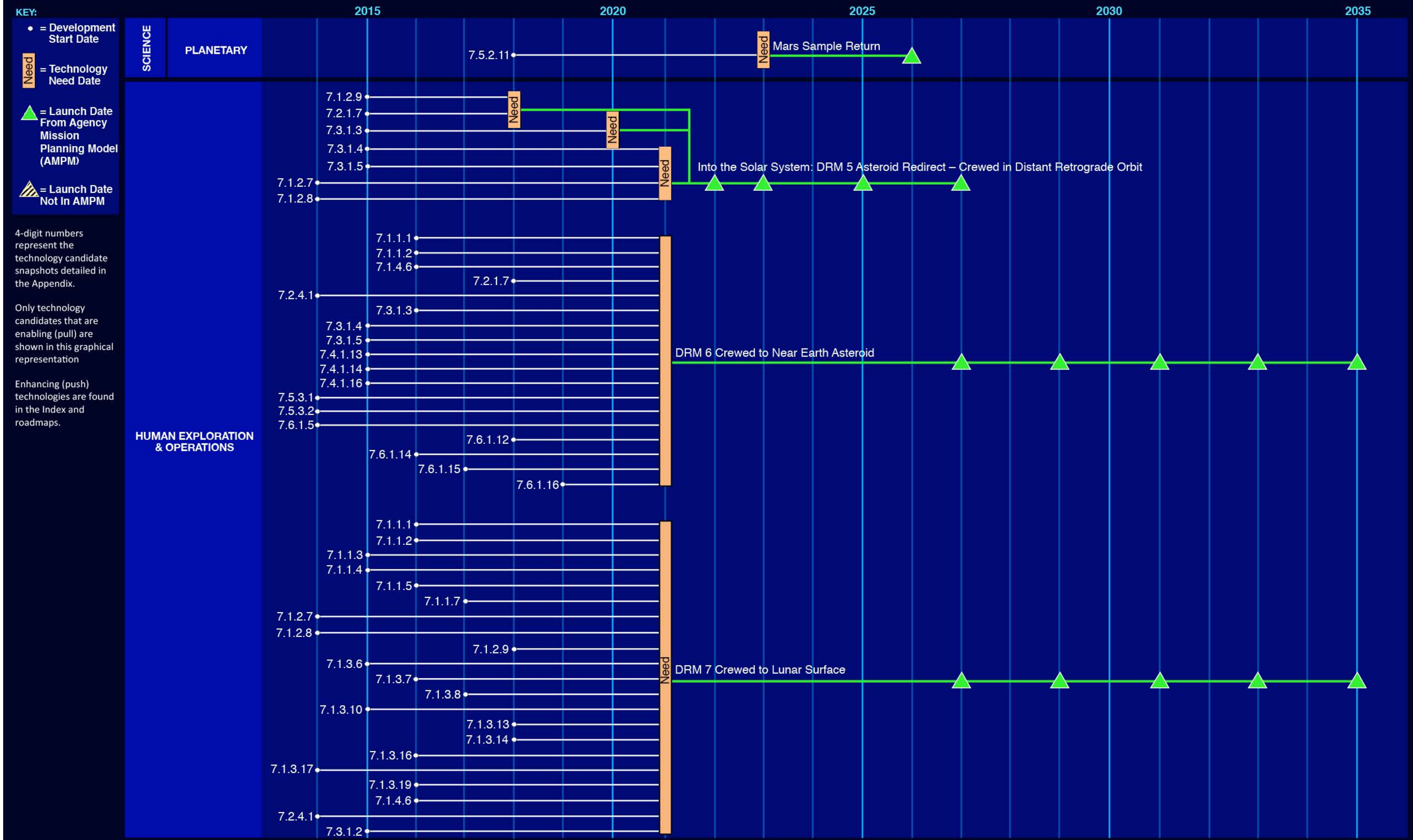


4-digit numbers represent the technology candidate snapshots detailed in the Appendix.

Only technology candidates that are enabling (pull) are shown in this graphical representation

Enhancing (push) technologies are found in the Index and roadmaps.

Figure 1. Technology Area Strategic Roadmap

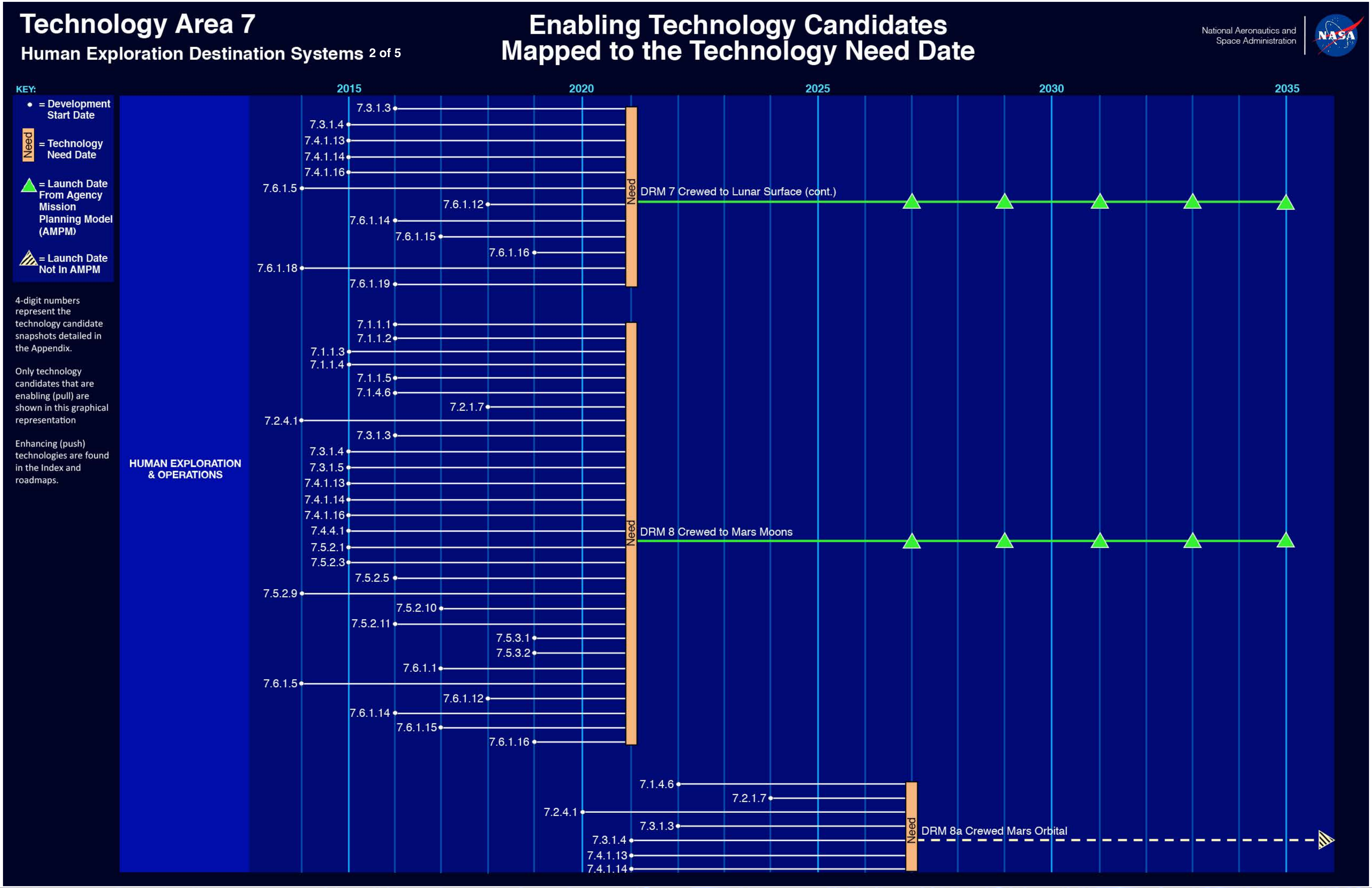


Figure 1. Technology Area Strategic Roadmap (Continued)

# Technology Area 7

## Human Exploration Destination Systems 3 of 5

# Enabling Technology Candidates Mapped to the Technology Need Date

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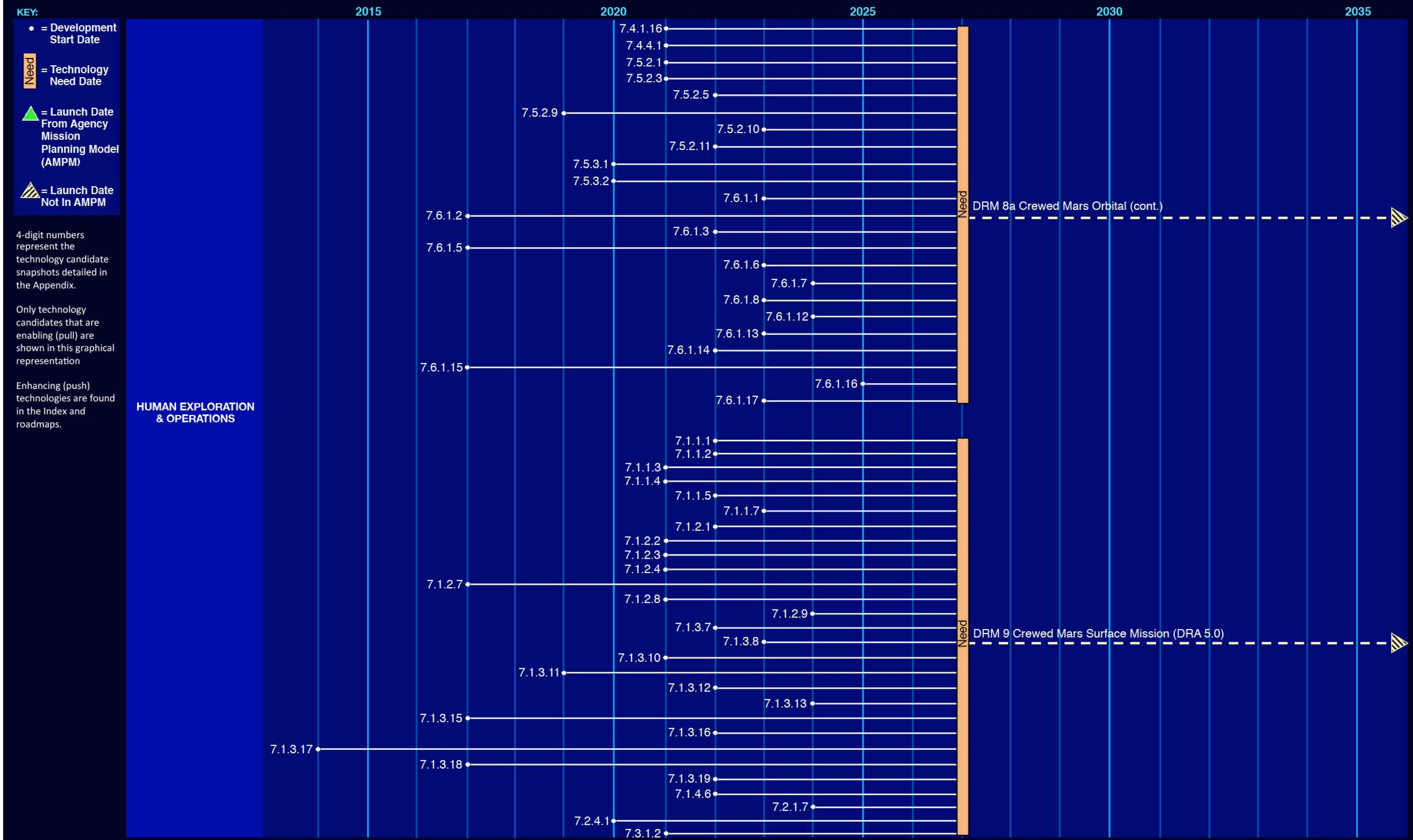


Figure 1. Technology Area Strategic Roadmap (Continued)

# Technology Area 7

## Human Exploration Destination Systems 4 of 5

# Enabling Technology Candidates Mapped to the Technology Need Date

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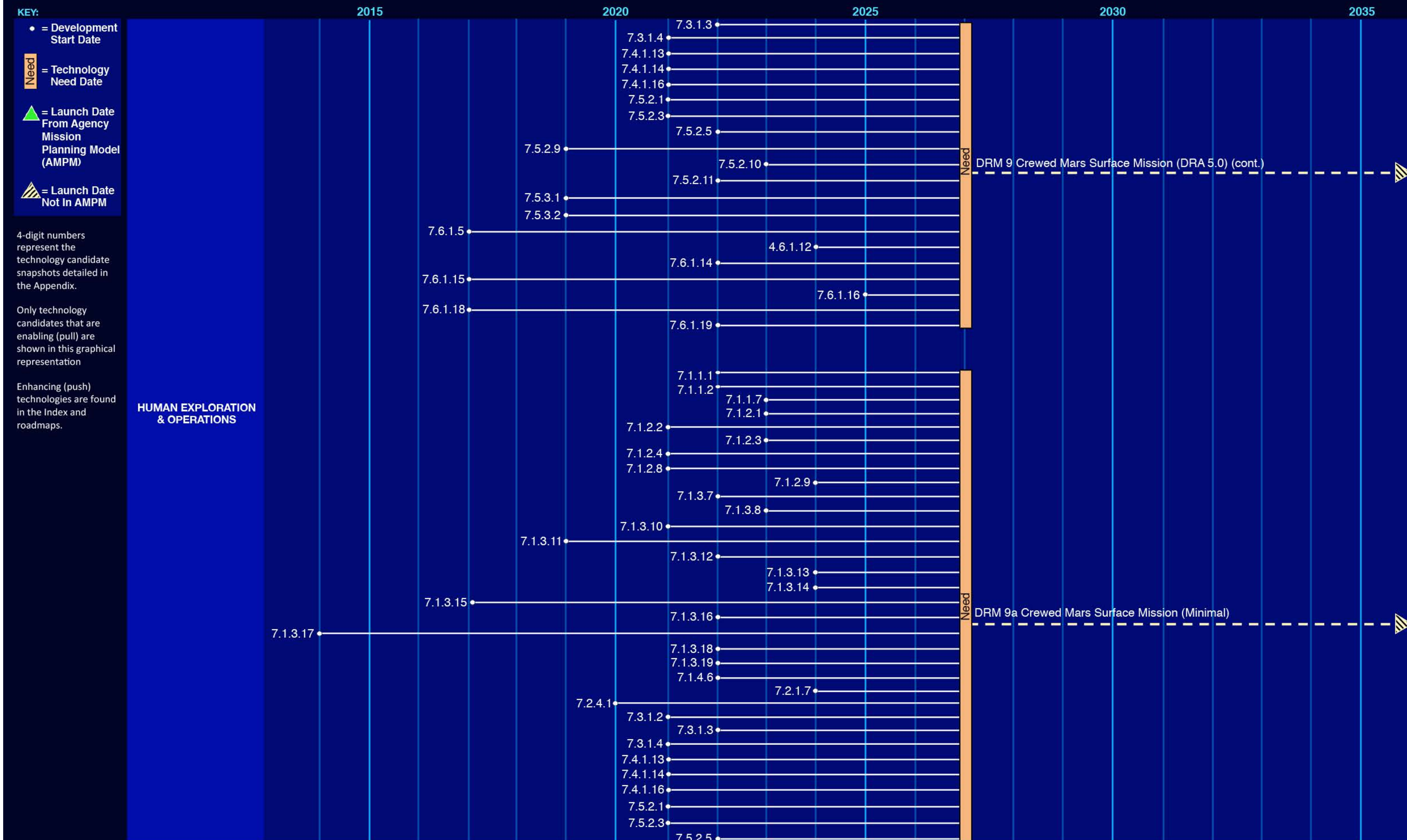


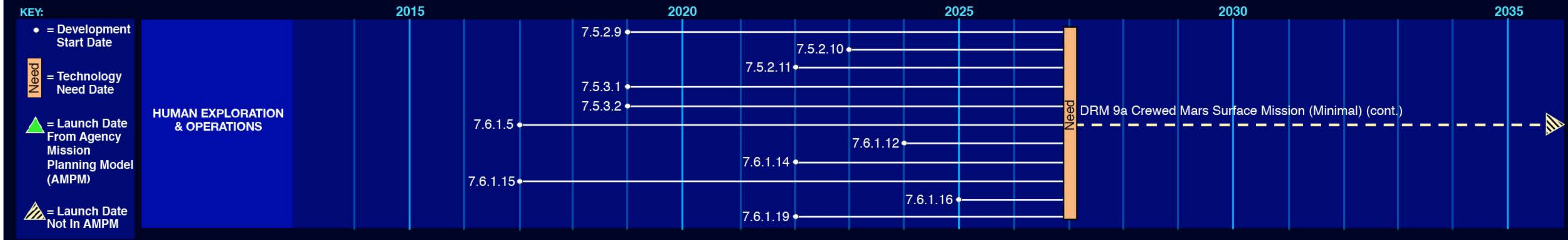

Figure 1. Technology Area Strategic Roadmap (Continued)

# Technology Area 7

## Human Exploration Destination Systems 5 of 5

# Enabling Technology Candidates Mapped to the Technology Need Date

National Aeronautics and Space Administration




4-digit numbers represent the technology candidate snapshots detailed in the Appendix.

Only technology candidates that are enabling (pull) are shown in this graphical representation

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Figure 1. Technology Area Strategic Roadmap (Continued)

# Introduction

Technology Area (TA) 7, Human Exploration Destination Systems, addresses technology candidates that enable, via human systems integration, sustained human exploration and support of NASA's missions and goals for the next 20 years. These technology candidates will enable a sustained human presence at NASA's exploration destinations, such as Lagrange points, low-Earth orbit (LEO), high-Earth orbit (HEO), geosynchronous orbit (GEO), the Moon, near-Earth objects (NEOs), Phobos, Deimos, Mars, and beyond.

This TA is broken into six sub-areas. The complete breakdown structure for TA 7 is shown in Figure 2.


**Figure 2. Technology Area Breakdown Structure for Human Exploration Destination Systems**

NASA's technology area breakdown structure (TABS) is in wide use in technology organizations around the globe. Because of this, any sections that were previously in the structure have not been removed, although some new areas have been added. Within these roadmaps, there were some sections of the TABS with no identified technology candidates. This is either because no technologies were identified which coupled with NASA's mission needs (either push or pull) within the next 20 years, or because the technologies which were previously in this section are now being addressed elsewhere in the roadmaps. These sections are noted in gray above and are explained in more detail within the write-up for this roadmap.

## *7.1 In-Situ Resource Utilization*

In-Situ Resource Utilization (ISRU) is the identification, acquisition, and utilization of local resources, both natural and discarded, for useful products and services. The purpose of ISRU is to significantly reduce the mass, cost, and risk of short-term and sustained human exploration by eliminating the need to launch large amounts of consumables, structures, and other items that are required for survival and for completing mission objectives successfully. ISRU also enables self-sufficiency at particular locations, especially destinations far from Earth. The ISRU domain is comprised of four components:

- **7.1.1 Destination Reconnaissance, Prospecting, and Mapping:** This addresses investigating, sampling, and mapping regolith, the atmosphere, and the environment for future mining and utilization.
- **7.1.2 Resource Acquisition:** This addresses extracting, collecting, recycling, pre-processing, and storing targeted "raw" in-situ resources.
- **7.1.3 Processing and Production:** This addresses producing, transferring, and storing consumable products, such as water, air, and propellants that are needed by the crew, as well as scientific equipment, robots, rovers, etc.
- **7.1.4 Manufacturing Products and Infrastructure Emplacement:** This addresses creating infrastructure (landing pads, blast walls, thermal wadi), fabricating tools and parts, and constructing items needed for safety, redundancy, and comfort, as well as using resources (metals, plastics, regolith, etc.) available in-situ.

## *7.2 Sustainability and Supportability*

Sustainability and Supportability includes technology candidates required to establish a self-sufficient, sustainable, and affordable human space exploration program. This area is comprised of four components:

- **7.2.1 Autonomous Logistics Management:** This addresses technologies needed to institute a centralized logistic depot to manage and optimize the use of consumables at the exploration destination and minimize human-specific logistics (i.e., food), as well as other logistics items that can be repurposed or recycled in order to reduce Earth dependency and logistics train.
- **7.2.2 Maintenance Systems:** This addresses technologies needed to perform routine system evaluation, preventive maintenance, and corrective actions on human exploration systems.
- **7.2.3 Repair Systems:** This addresses technologies that perform "wear-and-tear" repairs, as well as those that perform minimum or non-intrusive repair.
- **7.2.4 Food Production, Processing, and Preservation:** This addresses technologies that feed crew members and keep their food safe.

## *7.3 Human Mobility Systems*

Mobility systems include rovers, EVA tools, and translation aids that improve the safety and effectiveness of crews. They are essential for conducting surface operations and establishing architectural infrastructure. They enable the exploration of asteroids and missions to destinations like Mars. Many of the mobility core technologies are covered in TA 4 Robotics and Autonomous Systems. However, three specific applications are covered under this technology area:

- **7.3.1 EVA Mobility:** This addresses EVA tools, transition systems, and mobility aids to facilitate crew egress and ingress, and expedite the movement of crew on site.
- **7.3.2 Surface Mobility:** This addresses technologies for navigating rough surface terrain, allowing humans to work on the surface of terrestrial destinations.

- **7.3.3 Off-Surface Mobility:** This addresses technologies for navigating in the micro-gravity environment or at destinations with an atmosphere, including balloons and other airships.

## *7.4 Habitat Systems*

Habitat Systems enable safe, efficient, sustainable, and productive long-duration human exploration missions by using fully autonomous, resource-efficient habitats to significantly reduce the mass, cost, and human spaceflight risk associated with those missions. The Habitat Systems domain is comprised of four components:

- **7.4.1 Integrated Habitat Systems:** Addresses acoustical treatments and noise reduction; solar optic lighting and heating; low-toxicity, fire-retardant textiles; antimicrobial and surface coatings; and embedded sensors that monitor system performance. Additional dependency technologies that support Integrated Habitat Systems capabilities are being developed under other technology areas, such as TA 4 Robotics and Autonomous Systems, TA 6 Human Health, Life Support, and Habitation Systems, TA 8 Science Instruments, Observatories, and Sensor Systems, TA 11 Modeling, Simulation, Information Technology and Processing, and TA 12 Materials, Structures, Mechanical Systems and Manufacturing.
- **7.4.2 Habitat Evolution:** Addresses Exploration Habitat Systems Concurrent Engineering Modeling and Simulation. Maturing exploration habitat integrated concurrent model based engineering and model based systems engineering design environment and simulations capabilities are imperative to achieving overall design optimization, mass reduction, and crew performance optimization. Additional dependency technologies that support Habitat Evolution capabilities are being developed under other technology areas, such as TA 4 Robotics and Autonomous Systems, TA 6 Human Health, Life Support, and Habitation Systems, TA 8 Science Instruments, Observatories, and Sensor Systems, TA 11 Modeling, Simulation, Information Technology and Processing, and TA 12 Materials, Structures, Mechanical Systems and Manufacturing.
- **7.4.3 "Smart" Habitats:** Focuses on evolutionary, intelligent, and autonomous habitat capabilities that enable long-duration, deep-space human missions that increase crew productivity, as well as crew and mission safety, while reducing mass, power, and volume needs. Additional dependency technologies that support "Smart" Habitat capabilities are being developed under other technology areas, such as TA 4 Robotics and Autonomous Systems, TA 6 Human Health, Life Support, and Habitation Systems, TA 8 Science Instruments, Observatories, and Sensor Systems, TA 11 Modeling, Simulation, Information Technology and Processing, and TA 12 Materials, Structures, Mechanical Systems and Manufacturing.
- **7.4.4 Artificial Gravity (AG):** Includes spacecraft technologies that will reduce the detrimental effects of long-duration, zero-gravity on human physiology, including thrust vector navigation course correction of an AG (rotating) spacecraft in transit; technologies that manage the center of gravity (CG) balance of spacecraft while providing thrust to perform course correction; and momentum exchange for deployment of the AG spacecraft. These technologies will also benefit LEO and HEO commercial facilities development. Additional dependency technologies that support AG capabilities are being developed under other technology areas, such as TA 4 Robotics and Autonomous Systems, TA 6 Human Health, Life Support, and Habitation Systems, TA 8 Science Instruments, Observatories, and Sensor Systems, TA 11 Modeling, Simulation, Information Technology and Processing, and TA 12 Materials, Structures, Mechanical Systems and Manufacturing.

## *7.5 Mission Operations and Safety*

Mission Operations and Safety technology candidates manage space missions, usually from the point of launch through the end of the mission (i.e., the ‘start-to-finish’ development and delivery of highly complex robotic and human spaceflight operations). Mission operations entities across NASA centers provide time-appropriate failure analysis and response to protect crew and spacecraft in order to achieve mission objectives.

- **7.5.1 Crew Training:** Crew training for deep space, long-duration missions will be improved with immersive virtual reality and “real-time,” context-sensitive training. TA 11.3.4, Simulation-Based Training and Decision Support Systems, addresses crew-training needs for the purposes of Human Exploration Destination Systems.
- **7.5.2 Planetary Protection:** Planetary protection is a potentially significant challenge for human exploration. These technologies address threats to the Earth-Moon system from returning astronauts, hardware, and extraterrestrial samples.
- **7.5.3 Integrated Flight Operations Systems:** Integrated flight operations for long-duration, deep-space missions will require striking complex balances between ground and space operations, with a shift toward increasing crew autonomy that will benefit from autonomous systems and comprehensive, highly-integrated operational systems.
- **7.5.4 Integrated Risk Assessment Tools:** Integrated risk assessment tools for deep space, long-duration missions will help identify and analyze risks reducing threats to crew and missions.

## *7.6 Cross-Cutting Systems*

This section includes dust mitigation and technology candidates for construction, assembly, and deployment of destination systems hardware. It is comprised of two areas:

- **7.6.1 Particulate Contamination Prevention and Mitigation:** Includes a layered engineering defense that incorporates technologies for contamination prevention, exterior cleaning and protection, interior cleaning and protection, and preserving gas quality, as well as technologies associated with modeling plume and soil interactions.
- **7.6.2 Construction and Assembly:** Includes technologies for construction and assembly of in-space and surface structures and completing construction or assembly of deployable systems. Both traditional construction and assembly concepts and advanced deployable systems are included. Since most of the needed Construction and Assembly capability technologies are being developed under other technology areas (such as TA 4 Robotics and Autonomous Systems, TA 6 Human Health, Life Support, and Habitation Systems, TA 8 Science Instruments, Observatories, and Sensor Systems, TA 11 Modeling, Simulation, Information Technology and Processing, and TA 12 Materials, Structures, Mechanical Systems and Manufacturing), these technologies are focused on shape charges for excavation and fabric blast debris protection.

# TA 7.1: In-Situ Resource Utilization

The key steps in creating a complete ISRU capability are: 1) Destination Reconnaissance, Prospecting, and Mapping to identify what resources are available, where they are available, in what quantities and purity, and what in the surrounding environment will affect collection; 2) Resource Acquisition to collect and pre-process the 'raw' resources, both naturally occurring and discarded, or un-needed components brought from Earth; 3) Processing and Production to convert the raw resources into consumables for propulsion, power, and life support; and 4) Manufacturing Products and Infrastructure Emplacement to prepare the destination site for human explorers and provide the ability to manufacture new and replacement tools and components.

## *Sub-Goals*

The primary goal of ISRU is to dramatically reduce launch mass of human exploration missions, thereby reducing cost. Producing 25,000 kilograms of oxygen on Mars for ascent propulsion and life support saves 200,000 kilograms in mass required in LEO for a Crewed Mars Surface Mission (Design Reference Mission (DRM) 9). Producing 1,000 kilograms of oxygen from lunar materials will reduce launch mass by 8,000 kilograms for a Crewed to Lunar Surface mission (DRM 7). This technology will also completely change the Mars mission architecture, as the significant reduction in landed mass and ability to produce critical life-support consumables will also affect the requirements and design of entry, descent, and landing, descent propulsion, and life support systems.

Because the ISRU capability will change the mission architecture, the technology needs to be demonstrated at a technology readiness level (TRL) of 6 earlier than the standard target of the mission Preliminary Design Review (typically four to six years before mission launch). For a game-changing technology, the capability must be demonstrated to a high degree of confidence when the mission architecture is set, which is typically 10 years or more before mission launch.

ISRU capabilities also reduce mission risk, increase mission flexibility, and enable extended-duration missions. Other goals for in-situ manufacturing and infrastructure technologies include providing shelter and protection from the environment, and creating tools or parts on-demand to repair or replace existing tools, or creating new tools to meet changing mission needs.

**Table 2. Summary of Level 7.1 Sub-Goals, Objectives, Challenges, and Benefits**

| **Level 1** | | |
|---|---|---|
| 7.0 Human Exploration Destination Systems | Goals: | Sustain human presence in space and provide more time for performing core mission activities, while reducing reliance on Earth. |
| **Level 2** | | |
| 7.1 In-Situ Resource Utilization | Sub-Goals: | Leverage in-situ resources to dramatically reduce launch mass and cost of human exploration missions. |
| **Level 3** | | |
| 7.1.1 Destination Reconnaissance, Prospecting, and Mapping | Objectives: | Improve capabilities for investigating and mapping destinations. Create technologies to find exploration sites that have sufficient quantities of the right type of resources. |
| | Challenges: | Operation in nearer-to-surface planetary environment.<br>Operation in very low gravity levels where small disturbances may eject the soil.<br>Sampling the subsurface for life while meeting all planetary protection guidelines. |
| | Benefits: | Enables mission planners to select regions with the best, highest concentration, and most accessible resources for ISRU.<br>Produces a more complete characterization of the resource and therefore a better understanding of distribution across distance and at depth. |

**Table 2. Summary of Level 7.1 Sub-Goals, Objectives, Challenges, and Benefits - Continued**

| Level 3 | | |
|---|---|---|
| 7.1.2 Resource Acquisition | Objectives: | Develop low-power, low-mass regolith excavator and atmospheric compressor for collection of solid and gaseous resources. |
| | Challenges: | Generating reaction force other than mass offset; longevity of the metal bit, stem, shank, and other dynamically-loaded materials in extreme temperatures (down to 40 K in lunar polar regions) where metal embrittlement occurs; and effective removal of waste material during drilling without the use of consumables.<br>Minimize or eliminate jamming events.<br>Abrasiveness of the regolith and the effect on components and the system, including resistance.<br>Guaranteeing good flow through manufacturing equipment.<br>Motive force other than gravity.<br>Maintaining molten temperatures.<br>Minimizing pressure drop across the filtering device.<br>Regenerating filter material and remove the dust that has been collected. |
| | Benefits: | Improves reaction rates, lowers power, and reduces size and mass of the processing plant.<br>Minimizes mass, power, and maintenance. |
| 7.1.3 Processing and Production | Objectives: | Develop safe, efficient, autonomous in-situ production plants for production of large quantities of consumables for life support and propulsion. |
| | Challenges: | Optimize reaction efficiency and minimize power.<br>High-temperature materials that are impermeable to hydrogen, insensitive to potentially caustic byproducts, and can be repeatedly sealed in the presence of particles.<br>Processing temperatures.<br>Regenerating the device and removing collected particulates. |
| | Benefits: | Reduces mass, costs, and production of consumables at the exploration site.<br>Reduces mission risk, enables extended exploration stays, and if used for mobility systems, can greatly increase the surface area covered during exploration. |
| 7.1.4 Manufacturing Products and Infrastructure Emplacement | Objectives: | Improve safety, utility, and functionality with technologies to create infrastructure and fabricate tools and parts in-situ. |
| | Challenges: | Stabilize and densify the soil.<br>Mass, volume, and power consumption of the manufacturing capability, as well as the chemistry, density, and properties of the parts fabricated.<br>Forming pressure-tight seals and solid structural joints. |
| | Benefits: | Enables construction of roads, landing pads, habitats, and other structures that provide thermal and radiation protection and mitigate dust levitation due to human activity with minimal up-mass launched from Earth.<br>Decreases risk to humans and increases mission success.<br>Saves time and material by reducing waste and up-mass required for spares. |

## TA 7.1.1 Destination Reconnaissance, Prospecting, and Mapping

### *Technical Capability Objectives and Challenges*

Before a destination can be aggressively pursued for exploration, the first order of business is to better understand it. In the case of ISRU, the regolith and any atmosphere or environment should be properly investigated and mapped out for future mining and utilization of mission- and life-sustaining resources, including mineral and chemical compositions, quantities, etc. Many applicable technologies exist for analogous terrestrial applications. However, these will need to be miniaturized, repackaged, and tailored to the specific human exploration destination.

After determining whether to pursue a destination, samples should be collected for further in-situ analysis to finalize destination decisions. Technology candidates needed for this capability include: penetrometers; shear gauges; regolith compaction, density, and flow instruments; worms, scoops, and drills; and coring drills for collecting small samples and characterizing their geotechnical and physical properties, mineralogy and chemistry, and identifying hazardous materials. Collecting and characterizing atmospheric gases or dust is also vital for understanding the potential for ISRU applications. As technologies advance in this area, additional information, such as regolith traction and compaction behavior while driving or moving across it, will be collected. Electromagnetic data (i.e., dielectric properties) will be measured for the purpose of constructing landing pads or roads or extracting resources. The properties of regolith that govern its interaction with rocket exhaust plumes, such as porosity, rock abundance, and depth to bedrock, will also be measured to ensure safe landings and ensure that repeated missions in the same area will not damage emplaced hardware.

### *Benefits of Technology*

The ability to improve prospecting, mapping, and sample characterization not only increases NASA's return on exploration activities, but could also revolutionize mining, purification systems, the pharmaceutical industry, and other commercial industries as they realize the benefits of these types of technologies.

Characterizing the destination and analyzing its resources will benefit future missions by enabling mission planners to select regions with the best, highest concentration, and most accessible resources for ISRU. It will ensure that sufficient resources can be obtained to meet mission requirements. Characterizing the mechanical behavior of regolith will enable design of ISRU technologies such as excavators, drills, regolith conveying systems, and resource processing systems that can operate without mechanical jamming and that have minimized mass and power. Measuring resources using down-hole methods in drilling will produce a more complete characterization of the resource, which will yield a scientific benefit by providing a more complete view of the geologic history of the regolith and its volatiles. Measuring plume interactions with regolith will enable the design of spacecraft that can land safely with high confidence, and will set requirements for other plume mitigation technologies to protect hardware on the planetary surface. It will also set upper limits on vehicle mass that can land on bare regolith, enabling the development of mission architectures with or without landing pads.

**Table 3. TA 7.1.1 Technology Candidates – not in priority order**

| TA | Technology Name | Description |
|---|---|---|
| 7.1.1.1 | Penetrometers, Shear Gauges, Compaction, Density Instruments | Instruments to measure the mechanical properties of the soil. Handheld possibly, or mounted on rovers. |
| 7.1.1.2 | Flow Instruments | Tools to gather flow measurements of the regolith in-situ. |
| 7.1.1.3 | Drill Embedded Chemical Instrument – Laser Induced Breakdown Spectroscopy | Laser induced breakdown spectroscopy (LIBS) integrated into drill bit for downhole material chemical analysis. |
| 7.1.1.4 | Drill Embedded Chemical Instrument – Neutron Spectrometer | Neutron spectrometer integrated into drill bit for downhole material chemical analysis. |
| 7.1.1.5 | Drill Embedded Physical Instruments (Resistivity, Thermal, Shear, etc.) | Instrumentation on or in drill to detect material physical properties, such as hardness, etc. |
| 7.1.1.6 | Sensor to Measure Blowing Rate of Material During Landing | Used to calibrate plume-blowing models to protect outpost assets from repeated blast or scouring. |
| 7.1.1.7 | Instruments to Measure Chemical Compositions | Chemical and mineralogical detection and characterization of regolith materials or volatiles at or near ground level for ISRU. |

## TA 7.1.2 Resource Acquisition

### *Technical Capability Objectives and Challenges*

This ISRU area involves collecting, recycling, pre-processing, and storing "raw" in-situ resources. While terrestrial mining and excavation is well developed, the restrictive (time) and non-restrictive (mass, power, autonomy) factors on Earth are not the same for planetary mining. No effort to mine or collect large amounts of solid or gaseous resources has been attempted on the Moon, Mars, or other extraterrestrial bodies.

There are two basic types of naturally occurring resources: regolith and rock sources (i.e., solids, including 'wet' solids), and atmospheric sources (i.e., gaseous). These raw resources are turned into feedstock that will later be used to produce consumables such as water, air, and propellants. Another source of raw material is material brought from Earth (i.e., old, unused, or broken hardware, scrap material, consumed propellant, empty gas tanks, discarded food packaging, etc.), which can be turned into feedstock for another purpose or product. For example, metal tanks could be crushed and formed into wire or powder, then used to manufacture new components.

Resource acquisition from atmospheric sources is focused on capturing, purifying, and compressing carbon dioxide in the Mars atmosphere as the initial step in producing oxygen for Mars ascent. Cryo-freezers and rapid-cycle adsorption pumps have both been tested in sub-scale demonstrations to purify and compress carbon dioxide from 0.50 kPa up to 275 kPa or greater; both options still require significant effort to efficiently scale up to meet human exploration requirements. Advances in structural casings and low-power bearing concepts might also allow mechanical compressors to be a more competitive solution for compression than previous analysis has shown. Although currently at a lower TRL, carbon dioxide capture by task specific ionic liquids offers promise, especially if the technology can also be used for electrolysis to oxygen.

Prior to extraction and compression of the carbon dioxide, the atmospheric dust will need to be removed to protect downstream components. A large number of technology options have been proposed and tested to various readiness levels. Key challenges for all options include minimizing pressure drop across the filtering device and methods to regenerate filter material and remove the dust that has been collected.

**Small Lunar Excavator Prototype Demonstrated at Hawaii Field Tests**

Resource acquisition from hard regolith or rock sources requires drilling or deep digging into regolith consolidated by depth or cold, or both. With strong hydrogen signatures found across wide areas of Mars and at the lunar poles, there is a strong desire to mine for the water frozen below the surface. At Mars, the Phoenix lander showed the presence of brines, and the Phoenix arm reached icy soils as shallow as 3 centimeters below the surface, although there is no data detailing true quantities versus depth. While terrestrial hard rock and soil excavators can easily mine 200,000 tons per day to depths down to 3,800 meters, they have the advantage of relying on high mass to provide the reaction force and a relatively inexpensive source of consumable energy for high power to penetrate the hard materials. In addition, terrestrial cutting edges can be sharpened or replaced as needed, often on a weekly basis. Key challenges for extraterrestrial mining include generating reaction force other than mass offset; longevity of the metal bit, stem, shank, and other dynamically-loaded materials in extreme temperatures (down to 40 K in lunar polar regions) where metal embrittlement occurs; and effective removal of waste material during drilling without the use of consumables.

Resource acquisition from loose regolith requires scooping and transporting large quantities of regolith to the processing plant reactor. Pneumatic excavation and transport and auger transport have both been demonstrated in the laboratory and in some limited variable gravity tests. The key challenge for both of these options is to minimize or eliminate jamming events. Technologies for high-fidelity modeling of granular flow during collection and transport are needed to design equipment with high efficiencies and low failure rates.

After collecting raw resource, beneficiation to concentrate the targeted ore content or improve the particle size distribution can significantly improve the efficiency of the extraction process. Electrostatic or magnetic beneficiation to concentrate the ore can reduce the total quantity of regolith that must be heated to high temperature, thereby reducing total power requirements. Grinding or crushing frozen regolith or size sorting before processing can increase surface area and aid in reactor mixing, both resulting in decreased reaction time and reduced power. The primary challenge for sieves and grinders is to develop low-wear meshes and surfaces that are resistant to the abrasiveness of the regolith. For grinding discarded metal parts for reuse in manufacturing, the challenge is to crush or grind the metal into spherical or smooth particles to guarantee good flow through manufacturing equipment. If molten metal transport is needed to move the feedstock to the manufacturing equipment, key technical challenges include developing motive force other than gravity used in terrestrial processes, and maintaining molten temperatures throughout the system to avoid excessive loss and clogging of lines.

### *Benefits of Technology*

Resource acquisition is the first step in generating high-value products at the destination site. Delivering the resource in a timely manner is critical to efficient production. Beneficiation of the raw resource leads directly to improved reaction rates, lower power, and reduced size and mass of the processing plant.

**Table 4. TA 7.1.2 Technology Candidates – not in priority order**

| TA | Technology Name | Description |
|---|---|---|
| 7.1.2.1 | High-Efficiency Cryocoolers for Carbon Dioxide ($CO_2$) Freezing | Reduce temperature of targeted gaseous resource (Mars carbon dioxide) to freeze out of atmosphere stream. |
| 7.1.2.2 | Pressure- or Temperature-Swing Sorption Pumps | Adsorb atmospheric gas(es) of interest and desorb at higher pressure and purity. |
| 7.1.2.3 | High Pressure-Ratio Gas Compressors | Mechanically compress atmosphere to higher pressure. |
| 7.1.2.4 | Ionic Liquids for Selective Carbon Dioxide ($CO_2$) Adsorption | Use ionic liquids to absorb atmospheric gas(es) of interest and desorb at higher pressure and purity. |
| 7.1.2.5 | Cutting Tools for Cold/Hard Regolith and/or Rock/Metal | Dig or drill down through hard or frozen regolith, rock, or metals to gather resource. |
| 7.1.2.6 | Long-Life or Self-Renewing/ Repairing Cutting Edges | Cutting edges that can either be sharpened in place, preferably as part of natural use, or continually renewed by discarding used or dulled edge. |
| 7.1.2.7 | Discrete Element Method to Model Regolith | Lagrangian modeling of individual soil grains discretely using contact force and contact torque equations. |
| 7.1.2.8 | Eulerian Modeling of Regolith | Eulerian modeling of soil as a continuum using constitutive equations. |
| 7.1.2.9 | Pneumatic Excavation and Material Transport | Gather and transport unconsolidated regolith using pneumatics. |
| 7.1.2.10 | Auger Material Transport | Transfer and transport unconsolidated regolith. |
| 7.1.2.11 | Magnetic Material Transport | Transfer and transport unconsolidated regolith. |
| 7.1.2.12 | Regenerable/Scroll Media Filtration | Use filter media to remove dust from incoming gas stream; filter media are regenerable or can scroll to replace spent filter. |
| 7.1.2.13 | Cyclone Dust Separation | Use cyclones to remove dust from incoming gas stream. |

Table 4. TA 7.1.2 Technology Candidates – not in priority order - Continued

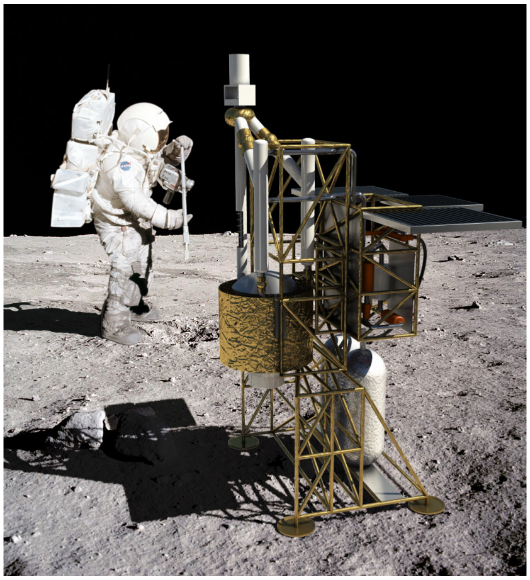
| TA | Technology Name | Description |
|---|---|---|
| 7.1.2.14 | Inertial Impactor Dust Separation | Use orifices and impaction plates or bands to collect particulate matter above a certain particle cut size; impaction plates or bands can be cleaned off by wipers or scrapers once loaded. |
| 7.1.2.15 | Electrostatic Separation | Use electrostatics to remove dust from incoming gas stream. |
| 7.1.2.16 | Electrostatic Beneficiation | Use electrostatics to separate regolith by particle sizes or by mineral content. |
| 7.1.2.17 | Magnetic Beneficiation | Use magnetism to separate regolith particles by mineral content. |
| 7.1.2.18 | Non-Clogging and/or Self-Cleaning Sieves | Process raw regolith through multiple sieves to obtain desired particle size range for processing. |
| 7.1.2.19 | Crushers/Grinders for Rock and Metal | Crush or grind large, hard resources to reduce to smaller particles. |
| 7.1.2.20 | Molten Metal Transport | Crucible, ladle, and bottle storage technologies for melting, storing, and transporting molten metal derived from ISRU and recycling sources. |
| 7.1.2.21 | Molten-to-Powder Metal Technologies | Gas atomizer for producing spherical powdered metal to convert molten metal to powdered feedstock for manufacturing. |

## TA 7.1.3 Processing and Production

### *Technical Capability Objectives and Challenges*

Once resources have been collected and pre-processed, the substances of interest are extracted using thermal, catalytic, chemical, and electrical processes. Most of the ISRU processes have been demonstrated in the laboratory at sub-scale levels and for limited durations. Extensive work is still needed to develop long-lasting systems that produce at rates that meet mission requirements.

This ISRU area includes technology candidates to process the in-situ feedstock, already gathered and (possibly) pre-processed, into consumables needed for life support, propulsion, and power. In addition to the reactors that perform the key step of converting resources into the desired product, this area covers technology candidates needed for all the ancillary system components required for heating and energy storage, same-phase or two-phase separation of species, dust and contaminants cleanup, and product liquefaction and storage.



**Artist's concept of lunar ISRU plant for production of 500 kilograms of oxygen per year from lunar regolith**

Processing methods for solid feedstock, such as the lunar or asteroid regolith, typically require high processing temperatures that present several unique challenges. Technologies are needed to thoroughly mix the solids with the processing gas to optimize reaction efficiency and minimize power. Reactors require high-temperature materials that are impermeable to hydrogen, insensitive to potentially caustic byproducts, and can be repeatedly sealed in the presence of particles. Lower TRL concepts such as using ionic liquids to enhance the extraction of oxygen from lunar regolith or metals from lunar regolith or metallic asteroids also hold promise if challenges with temperature, reaction rate, and ionic liquid recovery can be solved. Using gas reactants to process particulate feedstock results in some particles being mixed in with the product stream as it exits the main reactor. Gas and particle separation technologies are required to protect downstream components. Whether passive devices, such as scroll filters or cyclone separators, or active methods, such as electrostatic separation, are used, the biggest challenge is developing methods to regenerate the device and remove collected particulates.

Processing liquid and gaseous species is needed at all destinations, either as the primary reaction or for processing intermediate streams. Carbon dioxide is the primary atmospheric resource on Mars and is produced as an intermediate during carbothermal reduction of lunar regolith. Solid oxide electrolyzers have been used to extract oxygen from carbon dioxide, but much work is still needed to improve the area-specific resistance (to lower power), demonstrate high-temperature seal integrity over repeated thermal cycles, and improve packaging and flowpath integration for large-scale production. If a hydrogen source is available, carbon dioxide can also be processed into water and methane using the Sabatier process, or water and carbon monoxide using the reverse water gas shift process. While both of these reactions are relatively mature, large-scale flight hardware would benefit from improvements in substrates and catalyst application, catalyst infiltration methods, and catalyst bed packaging techniques, such as microchannels to improve single-pass efficiency and thermal management. Water electrolyzers are also needed to extract oxygen from water intermediary streams; details for water electrolysis technology are discussed in more detail in TA 6 Human Health, Life Support, and Habitation Systems. An expanded understanding of variable-gravity effects on the two-phase flow through freezers and condensers is needed for gas and liquid separation of the process streams. Many processing methods also require separation of two or more gas streams. While terrestrial methods such as membrane separation or the lower-TRL ionic liquids concept can be used, work is needed to tailor these methods to the specific conditions (both species and gravity environment) present at the exploration sites.

Most of the primary reactors operate at temperatures in excess of 900° C, and thermal management technologies are needed to reduce power requirements. Solar concentrators can be used to apply solar energy directly to the reactors; more details are discussed in TA 3 Space Power Energy Storage. Technologies such as heat pipes and phase change materials are needed to transfer thermal energy from one spent batch of regolith to the incoming batch. While these technologies are covered in TA 14 Thermal Management Systems, the ISRU systems require them to operate at higher temperatures than those for which they are typically designed.

There are also several advanced concepts for processing either the solid regolith feedstock or the Mars atmosphere. These include biological technology and artificial photosynthesis. While these concepts are both at a very low TRL, they offer the potential for significant improvements in mass, power, and production efficiency, and deserve some attention to determine whether their promising potential can be achieved.

Technologies such as integrated cryocoolers and radiators for liquefaction and storage of cryogenic products are discussed in detail in TA 14 Thermal Management Systems.

***Benefits of Technology***

The Mars Design Reference Architecture (DRA) 5.0 calls for in-situ production of 25,000 kilograms of oxygen for ascent propulsion and life support, an enabling capability for successful human exploration. Even assuming the most propulsively-efficient outbound trip, utilizing maximum aerobraking for Mars capture and descent, the gear ratio for mass savings back to Earth is 8:1, meaning the 25,000 kilograms of in-situ oxygen saves 200,000 kilograms in LEO. Previous studies for lunar surface stays required 1,000 kilograms of oxygen per year to close the loop for life support. The gear ratio from LEO to the lunar surface is also around 8:1, so the savings in LEO adds up to 8,000 kilograms per year for lunar exploration. In addition to mass (and cost) savings in LEO, production of consumables at the exploration site reduces mission risk, enables extended exploration stays, and if used for mobility systems can greatly increase the surface area covered during exploration.

### Table 5. TA 7.1.3 Technology Candidates – not in priority order

| TA | Technology Name | Description |
|---|---|---|
| 7.1.3.1 | Forced Flow Regolith Fluidization | Inject process gases into reactor filled with loose regolith with sufficient distribution and velocity to create a continuously fluidized bed. |
| 7.1.3.2 | Mechanical Regolith Mixing | Mechanically mix regolith and process gases inside a reactor with mechanical stirrers, tumbling, or other methods to create a continuously well-mixed solid or gas environment. |
| 7.1.3.3 | Vibrational Regolith Mixing | Mix regolith and process gases using vibration to fluidize the regolith. The reactor vessel itself is vibrated using methods such as electromagnetic shakers or off-center cams. Frequency and amplitude of vibration can be adjusted to accommodate design. No moving parts in contact with abrasive regolith. |
| 7.1.3.4 | High Temperature, Non-Hydrogen Permeable Materials | Materials that withstand the high temperatures of regolith processing while maintaining their impermeability to gaseous reactants such as hydrogen ($H_2$). |
| 7.1.3.5 | High-Cycle-Life, High-Temperature Valves and Seals | Valves that operate at elevated temperatures with high-cycle life and tolerate caustic gases, and extreme dirt exposure. |
| 7.1.3.6 | Acidic Ionic Liquids for Dissolution of Regolith for Electrolytic Oxygen Production or Metallic Asteroids for Pure Metals Production | Acidic ionic liquids show the potential to enhance oxygen and metals production from regolith and meteoritic metal via dissolution and electrolysis. |
| 7.1.3.7 | Solar/Thermal Energy Concentrators | Heat reactors with direct thermal energy (non-electrical) or heat regolith in-situ to passivate dust, stabilize for landing pads, and create thermal sinks. |
| 7.1.3.8 | Optical Fiber Cables with Thermal Receiver | Provide fiber optic transmission of thermal heat to the reactor or regolith in-situ. |
| 7.1.3.9 | Heat Storage/Transfer | Transfer or store heat energy from spent regolith before discarding and use to pre-heat fresh regolith batch to reduce total power requirement. Technologies include transfer using heat pipes and/or storage using phase change materials. |
| 7.1.3.10 | Proton Exchange Membrane (PEM) Electrolyzers | Electrolyze water using proton exchange membrane technology. |
| 7.1.3.11 | Solid Oxide Co-Electrolysis | Co-electrolyze water and carbon dioxide in a solid oxide stack to produce oxygen for storage and carbon dioxide, carbon monoxide, and hydrogen for conversion to methane in a Sabatier/methanation reactor. |
| 7.1.3.12 | Solid Oxide Carbon Dioxide Electrolyzers | Electrolyze atmospheric carbon dioxide into oxygen (product) and carbon monoxide. |
| 7.1.3.13 | Catalysts for Gas-Phase Chemical Reactions | Increase the reaction efficiency of gas-phase reactions such as the Sabatier reaction and the reverse water gas shift with improved catalysts and improved catalyst support structures and catalyst application methods. |
| 7.1.3.14 | New Membranes for Gas Separation and Cleanup | New high efficiency membranes for separating gases, used to separate methane and/or carbon monoxide from hydrogen and carbon dioxide for Sabatier or Reverse Water Gas Shift (RWGS) systems, and for separating carbon dioxide and carbon monoxide stream resulting from carbon dioxide electrolysis. |
| 7.1.3.15 | Ionic Liquids for Gas Separation and Co-Electrolysis | Ionic liquids for separating gas species in a mixed-gas stream, and possibly for co-electrolysis of water and carbon dioxide to produce oxygen for storage and carbon dioxide, carbon monoxide, and hydrogen for conversion to methane in a Sabatier/methanation reactor. |
| 7.1.3.16 | Freezers and Condensers | Separate mixed gas streams by condensing or freezing out higher vapor point species allowing lower vapor species to flow through as a gas. This is primarily for separating water gas out of mixed gas stream. |
| 7.1.3.17 | Biological Technology | Biological processes for extraction or conversion of raw feedstock such as active cultures, enzymes, microorganisms, or genetically modified synthetic engineered organisms. |

**Table 5. TA 7.1.3 Technology Candidates – not in priority order - Continued**

| TA | Technology Name | Description |
|---|---|---|
| 7.1.3.18 | Artificial Photosynthesis | Bio-inspired processes to achieve a net conversion of solar or thermal energy into chemical energy. Create a mimic of photosynthesis to generate oxygen and hydrocarbons from Mars carbon dioxide, light, and water. |
| 7.1.3.19 | Integrated Cryocoolers/Radiators | Integrate cryocoolers and radiators with storage tanks to convert gaseous products into more storable cryogenic liquids. |

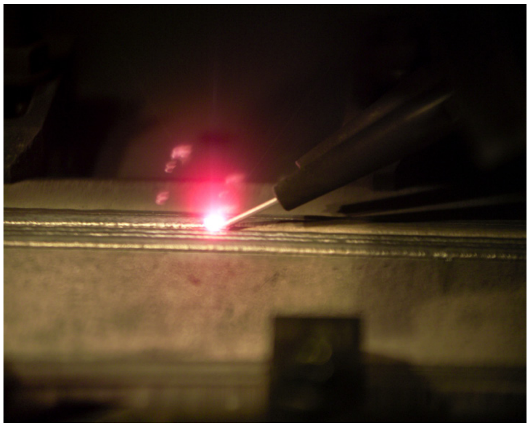
## TA 7.1.4 Manufacturing Products and Infrastructure Emplacement

### *Technical Capability Objectives and Challenges*

The ability to manufacture or fabricate parts, tools, and other necessary resources on demand in-situ decreases risk to humans and increases mission success. Electron beam, free-form fabrication, and additive manufacturing technologies currently used on Earth need to be adapted for space and planetary environments, focusing particularly on accounting for lower to near-zero gravity levels. Technologies for sintering or passivating the planetary surface to create landing pads and roads are not used on Earth and need to be developed.

This ISRU area develops technology candidates that use resources (metals, plastics, regolith, etc.) recycled from discarded materials or acquired from the land or environment in-situ to create infrastructure, fabricate tools and parts, and construct items needed for safety, redundancy, comfort, utility, and functionality, reducing the need to launch all items from Earth.

*In-situ infrastructure* technology candidates require techniques that will stabilize and densify the soil during crewed missions to the lunar surface (DRM 7) and beyond for exploring other worlds (DRM 8 Crewed to Mars Moons and DRM 9 Crewed Mars Surface Mission). Meeting these challenges will allow the use of lunar soil for thermal protection from night/day thermal cycles, provide for energy storage, stabilize the soil to support rovers and ascent/descent vehicles, and reduce dust levitation due to human activity.



**Additive Manufacturing**

*In-situ manufacturing* technology candidates include manufacturing capabilities that can be used to fabricate tools and parts and construct items as needed for safety, redundancy, comfort, utility, functionality, etc. Raw materials may be obtained by recycling discarded resources or may be acquired from the land or environment in-situ. Challenges are related to the mass, volume, and power consumption of the manufacturing capability, as well as the chemistry, density, and properties of the parts fabricated, to ensure their functionality for the intended purpose. Meeting these challenges will reduce the need to launch all necessary items from Earth and provide self-sufficiency for unforeseen contingencies.

*In-situ derived structures* technology candidates require use of ionic liquids or polymers combined with locally sourced regolith to create structures such as bricks, cast basalt, lunar/Mars-crete, glass, or composites that can be joined together into solid forms, like walls. Challenges include developing adhesive and sealing materials that can form pressure-tight seals and solid structural joints. Meeting these challenges allows large infrastructures to be developed for exploring other worlds using materials primarily obtained in-situ.

### *Benefits of Technology*

Technology candidates that enable the creation of infrastructure and fabrication of tools and parts in-situ improve safety, utility, and functionality and reduce mission launch requirements. Having the ability to build large-scale infrastructure using in-situ resources enables construction of roads, landing pads, habitats, and other structures that provide thermal and radiation protection and mitigate dust levitation due to human activity with minimal up-mass launched from Earth. On a smaller scale, the benefits of having the ability to manufacture or fabricate parts, tools, and other objects on demand in-situ include decreased risk to humans and increased mission success. These technology candidates save time and material by reducing waste and up mass required for spares, resulting in room for scientific instruments. These benefits apply to a crewed mission to the lunar surface, as well as follow-on missions to explore other worlds. The farther from Earth, the greater the benefits in reducing up mass for infrastructure support and development to safely and successfully accomplish further exploration mission objectives.

**Table 6. TA 7.1.4 Technology Candidates – not in priority order**

| TA | Technology Name | Description |
|---|---|---|
| 7.1.4.1 | Regolith Thermal Mass Formation | Consolidation of granular regolith using solar thermal, chemical, or resistive heating processing to produce solid mass with improved thermal diffusivity, enabling effective solar thermal energy storage. |
| 7.1.4.2 | Solar Heating of Regolith Thermal Mass | Depending on location, facilitate or direct unconcentrated solar flux to exposed surface of regolith thermal mass over extended periods to gradually store thermal energy for later retrieval. |
| 7.1.4.3 | Thermal Mass Interface with Mobile Asset | Develop standard conductive interface to provide heat to lunar surface asset during cold/night periods. |
| 7.1.4.4 | Radiative Insulation of Regolith Thermal Mass | Develop deployable radiative barrier to limit radiative heat loss to space from thermal mass and from protected lunar surface asset. |
| 7.1.4.5 | Sintering Regolith | Heating up of regolith to cause the material to form a hard, solid form. |
| 7.1.4.6 | In-Situ Fabrication Using Electron Beam Freeform Fabrication ($EBF^3$) | Metal additive manufacturing and repair technology using electron beam energy source and wire feed. |
| 7.1.4.7 | Microwave Sintering for Dust Passivation and/or Soil Stabilization | Using microwaves to sinter soil on the surface to create roads, landing pads, or dust-free zones. |
| 7.1.4.8 | Solar Concentrator Sintering for Dust Passivation and/or Soil Stabilization | Using solar concentrator to sinter soil on the surface to create roads, landing pads, or dust-free zones. |
| 7.1.4.9 | Other Methods of Sintering | Applying heat by various methods (other than solar concentrator) to get the soil to sinter. |
| 7.1.4.10 | Application of Polymers to the Soil for Dust Passivation and/or Soil Stabilization | Applying polymers to the soil with water evaporation curing, heat curing, ultraviolet (UV) curing, or other strategies that avoid use of water. |

# TA 7.2: Sustainability and Supportability

The Sustainability and Supportability technology area follows three major developmental phases. The near-term developmental phase (2015-2020) focuses on technology demonstration in a small scale and relative environment, such as the International Space Station (ISS) test bed, to increase the Technology Readiness Level. The mid-term developmental phase (2020-2025) focuses on technology development and applying the technology developed during the previous phase to human missions to LEO and beyond (i.e., crewed missions to HEO, NEO, near-Earth asteroid (NEA)). The long-term developmental phase (2025 and beyond) focuses on technology development as it relates to a crewed-Mars surface mission. To be fully implemented, early adoption of a sustainability and supportability paradigm must influence system architectures; enabling crewed or robotic maintenance and repair through common tools, effective human systems integration, processes, and materials; and increase accessibility for disassembly and reassembly. Minimizations of launch mass leads to more component-level maintenance and diagnostics. Supportability and Sustainability includes four areas: Autonomous Logistics Management, Maintenance Systems, Repair Systems, and Food Production, Processing, and Preservation.

## *Sub-Goals*

This TA includes all technology candidates required to establish a self-sufficient, sustainable, and affordable long-duration human space exploration program. For NASA's goal of extending human presence beyond LEO, the time required to resupply a crew is measured in months and years, and the ability to provide sustainability and supportability becomes critical. Technology candidates that enable supportability reduce the requirements for up mass, storage volume, and maintenance and logistics supplies and provide robust tools for performing repairs and fabricating replacement parts. In addition to reduced mass and volume requirements and reduced maintenance and logistics, these technology candidates contribute to mission success by reducing crew time spent on logistics management, tracking and locating logistics and mission hardware, and providing maintenance and repair tools to handle routine planned events and unforeseen contingencies.

**Table 7. Summary of Level 7.2 Sub-Goals, Objectives, Challenges, and Benefits**

| | | |
|---|---|---|
| **Level 1** | | |
| 7.0 Human Exploration Destination Systems | Goals: | Sustain human presence in space and provide more time for performing core mission activities, while reducing reliance on Earth. |
| **Level 2** | | |
| 7.2 Sustainability and Supportability | Sub-Goals: | Establish a self-sufficient, sustainable, and affordable long-duration human space exploration program. |
| **Level 3** | | |
| 7.2.1 Autonomous Logistics Management | Objectives: | Increase autonomy and efficiency of logistics management.<br>Reduce Earth dependency and logistics train. |
| | Challenges: | Inhomogeneous item population, spacecraft environment is typically a complex scattering environment for radio frequencies, and spacecraft cargo is densely packed for efficient use of spacecraft volume.<br>Attaining common sensing modalities (i.e., temperature, pressure, and strain) at sample rates on the order of kilo-samples per second. |
| | Benefits: | Improves accuracy of inventories.<br>Reduces ground support.<br>Improves volume efficiency thus reducing launch cost.<br>Enables situational awareness and reduces crew search time for items. |

**Table 7. Summary of Level 7.2 Sub-Goals, Objectives, Challenges, and Benefits - Continued**

| Level 3 | | |
|---|---|---|
| 7.2.2 Maintenance Systems | Objectives: | Develop system architectures and all hardware components to increase their maintainability and maintenance accessibility.<br>Design and optimize specialized processes and tools that are required to perform maintenance during human exploration missions. |
| | Challenges: | Accommodate access points and assemblies conducive to performing maintenance tasks using common, intuitive tools. |
| | Benefits: | Reduces crew time in pre-mission training and in performing maintenance tasks throughout the mission.<br>Reduces mass and stowage volume required for tools while improving mission sustainability and affordability.<br>Enables the crew to easily interact directly with the human exploration systems, including habitats, mobility systems, and life support systems, thereby enhancing mission success, particularly in response to unforeseen circumstances requiring human dexterity and ingenuity. |
| 7.2.3 Repair Systems | Objectives: | Perform repair of worn or damaged parts and unexpected failures.<br>Fabricate and certify replacement parts on-site to reduce sparing costs. |
| | Challenges: | Vibrations, power, size, mass, precision, and surface finish achieved in reduced-gravity environments for machining.<br>Power, size, mass, materials, quality, inspection, and thermal control for minimizing distortion for welding.<br>Power, size, mass, materials, quality, inspection, precision, and speed of additive manufacturing technologies.<br>Power, size, mass, materials, and precision of the sensors used in the inspection system.<br>Establishing a linkage between parts fabricated on the Earth and those fabricated on other exploration destinations. |
| | Benefits: | Reduces the requirements for sparing, storage volume, maintenance, and logistics supplies and provides a robust tool for fabricating and assembling structures in space.<br>Provides tools to handle unforeseen contingencies.<br>Makes use of recycled materials and feedstock refined from locally-sourced resources to further reduce up-mass requirements. |
| 7.2.4 Food Production, Processing, and Preservation | Objectives: | Reduce the quantity of food being resupplied.<br>Reduce the mass and volume of food packaging. |
| | Challenges: | Certify ingredient functionality, proper nutrition, sanitation, bulk stowage, and food growth, processing, and preparation in gravity and radiation environments of destinations. |
| | Benefits: | Decreases the amount of food that must be launched with the crew during long-duration missions.<br>Provides fresh food thus contributing to the psychological well-being of the crew. |

## TA 7.2.1 Autonomous Logistics Management

### *Technical Capability Objectives and Challenges*

The objective of this area is to reduce the dependency on Earth's logistics train by developing automated systems that do not require human intervention (either remote or by crew). Technology candidates include reconfigurable, multi-purpose cargo transfer bags; wireless tagging and monitoring systems for inventory tracking; and integrated software components that facilitate tracking, review, and management of the logistics chain.

Autonomous logistics management (ALM) technologies provide for the integrated localization, transfer, and status of logistics and mission hardware, as well as for hardware and software to facilitate autonomous and automatic decision-making and planning of consumable usage and spare availability. It also provides for logistics reuse and autonomous transfer, repackage, and stowage of internal logistics. One of the most important aspects of an ALM system is the ability to automatically track and update the location of hardware as it is moved around the vehicle or habitat. A database localization tool showing fewer than 0.01 percent of the items missing, in a complex environment, is the capability objective, which is far more accurate than modern commercial warehouse practices that achieve approximately 3 percent of inventory categorized as missing, typically in less complex environments.

Since most known approaches to ALM are based on radio frequency identification (RFID) to some degree, challenges associated with achieving this objective are related to radio frequency (RF) propagation and communication. Some notable challenges include: 1) an inhomogeneous item population, 2) the spacecraft environment is typically a complex scattering environment for radio frequencies, and 3) spacecraft cargo is densely packed for efficient use of spacecraft volume. Spacecraft volume is scarce, so tightly packed cargo is desirable at the expense of reducing line-of-sight (LOS) between RFID readers and tags. Deeper signal penetration and diffraction, which reduce LOS requirements, are better achieved with low-frequency RFID systems. However, localization accuracy and resolution, as well as system range, typically motivate higher RFID frequencies and wider bandwidths, thus conflicting with the desire for operation without LOS restrictions. Size, weight, and power must also be considered, since the accuracy and resolution of localization typically determine the size, weight, and power of the required RFID infrastructure.

The ability to autonomously transfer, re-package, and stow internal logistics calls for high accuracy, real-time localization systems. Although this capability can be partially satisfied using current active tag RFID solutions, technology advances might make this possible with passive tag solutions. Elimination of tag batteries is highly desirable due to battery life limitations.

The ability to provide constant awareness of mission hardware status is similarly challenging and is likely to be provided, to a great degree, by RFID technology. Due to the omission of batteries and wires, RFID technology can enable passive, wireless, ubiquitous sensing – a degree of situational awareness far beyond what would otherwise be feasible. Challenges include attaining common sensing modalities (i.e., temperature, pressure, strain) at sample rates on the order of kilo-samples per second.

ALM also includes repurposing materials to minimize logistical resupply from Earth. Logistical elements such as cargo bags and packaging foam should be reused and repurposed to reduce the logistical and trash burdens. Unloaded cargo bags and other carriers can be designed for reconfiguration for habitat outfitting. Similarly, logistical packaging foam can be formulated for later processing into additive manufacturing feedstock so that dedicated feedstock need not be flown.

### *Benefits of Technology*

Experiences on the ISS have strongly underscored the need for ALM. Inaccurate ISS inventories, for example, have resulted in temporarily short supplies of food. However, crew time spent searching for missing items has been a more consistent and more challenging problem. For LEO missions, crew search time allocation is typically limited, after which the decision is made to re-launch a replacement. For beyond LEO missions, this option would likely not exist, leaving only the options of investing additional crew time or enduring the consequences of terminating the search. Other items, such as science samples or unique experimental equipment, are often irreplaceable and represent a very large and sometimes incalculable cost. Logistics management for the ISS is also ground support intensive, with approximately 400 inventory database updates each day.

Packing of supplies for the ISS is typically driven by the crew's need to find items. As a result, like items are co-located for launch, and empty space within a cargo container is filled with foam. This practice represents volume inefficiency that increases launch cost. ALM capabilities have the potential to allow more efficient packing while retaining the crew's ability to rapidly locate items.

Autonomous transfer, repackage, and stowage of internal logistics are additional capabilities that reduce demands on crew time. In addition, these are operations that could be performed in advance of, and in preparation for, crew arrival, or upon crew departure using robotic assets.

Ubiquitous sensing provides obvious safety benefits by enabling situational awareness that would not otherwise be available. This capability can also reduce crew time, since a pervasive sensing capability eliminates the need for the crew to sample measurements throughout the vehicle on a recurring basis.

**Table 8. TA 7.2.1 Technology Candidates – not in priority order**

| TA | Technology Name | Description |
|---|---|---|
| 7.2.1.1 | Propellant Scavenging | Extract residual or ullage propellants from descent tanks, remove any unwanted pressurization gases such as helium or nitrogen, and send to existing fuel cells for power generation. Also generate water either through fuel cells or other means of combining the hydrogen (or methane) and oxygen, and store oxygen directly for life support after purifying. |
| 7.2.1.2 | Flexible, Vacuum-Rated Liquid Storage Bags | Water storage bags that can be collapsed or compressed for launch and are vacuum rated and capable of freeze/thaw cycles. |
| 7.2.1.3 | Power Scavenged Wireless Sensor Tag Systems | Sensor data is continuously sampled and stored in radio frequency identification (RFID) user memory banks to be gathered by an interrogator via RFID protocols. |
| 7.2.1.4 | Dense Zone Technology (Radio Frequency Identification Enclosure) | Sensing of dense collections of stowed assets for inventory and localization including direct interrogation of tagged items as well as smart containers that infer quantities or levels of contained non-tagged items. |
| 7.2.1.5 | Sparse Zone Technology | RFID based readers mounted in various ways (stationary, mobile, on free flyers) for all habitat areas exclusive of dense zones, including cracks and crevices. |
| 7.2.1.6 | Logistics Complex Event Processing (CEP) | Operational Intelligence software for complex logistics management, including three-dimensional (3D) localization and automated inventory updates. Operational intelligence to aggregate events and establish inferences to enable 3D asset localization in the absence of a complete data set. |
| 7.2.1.7 | Six Degrees of Freedom Logistics Tag System | Radio frequency identification (RFID) reader infrastructure and passive RFID tag that provides telemetry to the reader system to enable pose estimation. Current RFID technology is insufficient for high accuracy location and orientation. |
| 7.2.1.8 | Packaging Foam Additive Printer Feedstock | Modify packaging foam material to 3D manufacturing feedstock. Includes processing of foam (melt and extrude fiber or grind and filter) to provide useable feedstock. |
| 7.2.1.9 | Multipurpose Cargo Transfer Bag | A reconfigurable logistics stowage bag that unfolds into a flat panel. Flat panels can be used for outfitting crew structures and reduces stowage volume for empty bags. |

## TA 7.2.2 Maintenance Systems

### *Technical Capability Objectives and Challenges*

The objective of this area is to improve sustainability and affordability through optimizing system designs to ensure their maintainability. This includes hardware components for maintainability and maintenance accessibility, as well as specialized processes and tools required to perform crewed maintenance tasks in support of human exploration destination systems. Robotic and tele-robotic/autonomous maintenance systems, including non-destructive evaluation techniques, are addressed in TA 4 Robotics and Autonomous Systems.

A well-established maintenance program addresses the sustainability and affordability aspect of the human space exploration program. Maintenance tasks may be divided into three general categories, based upon how they are performed: robotic operations, tele-robotic or autonomous operations, and manual operations (conducted by the crew). To minimize the crew's workload, robotic or tele-robotic maintenance approaches are preferred whenever practical. These approaches are addressed in TA 4 Robotics and Autonomous Systems. However, because robotic systems are not designed to perform certain tasks, human intervention is most efficient or necessary in some cases. This is particularly true during unforeseen contingencies, but may also be planned because of specialized requirements or tools where human diagnostics and ingenuity are required to complete the tasks. The Maintenance Systems technology area specifically includes those technology candidates needed for unanticipated system evaluation, preventive maintenance, and corrective actions performed by the crew to support human exploration systems. Sensing technologies are needed that integrate with tools to capture events that occur during maintenance and repair tasks. System design must accommodate access points and assemblies conducive to performing maintenance tasks using common, intuitive tools that can easily be conducted by the crew. Meeting these challenges will enhance safety and mission success on future human exploration missions and provide the crew with tools for self-supportability.

### *Benefits of Technology*

A well-established maintenance program reduces crew time in pre-mission training and in performing maintenance tasks throughout the mission and reduces mass and stowage volume required for tools while improving mission sustainability and affordability. The designed maintenance program also enables the crew to easily interact directly with the human exploration systems, including habitats, mobility systems, and life support systems, thereby enhancing mission success, particularly in response to unforeseen circumstances requiring human dexterity and ingenuity.

**Table 9. TA 7.2.2 Technology Candidates – not in priority order**

| TA | Technology Name | Description |
|---|---|---|
| 7.2.2.1 | Ultrasonics For Electrical Connections | Ultrasonic sensors integrated into connectors to wirelessly detect and transmit location of loss of electrical connectivity. |

## TA 7.2.3 Repair Systems

### *Technical Capability Objectives and Challenges*

The objective of this area is to enable reusability, reconfigurability, and in-situ repairs by developing technologies that allow recovery from worn or damaged parts and unexpected failures. Technology candidates include systems that are designed to be easily repairable, allowing for minimum intrusive repairs and reusability of critical components; and basic support tools to enable more complex repairs and inspections, such as machining, welding, and additive manufacturing. Recycling and refinement of in-situ resources into useable feedstock for additive manufacturing are detailed in section TA 7.1.4.

Supportability and sustainability requires the ability to recover from worn or damaged parts and unexpected failures. For NASA's goal of extending human presence beyond LEO, the time required to resupply a crew is measured in months and years, and the ability to provide replacement parts on demand becomes critical. Deploying repair systems and designing for in-space repair will drastically reduce vehicle up-mass and provide greater flexibility to produce parts for planned repairs and unforeseen circumstances. The Repair Systems technology area includes those technology candidates needed to perform unanticipated system repairs, fabrication of replacement parts, and inspection of the repairs performed and components fabricated to ensure they are certifiable to be placed into service. Reusability and reconfigurability of discarded items can be accomplished using repair capabilities to reduce overall up-mass. Repair Systems addresses technology candidates used to perform the repairs for human exploration systems. These technology candidates are (1) Machining, (2) Welding, (3) Additive Manufacturing, and (4) Inspection and Certification.

*Machining* technology candidates include multi-axis machining and lathe capabilities, as well as management and reclamation of coolant fluids and chips. Challenges include vibrations, power, size, mass, precision, and surface finish achieved in reduced-gravity environments. Meeting these challenges enables a robust, precision capability for machining a wide variety of materials and parts to modify existing components and provide finishing operations for additively manufactured or welded parts.

*Welding* technology candidates include friction stir welding, electron beam welding, and arc/plasma welding capabilities. Challenges include power, size, mass, materials, quality, inspection, and thermal control for minimizing distortion. Selecting a welding technology compatible within the needs of the mission enables quick structural repairs of metallic structures. Welding has the added benefit of being useable for assembly and construction of large-scale infrastructure on other planetary surfaces.

*Additive Manufacturing* (also called 3D printing) technology candidates include plastics, metals, and electronics components built from feedstock in a layer-additive fashion. Challenges include power, size, mass, materials, quality, inspection, precision, and speed. Meeting these challenges enables an ability to build a large variety of different parts using feedstock brought from Earth, recycled from discarded resources, or refined from locally sourced resources. A wide variety of different parts can be designed on Earth and then manufactured quickly in space using data files transmitted from Earth.

*Inspection and Certification* technology candidates include geometric inspection for shape, internal flaw detection for quality, and may be separate or integrated into other repair technologies to provide inspection during repair. Challenges include power, size, mass, materials, precision of the sensors used in the inspection system, and establishing a linkage between parts fabricated on the Earth and those fabricated on other exploration destinations. Inspection sensors may be integrated into machining, welding, or additive manufacturing systems to enable in-situ inspection of parts while they are being built. Meeting these challenges enables certification of parts fabricated in space for use in-space.

#### *Benefits of Technology*

An effective repair and replacement strategy reduces the requirements for up-mass, storage volume, maintenance, and logistics supplies and provides a robust tool for fabricating and assembling structures in space. In addition to reduced mass and volume requirements and reduced maintenance and logistics, repair systems contribute to mission success and enhance autonomy and mission safety by providing tools to handle unforeseen contingencies. Repair systems can also make use of recycled materials and feedstock refined from locally sourced resources to further reduce up-mass requirements.

**Table 10. TA 7.2.3 Technology Candidates – not in priority order**

| TA | Technology Name | Description |
|---|---|---|
| 7.2.3.1 | Multi-Axis Subtractive Machining | Multi-axis subtractive machining in reduced gravity environment – manufacture of finished parts for repairs. |
| 7.2.3.2 | Multi-Axis Lathe Machining | Multi-axis lathe turning operations in reduced gravity; partial gravity required. |
| 7.2.3.3 | Machining Fluid and Chip Management | Management of machining chips and cutting fluids in reduced gravity; partial gravity required. |
| 7.2.3.4 | Machining Fluid and Chip Reclamation | Reclamation and recycling of machining chips and cutting fluids in reduced gravity; partial gravity required. |
| 7.2.3.5 | Welding | Micro-gravity or zero-gravity process for joining of metals using fusion or solid-state welding techniques. |
| 7.2.3.6 | Friction Stir Welding | Solid-state welding technique that minimizes distortion and thermal input using a high speed rotating tool. Heats and plasticizes metal but does not create a fusion (molten) pool. |
| 7.2.3.7 | Electron Beam Welding | Fusion welding technique that uses a focused electron beam in a vacuum environment to create narrow welds with small heat affected zones. Higher power enables deeper penetration in a single pass. |
| 7.2.3.8 | Arc/Plasma Welding | Fusion welding technique that uses an electrical arc or creates plasma to couple the work piece with wire fed in to create the weld bead. |
| 7.2.3.9 | Additive Manufacturing (Three-Dimensional (3D) Printing) | Freeform deposits plastic, elastomeric, or semiconductor components by extrusion or inkjet. |
| 7.2.3.10 | Three-Dimensional (3D) Scanning | Lightweight, low power surface precision measurements of parts requiring repair or modification and verification of repairs made in space for certification of quality. |
| 7.2.3.11 | Electron Beam Freeform Fabrication ($EBF^3$) | Metal additive manufacturing and repair technology using electron beam energy source and wire feed. |
| 7.2.3.12 | Laser Powder Systems | Melt metal powder with laser beam to form objects. |
| 7.2.3.13 | Ultrasonic Consolidation | Low thermal input bonding technology with integrated machining capability for fabrication and repair of metal parts. |
| 7.2.3.14 | Friction Stir Additive Process | Low thermal input metal additive process based on friction stir welding technology with integrated machining capability for fabrication and repair of metal parts. |
| 7.2.3.15 | In-Situ Manufactured Parts/ Components Verification and Certification | Lightweight, low power through-thickness non-destructive evaluation of parts fabricated in space for certification of quality. |

## TA 7.2.4 Food Production, Processing, and Preservation

### *Technical Capability Objectives and Challenges*

The objective of this area is to safely produce, handle, and store food to reduce up-mass and retain maximum nutritional value. It includes food production, processing, packaging, storage, and preparation during long-duration missions. Most technologies are addressed in the roadmap for TA 6 Human Health, Life Support, and Habitation Systems. This area addresses the development of a bioregenerative food system.

Logistic resupply for deep-space missions is a huge challenge, and one of the largest logistical components being consumed is food. The development of a bioregenerative food system can reduce the quantity of food being resupplied, provide fresh food to the crew, and even be tied into life-support systems. Food packaging mass and volume would also be minimized, due to the food being produced with minimal shelf-life requirements. Additionally, a bioregenerative food system could boost astronaut psychological well-being and morale, since growing food and consuming fresh food might have positive psychological impacts. This contribution of plants to crew well-being is an area that requires further research.

The challenge to the development of this technology is to be able to certify ingredient functionality, proper nutrition, sanitation, bulk stowage, and food growth, processing, and preparation. All of this would need to be demonstrated in the gravity and radiation environments of the Design Reference Missions, with particular shelf life and delivery plans.

### *Benefits of Technology*

Current space food is double-packaged to increase shelf life. However, current shelf life will not support missions lasting three or more years. A bioregenerative food system would provide food during the mission, decreasing the amount of food that must be launched with the crew and resupplied during the mission, but would increase infrastructure requirements for the vehicle. Fresh food is more nutrient dense than food packaged and stored for long shelf life. Additionally, a bioregenerative food system may contribute to the psychological well-being of the crew by boosting morale.

**Table 11. TA 7.2.4 Technology Candidates – not in priority order**

| TA | Technology Name | Description |
|---|---|---|
| 7.2.4.1 | Bioregenerative Food System | A food system that grows plants and stores until use. |

# TA 7.3: Human Mobility Systems

Existing human mobility systems were developed primarily for use on the ISS or for robotic science missions. Prior to that, human-rated systems were demonstrated during the Apollo lunar surface missions. For missions to asteroids or Mars moons, extravehicular activity mobility and anchoring, as well as off-surface technologies, will be needed to facilitate working in minimal-gravity environments. For a dual launch or split mission scenario such as a Mars surface mission, it will be necessary to pre-deploy assets to the Mars system. Some of the cargo will be consumables and support logistics for the crew to use upon arrival, while the remainder will be elements needed for surface infrastructure to enable crew operations. Extended missions will increase the demand for protective shielding from radiation, potential bombardment by micrometeoroids, and extreme thermal environments (see TA 6.5 Radiation). Many core mobility technologies are covered under TA 4 Robotics and Autonomous Systems. Supporting advanced life support technologies are also covered under TA 6 Human Health, Life Support, and Habitation Systems and advanced power systems are described in TA 3 Space Power and Energy Storage.

## *Sub-Goals*

Human mobility goals are primarily tied to enabling humans to perform work or scientific activities outside their primary spacecraft. The tools and systems required to enable mobility must be both safe and efficient, operating within the constraints of human mission operations. This means low mass, low power, and improved human interfaces are key attributes for enabling human mobility. Testing requirements for these systems must be considered up front and during the development phase. Mobility hardware must be tested in relevant environments. Resources are limited so advancing the performance goals while minimizing the dependence on high cost test facilities is critical.

**Table 12. Summary of Level 7.3 Sub-Goals, Objectives, Challenges, and Benefits**

| Level 1 | | |
|---|---|---|
| 7.0 Human Exploration Destination Systems | Goals: | Sustain human presence in space and provide more time for performing core mission activities, while reducing reliance on Earth. |
| **Level 2** | | |
| 7.3 Human Mobility Systems | Sub-Goals: | Enable humans to safely and efficiently perform work or scientific activities outside their primary spacecraft. |
| **Level 3** | | |
| 7.3.1 Extravehicular Activity (EVA) Mobility | Objectives: | Enable safe and efficient EVA operations in micro or low gravity. |
| | Challenges: | Microgravity anchoring, stability, and translation on non-engineered surfaces, sample collection for loosely adhered surface particles, sample collection and containment for break chips of larger geology samples in microgravity, subsurface (core) sampling, and in-situ high-grading instrumentation. |
| | Benefits: | Enhances the crew's ability to work in space, increases crew efficiency and EVA safety by providing secure access points.<br>Provides situational awareness and allows diagnosis and analysis of conditions and materials and then communicates the results. |

**Table 12. Summary of Level 7.3 Sub-Goals, Objectives, Challenges, and Benefits - Continued**

| Level 3 | | |
|---|---|---|
| 7.3.2 Surface Mobility | Objectives: | Transport crew, provide habitable volume, and enable mobile exploration and science for surface operations. |
| | Challenges: | Estimating drawbar pull and traction in loose planetary soils with uneven or uncertain terrains.<br>Operating in harsh environments (i.e., vibration, peak torques, regolith dust, and 40 K-400 K temperatures) compounds the difficulty.<br>Communication delays and potential loss of communications. |
| | Benefits: | Improves surface mobility with a concomitant increase in efficiency to crew operations and crew safety. |
| 7.3.3 Off-Surface Mobility | Objectives: | Improve human interfaces.<br>Incorporate longer mission times and delta V into a smaller package. |
| | Challenges: | Reduced mass of less than 75 pounds, delta V greater than 40 feet per second, operating time of 8 hours, single fault tolerance, rechargeable on-orbit, and a level of autonomy that includes attitude, position, obstacle avoidance, and remote commanding options for incapacitated crew. |
| | Benefits: | Provides a safe option for EVA in microgravity to reduce risk. |

# TA 7.3.1 EVA Mobility

### *Technical Capability Objectives and Challenges*

EVA Mobility is comprised of two categories: power-assisted exoskeletons and EVA mobility aids and tools. EVA tools are integral to the EVA system (see TA 6.2 Extravehicular Activity Systems) and have been successfully used for lunar surface science operations in the Apollo Program, as well as microgravity construction and maintenance tasks in the Skylab, Space Shuttle, and ISS Programs. However, the blending of natural sciences such as geology with the microgravity environment has yet to occur. This is applicable to NEAs and Mars moon operations, as those surfaces represent natural bodies for scientific investigation but do not have the benefit of significant gravity levels.

Challenges to EVA Mobility include microgravity anchoring, stability and translation on non-engineered surfaces, sample collection for loosely adhered surface particles, sample collection and containment for break chips of larger geology samples in microgravity, subsurface (core) sampling, and in-situ high-grading instrumentation. Robotic systems and arms that assist crew in EVA are described in TA 4 Robotics and Autonomous Systems.

### *Benefits of Technology*

Mobility systems enhance the crew’s ability to work in space and enable EVA. The technology candidates outlined for EVA Mobility increase crew efficiency and EVA safety by providing secure access points. They facilitate entry and egress and maintain the integrity of habitable volumes. EVA tools also provide situational awareness and allow diagnosis and analysis of conditions and materials and communication of results.

**Table 13. TA 7.3.1 Technology Candidates – not in priority order**

| TA | Technology Name | Description |
|---|---|---|
| 7.3.1.1 | Exoskeletons | Electro/mechanical assistive elements to augment human capability. |
| 7.3.1.2 | Suitport | A piece of hardware that replaces an airlock and allows a spacesuit to be mated to the side of a vehicle. The crew dons the suit through a rear entry hatch. In a suitport system, the dustiest parts of the suit (gloves, arms, boots, etc.) remain outside the pressurized cabin and reduce the possibility of dust from entering the cabin. The suitport can be used by itself or in conjunction with an airlock (often referred to as a “hybrid” or suitport-airlock). Suitport technology is most enabling for mobile assets such as pressurized rovers. |

**Table 13. TA 7.3.1 Technology Candidates – not in priority order - Continued**

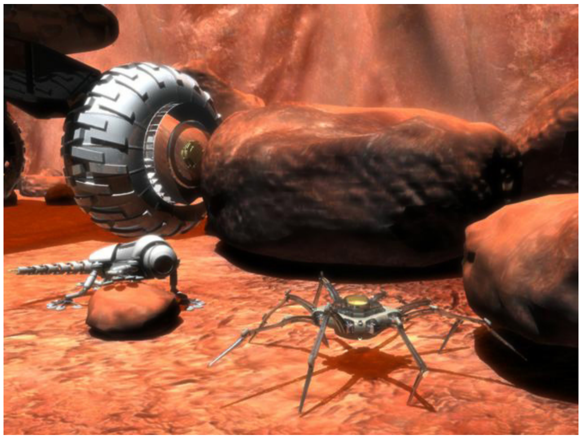
| TA | Technology Name | Description |
|---|---|---|
| 7.3.1.3 | Advanced Tools Development for Extravehicular Activity (EVA) | Tools used by crew member during extravehicular activity that enable collection and analysis of geology samples. |
| 7.3.1.4 | Sample Storage and Curation, Low Mass, Low Power | System to store sample at needed environment parameters |
| 7.3.1.5 | Anchoring | Restraint for human exploration of bodies and destinations where minimal gravity exist to support EVA of in-space assets like asteroids to safely acquire samples or perform in-place analysis of indigenous materials. |
| 7.3.1.6 | Advanced Airlock/Suitlock | A device that permits the passage of people and objects between a pressure vessel and its surroundings while minimizing the changes in pressure in the vessel and loss of air from it. |
| 7.3.1.7 | Incapacitated Extravehicular Activity (EVA) Crew Rescue Devices | Hardware and techniques for rescue of incapacitated EVA crew in partial gravity environments. |

## TA 7.3.2 Surface Mobility

### *Technical Capability Objectives and Challenges*

NASA's unmanned Mars rovers (top speed of 0.09 miles per hour (mph); 0.14 kilometers per hour) are the state of the art (SOA) for planetary rovers. Human-rated, battery-powered rovers with space heritage from the Apollo era were unpressurized and could reach a top speed of about 13 kilometers per hour (8 mph) to 18 kilometer per hour (11.2 mph) depending on the severity of the terrain. The Moon's cratered surface combined with suspension systems prevented the astronauts from driving too fast. The building block elements and systems for these surface mobility capabilities (i.e., wheels, drive trains, motors, suspension component technology, and algorithms for autonomy) are addressed in TA 4.2 Mobility.

To navigate the rough surface terrain, improvements in rover component and subsystems will be needed. Component development of wheels, drive trains, and similar high-duty subsystems are needed to meet the longer-life requirements (approximately 10,000 kilometers) for pressurized and non-pressurized rover systems that may carry up to 100 times their own weight. Advances in non-conventional models used to estimate drawbar pull and traction in loose planetary soils with uneven or uncertain terrains is needed to better predict performance and influence rover design. Operating in harsh environments (i.e., vibration, peak torques, regolith/dust, and 40 K-400 K temperatures) compounds the difficulty. Evolving to wheel-on-limb designs will provide multifunctional capabilities that can automate operation and minimize crew hours. Advanced rovers will likely have alternative power sources, some of which will be rechargeable and would benefit from automated docking and berthing mechanisms that facilitate ease of charging batteries.



**Gecko and Spider Robots**

Most of the mobility systems will have some level of autonomy to allow the crew to focus on other tasks or to perform work while the crew is not present. Because of the distance to Mars, round-trip communication delays of up to 44 minutes make it difficult and slow to control robotic mobility system. Robots may wait for further instructions before performing additional tasks if confronted with an impractical or unpredicted situation. Loss of communication could have serious consequences on a robot mission.

### *Benefits of Technology*

Surface mobility is critical to infrastructure emplacement, crew operations, and crew safety, and enables extended surface missions for lunar proving grounds or Mars. While many of the underlying technologies needed for Surface Mobility are described in TA 4 Robotics and Autonomous Systems, the integration of these capabilities into systems used by humans is the emphasis of TA 7, along with enabling human interfaces and appropriate human accommodations (i.e., life support, displays, etc.).

**Table 14. TA 7.3.2 Technology Candidates – not in priority order**

| TA | Technology Name | Description |
|---|---|---|
| 7.3.2.1 | Strontium Aluminate (Photoluminescent) Markers for Exterior Markings | A photo-luminescent material that can be formed into decals for labeling items outside a vehicle, spaceflight system, or path traveled. It is currently only used for interior marking, but could be made very useful for external non-powered lighting where it is charged by sunlight and then available for crew safety when portions of the spacecraft are in shadow due to operations. |
| 7.3.2.2 | Light Emitting Plasma (LEP) Technology | A solid state lighting technology that generates high quality broad-spectrum lighting at high lumen intensities at much lower power levels than other technologies such as High Intensity Discharge (HID). It was designed to provide a better alternative than light emitting diode (LED) for reduction of energy footprint for roadway lighting. Roadway lighting requires high lumen output. For LED implementations, this often requires large LED arrays, which become a mechanical and wind loading issue. LEP solves this problem by producing broad spectrum, high lumen, lightweight, low power, point source, minimal footprint solutions for the industries requiring solutions that typically would have required HID lamps. |

## TA 7.3.3 Off-Surface Mobility

### *Technical Capability Objectives and Challenges*

Upon reaching their destination, crews will be reliant on land vehicles for surface transportation. Propulsive systems for aerial travel over varying distances can be accomplished with jet packs or hoppers, but may rely on construction of infrastructure and off-surface taxis to facilitate transporting both crew and cargo. Propulsion building blocks that support this capability are mapped to TA 2.1 Chemical Propulsion. Human and suit interfaces are mapped to TAs 6.2.2 Portable Life Support System and 6.2.3 Power, Avionics, and Software, and power systems to TA 3.2.1 Batteries. Non-propulsive options are limited to mechanical hoppers or similar concepts whose suitability is destination dependent for partial gravity environments. Minimal atmosphere exist at destinations such as Mars to support glider concepts.

Advanced EVA jetpacks will be semi-autonomous and fault-tolerant, allowing them to be used as a primary mode of EVA mobility and to provide rescue capability for incapacitated EVA crew members. Navigation sensors and a communications system will be integrated for further development of jetpacks. This would improve safety and may provide capability to translate between orbiting space vehicles as an efficient solution for individuals to perform maintenance, assembly, and repairs. The system will be capable of being controlled either manually or via voice command by the EVA crew member, being tele-operated in either mode by an intra vehicular activity (IVA) crew member, and performing pre-defined tasks such as “translate to worksite A” or “emergency return to airlock.” The ability to be easily refueled and stowed is desirable to reduce mass and improve overall packaging of mission logistics. If multiple spacewalks are to be performed on a given flight, the ability to replenish propellant and power will be required.

To meet the requirements for future missions advanced EVA jetpacks must meet a variety of challenges to ensure crew safety and support extended EVA. Performance characteristics for advance EVA jetpacks include, but are not limited to: reduced mass of less than 75 pounds, delta V greater than 40 feet per second, operating time of 8 hours, single fault tolerance, rechargeable on-orbit, and a level of autonomy that includes attitude, position, obstacle avoidance, and remote commanding options for incapacitated crew.

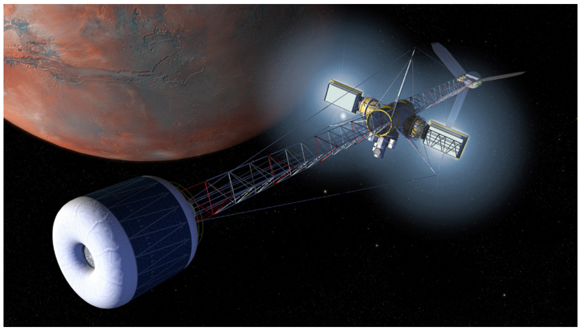
### *Benefits of Technology*

The Manned Maneuvering Unit (MMU) and Simplified Aid for EVA Rescue (SAFER) have flown in space and currently provide a rescue capability. Improvements over the current concept are needed to provide a safe option for EVA in microgravity to reduce risk.

**Table 15. TA 7.3.3 Technology Candidates – not in priority order**

| TA | Technology Name | Description |
|---|---|---|
| 7.3.3.1 | Advanced Extravehicular Activity (EVA) Jetpacks | System that provides extravehicular mobility for incapacitated crew members with hands-free or voice control. |

# TA 7.4: Habitat Systems



Deep Space Mission Habitat

Habitat Systems technologies, and subsequent capabilities, for exploration destinations are needed to support the approach for human exploration of deep-space destinations such as HEO, NEO, interplanetary travel, and planetary missions to Earth's Moon, Mars' moons, and the Mars surface. State of the art habitat systems technologies are those capabilities currently being used on the International Space Station. New spacecraft in development are incorporating limited advances in habitat systems, but they are primarily discussed in TA 6 Human Health, Life Support, and Habitation Systems. The primary challenge of habitat systems is that much of the technology development is considered enhancing rather than enabling, since they deal with crew psychological well-being. Overall, most exploration missions can be accomplished with little new technologies, but will suffer a mass, volume, and power performance penalty in addition to neglecting the crew's psychological well-being and productivity.

## *Sub-Goals*

The Habitat Systems goals focus on creating an autonomously operating spacecraft that promotes crew health and well-being while reducing required crew maintenance and servicing and optimizes resource utilization. Specifically, the Integrated Habitat Systems area seeks to increase human exploration safety, increase crew well-being and productivity, and reduce spacecraft and exploration habitat mass, power, and volume. The Habitat Evolution and "Smart" Habitat goals are to develop a fully-integrated habitat operating system with embedded sensors, algorithms, and an intelligent operating system throughout the spacecraft or habitat that enable it to operate independently and autonomously with or without crew, thereby reducing the crew's work load to maintain and manually operate it. The artificial gravity capability goals are to reduce crew health degradation on long-duration spaceflight missions by providing a partial or full-Earth's gravity environment during the journey to and from a destination, thereby increasing human exploration safety, crew well-being, and productivity.

**Table 16. Summary of Level 7.4 Sub-Goals, Objectives, Challenges, and Benefits**

| | | |
|---|---|---|
| **Level 1** | | |
| 7.0 Human Exploration Destination Systems | Goals: | Sustain human presence in space and provide more time for performing core mission activities, while reducing reliance on Earth. |
| **Level 2** | | |
| 7.4 Habitat Systems | Sub-Goals: | Develop an autonomously operating spacecraft that promotes crew health and well-being while reducing required crew maintenance and servicing and optimizing resource utilization. |
| **Level 3** | | |
| 7.4.1 Integrated Habitat Systems | Objectives: | Increase human exploration safety, crew well-being, and productivity.<br>Reduce spacecraft and exploration habitat mass, power, and volume. |
| | Challenges: | Longevity degradation of technologies, non-harmful off-gassing, and reliability. |
| | Benefits: | Minimizes the number of crew-hours required to operate and maintain a spacecraft or habitat on a long-duration mission while also reducing cost to achieve mission objectives.<br>Improves the crew's health and well-being due to the reducted internal cabin noise, improved crew spacecraft situational awareness, reduced micro-organisms, increased crew productivity, and more efficient use of spacecraft resources. |

**Table 16. Summary of Level 7.4 Sub-Goals, Objectives, Challenges, and Benefits - Continued**

| Level 3 | | |
|---|---|---|
| 7.4.2 Habitat Evolution | Objectives: | Provide an exploration habitat modeling and simulation capability that enables overall design optimization, mass reduction, and crew performance optimization. |
| | Challenges: | Linking to a database system infrastructure, able to run on multiple desktop platforms, and validating the models and simulations. |
| | Benefits: | Minimizes the number of crew-hours required to operate and maintain a spacecraft and habitat for a mission while also reducing cost to achieve mission objectives.<br>Increases effectiveness of the habitat by optimizing mass, power, and volume.<br>Provides onboard tools that allows the understanding of short to medium-term implications of the configuration changes made by crew members. |
| 7.4.3 "Smart" Habitats | Objectives: | Increase human exploration safety, crew well-being, and productivity.<br>Increase resource utilization, optimization, conservation, and use efficiency.<br>Reduce spacecraft and exploration habitat mass, power, and volume. |
| | Challenges: | Incorporation of failure detection isolation and recovery, longevity material degradation, and reliability of the software, sensors, and components. |
| | Benefits: | Enables a spacecraft or habitat to operate independently and autonomously with or without the crew present.<br>Reduces the crew's daily operations and monitoring while increasing safety and reducing resource consumption.<br>Minimizes the number of crew hours required to operate and maintain a spacecraft and habitat for a mission while also reducing mission costs.<br>Improves the crew's health and well-being due to the reduction of stress, improved situational awareness, and increased productivity. |
| 7.4.4 Artificial Gravity | Objectives: | Reduce crew health degradation on long-duration spaceflight missions. |
| | Challenges: | Spacecraft complexity, course correction, and maneuvering. |
| | Benefits: | Reduces the detrimental effects of long-duration zero-gravity on human physiology and increases crew productivity and well-being while reducing long-term human health and performance risks.<br>Allows for reconsidering the size and deployment sequence of several elements in the mission, which can result in a more flexible and compact packaging strategy on the launch vehicle. |

## TA 7.4.1 Integrated Habitat Systems

### *Technical Capability Objectives and Challenges*

Integrated Habitat Systems enable long-duration and deep-space human missions that will increase crew productivity and crew and mission safety, while reducing mass, power, and volume. For long-duration, deep space missions, the crew will require new multi-colored internal materials and colors that will be used in low-pressure, high-oxygen environments while being non-toxic. This area includes technology candidates focusing on acoustical treatments and noise reduction, solar optic lighting and heating, antimicrobial and surface coatings, low-toxicity fire-retardant advanced fabric textiles, bio-illumination, artificial illumination, self-cleaning biotechnology surface coatings, thin flexible visualization displays, and exploration habitat performance monitoring using embedded sensors.

*Acoustical treatments and noise reduction* must provide human spaceflight-qualified materials and acoustical lay-ups that are lightweight and provide sound blocking, sound absorption, vibration isolation, and vibration damping. Materials need to be cleanable, water-resistant, and contain specific sound reduction particulates, depending on the application. Noise cancellation or reduction technology may also be employed as a mitigation strategy in the event that equipment failures result in noise levels that are hazardous or that interfere with communication or sleep. These acoustical technologies need to provide vibration isolation for rotating equipment; provide materials and lay-ups that provide significant sound absorption; and provide close-out panels, locker designs, and lay-ups that provide significant sound blocking. Technology challenges include providing low toxicity flame retardant sound absorbent treatments, off-gassing, low mass, low volume, and longevity degradation of materials.

*Solar optic lighting and heating* capabilities focus on four technology areas of development: inlet optics, optical waveguide solar power transmission system, optical fiber cables with thermal power delivery component, and optical lighting panel. Performance goals are to: 1) enable natural solar lighting to enter the interior of the spacecraft using fiber optics, thus reducing dependence on artificial lighting; 2) use solar light to grow plants inside the habitat or spacecraft for food (wheat, lettuce, tomato, potato, etc.); 3) use solar power for thermochemical material processing, such as oxygen production from lunar regolith; and 4) use solar power for thermal production of construction materials, such as bricks, or to make tools using 3D printer technology. Technology challenges include providing low mass, highly reliable solar concentrators (see TA 3 Space Power and Energy Storage), transformer systems, and fiber optic cables to deliver natural light and thermal heat inside the habitat. Other challenges include longevity degradation of the concentrators; optimized sun tracking; wavelength conversion; fiber optic cable efficiencies and lengths; light and heat distribution; alternate lighting and heating for use during eclipse; and system reliability.

*Anti-microbial and surface coatings* must deter spacecraft microbial growth that is harmful to humans and subsystems or components on surfaces, filters, pipes, and mechanisms in a high oxygen, reduced pressure environment. The performance goal is to enable reduction or elimination of harmful microbial bacteria and fungi growth on surfaces and textiles within a spacecraft. Technology challenges include developing non-toxic anti-microbial coating that will result in a reduction in harmful microbial bacteria and fungi growth in a spacecraft. Other challenges include longevity degradation of the coating, non-harmful off-gassing, and human-rating the coating.

*Advanced fabric textile materials* must provide human spaceflight qualified multi-color fabrics for wall coverings, fabric walls, close-out panels, and crew systems to increase crew psychological well-being and safe operations of human exploration spacecraft and habitats. The textile fabrics could also be used for cargo transfer bags and then repurposed into other uses. The performance goal is to enable multiple colored fabrics with less mass, no toxicity, and flame retardant materials for spacecraft operating environments with pressures of 8.3 psia and 30 to 32 percent oxygen. Safety and functionality are of the utmost importance for the selection and development of new fabrics. This means that aside from toxicity and flammability, other characteristics must be present such as durability, dimensional stability, and retention of aesthetic quality. Technology challenges include developing non-toxic, flame retardant, multi-color, easy cleaning (or self-cleaning) textile fabrics that can be human-rated certified for operational use in an enclosed long-duration spacecraft environment.

*Bio-illumination* must provide non-powered biotechnology coatings that illuminate the spacecraft interior and exterior. This technology needs to provide natural or synthetic bio-coatings that will provide ambient lighting without the use of power. The performance goal is to reduce mass, power, and spare replacement needs. Technology challenges include developing natural or bio-engineered synthetic agents that will provide non-powered spacecraft ambient lighting. Other challenges include longevity degradation of the agent, non-harmful off-gassing, and reliability of the illumination.

*Artificial illumination* will be required for crew tasks and crew health when solar optical illumination is not available. Both internal and external artificial illumination technologies are required. Advances in space-qualified light emitting diode lighting technologies and controls are needed. Advanced illumination technology will need to have very low mass and volume much in same vain as flexible display technology and may have multi-purpose use as both displays and illumination. Such illumination technology should include spectral controls for circadian management and plant growth. Technical challenges include control of the spectrum transmitted to the spacecraft environment and variability of output. Research should be conducted into the application of strontium aluminate surface treatments of interior and exterior vehicle or habitat markings. This material requires artificial light or sunlight to charge and then hold its charge for eight or more hours. It provides a reliable "glow" for ambient lighting.

*Self-cleaning biotechnology surface coatings* will provide coatings and agents that will perform self-cleaning of surfaces, pipes, wiring, mechanisms, and components. The performance goal is to provide the ability to self-clean accumulating bacteria, fungi, dust, dirt, human, and other particulates, as well as potential toxins within the spacecraft while being non-toxic to humans and reducing mass, power, cleaning supplies, and trash. The goal is to keep the internal spacecraft "clean" without requiring the crew to perform housekeeping duties, such as wiping down or washing exposed and hard-to-reach surfaces. Technology challenges include providing agents that will perform self-cleaning of surfaces, pipes, wiring, mechanisms, and components. Other challenges include longevity degradation of the self-cleaning agent, non-harmful off-gassing, and reliability of the agent.

*Thin flexible visualization display* technology provides visual displays for situational awareness and sensory stimulation onto pressure vessel walls and internal wall coverings that will change color or imagery depending on human occupants as well as provide emergency situational awareness. The performance goal is to provide sensory stimulation via embedded, large format displays throughout the spacecraft that use thin flexible display technology that will increase crew productivity and psychological well-being while reducing the mass and power required to do so. Technology challenges include providing integrated sensors and organic light emitting diodes (OLED) into a pressure vessel wall and internal wall coverings that will change color or imagery depending on human occupants. Other challenges include longevity degradation of the display, low-power usage, non-harmful off-gassing, and reliability of the display.

*Exploration habitat performance monitoring* using embedded sensors must monitor exploration habitat systems and spacecraft performance and provide real-time feedback wirelessly to the smart habitat or intelligent habitat (iHab) operating system. This technology should provide long-life, reliable battery operated wireless sensors that will be incorporated into fabrics, floors, walls, surfaces, mechanisms, subsystems, and components to monitor performance and link wirelessly to the iHab operating system. The iHab operating system provides autonomous monitoring, automated failure isolation and recovery, and situational awareness to the crew. The performance goal is to monitor performance of spacecraft mechanisms, subsystems, and components and to provide 100 percent spacecraft coverage, 100 percent integration into smart operating systems, and 75 percent reduction in crew time to monitor and check systems, subsystems, assemblies, and components. Technology challenges include providing reliable wireless sensors, low power, long battery life, and integrated operating systems with high data rates.

### *Benefits of Technology*

These technology candidates will minimize the number of crew-hours required to operate and maintain a spacecraft or habitat on a long-duration mission while also reducing cost to achieve mission objectives. The crew's health and well-being will be improved due to the reduction of internal cabin noise, better crew spacecraft situational awareness, a reduction in micro-organisms, an increase in crew's productivity, and more efficient use of spacecraft resources.

**Table 17. TA 7.4.1 Technology Candidates – not in priority order**

| TA | Technology Name | Description |
|---|---|---|
| 7.4.1.1 | Low-Toxicity, Fire-Retardant Textiles | Textile materials that operate in a low pressure, high oxygen environment to enable crew psychological well-being and safe operations of human exploration spacecraft and habitats. |
| 7.4.1.2 | Anti-Microbial Coatings | A thin layer covering a surface that deters microbial growth harmful to humans, filters, pipes, and mechanisms in a high oxygen ($O_2$) environment. |

### Table 17. TA 7.4.1 Technology Candidates – not in priority order - Continued

| TA | Technology Name | Description |
|---|---|---|
| 7.4.1.3 | Exploration Habitat Performance Monitoring Embedded Sensors | Subsystem performance sensors to monitor and provide real-time feedback wirelessly to the Intelligent Habitat (iHab) operating system. |
| 7.4.1.4 | Bio-Illumination | Non-powered biotechnology coatings for spacecraft interior and exterior illumination. |
| 7.4.1.5 | Self-Cleaning Biotechnology Surface Coatings | Biotechnology coatings that will enable self-cleaning of spacecraft internal surfaces. Consider "visibly clean" as well as the microbial clean parameter in assessing this techology, as microbial requirements may not cover particulates, greases, etc. |
| 7.4.1.6 | Thin Flexible Visualization Display | Visual displays for situational awareness and sensory stimulation onto pressure vessel walls and internal wall coverings that will change color or imagery depending on human occupants –intelligent awareness. |
| 7.4.1.7 | Inlet Optics | Micro-reflector cone array (or microlens matrix) that injects the concentrated solar radiation into individual optical fiber for transmission. Transmitted solar radiation can be used for thermal, thermochemical, or Photosynthetically Active Radiation (PAR) for growing plants or lighting interior of a spacecraft or habitat. |
| 7.4.1.8 | Optical Waveguide Solar Power Transmission System | Optical waveguide transmission PAR to grow plants and illuminate the habitat via fiber optic transmission of solar radiation. |
| 7.4.1.9 | Optical Fiber Cables with Thermal Power Delivery Component | Transmit solar radiation for thermal and thermochemical applications (such as oxygen production, making construction materials, and tool making by 3D printing). |
| 7.4.1.10 | Optical Lighting Panel | Optical lighting panel for distribution of the PAR via fiber optic transmission of thermal heat and solar lighting to the interior of a spacecraft and habitat. |
| 7.4.1.11 | Bioregenerative Resources | Bioregenerative engineered resources and materials (construction materials) to be used by crew and spacecraft. |
| 7.4.1.12 | Acoustical Treatments | Human spaceflight qualified materials and lay-ups that are lightweight and provide the following acoustic functions: sound blocking, sound absorption, vibration isolation, and vibration damping. Materials may also need to be cleanable, water-resistant, and contain particulates, depending on the application. |
| 7.4.1.13 | Sound Blocking | Human spaceflight qualified materials, close-out panels, locker designs and lay-ups that are lightweight and provide significant sound blocking. Materials may also need to be cleanable and water-resistant. |
| 7.4.1.14 | Sound Absorption | Human spaceflight qualified materials and lay-ups that are lightweight and provide significant sound absorption. Materials may also need to be cleanable, water-resistant, and contain particulates, depending on the application. |
| 7.4.1.15 | Vibration Isolation | Human spaceflight qualified materials that are lightweight and provide vibration isolation for rotating equipment. |
| 7.4.1.16 | Acoustic Blanket Lay-Ups | Human spaceflight qualified materials lay-ups that are lightweight and provide sound blocking and sound absorption. Materials also need to be cleanable, water-resistant, and contain particulates, depending on the application. |
| 7.4.1.17 | Fiber Optic Paneling for Remote Diffuse Lighting Applications | Woven fiber optic paneling is a material that can be formed into any flat shape and be connected to any point source light. The result is a uniquely sized panel that provides diffuse lighting for the intended application. |

## TA 7.4.2 Habitat Evolution

### *Technical Capability Objectives and Challenges*

Habitat Evolution focuses on Exploration Habitat Systems Concurrent Engineering Modeling and Simulation. Maturing an exploration habitat modeling and simulation capability is imperative to overall design optimization, mass reduction, and crew performance optimization. This area includes habitat technology candidates that will enable deep-space habitats that support a sustained human presence in space. Habitat Evolution includes human-occupied structures that enable long-duration, deep space, human missions that increase crew productivity and mission safety while reducing mass, power, and volume needs.

Exploration Habitat Systems Concurrent Engineering Modeling and Simulation must provide a fully integrated flight hardware-based design tool for exploration habitat analysis, modeling, and simulation. This technology provides a fully integrated and hardware data-linked based exploration habitat design and analysis simulator that combines: system model language requirements, computer aided design/computer aided manufacturing (CAD/CAM), multi-domain modeling (MDM), building information modeling (BIM), cost estimation, algorithms, event simulations, virtual reality (VR), simulation "caves," OLED curved large format displays and rooms, and high data-rate processors. This technology could be used to perform design, development, test, and engineer (DDT&E) throughout its project life cycle—with emphasis on an early project life cycle rapid prototyping environment. One of the benefits of this approach is the ability to change a requirement parameter and see the cause and effect of the requirement change near real-time throughout the design. Challenges include being able to link a database system infrastructure, being able to run on multiple desktop platforms, and validating the models and simulations.

### *Benefits of Technology*

The benefits of this technology candidate will include the minimization of the number of design and development hours as well as crew-hours required to operate and maintain a spacecraft and habitat for a mission while also reducing cost to achieve mission objectives. Another benefit is the transition and inclusion of the intelligent operating system being developing, in addition to the synergy of dependencies and interdependencies. The overall effectiveness of the habitat will be manifested in optimized mass, power, and volume savings.

**Table 18. TA 7.4.2 Technology Candidates – not in priority order**

| TA | Technology Name | Description |
|---|---|---|
| 7.4.2.1 | Exploration Habitat Systems Concurrent Engineering Modeling and Simulation | Provide a fully integrated parametrically based habitat design tool for Exploration Habitat modeling and simulation. |

## TA 7.4.3 "Smart" Habitats

### *Technical Capability Objectives and Challenges*

Intelligent or "Smart" Habitats, also known as iHab, emphasize evolutionary, autonomous habitat operations and capabilities to enable long-duration and deep space human missions that increase crew productivity and crew and mission safety while reducing mass, power, and volume needs. This area includes technology candidates focusing on integration of intelligent structures (see TA 12 Materials, Structures, Mechanical Systems, and Manufacturing), as well as integrated software controls, sensors, self-repairing technology, biotechnology, and nanotechnology for unpressurized and pressurized structures to sustain human presence of long-duration, deep-space human missions. Applications include habitats, laboratories, unpressurized shelters, underground facilities, storage containers or shelters, telescopes, rovers, antennas, and hybrid suitlocks. The primary challenges of "Smart" Habitat technologies include incorporation of failure detection isolation and recovery, longevity material degradation, and reliability of the software, sensors, and components.

### *Benefits of Technology*

Intelligent habitat includes technology candidates that enable a spacecraft or habitat to operate independently and autonomously with or without the crew present. When the crew is present, the intelligent habitat reduces the crew's daily operations and monitoring while increasing safety and reducing resource consumption. These technology candidates will minimize the number of crew-hours required to operate and maintain a spacecraft and habitat for a mission while also reducing mission costs. The crew's health and well-being will be improved due to the reduction of stress, improved situational awareness, and increased productivity.

**Table 19. TA 7.4.3 Technology Candidates – not in priority order**

| TA | Technology Name | Description |
|---|---|---|
| 7.4.3.1 | Auto-Lighting Control | Context- and task-aware environments that automatically and responsively provide appropriate lighting to support crew activity and health, and preserve resources. |
| 7.4.3.2 | Auto-Responsive Environment Control | Crew context- and task-aware environments that automatically and responsively provide appropriate crew environment (air flow, temperature, etc.) to support crew activity and health, and preserve resources. |
| 7.4.3.3 | Crew Recognition | Crew recognition and context- and task-aware environments that automatically and responsively provide an appropriate crew well-being support environment that supports crew activity and health while preserving resources. |

## TA 7.4.4 Artificial Gravity

### *Technical Capability Objectives and Challenges*

Artificial gravity (AG) spacecraft have been researched for years as a means for reducing the deleterious effects of long-duration, zero gravity spaceflight on human's physiology. This area includes technology candidates and research of AG spacecraft for long-duration, deep space missions, focusing on developing an AG spacecraft or station capability. Technology candidates include thrust vector navigation course correction of an AG (rotating) spacecraft in transit, managing the center of gravity (CG) balance of the spacecraft, providing thrust to perform course correction while not throwing the spacecraft off its trajectory path, and momentum exchange for deployment of AG systems. The goal of AG is to reduce crew health degradation on long-duration spaceflight missions as well as LEO and HEO station facilities. The AG development challenge is with the spacecraft complexity transition of spin-up and spin-down, and maneuvering the spacecraft through space.

### *Benefits of Technology*

These technology candidates will reduce the detrimental effects of long-duration zero gravity on human physiology and increase crew productivity and well-being while reducing long-term human health and performance risks. The crew's health and well-being will be improved due to the reduction of zero-gravity exposure, crew physiological degradation, and an increase in crew's productivity. Additionally, since the crew will not be debilitated upon landing on Mars, the architecture can be designed to take advantage of their ability to perform an EVA shortly after arrival. This allows for reconsidering the size and deployment sequence of several elements in the mission, which can result in a more flexible and compact packaging strategy on the launch vehicle.

**Table 20. TA 7.4.4 Technology Candidates – not in priority order**

| TA | Technology Name | Description |
|---|---|---|
| 7.4.4.1 | Off-Center of Gravity Thrust Technology | Provides steering, control, and course correction of artificial gravity rotating and spinning spacecraft. |
| 7.4.4.2 | Controlled Energy Release Mechanisms | Controlled energy release mechanisms for deployable and retracting mechanism. |

# TA 7.5: Mission Operations and Safety

The goal of this TA is to manage space missions, usually from the point of launch through the end of the mission. To that end, mission operations entities provide time-appropriate failure analysis and response to protect crew and spacecraft safety in order to achieve mission objectives. Crew training, planetary protection, integrated flight operations, and integrated risk assessment tools are four critical areas. Planetary protection is a potentially significant challenge regarding human exploration. Advancements are needed in space-qualified microbial detection and monitoring, hardware cleaning and decontamination, and mitigation of threats to the Earth-Moon system from returning astronauts, hardware, and extraterrestrial samples. Integrated flight operations for long-duration, deep-space missions will require achieving a complex balance between ground and space operations. Operations should shift toward increasing crew autonomy while enabling personnel to respond quickly to complex and dynamic situations.

## *Sub-Goals*

Planetary protection has a number of goals and challenges that can be classified into four different categories: 1) developing comprehensive and highly-sensitive, space-qualified microbial detection and monitoring systems, 2) ensuring spacecraft system performance from a biological cleanliness perspective, 3) developing advanced, space-qualified cleaning and decontamination technologies, and 4) mitigating potential biological threats associated with returning astronauts, spacecraft hardware, and extraterrestrial samples to the Earth-Moon system.

A primary goal and challenge of integrated flight operations is to facilitate crew autonomy for long-duration, deep space missions while integrating with ground-based operations. These needs could be met partly by robust, integrated operational software, including advanced situational awareness and system autonomy in space and on Earth. Such software systems will allow many critical activities to be quickly, effectively, and safely executed by crew members by giving them the time to focus on emerging operational challenges during long-duration, deep-space missions.

**Table 21. Summary of Level 7.5 Sub-Goals, Objectives, Challenges, and Benefits**

| Level 1 | | |
|---|---|---|
| 7.0 Human Exploration Destination Systems | Goals: | Sustain human presence in space and provide more time for performing core mission activities, while reducing reliance on Earth. |
| **Level 2** | | |
| 7.5 Mission Operations and Safety | Sub-Goals: | Manage space missions from the point of launch through the end of the mission for long-duration missions and over long time delays. |
| **Level 3** | | |
| 7.5.1 Crew Training | Objectives: | Enable the right type of crew training when needed on long-duration missions. |
| | Challenges: | Intelligent software utilizing expert system and data mining algorithms and advanced or intelligent hardware. |
| | Benefits: | Enables the crew to respond to changes during demanding long-duration missions.<br>Reduces crew preparation time prior to the mission. |

**Table 21. Summary of Level 7.5 Sub-Goals, Objectives, Challenges, and Benefits - Continued**

| Level 3 | | |
|---|---|---|
| 7.5.2 Planetary Protection | Objectives: | Provide sensitive monitoring and decontamination methods.<br>Mitigate threats from returning extraterrestrial material to the Earth-Moon system. |
| | Challenges: | Microbial detection and monitoring, biological cleanliness of spacecraft, hardware cleaning and decontamination.<br>Preventing release of unsterilized extraterrestrial material into the terrestrial biosphere from crew, spacecraft, and sampling systems with a high degree of confidence. |
| | Benefits: | Protects the crew and human space destinations, as well as protecting the Earth-Moon system when crew members, systems, and samples return to Earth. |
| 7.5.3 Integrated Flight Operations Systems | Objectives: | Facilitate crew autonomy for long-duration deep space missions. |
| | Challenges: | Transitioning responsibility from ground to crew, automating functions done by the vehicle, expanding autonomy from simple to complex tasks, scaling autonomy from smaller to larger systems, and expanding autonomy to more types of systems. |
| | Benefits: | Provides the crew and ground personnel with time and the proper situational awareness to strike operational balances in what are likely to be dangerous and constantly changing mission conditions. |
| 7.5.4 Integrated Risk Assessment Tools | Section 7.5.4 is now covered in 11.3.6 Uncertainty Quantification and Nondeterministic Simulation Methods. | |

## TA 7.5.1 Crew Training

Crew training for deep space, long-duration missions will be improved with immersive virtual reality (VR) and "real-time," context-sensitive training, which will need advancements in micro-gravity operability and higher-fidelity intelligent simulations with decision aiding. TA 11.3.4 Simulation-Based Training and Decision Support Systems addresses crew-training needs for the purposes of Human Exploration Destination Systems, but this section contributes additional thoughts related to TA 11.3.4. Although the gaming industry is rapidly advancing affordable lightweight off-the-shelf VR capabilities, these systems are not designed for use in space conditions. VR systems may also need to be packaged differently for crew use, and enhancements in how underlying training material is created and managed will be needed to enable crew to work with the tools independent from ground interaction. Existing training infrastructure needs to be more 'intelligent' to provide context-sensitive material that adapts to both the current onboard plans and to each crew member's training response. Context-sensitive training should incorporate aspects of real world visuals, ranging from space system hardware to planetary terrains and perhaps even planetary weather, such as Martian dust storms.

A key objective and set of challenges worth emphasizing is that "just in time," context-sensitive training will be important for long-duration, deep space missions. This will require intelligent software utilizing expert systems, data mining algorithms, advanced or intelligent hardware (such as lightweight, low-power VR systems, situational awareness sensors, etc.) to provide real-world context and associated training to allow crew members to receive training during missions, as well as to train for unforeseen circumstances that might emerge during a long-duration deep space mission.

## TA 7.5.2 Planetary Protection

### *Technical Capability Objectives and Challenges*

Planetary protection arises from the scientific need to preserve planetary conditions for future biological and organic constituent exploration – especially when it comes to exobiology and astrobiology. It also aims to protect the Earth and its biosphere from potential extraterrestrial sources of contamination. The need for planetary protection measures is strongest for missions designed to return a sample from another planet or celestial body to the Earth and for human exploration missions to other solar system bodies, such as Mars.

Methods for detecting and monitoring the presence of microbes can use many bioindicator molecules, and current terrestrial medical and forensic technologies allow sensitive and specific analysis of individual target organisms, as well as the ability to screen entire microbial communities. However, most of these technologies have not yet flown in space and would need to be stand-alone and space-qualified. To date, microbial cleaning, decontamination, and sterilization have been unnecessary for missions to LEO. However, terrestrial medical and manufacturing applications have developed a range of physical and chemical technologies that, combined with standardized methodologies, achieve reliable microbial cleanliness across a range of applications. Future missions would likely need highly efficient, redundant space-qualified cleaning and decontamination technologies. The safe return of crew and samples from Mars will also require containment, isolation, and verification. Technology needs to be developed to verify that release of unsterilized Martian material into the terrestrial biosphere from crew, spacecraft, and sampling systems can be prevented with a high degree of confidence.

There are four major areas of technical challenges for planetary protection for human exploration missions:

- *Microbial detection and monitoring.* Methods for detecting and monitoring the presence of microbes can use many molecules, including nucleic acids, proteins, lipids, and other metabolites.
- *Spacecraft system performance from a biological cleanliness perspective.* The threat to the Martian environment from human exploration is unknown on two levels. First, the ability of terrestrial organisms to survive (and contaminate) the Martian environment is unknown. Second, the ability of spacecraft systems to carry terrestrial organisms is unknown or not specified.
- *Hardware cleaning and decontamination.* To date, cleaning, decontaminating, and sterilizing a spacecraft has been unnecessary for LEO missions. However, many terrestrial medical and manufacturing technologies achieve reliable microbial cleanliness across a range of applications, at different scales, and on articles of varying complexity.
- *Mitigation of threats to the Earth-Moon system by returning astronauts, spacecraft hardware, and extraterrestrial samples.* An additional challenge is to ensure the safe return of crew and samples from Mars, for which containment, isolation, and verification will play a critical role. Technologies have been developed for handling samples in containment in NASA and non-NASA applications, and these will be leveraged for crewed exploration missions. TA 4.4.8 Remote Interaction is a key area that could help further this kind of planetary protection strategy.

### *Benefits of Technology*

Planetary protection is subject to international scrutiny, and human space exploration missions—particularly to the surface of Mars—will have many challenges associated with properly protecting the crew and human space destinations, as well as protecting the Earth-Moon system when crew members, systems, and samples are returned to Earth. Developing planetary protection technologies will reduce national and international concerns regarding planetary protection and crew safety and may also allow NASA to make progress on technologies that can also be used to detect and understand extraterrestrial life.

**Table 22. TA 7.5.2 Technology Candidates – not in priority order**

| TA | Technology Name | Description |
|---|---|---|
| 7.5.2.1 | Active Sterilization | Advanced, compact, and efficient sterilization of spacecraft and space operations bioburden through application of heat, ultraviolet, plasma, radiation, reactive gas-phase processes and other means. |
| 7.5.2.2 | Cleanable Adhesive Surfaces for Variable Gravity | Advanced, reusable surfaces which capture particulate contamination that may also host molecular organic/microbial material. |
| 7.5.2.3 | Cleaning Systems | Processes, chemicals, and treatments that require few consumables and produce negligible waste byproducts to clean spacecraft hardware to sterility. |
| 7.5.2.4 | Microbial Burden Identification and Monitoring | Reliable assay techniques for spacecraft, spacecraft subsystems, and planetary environments which identify and monitor the specific microbiology present (microbial burden). |
| 7.5.2.5 | Recontamination Prevention | Biobarrier materials. |
| 7.5.2.6 | Debris Quantification for Planetary Material Containment | Modeling and simulation tools to quantify risks posed by orbital and in-space debris to planetary material containment systems. |
| 7.5.2.7 | Particle Transport Modeling | Monte Carlo, discrete event, and human-in-the-loop simulations to predict particle transport in a Mars environment. |
| 7.5.2.8 | Dust Analyzer | Mars environmental monitoring system measuring dust density, distribution, composition, and behavior. |
| 7.5.2.9 | Containment Sensors | Systems that allow instantaneous verification of containment integrity. |
| 7.5.2.10 | Post-Return Sample Containment | Biosafety Level (BSL) 4 or greater laboratories which offer effective sample containment while preserving the cleanliness of the sample. |
| 7.5.2.11 | Sample Containment Systems | Hermetically sealed containers. |

## TA 7.5.3 Integrated Flight Operations Systems

### *Technical Capability Objectives and Challenges*

A primary objective of integrated flight operations is to facilitate crew autonomy for long-duration, deep-space missions while at the same time also striking the balances needed for integrating effectively with ground-based operations. These needs could be met partly with robust, integrated operational software, including software that provides advanced situational awareness and system autonomy in space and on Earth. Such software systems will allow many critical activities to be quickly, effectively, and safely executed by crew members by giving them the time to focus on emerging operational challenges during missions. Crew members need to have highly reliable capabilities to monitor information, manage faults, modify plans, and execute procedures with limited interaction with the ground.

Extending autonomy requires transitioning responsibility from ground to crew (e.g., autonomous procedure execution), automating functions done by people (e.g., procedure automation), expanding autonomy from simple to complex tasks (e.g., from single procedures to managing entire system), scaling autonomy from smaller to larger systems (e.g., one power bus to four), and expanding autonomy to more types of systems (e.g., power, environment control life support systems (ECLSS), and thermal). Crew may have to execute thousands of procedures during a mission, and hundreds of activities a day, working toward a predetermined timeline with less mission control oversight. This will require systems to detect, isolate, and recover from faults. The ISS currently involves tens of thousands of commands and data items, approximately 9,000 fault conditions, and over 1,000 procedures and displays.

Ground control will need to have protocols and technology to accurately transmit tens of thousands of commands and telemetry items with delays of up to eight minutes, one way. Ground controllers will benefit from having displays and other methods and drawing attention to the right things given an extremely large amount of data available – e.g., software and methods for identifying slowly-developing trends of data towards off-nominal performance. Other technologies that enable autonomous crew and ground operations are included in TA 4 Robotics and Autonomous Systems.

### *Benefits of Technology*

Long-duration, deep space missions will almost certainly not be effective or safe, or even possible at all, if the crew is heavily dependent on ground control. Integrated autonomous systems and intelligent software will provide the crew and ground personnel with time and the proper situational awareness to strike operational balances in what are likely to be dangerous and constantly changing mission conditions.

**Table 23. TA 7.5.3 Technology Candidates – not in priority order**

| TA | Technology Name | Description |
|---|---|---|
| 7.5.3.1 | Autonomous Crew Operations | Ability of the crew to monitor information, manage faults, modify plans, and execute procedures with limited interaction with the ground. |
| 7.5.3.2 | Autonomous Ground Operations | Enable effective ground support of increasingly autonomous crew activities as mission duration and distance increase, by providing capability to manage operational constraints, perform procedures, and manage plans without contact with Earth-based mission control. |

## TA 7.5.4 Integrated Risk Assessment Tools

Section 7.5.4 is now covered in 11.3.6 Uncertainty Quantification and Nondeterministic Simulation Methods.

# TA 7.6: Cross-Cutting Systems

This section focuses on the advances needed to manage particulate contamination transported by operations, lander plume ejecta, and larger-scale construction and assembly technologies. As humans begin to interact with the local environment at destinations such as the Moon and Mars, dust from the surface can cause a significant impact on all of the systems humans need to survive and work. Prior to the first Apollo Moon-landing mission, designers were not aware of the significant issues that would be encountered as crews interacted with lunar dust. Therefore mitigation strategies were not considered. Before each subsequent flight, engineers included some dust mitigation features in their systems as time allowed, however, the problems were not solved during the life of the program. EVA suit seals and zippers, visor mechanisms, and umbilical connectors were difficult to operate. Displays, science instruments, tools, cameras, helmet visors, rover thermal systems, cabin air handling and sample container seal performance were degraded due to dust contamination. Dust inside the crew capsule caused eye and skin irritation and hay fever type reactions. The Apollo missions were the last extensive human interaction with extraterrestrial particulate, but more recent robotic missions have gathered data and tested techniques as well. Contamination prevention, exterior cleaning and protection, interior cleaning and protection, and gas quality preservation technologies have been developed to TRL levels 3 through 7. Tools have been developed to model the effects of landing plumes on surface soils for both Mars and the Moon, but considerable progress is needed to fully rely on these simulations. There have been very few construction- or assembly-oriented activities in extraterrestrial environments to date. While the ISS represents the SOA for assembling large objects in space, many of the techniques relied upon microgravity and proximity to Earth to be successful.

## *Sub-Goals*

The goal of particulate contamination prevention and mitigation is to ensure the long-term reliability of systems operating in extraterrestrial environments and to protect the health of the crew who will live and work in those environments. Other goals in this area are related to minimizing the mission impact of the necessary protections by reducing size, weight, power, and crew time required for mitigation.

The goal of construction and assembly is to provide the ability to launch smaller units and infrastructure required for in-space and surface systems. Additional goals are to increase human exploration safety; increase crew well-being and productivity; reduce human spaceflight mission overall mass, power, and volume; and provide the ability to support human spaceflight in space and surface infrastructure development and operations.

**Table 24. Summary of Level 7.6 Sub-Goals, Objectives, Challenges, and Benefits**

| Level 1 | | |
|---|---|---|
| 7.0 Human Exploration Destination Systems | Goals: | Sustain human presence in space and provide more time for performing core mission activities, while reducing reliance on Earth. |
| **Level 2** | | |
| 7.6 Cross-Cutting Systems | Sub-Goals: | Manage particulate contamination transported by operations, lander plume ejecta, and larger-scale construction and assembly technologies. |

**Table 24. Summary of Level 7.6 Sub-Goals, Objectives, Challenges, and Benefits - Continued**

| Level 3 | | |
|---|---|---|
| 7.6.1 Particulate Contamination Prevention and Mitigation | Objectives: | Prevent dust transport onto and into destination systems and technologies that remove dust after it has accumulated.<br>Predict, prevent, or block ejecta to control or mitigate plume ejecta and cratering. |
| | Challenges: | Complexity of modeling plume and soil interaction.<br>Physics of plume and soil not well enough understood to reduce to a more computable set of equations without the risk of throwing away important details.<br>Sintering soil. |
| | Benefits: | Ensures a dust-free living environment for the crew and that surface systems operate within their performance requirements with high reliability.<br>Reduces crew time associated with constant cleaning.<br>Reduces the risk and prolongs the life of ISRU capability.<br>Inform mission planners on how to safely land larger, human-class spacecraft on planetary surfaces and protect surrounding hardware at an outpost.<br>Permits in-situ radiation protection and reduces mass needed. |
| 7.6.2 Construction and Assembly | Objectives: | Reduce mass and extend life of systems used to construct natural shielding for surface assets.<br>Develop ejecta barriers that have a high probability of no-penetration, low specific mass, and are deployable or erectable |
| | Challenges: | Lower gravity, minimal or total lack of atmosphere, and differences in surface structural characteristics. |
| | Benefits: | Reduces mass and extends life of system. |

## TA 7.6.1 Particulate Contamination Prevention and Mitigation

### *Technical Capability Objectives and Challenges*

For crosscutting challenges such as regolith contamination, an integrated systems strategy – a layered engineering defense – is needed. The fundamental basis of the design relies on selecting materials that do not accumulate dust and dirt, innovative material fabrication and processing, engineering design that incorporates design for cleaning, robustness and reliability, and effective operational procedures. The layered engineering defense incorporates contamination prevention, exterior cleaning and protection, interior cleaning and protection, and gas quality maintenance. This strategy was developed through a series of studies, workshops, focus groups, technical interchange meetings, and NASA Lunar Regolith Community of Practice webinars. The community surveyed particulate management best practices and technologies across NASA centers, industry, academia, and other government agencies. The approach also includes lessons learned from Apollo surface missions. It depends mostly on sound operations and engineering design though technology developments will be required. Lander plume interaction models with the soils of the Moon or Mars have been developed and tested with Earth analogs. Considerably more work is needed to develop the models of deep regolith interactions expected for human-class Mars landings and to study the ramifications on both landing systems and the infrastructure needed to support human missions.

Particulate challenges for destination systems include both low-energy transport of dust and high-energy transport of rocket exhaust ejecta. Physical and health problems associated with lunar dust during the Apollo missions are well documented. Reduction of power from solar cells during robotic Mars missions also demonstrates the deleterious effects of dust accumulation. ISRU systems that must work with and in the dust for a long time may have problems with seals leaking or mechanisms jamming if they are not designed to prevent or mitigate settled dust. This area covers technology candidates that will prevent dust transport onto and into destination systems and technology candidates that remove dust after it has accumulated.

High-energy transport from rocket exhaust plumes may include rocks and gravel, as well as sand and dust. In vacuum, dust and sand may travel long distances at hundreds or thousands of meters per second as a highly abrasive spray, whereas rocks and gravel may cause localized mechanical damage upon impact. Damage may occur to the landing spacecraft or to surrounding hardware that has been placed on the surface at an earlier time. Blowing ejecta may also block visibility for the crew or sensors during landing. In addition to these problems, the crater that may form beneath a landing spacecraft presents the risk of ground instability and spacecraft tilting. Best estimates of human-class Mars landings on the loose Martian regolith predict that very deep craters will form (unless bedrock is near the surface), channeling ejecta up toward the landing vehicle and creating a region of unstable regolith after landing that is as wide as the landed spacecraft. Technologies onboard a spacecraft to control plume ejecta and cratering are covered by TA 9 Entry, Descent, and Landing Systems. Technologies on the planetary surface to control or mitigate plume ejecta and cratering are covered in this technology area.

*Dust Prevention and Mitigation* technology candidates include those that both prevent and mitigate dust contamination. Dust that exists in planetary environments where there is no rainfall to enable geological sorting and weathering of the particles tends to be very fine and have complex particle morphologies. Fine, complex dust clings to surfaces, gets embedded in fabrics, and is difficult to remove. This dust might also travel deep into human lungs, which may cause long-term health problems. In vacuum, without humidity to coat the dust, the particles may have chemically active bonding sites that are more hazardous to human health. Dust prevention and cleaning capabilities include surface stabilization, pressurized “tunnels” to minimize regolith transport in lieu of EVA, suitlock, sample handling, passive cleaning, active cleaning, dust tolerant mechanisms, dust covers, maintainability, air and airlock cleaning, low consumable filtration, gas cleaning, failure isolation and detection, and simulants.

*Plume Ejecta Prevention and Mitigation* technology candidates predict, prevent, and block ejecta. Predicting regolith ejecta and cratering requires the development of high-fidelity plume and soil simulation software. This is challenging because the physics are too complex to model explicitly in full detail (modeling every sand grain, for example), and they are not well enough understood to reduce to a more computable set of equations without the risk of throwing away important details in the physics. No code has yet been developed that can handle regolith transitions from solid-like mechanics to a chaotic, turbulent, fluidized state energized by injection of a supersonic jet, along with ejecta dynamics as the gas expands into vacuum. Prediction via numerical simulation is important because granular phenomena are known not to scale well to smaller sizes, and it is impossible to perform larger-scale experiments with rocket exhaust in reduced-gravity aircraft and vacuum chambers.

Predicting the violence of a cratering event under a large, human-class Mars lander is important to determine whether they can land with sufficient safety margin on unprepared regolith, or whether landing pads must be built first. If landing pads are required, that changes the architecture of the Mars campaign and imposes requirements on landing accuracy. If landing on unprepared regolith is possible only with smaller spacecraft this changes the architecture of the Mars campaign and vehicle design to minimize the cratering and ejecta.

Prevention of plume ejecta may include technologies on the spacecraft, such as Sky Cranes to keep the engines higher above the surface (covered by TA 4 Robotics and Autonomous Systems) or it may include creating a competent launch and landing surface. That may be accomplished by sintering the soil or by adding polymers or other binders, all of which are covered in TA 7.1.4. It may also be accomplished by deploying a mat, fabric, or solid foldout surface, or by creating a concrete that utilizes local resources to the maximum extent possible. Landing surfaces must also withstand the high temperatures that occur directly under the nozzle, which is challenging for polymers and many fabrics and other materials. Sintering is challenging because sinter quality is highly dependent on the process, which is difficult to control robotically with heterogeneous regolith including cobbles, and poor sintering results in weak surfaces that crumble. Mitigation of plume ejecta may include blocking the ejecta by building berms out of regolith, which requires robotic bulldozers (covered in TA 4 Robotics and Autonomous Systems), or the deployment of erectable blast curtains.

### *Benefits of Technology*

Preventing and managing dust contamination, especially for long-duration missions, will ensure a dust-free living environment for the crew and that surface systems operate within their performance requirements. This is especially important for missions to Mars where microbes may be transported via dust particles. It will also reduce the significant crew time associated with constant cleaning. Preventing and managing excessive dust buildup on ISRU systems that interact directly with the surface regolith will reduce the risk and prolong the life of this enabling ISRU capability. The ability to confidently predict the extent of plume-soil interactions will inform mission planners as to the necessary technology approach to ensure safe landing of the larger, human-class spacecraft on planetary surfaces and protect surrounding hardware at an outpost.

**Table 25. TA 7.6.1 Technology Candidates – not in priority order**

| TA | Technology Name | Description |
|---|---|---|
| 7.6.1.1 | "Tunnels" to Minimize Regolith Transfer During Extravehicular Activities (EVAs) | Passageways that incorporate technologies such as Active-Active Mating Adapter and Articulating Jetways to reduce the amount of dust transported during EVA operations. |
| 7.6.1.2 | Air and Airlock Cleaning | Spacesuit, tools, and other system cleaning within suitlock or airlock to prevent dust from entering habitable volumes and create a clean environment for suit maintenance and repair. Possible technologies include low power, low mass air shower, low power, low mass air handler, low power, low mass vent hood, electrostatic precipitator, electrospray, and water shower. |
| 7.6.1.3 | Sample Handling | A sealed container with exterior ports that enables a person to manipulate objects, where a separate atmosphere is desired |
| 7.6.1.4 | Dust Covers | Umbilical dust covers, modular suit cover system, and strippable coatings that minimize dust intrusion. |
| 7.6.1.5 | Dissipation, Reduction, and/or Elimination of Triboelectric Charge Build-Up | Systems to eliminate internal spacecraft triboelectric charging. |
| 7.6.1.6 | Passive Cleaning | Lotus and gecko coatings. |
| 7.6.1.7 | Dust Repellant, Dust Shedding Materials, and Coatings for Thermal Control Surfaces | Functional surface treatments or coatings that prevent dust adhesion or enables effective dust removal from thermal control surfaces. |
| 7.6.1.8 | Dust Repellant, Dust Shedding Materials, and Coatings for Photovoltaic Surfaces | Functional surface treatments or coatings that prevent dust adhesion or enables effective dust removal from photovoltaic surfaces. |
| 7.6.1.9 | Dust Repellant, Dust Shedding Materials, and Coatings for Wear Surfaces | Abrasion protective coatings for exposed wear surfaces. |
| 7.6.1.10 | Electrodynamic Removal | A multi-phase alternating current (AC) signal applied to sets of electrodes embedded in substrate generate a dynamic electric field that carries along electrostatically charged dust particles (metallic or non-metallic). |
| 7.6.1.11 | Electron Discharge and Bombardment | Electron gun provides current at surface to cause particles to repel one another. |
| 7.6.1.12 | Magnetic Brush | Bar that is moved over a surface or spacesuit to attract and remove the dust. |
| 7.6.1.13 | Dust Removal Brushes | Brushes with bristles optimized for dust removal for each destination. |
| 7.6.1.14 | Self-Cleaning Connectors | Various types of connectors (electrical, fluid, optical, etc.) that actively prevent dust from getting inside as well as passively or actively removing dust after it gets inside the vehicle or suit. |
| 7.6.1.15 | Forced Gas Showers | Use gas,(air, carbon dioxide, nitrogen) showers to decontaminate astronauts prior to entering the habitat by forcibly blowing it off the suit or item. |

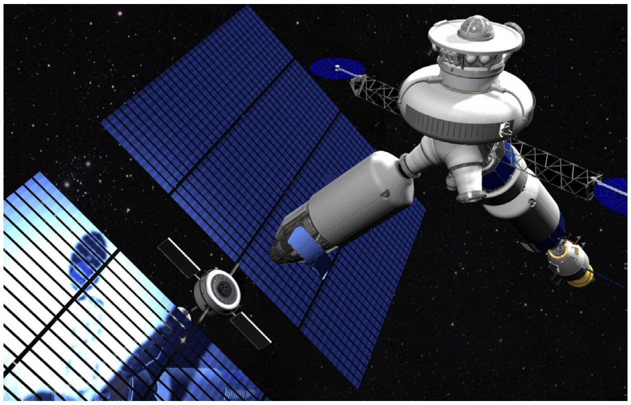
**Table 25. TA 7.6.1 Technology Candidates – not in priority order - Continued**

| TA | Technology Name | Description |
|---|---|---|
| 7.6.1.16 | Forced Gas Cleaning of Hard Surfaces | Use jets of (pulsed, steady, vortices, etc.) to removed dust that is adhered onto solid surfaces by creating sufficient shear stress or turbulent kinetic energy in the gas at the bottom of the boundary layer to overcome dust adhesion. |
| 7.6.1.17 | Failure Isolation, Detection, and Recovery (FIDR) | Dust detector and dust alarm to alert crew when dust exposure limits are exceeded. |
| 7.6.1.18 | Plume Mitigation | Technologies to mitigate the plume blast effects from landing spacecraft on planetary surfaces. |
| 7.6.1.19 | Deployable Landing Surfaces | Material that can be used as a landing pad on an asteroid, moon, or planetary surface. |
| 7.6.1.20 | Deployable/Erectable Blast Curtain Around Landing Site | Lightweight, withstand ultraviolet, self-healing, and anchored. |
| 7.6.1.21 | Plume Resistant Concrete | Repeated use landing and launch pads. |
| 7.6.1.22 | High Fidelity Two-Phase Flow Modeling for Plume-Soil Interaction | Plume flow software capable of predicting the interaction of high velocity gas with regolith in the planetary environment. For Mars, the plume will dig deep into the regolith and fluidize a large volume, causing chaotic flow behavior and leaving a deep/wide region of soil in an unstable mechanical state. For the Lunar case, the plume primarily scours the surface and throws ejecta outward at high velocity. Asteroidal cases are to be determined. |

## TA 7.6.2 Construction and Assembly

### *Technical Capability Objectives and Challenges*

The objective of this capability is to provide technologies for construction and assembly of in-space and surface systems, infrastructure, and remote deployable systems. Examples include the ability to assemble a Lagrangian point space station outpost or to prepare, excavate, and emplace planetary outpost infrastructure. Many of the technologies required for emplacement of in-space assembly of vehicles and infrastructure and surface assets, such as actuators, grappling devices, pneumatic muscles, tracks and traction, anchoring, shape memory alloys, cabling, and sensing are now covered under TA 4 Robotic and Autonomous Systems, TA 8 Science Instruments, Observatories, and Sensors Systems, and TA 12 Materials, Structures, Mechanical Systems, and Manufacturing. Therefore, this Construction and Assembly area is focused on the challenge of providing natural shielding for surface assets, such as nuclear power systems or habitats to protect the crew from both man-made and natural radiation sources. While excavators could be used to dig deep holes to bury nuclear reactors and associated power cabling, or to excavate shallower trenches for habitats and then bury with additional regolith, an alternative method common on Earth is to use “shaped charges” to create holes of the required depth and size. The lower gravity, minimal or total lack of atmosphere, and differences in surface structural characteristics present the primary challenges to developing this capability.



**Gateway Swap**

Shape charges and explosives must be high-strength, long-life, lightweight, durable, flexible, and radiation-tolerant, as well as minimize blast ejecta. Other challenges include safe storage of explosive charges, safe handling of the explosive materials, and safe detonation of the devices, minimizing out-gassing into the lunar or Martian environment, reducing the long-term material degradation caused by the hostile space environment, and reducing the mass and volume for transport and deployment of the blast barriers.

### *Benefits of Technology*

The ability to protect crew from nuclear power source radiation hazards by burying it may be enabling for this type of surface power. Without the ability to use in-situ mass for radiation protection, the mass of shielding required from Earth, or for extended cabling for remote emplacement, could be prohibitive. Similarly, using in-situ mass to provide the habitats with extra protection from natural radiation sources will greatly reduce the habitat mass and enhance crew health and safety.

**Table 26. TA 7.6.2 Technology Candidates – not in priority order**

| TA | Technology Name | Description |
|---|---|---|
| 7.6.2.1 | Shaped Charges and Explosives | Explosives to create holes of the required depth and size in the planetary surface to provide natural radiation shielding for outpost infrastructure. |
| 7.6.2.2 | Ballistic Fabric Barriers | Deployable and erectable blast shield barriers using tensile fabrics. |

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# Appendix

## *Acronyms*

| | |
|---|---|
| AG | Artificial Gravity |
| ALM | Autonomous Logistics Management |
| ASR | Area Specific Resistance |
| BIM | Building Information Modeling |
| BSL | BioSafety Level |
| CAD/CAM | Computer Aided Design/Computer Aided Manufacturing |
| CAVE | CERES/ARM Validation Experiment |
| CEP | Complex Event Processing |
| CG | Center of Gravity |
| CNC | Computer Numerically Controlled |
| COTS | Commercial-Off-The-Shelf |
| CTB | Cargo Transfer Bag |
| DDT&E | Design, Development, Test, and Engineer |
| DEM | Discrete Element Method |
| DNA | DeoxyriboNucleic Acid |
| DOF | Degrees Of Freedom |
| DRA | Design Reference Architecture |
| DRATS | Desert Research And Technologies Studies |
| DREAMS | Dust characterization, Risk assessment and Environment Analyzer for Martian Surface |
| DRM | Design Reference Mission |
| DRO | Direct Retrograde Orbit |
| $EBF^3$ | Electron Beam FreeForm Fabrication |
| ECLSS | Environment Control Life Support Systems |
| EMU | Extravehicular Mobility Unit |
| EPC | Enhanced Power Conversion |
| EVA | ExtraVehicular Activity |
| EVR | ExtraVehicular Robotics |
| FDIR | Fault Detection, Isolation, and Recovery |
| FIDR | Failure Isolation, Detection, and Recovery |
| FSP | Fission Surface Power |
| GEO | GEosynchronous Orbit |
| GN&C | Guidance, Navigation, and Control |
| GPU | Graphics Processing Unit |
| HEO | High-Earth Orbit |
| HEPA | High-Efficiency Particulate Air |
| HID | High Intensity Discharge |
| HSF | Human Space Flight |

| | |
|---|---|
| iHab | Intelligent Habitat |
| IL | Ionic Liquid |
| IR | InfraRed |
| ISHM | Integrated System Health Management |
| ISRU | In-Situ Resource Utilization |
| ISS | International Space Station |
| IVA | IntraVehicular Activity |
| JWST | James Webb Space Telescope |
| LED | Light Emitting Diode |
| LEO | Low-Earth Orbit |
| LIBS | Laser Induced Breakdown Spectroscopy |
| LOCAD-PTS | Lab-On-a-Chip Application Development – Portable Test System |
| LOS | Line-Of-Sight |
| LRV | Logarithmic Reduction Value |
| MCTB | Multipurpose Cargo Transfer Bag |
| MDM | Multi-Domain Modeling |
| MMOD | MicroMeteoroids and Orbital Debris |
| MMU | Manned Maneuvering Unit |
| MSG | Microgravity Science Glovebox |
| MSR | Mars Sample Return |
| MTBF | Mean Time Between Failures |
| MTBR | Mean Time Between Replacement |
| NASA | National Aeronautics and Space Administration |
| NDE | Non-Destructive Evaluation |
| NEA | Near-Earth Asteroid |
| NEO | Near-Earth Object |
| NSI | NASA Standard Initiator |
| OCT | Office of the Chief Technologist |
| OLED | Organic Light Emitting Diodes |
| OML | Out Mold Line |
| ORU | Orbital Replacement Unit |
| OSIRIS-REx | Origins-Spectral Interpretation-Resource Identification-Security-Regolith Explorer |
| PAR | Photosynthetically Active Radiation |
| PEM | Proton Exchange Membrane |
| PI | Probability of Impacts |
| PLSS | Portable Life Support System |
| PNI | Probability of Non-critical Impacts |
| RATS | Research And Technology Studies |
| RDX | Research Department eXplosive |
| RESOLVE | Regolith and Environment Science and Oxygen and Lunar Volatile Extraction |
| RF | Radio Frequency |
| RFID | Radio Frequency IDentification |

| | |
|---|---|
| RPOD | Rendezvous, Proximity Operations, and Docking |
| RWGS | Reverse Water Gas Shift |
| SAFER | Simplified Aid For EVA Rescue |
| SAL | Sterility Assurance Level |
| SAM | Sample Analysis at Mars |
| SMAC | Spacecraft Maximum Allowable Concentrations |
| SOA | State Of the Art |
| SPH | Soft Particle Hydrocodes |
| SSLM | Solid-State Lighting Module |
| SysML | System-based Modeling Language |
| TA | Technology Area |
| TABS | Technology Area Breakdown Structure |
| TEGA | Thermal and Evolved-Gas Analyzer |
| TNT | TriNitroToluene |
| TRL | Technology Readiness Level |
| UV | UltraViolet |
| VR | Virtual Reality |

# *Abbreviations and Units*

| Abbreviation | Definition |
|---|---|
| asr | Area Specific Resistance |
| C | Celsius |
| CD | Charge Diameter |
| CFU | Colony-Forming Unit |
| Cfm | Cubit-Feet per Minute |
| cm | Centimeters |
| CO | Carbon Monoxide |
| $CO_2$ | Carbon Dioxide |
| dB | Decibels |
| dBi | Decibels-Isotropic |
| deg | Degrees |
| $ft^3$ | Cubic Feet |
| g | Gram |
| $H_2O$ | Water |
| hr | Hour |
| in | Inches |
| K | Kelvin |
| kg | Kilogram |
| kPa | Kilopascal |
| kWe | Kilowatt Electricity |
| kWth | KiloWatt Thermal |
| LOX | Liquid Oxygen |
| m | Meters |
| mA | Milliamps |
| min | Minute |
| mm | Millimeter |
| mph | Miles per Hour |
| $N_2$ | Nitrogen |
| NC | Noise Criterion |
| Nm | Nanometer |
| $O_2$ | Oxygen |
| Pa | Pascal |
| psi | Pounds per Square Inch |
| psia | Pounds per Square Inch Absolute |
| rpm | Revolutions per Minute |
| s | Seconds |
| Sols | Mars Solar Day (24 hours, 39 minutes, 35.244 seconds) |

| Abbreviation | Definition |
| --- | --- |
| t | Ton |
| TNT | Trinitrotoluene |
| μm | Micrometers |
| W | Watt |
| $W_e$ | Watt Electricity |
| Wth | Watt Thermal |
| α | Absorption Coefficient |
| dBA (and dBB, dBC) | Sound Decibels A, B, or C |
| μmole/s | Micromole ($10^{-6}$ mole) photon flows per second |

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# Technology Candidate Snapshots

7.1 In-Situ Resource Utilization
7.1.1 Destination Reconnaissance, Prospecting, and Mapping

## 7.1.1.1 Penetrometers, Shear Gauges, Compaction, Density Instruments

### TECHNOLOGY

**Technology Description:** Instruments to measure the mechanical properties of the soil. Hand held possibly, or mounted on rovers.

**Technology Challenge:** Lunar soil is more homogeneous across the body with less knowledge of conditions in polar areas where water content exists. Mars soil, and therefore properties, is more heterogeneous. For asteroid case, the challenge is learning how to take the measurements in ultra-low gravity where small disturbances may eject the soil.

**Technology State of the Art:** Lunar in-situ (Apollo era): cone penetrometer, vane shear, neutron flux probe down pre-drilled holes.

Mars: inferred from footpad, wheel tracks, airbag tracks, and landslides. Some measurement of shear strength by spinning rover wheels. Asteroid: Essentially no work has been done for asteroid surfaces.

**Parameter, Value:**

Lunar experience with inferred and in-situ results varied ± 100% from current accepted value based on returned samples

**TRL**

1

**Technology Performance Goal:** Increase accuracy of in-situ measurements that do not rely on returned samples for correlation. Adapt techniques to low gravity and other environmental conditions of the destination.

**Parameter, Value:**

% error from actual soil property –

Lunar: 10%

Mars: 25%

Asteroid: 100%

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Soil geotechnical characterization.

**Capability Description:** Characterize soil mechanical properties sufficiently that other technologies can then be designed to work with the soil, including excavators, foundations for habitats, in-situ resource utilization (ISRU) processing of soil, etc.

**Capability State of the Art:** Lunar properties were determined from a combination of remote sensing, in-situ measurements by rovers and Apollo astronauts, and analysis of returned samples (listed in order of increasing accuracy). Many laboratory instruments have been developed.

**Parameter, Value:**

Lunar experience with inferred and in-situ results varied ± 100% from current accepted values based on returned

**Capability Performance Goal:** Reduce mass and increase reliability of instrument and reduce uncertainty in each measurement.

**Parameter, Value:**

Measurement: Density (g/cm³), Internal friction angle (deg), Soil-Tool friction angle (deg), Cohesion (Pa), Adhesion (Pa), Dilatancy Angle (deg)

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enabling | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 5 years |

7.1 In-Situ Resource Utilization
7.1.1 Destination Reconnaissance, Prospecting, and Mapping

## 7.1.1.2 Flow Instruments

### TECHNOLOGY

**Technology Description:** Tools to gather flow measurements of the regolith in-situ.

**Technology Challenge:** Use in reduced gravity.

**Technology State of the Art:** Tools exist for terrestrial industrial powders for testing in controlled laboratory environment. While triaxial and rotational methods are commonly used, shear-vane tests where a pre-shear condition can be set provides the most useful suite for measurements necessary, for example, for hopper designs.

**Parameter, Value:** Extensive tests on the flowability of a lunar surface simulant created by Johnson Space Center showed variations in internal friction angle of 40 degrees when pre-sheared to 60 to 68 degrees without pre-shear (i.e., range of ± 50%)

**TRL:** 3

**Technology Performance Goal:** Increased accuracy to reduce amount of over-design. Ability to measure in-situ with robotic probes.

**Parameter, Value:** 10% error in flowability measurement

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Regolith granular flow characterization.

**Capability Description:** Characterize granular flow properties sufficiently that other technologies can then be designed to work with the regolith, including excavators, in-situ resource utilization (ISRU) processing of soil, etc.

**Capability State of the Art:** Does not exist for spaceflight. Many field instruments have been developed for handheld or vehicle-mounted use. Many laboratory instruments have been developed.

**Parameter, Value:** Does not exist for spaceflight

**Capability Performance Goal:** Develop capability for accurate measurements in-situ with robotic probes. Reduce mass and increase reliability of instruments and reduce uncertainty in each measurement.

**Parameter, Value:** 10% error in flowability measurement

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enabling | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 5 years |

7.1 In-Situ Resource Utilization
7.1.1 Destination Reconnaissance, Prospecting, and Mapping

# 7.1.1.3 Drill Embedded Chemical Instrument – Laser Induced Breakdown Spectroscopy

## TECHNOLOGY

**Technology Description:** Laser Induced Breakdown Spectroscopy (LIBS) integrated into drill bit for downhole material chemical analysis.

**Technology Challenge:** Repackaging the instruments to fit inside a drill string with other components connected at the top of the string as required.

**Technology State of the Art:** Optics have been integrated in a drill auger while laser/spectrometer was on the surface. Demonstration performed in packing peanuts in lieu of regolith since the drill diameter was > 2 inches and hence tough to drill into anything. The next step would be to put a small laser and spectrometer in a drill, reduce the drill size, and demonstate drilling and LIBS in the same hole.

| Parameter, Value: | TRL |
|---|---|
| Complete packaging inside drill bit has not been achieved | 3 |

**Technology Performance Goal:** Integrate entire LIBS system into a drill string and test in a relevant environment.

| Parameter, Value: | TRL |
|---|---|
| Diameter of drill: ≤ 2.5 centimeters | 6 |

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Down hole material chemical analysis.

**Capability Description:** Instrumentation on drill to detect material drilling through (chemical, etc.). Many systems for detecting mineralogy or volatile identification and concentration are mature and in use in terrestrial industry or remote sensing. What is needed is to miniaturize these systems and embed them directly into the drill string.

**Capability State of the Art:** Does not exist for spaceflight. Several drill-embedded technologies have been partially tested in the laboratory including a drill-embedded neutron spectrometer and LIBS.

**Parameter, Value:**

Does not exist for spaceflight

**Capability Performance Goal:** Fit existing chemical and mineralogical analysis tools into drill strings without compromising their ability to make measurements.

**Parameter, Value:**

Diameter of instrument (to fit inside drill): ≤ 2.5 centimeters;

Mass of instrument: grams

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 6 years |

7.1 In-Situ Resource Utilization
7.1.1 Destination Reconnaissance, Prospecting, and Mapping

# 7.1.1.4 Drill Embedded Chemical Instrument – Neutron Spectrometer

## TECHNOLOGY

**Technology Description:** Neutron spectrometer integrated into drill bit for downhole material chemical analysis.

**Technology Challenge:** Repackaging the instruments to fit inside a drill string with other components connected at the top of the string as required.

**Technology State of the Art:** The detectors have been integrated inside a drill string and lowered into a predrilled hole and acquired data. The next step would be to decrease the size of the drill auger and perform drilling tests and measurements.

**Parameter, Value:** 2.5 centimeter diameter drill bit

**TRL:** 3

**Technology Performance Goal:** Decrease the diameter of the drill auger and perform testing for Technology Readiness Levels 4, 5, and 6.

**Parameter, Value:** Diameter of instrument (to fit inside drill): ≤ 2.5 centimeters

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Down hole material chemical analysis.

**Capability Description:** Instrumentation on drill to detect material drilling through (chemical, etc.). Many systems for detecting mineralogy or volatile identification and concentration are mature and in use in terrestrial industry or remote sensing. What is needed is to miniaturize these systems and embed them directly into the drill string.

**Capability State of the Art:** Does not exist for spaceflight. Several drill-embedded technologies have been partially tested in the laboratory including a drill-embedded neutron spectrometer and Laser Induced Breakdown Spectroscopy (LIBS).

**Parameter, Value:** Does not exist for spaceflight.

**Capability Performance Goal:** Fit existing chemical and mineralogical analysis tools into drill strings without compromising their ability to make measurements.

**Parameter, Value:** Diameter of instrument (to fit inside drill): ≤ 2.5 centimeters;
Mass of instrument: grams

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 6 years |

7.1 In-Situ Resource Utilization
7.1.1 Destination Reconnaissance, Prospecting, and Mapping

## 7.1.1.5 Drill Embedded Physical Instruments (Resistivity, Thermal, Shear, etc.)

### TECHNOLOGY

**Technology Description:** Instrumentation on or in drill to detect physical material properties, such as hardness, etc.

**Technology Challenge:** Repackaging/redesign of terrestrial instruments to fit inside a drill string with other components connected at the top of the string as required.

**Technology State of the Art:** Sensors have been integrated into drills for operation in field tests. Algorithms have been developed to infer material being drilled into using real-time data on torque, thrust, rotary speed, hydraulic pressures, vibration, and drill position.

**Parameter, Value:** Varies depending on parameter of interest

**TRL:** 4

**Technology Performance Goal:** Fit existing physical analysis tools into drill strings without compromising their ability to make measurements.

**Parameter, Value:** Varies depending on parameter of interest

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Downhole physical characterization.

**Capability Description:** Instrumentation embedded in the drill to measure the physical properties of the subsurface materials so that measurements are made continuously without extracting the bit at intervals to bring material to the surface for testing.

**Capability State of the Art:** Drills for space applications commonly have torque and speed sensors and prototypes have temperature sensors, but do not have more sophisticated sensors.

**Parameter, Value:**

Temperature accuracy (K);

Resistivity accuracy (ohms);

Shear strength accuracy (Pa)

**Capability Performance Goal:** Downhole measurement of temperature, resistivity, and shear stress.

**Parameter, Value:**

Accuracy measures for extra terrestrial environments are still be developed

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 5 years |

7.1 In-Situ Resource Utilization
7.1.1 Destination Reconnaissance, Prospecting, and Mapping

# 7.1.1.6 Sensor to Measure Blowing Rate of Material During Landing

## TECHNOLOGY

**Technology Description:** Used to calibrate plume-blowing models to protect outpost assets from repeated blast and scouring.

**Technology Challenge:** No identifed technology challenges.

**Technology State of the Art:** Key components have had performance quantified. Further testing with lunar samples is in-work.

**Parameter, Value:**
No measurements validated for relevant environment

**TRL:** 4

**Technology Performance Goal:** Accuracy of measuring soil mass ejection rate per surface area of regolith (kg/m²/s).

**Parameter, Value:**
Soil mass ejection rate accuracy: ±100%;
Instrument Mass: < 1 kilogram

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Regolith blowing sensors. Must be usable by the crew, looking down to measure how much dust and regolith are being ejected by the landing engines.

**Capability Description:** From vantage point of a landing spacecraft, look down and measure how much dust and regolith are being ejected per second by the landing engines. This would be used to calibrate plume-blowing models to protect outpost assets from repeated blast/ scouring.

**Capability State of the Art:** There has been no effort to measure the velocity or density of the dust plume during descent/ landing.

**Parameter, Value:**
No measurements have been attempted

**Capability Performance Goal:** Need to measure dust quantity and velocities caused by the propulsive landing.

**Parameter, Value:**
Dust density: particles/cm³;
Dust velocity: m/s;
Measures need to be developed in future missions

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 5 years |

7.1 In-Situ Resource Utilization
7.1.1 Destination Reconnaissance, Prospecting, and Mapping

## 7.1.1.7 Instruments to Measure Chemical Compositions

### TECHNOLOGY

**Technology Description:** Chemical/mineralogical detection and characterization of regolith materials and/or volatiles at or near ground level for in-situ resource utilization (ISRU).

**Technology Challenge:** Specific to particular applications.

**Technology State of the Art:** Technologies are mature but need to be miniaturized and packaged for the particular needs of ISRU.

**Parameter, Value:** Varies depending on the instrument type.

**TRL:** 5

**Technology Performance Goal:** Miniaturize (if needed), package for particular application, and perform environmental testing.

**Parameter, Value:** Varies depending on the instrument type.

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Prospecting sensors.

**Capability Description:** Chemical detection of regolith and/or volatiles at or near ground level for prospecting resources for ISRU. Mars Rover instruments have been developed for the Martian atmosphere and power availability, generally long mission durations and several instruments depend on sample preparation or generation not included in the sensor.

**Capability State of the Art:** Mars Exploration Rover uses Mossbauer Spectrometer and Alpha Particle X-Ray Spectrometer. Mars Science Lab uses Alpha Particle X-Ray Spectrometer, X-Ray Diffraction and Fluorescence Analyzer, Laser Induced Breakdown Spectroscopy (LIBS), Quadrupole Mass Spectrometer, Gas Chromatograph, active neutron sounding, and a Tunable Laser Spectrometer.

**Parameter, Value:** Varies depending on the instrument type.

**Capability Performance Goal:** Varies depending on the instrument type, these instruments have flight heritage but would require modifications for use in a lunar environment (vacuum, temperature range), and require mobility and sample generation (mobile arm, sample generation for volatile release). These instruments would be modified to look for resources such as oxygen (or oxide minerals), water or hydrated minerals, hydrogen, and other resources. The instrument suite was designed to look for signs of life and require modifications to look for resources.

**Parameter, Value:** Varies depending on the instrument type.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 4 years |

7.1 In-Situ Resource Utilization
7.1.2 Resource Acquisition

## 7.1.2.1 High-Efficiency Cryocoolers for Carbon Dioxide ($CO_2$) Freezing

### TECHNOLOGY

**Technology Description:** Reduce temperature of targeted gaseous resource (Mars carbon dioxide) to freeze out of atmosphere stream.

**Technology Challenge:** None.

**Technology State of the Art:** High-efficiency cryocoolers.

**Parameter, Value:**
Cooling capacity: 1 W at 20 K;
Specific power: 200 W/W

**TRL** 9

**Technology Performance Goal:** Cryocoolers need to produce a certain amount of cooling 'lift' to freeze carbon dioxide ($CO_2$) out of the Mars atmosphere. Efficiency is electrical power required to produce cooling lift.

**Parameter, Value:**
Cooling Capacity: 2 kWth of cooling;
Efficiency: < 5 We / Wth

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** Two-phase (gas-liquid) fluid dynamics in partial or microgravity.

### CAPABILITY

**Needed Capability:** Atmospheric resource acquisition and pre-processing.

**Capability Description:** Capture, purify, and compress atmospheric gases for processing.

**Capability State of the Art:** Not currently in use in planetary application.

**Parameter, Value:**
No currently measured values.

**Capability Performance Goal:** Need to acquire $CO_2$ from the Martian atmosphere at a rate sufficient to produce desired oxygen at desired rate. The $CO_2$ rate is dependent on efficiency/completeness of oxygen ($O_2$) production technology (discussed in TA 7.1.3).

**Parameter, Value:**
Rate: 12.1 kilograms of $CO_2$ per hour to produce 2.2 kilograms of $O_2$ per hour for Mars crew ascent;
Purity: depends on downstream processing method – sabatier, reverse water gas shift, and solid oxide electrolysis might all have different sensitivity to other gases in the feed stream; Pressure: ~200 kPa

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 4 years |

7.1 In-Situ Resource Utilization
7.1.2 Resource Acquisition

## 7.1.2.2 Pressure- or Temperature-Swing Sorption Pumps

### TECHNOLOGY

**Technology Description:** Adsorb atmospheric gas(es) of interest and desorb at higher pressure and purity.

**Technology Challenge:** Sorbants work through pressure and temperature swing. The initial concept was to adsorb a full day's amount of carbon dioxide ($CO_2$) during the Mars night then desorb in the morning to high pressure, but because sorbent materials are very low density, they require a large volume as total $CO_2$ adsorption requirement increases. Therefore cold adsorption quantity needs to increase while not requiring too much energy to drive off at high temperatures. This reduces adsorbant volume resulting in lower parasitic heating losses to repeatedly heated and cooled structures. Advanced technology for structures (microchannels) is needed to reduce structure-to-sorbant mass ratio. System-level work is needed to enable rapid sorption/desorption cycles to minimize total volume and mass.

**Technology State of the Art:** Zeolites (porous crystalline aluminosilicates) typically used as sorption material. Microchannel technology to enable rapid cycling has recently been demonstrated as an improvement over previous large-volume sorbent beds.

**Parameter, Value:** — **TRL** 4

Cold adsorption at simulated Mars ambient conditions (~800 Pa, 0° C): ~ 0.080 grams of $CO_2$ per gram of adsorbant;

Warm adsorption at 100 kPa (100° C): 0.120 grams of $CO_2$ per gram of adsorbant;

Ratio of structure mass to adsorbant mass: ~ 35:1

**Technology Performance Goal:** Cold adsorption at Mars ambient conditions (want this value as high as possible). Warm adsorption (want this low compared to cold adsorption to maximize the amount of $CO_2$ desorbed to high pressure upon temperature swing). Ratio of structure mass to adsorbant mass.

**Parameter, Value:** — **TRL** 6

Cold adsorption at Mars ambient conditions (7 torr, -50° C): > 0.15 grams of $CO_2$ per gram of adsorbant;

Warm adsorption (~200 kPa, 100 °C): < 0.10 grams of $CO_2$ per gram of adsorbant;

Ratio of structure mass to adsorbant mass: < 5:1;

Sorption cycles: order of minutes

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Atmospheric resource acquisition and pre-processing.

**Capability Description:** Capture, purify, and compress atmospheric gases for processing.

**Capability State of the Art:** Not currently in use in planetary application.

**Parameter, Value:**

Nothing currently measured

**Capability Performance Goal:** Need to acquire $CO_2$ from the Martian atmosphere at a rate sufficient to produce desired oxygen ($O_2$) at desired rate. $CO_2$ rate is dependent on efficiency/ completeness of $O_2$ production technology (discussed in TA 7.1.3).

**Parameter, Value:**

Rate: 12.1 kilograms of $CO_2$ per hour to produce 2.2 kilograms of $O_2$ per hour for Mars crew ascent;

Purity: depends on downstream processing method – sabatier, reverse water gas shift, and solid oxide electrolysis might all have different sensitivity to other gases in the feed stream;

Pressure: ~ 200 kPa.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 6 years |

7.1 In-Situ Resource Utilization
7.1.2 Resource Acquisition

## 7.1.2.3 High Pressure-Ratio Gas Compressors

### TECHNOLOGY

**Technology Description:** Mechanically compress atmosphere to higher pressure.

**Technology Challenge:** Reduced leakage seals between multiple-stage compressors. Flight-weight, yet structurally sound casings for high revolutions per minute (rpm) turbines. Intercoolers that work in low-atmospheric environment (i.e., little convective external cooling).

**Technology State of the Art:** No compressor companies are designing to conditions (compressing 0.8 kPa to ~ 200 kPa).

**Parameter, Value:**

Very limited testing with off-the-shelf axial blower and custom blower achieving pressure rise < 1.5:1 at low flow rates < 0.12 kilograms of carbon dioxide ($CO_2$) per hour

**TRL** 3

**Technology Performance Goal:** Pressure ratio: need to compress low pressure/density resource to reduce volume/mass of downstream reactors and processing components. Efficiency: kW of power / kilogram per hour gas compression. Mass: total mass of production plant needs to be significantly less than mass of propellant produced.

**Parameter, Value:**

Pressure ratio: > 100:1;

Efficiency: < 1 kWe per kilogram per hour of gas compressed;

Flow rate: ~ 12 kilograms of $CO_2$ per hour;

Mass: total plant mass < 200 kilograms

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Atmospheric resource acquisition and pre-processing.

**Capability Description:** Capture, purify, and compress atmospheric gases for processing.

**Capability State of the Art:** Closest current capability example is vacuum pump that has flown on Mars Science Lander to evacuate instrument volumes before measurements.

**Parameter, Value:**

Pressure reduction: ~ 6 torr down to 1E-6 torr;

Flow capacity: not measured

**Capability Performance Goal:** Need to acquire carbon dioxide ($CO_2$) from the Martian atmosphere at a rate sufficient to produce desired oxygen ($O_2$) at desired rate. $CO_2$ rate is dependent on efficiency/ completeness of $O_2$ production technology (discussed in TA 7.1.3).

**Parameter, Value:**

Rate: 12.1 kilograms of $CO_2$ per hour to produce 2.2 kilograms of $O_2$ per hour for Mars crew ascent;

Purity: depends on downstream processing method – sabatier, reverse water gas shift, and solid oxide electrolysis might all have different sensitivity to other gases in the feed stream; Pressure: 15 - 40 psia

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 4 years |

7.1 In-Situ Resource Utilization
7.1.2 Resource Acquisition

# 7.1.2.4 Ionic Liquids for Selective Carbon Dioxide ($CO_2$) Adsorption

## TECHNOLOGY

**Technology Description:** Use ionic liquids (ILs) to absorb atmospheric gas(es) of interest and desorb at higher pressure and purity.

**Technology Challenge:** The proper electrocatalyst and electrolytic cell design (e.g., maintaining separation of products during operation) are needed. ILs that selectivity absorb carbon diodixe ($CO_2$) while maintaining low viscosity are needed. Demonstrate good absorption at very low pressures of Mars environment.

**Technology State of the Art:** ILs rapidly absorb significant amounts of $CO_2$, even at low pressures without viscosity increase (e.g., 1 mole $CO_2$/mole IL = 7 weight percent and 6 weight percent as low as 3,500 Pa, equilibrium in < 20 min.).

**Parameter, Value:**

$CO_2$ capacity: 6% to 7%;

Beginning $CO_2$ pressure: 3,500 Pa;

Time to equilibrium: < 20 min.

**TRL**
2

**Technology Performance Goal:** Cold adsorption at Mars ambient conditions (want this value as high as possible). Warm adsorption (want this low compared to cold adsorption to maximize the amount of $CO_2$ desorbed to high pressure upon temperature swing).

**Parameter, Value:**

$CO_2$ capacity at Mars ambient conditions (800 Pa, -50° C): > 10 weight percent;

$CO_2$ capacity at warm desorption conditions (~200 kPa, 100° C): < 5 weight percent;

Time to equilibrium: to be determined (system-level requirement)

**TRL**
6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Atmospheric resource acquisition and pre-processing.

**Capability Description:** Capture, purify, and compress atmospheric gases for processing.

**Capability State of the Art:** Not currently in use in planetary application.

**Parameter, Value:**

Nothing currently measured

**Capability Performance Goal:** Need to acquire $CO_2$ from the Martian atmosphere at a rate sufficient to produce oxygen ($O_2$) at desired rate. $CO_2$ rate is dependent on efficiency/completeness of $O_2$ production technology (discussed in TA 7.1.3).

**Parameter, Value:**

Rate: 12.1 kilograms of $CO_2$ per hr to produce 2.2 kilograms of $O_2$ per hour with no recycling for Mars crew ascent;

Pressure: ~ 200 kPa

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 6 years |

7.1 In-Situ Resource Utilization
7.1.2 Resource Acquisition

## 7.1.2.5 Cutting Tools for Cold/Hard Regolith and/or Rock/Metal

### TECHNOLOGY

**Technology Description:** Dig or drill down through hard/frozen regolith, rock, or metals to gather resources.

**Technology Challenge:** Ability to generate reaction force using other than mass offset. Longevity of bit, stem, shank, and other dynamically loaded materials in extreme temperatures (down to 40 K in lunar polar regions) – metal embrittlement occurs at these temperatures. Effective waste material removal during drilling (terrestrial deep digging typically uses large amounts of consumables such as water or compressed gas).

**Technology State of the Art:** Terrestrial mining, drilling, and deep digging equipment achieves deep depths and large rates of mass excavated, but relies on high-mass machines to provide reaction force and high power to penetrate hard materials.

**Parameter, Value:**

Terrestrial ‘small’ excavator mass: 10 to 20 kilogram vehicle mass per kilogram per hour excavation rate; Terrestrial peak power: ~ 0.07 kW power per kilogram per hour excavation rate;

Depth: terrestrial depths down to 3,800 meters;

Quantity: up to 200,000+ tonnes per day

**TRL:** 3

**Technology Performance Goal:** Need to provide reaction force using means other than pure mass offset, especially on moon or asteroids where gravity is very low. Need to minimize power requirement.

**Parameter, Value:**

Mass: < 2 kilogram vehicle mass per kilogram per hour excavation rate; Power: < 0.007 kW per kilogram per hour excavation rate;

Depth: 1 to 2 m;

Quantity: 0.5 to 1 tonne per day

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Solids resource acquisition.

**Capability Description:** Digging/drilling into cold, hard regolith and drilling in rock and metal ores.

**Capability State of the Art:** Phoenix Robotic Arm has scooped and trenched icy soils.

**Parameter, Value:**

Scoop chattered upon reaching icy soils as shallow as 2.5 - 3 centimeters. Trenched as deep as 18 centimeters in non-icy soil.

**Capability Performance Goal:** Need to acquire water resource from icy soils that are some depth below surface.

**Parameter, Value:**

Mars: Depth: > 3 centimeters below surface at polar locations;

Quantity rate: 400 kilogram of soil per day (at 8% water content) to > 1,000 kilograms of soil per day (at 3% water content).

Lunar: Depth: > 10 centimeters and as deep as 1 meter;

Quantity rate: 100 kilograms of soil per day (5% water content) to > 550 kilograms of soil per day (1% water content).

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015 -2021 | 4 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 4 years |

7.1 In-Situ Resource Utilization
7.1.2 Resource Acquisition

## 7.1.2.6 Long-Life or Self-Renewing/Repairing Cutting Edges

### TECHNOLOGY

**Technology Description:** Cutting edges that can either be sharpened in place, preferably as part of natural use, or continually renewed by discarding used/dulled edge.

**Technology Challenge:** Need to develop new cutting/digging techniques that reduce trauma/wear to cutting edges. Need methods to reshape or renew cutting edges autonomously while minimizing total mass over life of cutting edge/tool.

**Technology State of the Art:** Blades on terrestrial hard-rock digging/drilling tools are replaced or sharpened when damaged or dulled.

**Parameter, Value:**

Terrestrial: Replaced or sharpened daily to weekly;

Lunar/Mars: no edge-life data available due to minimal use.

**TRL** 2

**Technology Performance Goal:** Mean time between replacement.

**Parameter, Value:**

Lunar: 1 year;

Mars: 4 years

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Solids resource acquisition.

**Capability Description:** Digging/drilling into cold, hard regolith and drilling in rock and metal ores to acquire large amounts of resources over an extended time period.

**Capability State of the Art:** Apollo regolith coring tools used in compacted, but not frozen, regolith. Phoenix Robotic Arm has scooped and trenched icy soils.

**Parameter, Value:**

Apollo tools used a few times each to gather subsurface samples. Phoenix arm dug multiple shallow trenches over a period of ~30 different days.

**Capability Performance Goal:** Need to acquire water resource from icy soils that are some depth below surface.

**Parameter, Value:**

Mars: Depth: 1 to 2 cm in polar location;

Quantity rate: sample/test quanities only.

Lunar: Depth: 70 cm (core tubes) up to 3 m (core drilling);

Quantity rate: sample quanities only.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015 -2021 | 5 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 5 years |

7.1 In-Situ Resource Utilization
7.1.2 Resource Acquisition

## 7.1.2.7 Discrete Element Method to Model Regolith

### TECHNOLOGY

**Technology Description:** Lagrangian modeling of individual soil grains discretely using contact force and contact torque equations.

**Technology Challenge:** Develop methods to model very broad particle size distributions where there are more particles than can be computationally handled, without introducing ad hoc methods that destroy the predictive power of the method.

**Technology State of the Art:** Some progress has been made in Discrete Element Method (DEM), and in Soft Particle Hydrocodes (SPH). Less progress has been made in Eulerian Finite Element Methods due to the high strain and due to lack of appropriate constitutive models.

**Parameter, Value:**

Runtime to converge to solution on a desktop workstation: several days to a month or longer;

Percent error in shear stress predictions: 50%;

Percent error in soil dilation predictions: 50%

**TRL** 4

**Technology Performance Goal:** Improve accuracy, increase speed, extend to a wider variety of cases, develop more predictive power so the code predicts from first-principles without post-hoc tuning of parameters to match known empirical results.

**Parameter, Value:**

Runtime to converge to solution on a desktop workstation: a few hours; Percent error in shear stress predictions: 10%;

Percent error in soil dilation predictions: 10%

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Computer models for soil flows and soil-tool interactions.

**Capability Description:** Computer models that accurately replicate the dynamics of granular materials on micro, meso, and macro scales, with or without ice and other volatiles in the regolith, with or without applied gas flow or mechanical interaction from exploration technology, in extraterrestrial environments (low gravity, vacuum, electrostatics, etc.), providing true predictive power to enable virtual testing of hardware in the extraterrestrial worlds where the hardware will operate, where routine testing of the hardware is not possible.

**Capability State of the Art:** Some codes have been developed with limited application to robotic space exploration missions (Curiosity rover wheels, Origins-Spectral Interpretation-Resource Identification-Security-Regolith Explorer (OSIRIS-Rex) regolith sampler), but the codes are not fully predictive and can be trusted only in situations similar to what has been experimentally tested to permit fine-tuning of the model's parameters. In some models, the regions of predictive power are being successfully extended.

**Parameter, Value:**

Runtime to converge to solution on a desktop workstation: several days to a month or longer;

Percent error in shear stress predictions: 50%;

Percent error in soil dilation predictions: 50%

**Capability Performance Goal:** Converge more rapidly to a solution so the modeling can support real-time decision making and support rapid engineering design cycles. Predict soil behavior more accurately so it provide real predictive power where no empirical data exist (such as on bodies where few spacecraft have landed).

**Parameter, Value:**

Runtime to converge to solution on a desktop workstation: a few hours;

Percent error in shear stress predictions: 10%;

Percent error in soil dilation predictions: 10%

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enabling | 2022 | 2022 | 2021 | 7 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 7 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 7 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 10 years |

7.1 In-Situ Resource Utilization
7.1.2 Resource Acquisition

## 7.1.2.8 Eulerian Modeling of Regolith

### TECHNOLOGY

**Technology Description:** Eulerian modeling of soil as a continuum using constitutive equations.

**Technology Challenge:** Integrate all the complexities of realistic regolith into a single set of constitutive equations.

**Technology State of the Art:** Kinetic theory has been extended to granular media and has been advanced for broad particle size distribution soils. Algorithms have been developed for rough particle shapes. These theories and algorithms have not yet been incorporated into an integrated model for extraterrestrial soil.

**Parameter, Value:** TRL 1

No currently measured value.

**Technology Performance Goal:** Integrate new physics into an integrated modeling code and benchmark it against lunar and Martian soil mechanics. Increase fidelity until code becomes truly predictive.

**Parameter, Value:** TRL 6

Runtime to converge to solution on a desktop workstation: a few hours;

Percent error in shear stress predictions: 10%;

Percent error in soil dilation predictions: 10%

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Computer models for soil flows and soil-tool interactions.

**Capability Description:** Computer models that accurately replicate the dynamics of granular materials on micro, meso, and macro scales, with or without ice and other volatiles in the regolith, with or without applied gas flow or mechanical interaction from exploration technology, in extraterrestrial environments (low gravity, vacuum, electrostatics, etc.), providing true predictive power to enable virtual testing of hardware in the extraterrestrial worlds where the hardware will operate, where routine testing of the hardware is not possible.

**Capability State of the Art:** Not used for modeling soils in the space environment.

**Parameter, Value:**

Runtime to converge to solution on a desktop workstation: does not yet exist

**Capability Performance Goal:** Converge more rapidly to a solution so the modeling can support real-time decision making and support rapid engineering design cycles. Predict soil behavior more accurately so it provide real predictive power where no empirical data exist (such as on bodies where few spacecraft have landed).

**Parameter, Value:**

Runtime to converge to solution on a desktop workstation: a few hours;

Percent error in shear stress predictions: 10%;

Percent error in soil dilation predictions: 10%

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enabling | 2022 | 2022 | 2015 -2021 | 7 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 7 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 7 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 6 years |

7.1 In-Situ Resource Utilization
7.1.2 Resource Acquisition

## 7.1.2.9 Pneumatic Excavation and Material Transport

### TECHNOLOGY

**Technology Description:** Gather and transport unconsolidated regolith using pneumatics.

**Technology Challenge:** No challenge is identified until mission architecture sets the next goal.

**Technology State of the Art:** Prototypes have been tested and their performance measured in reduced gravity flights in vacuum (and at analog sites in some cases).

**Parameter, Value:**

Transport intensity: On the order of 0.5 kg/hr soil transported per kg equipment;

Jamming rate: not measured

Mass efficiency: ranges from 1,000 to 5,500 kg soil/kg transport gas

**TRL**
4

**Technology Performance Goal:** Excavate and transport regolith to the reactor to meet processing needs with minimal loss of transport gases.

**Parameter, Value:**

Transport intensity: > 2 kg/hr soil transported per kg equipment;

Jamming rate: 0 (non-self-correcting) jamming events per year;

Mass efficiency: > 10,000 kg soil moved/kg transport gas

**TRL**
6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Excavation and conveyance of regolith.

**Capability Description:** Excavate regolith to use as a resource for in-situ resource utilization (ISRU), and convey the regolith internally to the hardware during ISRU processing and utilization activities.

**Capability State of the Art:** Not currently used in the space environment.

**Parameter, Value:**

Nothing currently measured

**Capability Performance Goal:** Provide all the regolith required to the ISRU processing plant to support mission objectives.

**Parameter, Value:**

Mars quantity rate: 400 kg of soil per day (at 8% water content) to > 1,000 kg of soil per day (1t 3% water content);

Lunar wet regolith quantity rate:  100 kg of soil per day (5% water content) to > 550 kg of soil per day (1% water content);

Lunar dry regolith quantity rate: 10 kg of soil per day (high-yield processing technology) to 200 kg of soil per day (low-yield processing technology)

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enabling | 2022 | 2022 | 2015 -2021 | 3 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 3 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 3 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 3 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 3 years |

7.1 In-Situ Resource Utilization
7.1.2 Resource Acquisition

## 7.1.2.10 Auger Material Transport

### TECHNOLOGY

**Technology Description:** Transfer and transport unconsolidated regolith.

**Technology Challenge:** Minimize mass of transport device relative to mass of soil moved. Need to demonstrate movement of regolith in vacuum environment where there is nothing to lubricate the regoliths movement through the auger. Also need to minimize loss of volatiles during transport.

**Technology State of the Art:** Prototypes have been tested at analog field tests.

**Parameter, Value:**

Transport intensity: not measured

Jamming rate: not measured

**TRL** 4

**Technology Performance Goal:** Transport regolith to the reactor to meet processing rates.

**Parameter, Value:**

Transport intensity: > 2 kg/hr soil transported per kg equipment;

Jamming rate: 0 (non-self-correcting) jamming events per year

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Conveyance of regolith.

**Capability Description:** Convey regolith to use as a resource for in-situ resource utilization (ISRU) from excavator into the hardware for ISRU processing and utilization activities.

**Capability State of the Art:** Not currently used in the space environment.

**Parameter, Value:**

Nothing currently measured

**Capability Performance Goal:** Provide all the regolith required to the ISRU processing plant to support mission objectives.

**Parameter, Value:**

Mars quantity rate: 400 kilogram of soil per day (at 8% water content) to > 1,000 kg of soil per day (1t 3% water content);

Lunar wet regolith quantity rate: 100 kg of soil per day (5% water content) to > 550 kg of soil per day (1% water content);

Lunar dry regolith quantity rate: 10 kg of soil per day (high-yield processing technology) to 200 kg of soil per day (low-yield processing technology)

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 3 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 3 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 3 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 3 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 3 years |

7.1 In-Situ Resource Utilization
7.1.2 Resource Acquisition

# 7.1.2.11 Magnetic Material Transport

## TECHNOLOGY

**Technology Description:** Transfer and transport unconsolidated regolith.

**Technology Challenge:** Demonstrate soil conveyance weight and jamming rate are sufficiently low to offset the energy cost.

**Technology State of the Art:** Laboratory testing demonstrated that magnetic pulses can un-jam material falling vertically from a hopper, but horizontal transport has not been demonstrated.

**Parameter, Value:** TRL 2

Transport intensity: not demonstrated for horizontal transport;

Transport energy efficiency: not measured for horizontal transport

Jamming rate: not demonstrated for horizontal transport.

**Technology Performance Goal:** Transport regolith to the reactor to meet processing rates.

**Parameter, Value:** TRL 6

Transport intensity: > 2 kg/hr soil transported per kg equipment;

Transport energy efficiency: > 50 kg/soil transported per kWh of energy consumed;

Jamming rate: 0 (non-self-correcting) jamming events per year

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Conveyance of regolith.

**Capability Description:** Convey regolith to use as a resource for in-situ resource utilization (ISRU) from excavator into the hardware for ISRU processing and utilization activities.

**Capability State of the Art:** Not currently used in the space environment.

**Parameter, Value:**

Nothing currently measured

**Capability Performance Goal:** Provide all the regolith required to the ISRU processing plant to support mission objectives.

**Parameter, Value:**

Mars quantity rate: 400 kilogram of soil per day (at 8% water content) to > 1,000 kg of soil per day (1t 3% water content);

Lunar wet regolith quantity rate: 100 kg of soil per day (5% water content) to > 550 kg of soil per day (1% water content);

Lunar dry regolith quantity rate: 10 kg of soil per day (high-yield processing technology) to 200 kg of soil per day (low-yield processing technology)

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015 -2021 | 5 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 5 years |

7.1 In-Situ Resource Utilization
7.1.2 Resource Acquisition

## 7.1.2.12 Regenerable/Scroll Media Filtration

### TECHNOLOGY

**Technology Description:** Use filter media to remove dust from incoming gas stream; filter media are regenerable or can scroll to replace spent filter.

**Technology Challenge:** Reducing mass of motor and rotating components. Adding proper seals.

**Technology State of the Art:** SOA filter media technology is well established, but no regeneration is available. Typically media is replaced periodically (every three months to a year, based on moderate loading).

**Parameter, Value:**

Capturing Efficiency: 60 to 99.9%; Pressure drop: < 250 Pa. (beginning of life);

Particle size removed: > 20 microns for in-situ resource utilization (ISRU) processes, > 1 micron for human health;

Regeneration: sufficent to provide > 510 days life (tied to filter design parameters)

**TRL** 5

**Technology Performance Goal:** To provide medium to high capturing efficiencies, longer filter life, and allow for multiple regeneration cycles.

**Parameter, Value:**

Efficiency: 60 to 99.9%;

Pressure drop: < 250 Pa;

More than 2 regeneration cycles

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Dust filtration from gas flow.

**Capability Description:** Remove dust from incoming gas stream for ISRU processing.

**Capability State of the Art:** Capture efficiency: 60 to 99.9%;

Pressure drop: < 250 Pa (dependent on filter type/particle size requirement);

Particle size removed: < 0.1 micron depending on filter (affects pressure drop);

Regeneration: none

**Parameter, Value:**

Capturing Efficiency: 60 to 99.9%;

Pressure drop: < 250 Pa;

No regeneration cycles

**Capability Performance Goal:** Reduce particulate loading in the gas flow to protect ISRU hardware against failure by dust accumulation. Remove respirable particles from gas flow that will be used for crew breathing air supply.

**Parameter, Value:**

Remove all particles > 20 microns for ISRU processes;

Remove all particles > 1 micron for human health

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015 - 2021 | 3 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 3 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 3 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 3 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 3 years |

7.1 In-Situ Resource Utilization
7.1.2 Resource Acquisition

## 7.1.2.13 Cyclone Dust Separation

### TECHNOLOGY

**Technology Description:** Use cyclones to remove dust from incoming gas stream.

**Technology Challenge:** Reduce mass and size, pressure drop, and particle cut size (capturing of smaller particles).

**Technology State of the Art:** Cyclones were used to clean gas flow in regolith conveyance system in in-situ resource utilization (ISRU) 2012 Field Test on Mauna Kea. SOA cyclones are used mostly for industrial process, and vacuum cleaner systems. They are designed for bulk particulate matter or material collection. They are not adequate for capturing of fine particles of several microns and smaller. They require high flows, high velocities, produce high pressure drops, and have large volumes.

**Parameter, Value:**

Particle cut size: several microns;

Pressure drop: several in $H_2O$

**TRL** 4

**Technology Performance Goal:** Reduce pressure drop, increase collection capacity, and provide multiple regeneration cycles.

**Parameter, Value:**

Cut sizes of 1 to 5 microns;

Collection capacity (not determined yet);

Regeneration cycles: several

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Dust filtration from gas flow.

**Capability Description:** Remove dust from incoming gas stream for ISRU processing.

**Capability State of the Art:** Static filter media. No cleaning or replenishment capability. Spent filters must be manually replaced and old filters discarded.

**Parameter, Value:**

Capturing Efficiency: 60 to 99.9%;

Pressure drop: < 250 Pa;

No regeneration cycles

**Capability Performance Goal:** Reduce particulate loading in the gas flow to protect ISRU hardware against failure by dust accumulation. Remove respirable particles from gas flow that will be used for crew breathing air supply.

**Parameter, Value:**

Remove all particles > 20 microns for ISRU processes;

Remove all particles > 1 micron (ideally) for human health

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015 - 2021 | 4 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 4 years |

7.1 In-Situ Resource Utilization
7.1.2 Resource Acquisition

# 7.1.2.14 Inertial Impactor Dust Separation

## TECHNOLOGY

**Technology Description:** Uses orifices and impaction plates/bands to collect particulate matter above a certain particle cut size. The impaction plates or bands can be cleaned off by wipers or scrapers once loaded.

**Technology Challenge:** Reduce mass and size, pressure drop, and particle cut size (capturing of smaller particles).

**Technology State of the Art:** Has been developed and tested in the laboratory environment.

**Parameter, Value:**

Cut size of several microns to tens of microns;
Pressure drop: ~ high;
Collection capacity: limited

**TRL** 4

**Technology Performance Goal:** Reduce pressure drop, increase collection capacity, and provide multiple regeneration cycles.

**Parameter, Value:**

Cut sizes of 1 to 5 microns;
Collection capacity: not determined yet;
Regeneration cycles: several

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Dust filtration from gas flow.

**Capability Description:** Remove dust from incoming gas stream for in-situ resource utilization (ISRU) processing.

**Capability State of the Art:** Static filter media. No cleaning or replenishment capability. Spent filters must be manually replaced and old filters discarded.

**Parameter, Value:**

Capturing Efficiency: 60 to 99.9%;
Pressure drop: < 250 Pa;
No regeneration cycles

**Capability Performance Goal:** Reduce particulate loading in the gas flow to prevent ISRU protect hardware against failure by dust accumulation. Remove respirable particles from gas flow that will be used for crew breathing air supply.

**Parameter, Value:**

Remove all particles > 20 microns for ISRU processes;
Remove all particles > 1 micron for human health

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 4 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 4 years |

7.1 In-Situ Resource Utilization
7.1.2 Resource Acquisition

## 7.1.2.15 Electrostatic Separation

### TECHNOLOGY

**Technology Description:** Use electrostatics to remove dust from incoming gas stream.

**Technology Challenge:** Achieve high filtration with reasonable power levels and minimal pressure drop across the filter. Develop and demonstrate a method of actively cleaning the system to remove filtered dust.

**Technology State of the Art:** The basic physics has been demonstrated.

**Parameter, Value:**

Has not been measured

**TRL** 2

**Technology Performance Goal:** Demonstrate critical function achieving particle cut below 20 microns or 1 micron to show applicability to in-situ resource utilization (ISRU) or crew health filtering.

**Parameter, Value:**

Remove all particles > 20 microns for ISRU processes;

Remove all particles > 1 micron for human health

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Dust filtration from gas flow.

**Capability Description:** Remove dust from incoming gas stream for ISRU processing.

**Capability State of the Art:** Static filter media. No cleaning or replenishment capability. Spent filters must be manually replaced and old filters discarded.

**Parameter, Value:**

Capturing Efficiency: 60 to 99.9%;

Pressure drop: < 250 Pa;

No regeneration cycles

**Capability Performance Goal:** Reduce particulate loading in the gas flow to prevent ISRU protect hardware against failure by dust accumulation. Remove respirable particles from gas flow that will be used for crew breathing air supply.

**Parameter, Value:**

Remove all particles > 20 microns for ISRU processes;

Remove all particles > 1 micron for human health

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 7 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 7 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 7 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 10 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 10 years |

7.1 In-Situ Resource Utilization
7.1.2 Resource Acquisition

## 7.1.2.16 Electrostatic Beneficiation

### TECHNOLOGY

**Technology Description:** Use electrostatics to separate regolith by particle sizes and/or by mineral content.

**Technology Challenge:** Need funding to build full-scale system and test. Need access to representative samples of Mars, asteroidal, and hydrated minerals to adapt to those cases.

**Technology State of the Art:** Engineering units have been tested in the lab and in reduced gravity flights using lunar soil. Needs to be scaled up. Has not been adapted for asteroid or Mars minerals, or for hydrated minerals.

**Parameter, Value:**

Nothing currently measured

**TRL:** 4

**Technology Performance Goal:** Obtain energy reduction that can be evaluated in the trade space for hardware launch cost versus power reduction. A suitable goal might be 75% reduction in power to produce oxygen ($O_2$).

**Parameter, Value:**

Energy reduction for oxygen production, kWhr per kilogram of $O_2$;

Value needed depends on architectural trades of hardware mass versus energy expenditures

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Regolith beneficiation.

**Capability Description:** Separate regolith by particle sizes and/or by mineral content.

**Capability State of the Art:** Not currently used in the space environment.

**Parameter, Value:**

Nothing currently measured

**Capability Performance Goal:** Obtain energy reduction that can be evaluated in the trade space for hardware launch cost versus power reduction. A suitable goal might be 75% reduction in power to produce $O_2$.

**Parameter, Value:**

Energy reduction for oxygen production, kWhr per kilogram of $O_2$;

Value needed depends on architectural trades of hardware mass versus energy expenditures percent concentration enhancement of minerals

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 7 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 7 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 7 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 7 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 7 years |

7.1 In-Situ Resource Utilization
7.1.2 Resource Acquisition

## 7.1.2.17 Magnetic Beneficiation

### TECHNOLOGY

**Technology Description:** Use magnetism to separate regolith particles by mineral content.

**Technology Challenge:** It is challenging to make it work because dust is superparamagnetic and responds to a magnetic field regardless of the minerals, whereas larger particles are only paramagnetic, which is relatively weak. But superparamagnetism is less important at low temperatures.

**Technology State of the Art:** Critical function has been tested but it did not work. It has been hypothesized that it can be made to work by controlling temperatures, which original tests did not do.

**Parameter, Value:** No enhanced concentration achieved to-date

**TRL:** 1

**Technology Performance Goal:** Demonstrate concentration enhancement of minerals.

**Parameter, Value:** % concentration

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Regolith beneficiation.

**Capability Description:** Separate regolith by mineral content.

**Capability State of the Art:** Not currently used in the space environment.

**Parameter, Value:** Nothing currently measured

**Capability Performance Goal:** Obtain energy reduction that can be evaluated in the trade space for hardware launch cost versus power reduction. A suitable goal might be 75% reduction in power to produce oxygen ($O_2$).

**Parameter, Value:** Energy reduction for oxygen production, kWhr per kilogram of $O_2$; Value needed depends on architectural trades of hardware mass versus energy expenditures percent concentration enhancement of minerals

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 7 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 7 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 7 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 10 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 10 years |

7.1 In-Situ Resource Utilization
7.1.2 Resource Acquisition

## 7.1.2.18 Non-Clogging and/or Self-Cleaning Sieves

### TECHNOLOGY

**Technology Description:** Process raw regolith through multiple sieves to obtain desired particle size range for processing.

**Technology Challenge:** Abrasion of regolith against mesh causes wear, particularly for more effective sifters which force regolith through with a blade. Potential clogging of mesh is also a risk.

**Technology State of the Art:** Sifters (blade over screen) and vibrational sieves – tested in vacuum and lunar gravity environment (separately). Sifter worked best in lunar-g, but optimization needed.

**Parameter, Value:** Percent of particles passed through sieve

**TRL:** 4

**Technology Performance Goal:** Return enough soil in the 50-150 micron range to support oxygen ($O_2$) production needs of 1,000 kilograms of oxygen per year.

**Parameter, Value:** Process lifetime 200,000 kilograms of soil, resulting in 40,000 kilograms of returned soil in 50-150 micron range

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Regolith beneficiation.

**Capability Description:** Separate regolith resource by size and/or mineral content.

**Capability State of the Art:** Phoenix lander had 1 x 1 mm screens above Thermal and Evolved-Gas Analyzer (TEGA) crucibles and a vibrational capability to 'shake' regolith through. Very limited success with wet/highly cohesive regolith.

**Parameter, Value:** 1 x 1 mm

**Capability Performance Goal:** Sort particle size of soil to accommodate: reaction rate, reactor size, and soil conveyance techniques.

**Parameter, Value:**
50-150 micron;
Process 200,000 kilograms of soil in lifetime (1,000 kilograms of $O_2$ per year, yield of 2.5%, ~ 20% soil in size range micron)

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 7 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 5 years |

7.1 In-Situ Resource Utilization
7.1.2 Resource Acquisition

## 7.1.2.19 Crushers/Grinders For Rock and Metal

### TECHNOLOGY

**Technology Description:** Crush or grind large, hard resources (metal or rock) to reduce to smaller particles.

**Technology Challenge:** For rock or ore natural resources, need low wear crushing or grinding surfaces to process large quantities. For recycling of metals to provide feedstock for manufacturing, need to develop crushing or grinding methods that produce spherical or smooth particles to good flow through manufacturing equipment. All terrestrial grinders and crushers rely on gravity for maintaining feedstock against cutting surfaces, and for collecting ground product.

**Technology State of the Art:** Small laboratory scale: high revolutions per minute (rpm) grinders for creating laboratory-scale quantities of solid reactants. Industrial: Shredders and grinders for industrial processes such as blast furnaces to reduce raw (plastic-based) waste into smaller sizes to increase combustion speed/efficiency. Grinder used on consolidated core samples in field demo in Hawaii. No work done in low and micro-gravity environment.

**Parameter, Value:**

Continuous grinding down to 0.25 centimeters;

Plastics reduction down to 200 to 400 micron pellets;

Process tonnes a day;

Ground consolidated core to 1 mm size for entry into reactor in 100 gram batches

**TRL** 3

**Technology Performance Goal:** Size of native resource prepared for chemical or thermal processing. Size and shape of recycled metallic resource.

**Parameter, Value:**

< 150 micron size: < 100 micron;

Morphology: spherical (or at a minimum, smooth)

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Resource pre-processing.

**Capability Description:** Reduce size of raw resource to granular or powder form in preparation for processing through chemical or thermal reactions or as feedstock for manufacturing processes. Raw resource can be either native resources such as rock and ores, or discarded resources such as metal parts.

**Capability State of the Art:** Not currently in use in space or planetary application.

**Parameter, Value:**

Nothing currently measured.

**Capability Performance Goal:** For extraction of desired component from raw resource, smaller particles have a higher surface-to-volume ratio and will react more quickly in chemical or thermal reactions. For feedstock in metal additive manufacturing processes, powder size and morphology/shape is critical to create a smooth flowing feed.

**Parameter, Value:**

< 125 micron size: < 100 micron;

Morphology: spherical (or at a minimum, smooth)

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 5 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 3 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 3 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 3 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 3 years |

7.1 In-Situ Resource Utilization
7.1.2 Resource Acquisition

## 7.1.2.20 Molten Metal Transport

### TECHNOLOGY

**Technology Description:** Crucible, ladle, and bottle storage technologies for melting, storing, and transporting molten metal derived from in-situ resource utilization (ISRU) and recycling sources.

**Technology Challenge:** System design to aid flow and avoid premature solidification requires pressurized system.

**Technology State of the Art:** Commercial-off-the-shelf (COTS) technology in casting and foundry applications.

**Parameter, Value:** Gravity-flow systems for transferring molten metal from crucible to ladle to bottles/molds.

**TRL** 4

**Technology Performance Goal:** Efficient transport of molten metal derived from ISRU resources with minimal losses.

**Parameter, Value:** Percentage of molten metal transported to casting into useable feedstock verses amount of metal extracted from local resources.

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Transfer molten metal derived from ISRU and recycling sources to processing/manufacturing stage.

**Capability Description:** Transfer molten metal to processing/manufacturing stage.

**Capability State of the Art:** Not in use in reduced gravity environment; modification of Earth-based systems required due to reduced gravity.

**Parameter, Value:** System design with sufficient heating/thermal insulation to prevent solidification of molten metal in transport; pressurized system required to aid flow due to reduced gravity environment.

**Capability Performance Goal:** Pressurized system required to aid flow due to reduced gravity environment.

**Parameter, Value:** System design with sufficient heating/thermal insulation to prevent solidification of molten metal in transport; pressurized system required to aid flow due to reduced gravity environment.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 3 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 3 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 3 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 3 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 3 years |

7.1 In-Situ Resource Utilization
7.1.2 Resource Acquisition

# 7.1.2.21 Molten-to-Powder Metal Technologies

## TECHNOLOGY

**Technology Description:** Gas atomizer for producing spherical powdered metal to convert molten metal to powdered feedstock for manufacturing.

**Technology Challenge:** Minimizing mass, volume, and power; maximize powder yield and techniques for separating out appropriate mesh size for additive manufacturing processes.

**Technology State of the Art:** Commercial-off-the-shelf (COTS) technology in Earth powdered metal industry.

**Parameter, Value:**

Powder yields in appropriate mesh sizes for additive manufacturing are 20-40%, and require additional handling to separate out coarse and fine particles.

**TRL** 5

**Technology Performance Goal:** Space-based gas atomizing capability.

**Parameter, Value:**

Maximize powder yield in appropriate mesh sizes for flow in additive manufacturing processes.

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** Powdered metal creation

## CAPABILITY

**Needed Capability:** Gas atomizer for producing spherical powdered metal.

**Capability Description:** Convert molten metal to powdered feedstock for manufacturing; spherical powder is desired for ease of flow and compaction in additive manufacturing processes.

**Capability State of the Art:** Not in use in reduced gravity environment; modification of Earth-based systems required due to reduced gravity.

**Parameter, Value:**

Since gas atomization on earth uses moderate pressures, the primary focus of making the system operable in reduced gravity are minimizing mass, volume, and power.

**Capability Performance Goal:** Atomization is accomplished by forcing a molten metal stream through an orifice at moderate pressures.

**Parameter, Value:**

Parameter development to maximize powder yield in appropriate mesh sizes for flow in additive manufacturing processes.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 3 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 3 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 3 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 3 years |

7.1 In-Situ Resource Utilization
7.1.3 Processing and Production

## 7.1.3.1 Forced Flow Regolith Fluidization

### TECHNOLOGY

**Technology Description:** Inject process gases into reactor filled with loose regolith with sufficient distribution and velocity to create a continuously fluidized bed.

**Technology Challenge:** Maintaining good mixing at larger scales needed to meet production goals is challenging. Gas injectors at bottom of reactor are typical but can get clogged when not fluidizing, and the bottom is also the preferred location for emptying the reactor. Need to have regolith evenly fluidized without over-charging and blowing large quantities out of reactor.

**Technology State of the Art:** Forced flow fluidization during hydrogen reduction has been demonstrated at subscale in multiple lab tests. Forced flow fluidization mixing during heating only has been demonstrated in a lab at full scale to temperatures 150-200° C lower than the 900–1,000° C temperature required.

**Parameter, Value:** ~ 95% of theoretical oxygen yield at batch sizes of 0.005 kilograms. Good mixing of 10 kilograms of regolith was achieved as indicated by temperature uniformity (no reaction tests were performed). However, > 20% of regolith was transported out the top of the chamber indicating significant over-fluidization.

**TRL:** 3

**Technology Performance Goal:** Provide complete and continuous mixing of the regolith and any processing gases to provide fresh reactant around all solid particles thereby maintaining peak oxygen extraction rate resulting in maximum total yield. Mix regolith batch sizes sufficient to obtain yearly oxygen yield while minimizing total energy.

**Parameter, Value:** > 95% of theoretical oxygen yield at batch sizes of 10-20 kilograms.

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Gas/solids mixing.

**Capability Description:** Mix regolith resource and processing gases.

**Capability State of the Art:** Not currently in use in spaceflight.

**Parameter, Value:** Nothing currently measured.

**Capability Performance Goal:** Provide complete and continuous mixing of the regolith and any processing gases to provide fresh reactant around all solid particles thereby maintaining peak oxygen extraction rate resulting in maximum total yield. Mix regolith batch sizes sufficient to obtain yearly oxygen yield while minimizing total energy.

**Parameter, Value:** > 95% of theoretical oxygen yield at given operating conditions; 10-20 kilogram regolith batch sizes.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 6 years |

7.1 In-Situ Resource Utilization
7.1.3 Processing and Production

# 7.1.3.2 Mechanical Regolith Mixing

## TECHNOLOGY

**Technology Description:** Mechanically mix regolith and process gases inside a reactor with mechanical stirrers, tumbling, or other methods to create a continuously well-mixed solid/gas environment.

**Technology Challenge:** Maintaining good mixing at larger scales needed to meet production goals is challenging. Rotating seals of some type will be required whether internal mixing device or external tumbling is utilized and long-life performance in a hot, dusty environment is a significant challenge. Design of internal mixers to provide good lift/mixing across the entire diameter is a granular flow challenge. Location and distribution of heat for uniform heating without overheating and sintering to mixing device surfaces is a challenge at the larger scales. For external tumblers, need to reduce thermal mass of structure to improve thermal efficiency.

**Technology State of the Art:** Mechanical regolith mixing with internal auger has been demonstrated at subscale in the lab and at field demonstration in Hawaii. Full-scale rotating reactor has been demonstrated in a field demo in Hawaii.

**Parameter, Value:**

100 gram batch size;

Limited reaction data available;

~ 95% of theoretical yield in batch sizes of 1.5 kilograms;

Reactor non-optimized for mass and power.

**TRL**

3

**Technology Performance Goal:** Provide complete and continuous mixing of the regolith and any processing gases to provide fresh reactant around all solid particles thereby maintaining peak oxygen extraction rate resulting in maximum total yield. Mix regolith batch sizes sufficient to obtain yearly oxygen yield while minimizing total energy.

**Parameter, Value:**

> 95% of theoretical oxygen yield at batch sizes of 10-20 kilograms.

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Gas/solids mixing.

**Capability Description:** Mix regolith resource and processing gases.

**Capability State of the Art:** Not currently in use in spaceflight.

**Parameter, Value:**

Nothing currently measured.

**Capability Performance Goal:** Provide complete and continuous mixing of the regolith and any processing gases to provide fresh reactant around all solid particles thereby maintaining peak oxygen extraction rate resulting in maximum total yield. Mix regolith batch sizes sufficient to obtain yearly oxygen yield while minimizing total energy.

**Parameter, Value:**

95% of theoretical oxygen yield at given operating conditions;

10-20 kilogram regolith batch sizes.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 6 years |

7.1 In-Situ Resource Utilization
7.1.3 Processing and Production

## 7.1.3.3 Vibrational Regolith Mixing

### TECHNOLOGY

**Technology Description:** Mix regolith and process gases using vibration to fluidize the regolith. The reactor vessel itself is vibrated using methods such as electromagnetic shakers or off-center cams. Frequency and amplitude of vibration can be adjusted to accommodate design. No moving parts in contact with abrasive regolith.

**Technology Challenge:** For hydrogen reduction extraction of oxygen, reaction rate drops sharply as operating temperature decreases, and there is a danger of regolith sintering at temperatures above operating conditions leading to reactor clogging and eventual loss. Maintaining good mixing at larger scales needed to meet production goals is challenging. Appropriate vibrational frequency and amplitude is design specific and will be impacted by mass and particle size distribution. Gravity dependencies will be difficult to test on Earth.

**Technology State of the Art:** Vibrational regolith mixing has been characterized in terms of heat transfer through numerous subscale laboratory tests including pressure dependency, vibration parameters, and regolith particle size. Volatile loss (lower temperature) has been demonstrated, but not hydrogen reduction. Resonant frequency, once found, can be used to maximize fluidization at reduced power settings. Vibrational mixing in full scale reactors during heating only has been demonstrated to temperatures 150-200° C lower than required.

| Parameter, Value: | TRL |
|---|---|
| No oxygen production tests performed so no yield data. Limited reaction data for low temperature volatile evolution only. Apparent thermal conductivity and temperature uniformity of regolith during vibration from numerous subscale tests at ~0.1 kilogram batch size. Heating tests to 600-700° C with 10 kilogram batch size | 3 |

**Technology Performance Goal:** Provide complete and continuous mixing of the regolith and any processing gases to provide fresh reactant around all solid particles thereby maintaining peak oxygen extraction rate resulting in maximum total yield. Mix regolith batch sizes sufficient to obtain yearly oxygen yield while minimizing total energy.

| Parameter, Value: | TRL |
|---|---|
| > 95% of theoretical oxygen yield at batch sizes of 10-20 kilogram | 6 |

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Gas/solids mixing.

**Capability Description:** Mix regolith resource and processing gases.

**Capability State of the Art:** Not currently in use in spaceflight.

**Parameter, Value:**

Nothing currently measured.

**Capability Performance Goal:** Provide complete and continuous mixing of the regolith and any processing gases to provide fresh reactant around all solid particles thereby maintaining peak oxygen extraction rate resulting in maximum total yield. Mix regolith batch sizes sufficient to obtain yearly oxygen yield while minimizing total energy.

**Parameter, Value:**

95% of theoretical oxygen yield at given operating conditions;
10-20 kilogram regolith batch sizes.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 6 years |

7.1 In-Situ Resource Utilization
7.1.3 Processing and Production

## 7.1.3.4 High Temperature, Non-Hydrogen Permeable Materials

### TECHNOLOGY

**Technology Description:** Materials that withstand the high temperatures of regolith processing while maintaining their impermeability to gaseous reactants such as hydrogen ($H_2$).

**Technology Challenge:** Need lightweight, high-temperature materials that are non-permeable to hydrogen gas and resistant to corrosion from possible caustic by-products. Materials must maintain strength at high temperature with reasonable wall thicknesses such that the reactor mass is not significantly greater than the regolith mass creating a thermal inefficiency by having to heat up a large reactor thermal mass. Need to incorporate inlet and outlet system (valves) that are capable of high-temperature, and maintain seal with dirt and dust on surfaces.

**Technology State of the Art:** High temperature reactors have been built and tested in various laboratory tests at scales ranging from 5 grams to 10 kilograms. Not flight-weight. Two small scale hydrogen reduction reactors were built and demonstrated as part of Regolith and Environment Science and Oxygen and Lunar Volatile Extraction (RESOLVE) field demonstrations in Hawaii.

**Parameter, Value:**

Hydrogen reduction: 800-1,000° C;

Carbothermal reduction: > 1,350° C using regolith as insulating material;

Molten Oxide reduction: > 1,600° C;

Cycle life: 10's of cycles;

Reactor mass / batch size: ~ 4:1;

$H_2$ Loss: not measured in tests to date

**TRL** 4

**Technology Performance Goal:** Containers must be able to maintain adequate strength at high temperatures with reasonable wall thicknesses so as to minimize reactor mass.

**Parameter, Value:**

High temperature: 900-1,600° C;

Cycle life: 4,500 heating/cooling cycles;

Reactor mass / batch size: to be determined;

$H_2$ permeability: < 0.00075 $cm^3/(cm^2*min*psi)$ at 1,000° C.

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** High temperature regolith batch reactors.

**Capability Description:** Process solid (regolith) resources at high temperature to extract products.

**Capability State of the Art:** Sample Analysis at Mars (SAM) instrument currently on the Curiosity rover; Thermal Evolved Gas Analyzer (TEGA) instrument on Mars Phoenix lander.

**Parameter, Value:**

~1 gram of regolith to 800-1,100° C;

8 very small samples heated to 1,000° C

**Capability Performance Goal:** Containers that can be repeatedly heated to high temperatures at pressures < 50 psia and are compatible with processing gases (hydrogen, methane) and potentially caustic gaseous by-products resulting from chemical processing of the regolith.

**Parameter, Value:**

Hydrogen reduction: > 900° C;

Carbothermal reduction: >1,350° C;

Molten Oxide reduction: > 1,600° C;

Cycle life: 4,500 heating/cooling cycles;

Reactor mass / batch size: unknown;

$H_2$ permeability: < 0.00075 $cm^3/(cm^2*min*psi)$ at 1,000° C.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 6 years |

7.1 In-Situ Resource Utilization
7.1.3 Processing and Production

## 7.1.3.5 High-Cycle-Life, High-Temperature Valves and Seals

### TECHNOLOGY

**Technology Description:** Valves that operate at elevated temperatures with high-cycle life and tolerate caustic gases, and/or extreme dirt exposure.

**Technology Challenge:** High-cycle-life, high-temperature valves and seals challenges have not been proven at these extremes.

**Technology State of the Art:** Regolith and Environment Science and Oxygen and Lunar Volatile Extraction (RESOLVE) Engineering breadboard unit 2 (EBU2) tested at field demonstrations in Hawaii used a double ball valve design with ceramic felt seat on inner valve to contain dust and PolyEther Ether Ketone material on outer valve to maintain pressure.

**Parameter, Value:**

40 heating and cooling cycles demonstrated in lab with some success

**TRL:** 3

**Technology Performance Goal:** Valves and seals capable of high number of cycles in the presence of abrasive particles.

**Parameter, Value:**

Temperature: > 900° C;

Cycle life: 4,500 heating/cooling cycles

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** High temperature regolith batch reactors.

**Capability Description:** Process solid (regolith) resources at high temperature to extract products.

**Capability State of the Art:** Sample Analysis at Mars (SAM) instrument currently on the Curiosity rover; Thermal and Evolved-Gas Analyzer (TEGA) instrument on Mars Phoenix lander.

**Parameter, Value:**

SAM soil sample placed in sample cup which was then dropped into oven and sealed. Therefore, oven valves were not exposed to regolith.

**Capability Performance Goal:** Valves for containers that can be repeatedly heated to high temperatures at pressures < 50 psia, are compatible with processing gases (hydrogen, methane) and potentially caustic gaseous by-products resulting from chemical processing of the regolith, and can seal repeatedly with possible regolith particles/dust on sealing surfaces.

**Parameter, Value:**

Reactor temperatures > 900° C;

Cycle life: 4,500 heating/cooling cycles

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 6 years |

7.1 In-Situ Resource Utilization
7.1.3 Processing and Production

# 7.1.3.6 Acidic Ionic Liquids for Dissolution of Regolith for Electrolytic Oxygen Production or Metallic Asteroids for Pure Metals Production

## TECHNOLOGY

**Technology Description:** Acidic Ionic Liquids (ILs) show the potential to enhance oxygen and metals production from regolith and meteoritic metal via dissolution and electrolysis.

**Technology Challenge:** Need to demonstrate extraction of oxygen ($O_2$) and metals from regolith/metallic meteorites at moderate temperatures in acidic ILs. Dissolution must be fast with minimal pretreatment of the feed materials and nearly 100% recovery of the IL. Electroplating of metals must be reproducible and the metals be easily removed from the electrode for further use.

**Technology State of the Art:** Acidic ILs have been used to dissolve small amounts of Johnson Space Center (JSC) lunar soil simulant (JSC-1A), a lunar meteorite, and a Martian meteorite with conversion of the water formed into $O_2$ + hydrogen ($H_2$) to regenerate the IL. A small metallic meteorite was dissolved in the IL and metallic iron and metallic nickel electroplated separately.

**Parameter, Value:**

Technology level too immature

**TRL** 2

**Technology Performance Goal:** Processing rate to meet $O_2$ production needs. $O_2$ and metals production with regeneration and recovery of the IL.

**Parameter, Value:**

Processing rate: 1,000 kilograms of $O_2$ per year (~ 6,000 hours);

Recovery of IL: > 95%

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Production of oxygen and metals from regolith and asteroids.

**Capability Description:** Produce oxygen from lunar regolith by extracting it from metal oxides.

**Capability State of the Art:** High temperature hydrogen reduction reactors have been built and tested in various laboratory tests at scales ranging from 5 grams to 10 kilograms. Not flight-weight. Two small scale hydrogen reduction reactors were built and demonstrated as part of Regolith and Environment Science and Oxygen and Lunar Volatile Extraction (RESOLVE) field demonstrations in Hawaii. A solar-concentrator powered carbothermal reduction reactor was also demonstrated during a field demonstration in Hawaii.

**Parameter, Value:**

Oxygen produced in lab test via hydrogen reduction at equivalent rate < 1 kilogram of $O_2$ per year;

Oxygen produced in field demonstrations via carbothermal reduction at equivalent rate of ~ 50 kilograms of $O_2$ per year;

Demonstrated life of reactors: order of 10's of hours.

**Capability Performance Goal:** Need minimum annual production rate based on DRM-7 oxygen needs for lunar human missions (assuming 1,000 kilograms of $O_2$ per year for life support air from Constellation Surface Architecture studies). Need minimum operation time.

**Parameter, Value:**

1,000 kilograms of $O_2$ per year;

Minimum operation time: ~ 6,000 hours

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5: Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 6 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 6 years |

7.1 In-Situ Resource Utilization
7.1.3 Processing and Production

## 7.1.3.7 Solar/Thermal Energy Concentrators

### TECHNOLOGY

**Technology Description:** Heat reactors with direct thermal energy (non-electrical) or heat regolith in-situ to passivate dust, stabilize for landing pads, and/or create thermal sinks.

**Technology Challenge:** Need deployable concentrators that maintain shape and surface finish for high-flux capture. Need tracking mechanisms to follow the Sun. Need lightweight materials that will not overheat. Need surfaces that won't delaminate over time.

**Technology State of the Art:** Solar/thermal energy concentrators.

**Parameter, Value:**

Efficiency: <29%

Deployment Ratio: ≤ 2

System specific mass: 2kg/m2

**TRL** 9

**Technology Performance Goal:** High efficiency energy capture, defined by watts delivered to hardware divided by solar flux times concentrator area. Deployable concentrators defined as ratio of deployed volume (envelope) to stowed volume (envelope). Low specific mass, kg/$m^2$.

**Parameter, Value:**

Efficiency: > 70%;

Deployment Ratio: ≥ 5;

System specific mass: 2 kg/$m^2$.

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Low (electrical) power heating.

**Capability Description:** Heat reactors or regolith in-situ to high temperatures at low (electrical) power to process solid (regolith) resources to extract products or to change surface characteristics.

**Capability State of the Art:** Not currently in use in spaceflight.

**Parameter, Value:**

Not currently measured

**Capability Performance Goal:** Need to heat reactors to processing temperatures (varies based on processing method). Need to heat regolith in-situ to melting temperature to passivate surface dust (surface only), or deeper heating to increase density/strength/thermal conductivity.

**Parameter, Value:**

Hydrogen reduction: > 900° C;

Carbothermal reduction: > 1,350° C;

Molten Oxide reduction: > 1,600° C;

Regolith in-situ: > 1,350° C

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 5 years |

7.1 In-Situ Resource Utilization
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## 7.1.3.8 Optical Fiber Cables with Thermal Receiver

### TECHNOLOGY

**Technology Description:** Provide fiber optic transmission of thermal heat to the reactor or regolith in-situ.

**Technology Challenge:** Need improved efficiency at longer lengths; lower cable mass; small bend radius for attachment to reactor systems.

**Technology State of the Art:** Hard polymer-clad fused silica fibers.

**Parameter, Value:**
Fiber cable bend radius per cable diameter: cm / cm;
Transmission efficiency: 86% for 10 meter cable;
Specific mass: kg / m

**TRL** 4

**Technology Performance Goal:** Need to transfer high temperature heat energy from solar concentrator to reactor or to regolith surface over some length of flexible, lightweight cable with high efficiency (low power loss) to minimize required concentrator size.

**Parameter, Value:**
Fiber cable bend radius: cm; Transmission efficiency: > 90% for 15 meter length;
Specific mass: kg / m.

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Low (electrical) power heating.

**Capability Description:** Heat reactors or regolith in-situ to high temperatures at low (electrical) power to process solid (regolith) resources to extract products or to change surface characteristics.

**Capability State of the Art:** Not currently in use in spaceflight.

**Parameter, Value:**
No currently measured value

**Capability Performance Goal:** Need to heat reactors to processing temperatures (varies based on processing method). Need to heat regolith in-situ to melting temperature to passivate surface dust (surface only), or deeper heating to increase density/strength/thermal conductivity.

**Parameter, Value:**
Hydrogen reduction: > 900° C;
Carbothermal reduction: > 1,350° C;
Molten Oxide reduction: > 1,600° C.
Regolith in-situ: > 1,350° C.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 4 years |

7.1 In-Situ Resource Utilization
7.1.3 Processing and Production

## 7.1.3.9 Heat Storage/Transfer

### TECHNOLOGY

**Technology Description:** Transfer/store heat energy from spent regolith before discarding and use to pre-heat fresh regolith batch to reduce total power requirement. Technologies include transfer using heat pipes and/or storage using phase change materials.

**Technology Challenge:** Operating temperatures of > 900° C are significantly greater than current heat pipe or phase change materials are being developed for.

**Technology State of the Art:** Internal/external two-loop architecture.

| Parameter, Value: | TRL |
|---|---|
| < 25% heat energy recovery | 3 |

**Technology Performance Goal:** Need to heat incoming fresh regolith to maximum temperature possible with non-electrical means before using electrical heaters.

| Parameter, Value: | TRL |
|---|---|
| > 50% heat energy recovery (resulting in > 450° C regolith temperature without electrical heaters). | 6 |

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Low (electrical) power heating.

**Capability Description:** Heat reactors to high temperatures at low (electrical) power to process solid (regolith) resources to extract products.

**Capability State of the Art:** Not currently in use in spaceflight.

**Parameter, Value:**
No currently measured value.

**Capability Performance Goal:** Need to heat reactors to processing temperatures (varies based on processing method).

**Parameter, Value:**
Hydrogen reduction: > 900° C

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 6 years |

7.1 In-Situ Resource Utilization
7.1.3 Processing and Production

## 7.1.3.10 Proton Exchange Membrane (PEM) Electrolyzers

### TECHNOLOGY

**Technology Description:** Electrolyze water using PEM technology.

**Technology Challenge:** The International Space Station (ISS) PEM system is very complex. Need to simplify the balance of plant that supports the electrolysis process. Need to develop stacks capable of efficient, balanced high-pressure operation.

**Technology State of the Art:** ISS PEM system.

**Parameter, Value:**

Current efficiency: 60%;

Voltage efficiency: 80%;

Both at current density of 200 mA/cm$^2$ and pressure ≥ 2,000 psi operating pressure

**TRL:** 9

**Technology Performance Goal:** Current efficiency is a measure of the net production of gaseous reactants resulting from the applied electrical current. Voltage efficiency is a comparison of the operating voltage to the theoretical voltage for the decomposition of water. Both of these depend on a variety of design and operating parameters.

**Parameter, Value:**

For example, at current density of 200 mA/cm$^2$ and pressures ≥ 2,000 psi, want current and voltage efficiency ≥ 90%

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** Two-phase (gas-liquid) fluid dynamics in partial or microgravity.

### CAPABILITY

**Needed Capability:** Water electrolysis.

**Capability Description:** Electrolyze intermediate water species into oxygen (product) and hydrogen (processing fluid).

**Capability State of the Art:** Oxygen ($O_2$) generation assembly on ISS using PEM electrolyzer.

**Parameter, Value:**

9 kilograms of oxygen per day (~ 0.5 kilograms per hour assuming 18 hours a day operation).

**Capability Performance Goal:** If oxygen on Moon is generated via hydrogen reduction, the water is formed as an intermediate. Assuming a need of 1,000 kilograms of $O_2$ per year on the Moon for life support. If $O_2$ on Mars is generated through a reverse-water-gas-shift or via sabatier, then water is formed as an intermediate.

**Parameter, Value:**

Lunar: 0.183 kilograms per hour of water electrolyzed to generate 0.163 kilograms per hour of oxygen;

Mars: 2.5 kilograms per hour of water electrolyzed to generate 2.2 kilograms per hour of oxygen.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 6 years |

7.1 In-Situ Resource Utilization
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## 7.1.3.11 Solid Oxide Co-Electrolysis

### TECHNOLOGY

**Technology Description:** Co-electrolyze water and carbon dioxide in a solid oxide stack to produce oxygen for storage and carbon dioxide, carbon monoxide, and hydrogen for conversion to methane in a Sabatier/ methanation reactor.

**Technology Challenge:** Solid oxide electrolyzers operate at high temperatures (> 800° C) and therefore require high-temperature seals of the ceramic cells. For in-situ resource utilization (ISRU) applications powered by solar arrays, repeated thermal cycles challenge the structural integrity especially for the higher ramp rates (heat-up and cool-down rates) desired to maximize operational time. To obtain high throughput required for crewed mission requires concepts to stack large number of cells together in a mass- and volume-efficient manner.

**Technology State of the Art:** Predominantly single-cell lab scale testing for proof-of-concept and basic performance.

**Parameter, Value:**

Area specific resistance:

Conversion (water ($H_2O$)): ~70-80%;

Ramp rate: 3° C per minute.

**TRL** 3

**Technology Performance Goal:** Area specific resistance is a measure of power efficiency (ohms-cm$^2$) where lower resistance results in lower power; High conversion of $H_2O$ also drives high conversion of carbon dioxide ($CO_2$) for better overall product (oxygen and methane) and reduced recycling of unreacted species.

**Parameter, Value:**

Area specific resistance: dependent on system-level trades;

High conversion ($H_2O$): > 90%;

Ramp rate: > 6° C per minute.

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Production of oxygen and fuel from Mars atmosphere.

**Capability Description:** Produce oxygen and fuel on Mars by extracting oxygen from the atmospheric $CO_2$ and soil water, and producing methane from in-situ carbon (from atmospheric $CO_2$) and hydrogen (from soil water).

**Capability State of the Art:** Not currently used in spaceflight.

**Parameter, Value:**

No currently measured value.

**Capability Performance Goal:** Need minimum hourly production rate of oxygen based on DRM 5.0 propellant needs for human ascent to orbit and mission length. Need minimum operation time.

**Parameter, Value:**

2.2 kilograms of $O_2$ per hour;

0.63 kilograms of methane ($CH_4$) per hour;

> 1,200 Mars sols operational life (~30,000 hours)

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 8 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 8 years |

7.1 In-Situ Resource Utilization
7.1.3 Processing and Production

# 7.1.3.12 Solid Oxide Carbon Dioxide Electrolyzers

## TECHNOLOGY

**Technology Description:** Electrolyze atmospheric carbon dioxide into oxygen (product) and carbon monoxide.

**Technology Challenge:** Decreases in area specific resistance (primarily in interconnect methods/materials) to increase production per power ratio. Fabrication methods for robust seals over repeated thermal cycles. Improved tolerance to thermal stress during normal start-stop thermal cycles and sudden loss of power shutdown. Elimination of issue of electrode delamination over time. Increased tolerance to oxidizing environments. Improved methods for robust connection of ceramic to metal flowpaths.

**Technology State of the Art:** NASA: multi-cell planar bi-supported stacks tested as fuel cell (primarily) and some carbon dioxide ($CO_2$) electrolyzers;

Industry: multi-cell planar anode supported stacks tested as fuel cells, co-electrolysis and some $CO_2$ electrolysis. Tubular geometry tested as fuel cells as $CO_2$ electrolysis.

**Parameter, Value:**

~ 0.003 kilograms of oxygen ($O_2$) per hour in 3-cell stack;

~ 0.003 kilograms of $O_2$ per hour in 3-cell stack via co-electrolysis;

~ 0.05 kilograms of $O_2$ per hour in multi-tube bundle;

Life: limited life demonstrations (< 1,000 hours)

**TRL:** 4

**Technology Performance Goal:** Need minimum hourly production rate based on Design Reference Mission (DRM) 5.0 propellant needs for human ascent to orbit and mission length. Need minimum operation time.

**Parameter, Value:**

2.2 kilograms of $O_2$ per hour;

> 1,200 Mars sols operational life (~30,000 hours);

Area Specific Resistance (ASR): < 3 ohm / $cm^2$.

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Production of oxygen from Mars atmosphere.

**Capability Description:** Produce oxygen on Mars by extracting oxygen from atmospheric carbon dioxide.

**Capability State of the Art:** Not currently in use in spaceflight.

**Parameter, Value:**

No currently measured value.

**Capability Performance Goal:** Need minimum hourly production rate based on DRM 5.0 propellant needs for human ascent to orbit and mission length. Need minimum operation time.

**Parameter, Value:**

2.2 kilograms of $O_2$ per hour;

> 1,200 Mars sols operational life (~30,000 hours)

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 5 years |

7.1 In-Situ Resource Utilization
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# 7.1.3.13 Catalysts for Gas-Phase Chemical Reactions

## TECHNOLOGY

**Technology Description:** Increase the reaction efficiency of gas-phase reactions such as the Sabatier reaction and the reverse water gas shift with improved catalysts and improved catalyst support structures and catalyst application methods.

**Technology Challenge:** Maintaining uniform temperature distribution and uniform flow in larger catalyst beds needed for larger production rates. Advanced technology for structures such as microchannels to improve thermodynamics of reactor system.

**Technology State of the Art:** Carbon Dioxide Reduction System on the International Space Station (ISS) recovers oxygen ($O_2$) from crew-produced carbon diodixe ($CO_2$) using Sabatier reaction and hydrogen supplied from excess water.

**Parameter, Value:**

~ 0.25 kilograms of $CO_2$ per hour flight component capability;

~ 0.1 kilograms of $CO_2$ per hour (2.5 kilograms of $CO_2$ per day) processed into methane in the flight system

**TRL** 5

**Technology Performance Goal:** Need to process sufficient $CO_2$ to produce the target oxygen production rates. Need high single-pass conversion efficiency to minimize downstream components required for separation of mixed gases and recycling of unconverted $CO_2$.

**Parameter, Value:**

~3.2 kilograms of $CO_2$ per hour to produce 2.2 kilograms of $O_2$ per hour at conversion of > 95%

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Production of oxygen from atmosphere (Mars) or from regolith (lunar).

**Capability Description:** Produce oxygen on Mars by extracting oxygen from atmospheric carbon dioxide. Produce oxygen on the moon by extracting oxygen from the lunar regolith through carbothermal reduction which produces carbon dioxide as an intermediate species.

**Capability State of the Art:** Not currently in use in spaceflight.

**Parameter, Value:**

No currently measured value.

**Capability Performance Goal:** Need minimum hourly production rate based on Design Reference Mission (DRM) 5.0 propellant needs for Mars human ascent to orbit and mission length. Need minimum operation time. Assuming need for 1,000 kilograms of $O_2$ per year on the Moon for life support.

**Parameter, Value:**

Mars: 2.2 kilograms of $O_2$ per hour;

Lunar: 0.16 kilograms of $O_2$ per hour;

> 1,200 Mars sols operational life (~30,000 hours)

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 3 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 3 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 3 years |

7.1 In-Situ Resource Utilization
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# 7.1.3.14 New Membranes for Gas Separation and Cleanup

## TECHNOLOGY

**Technology Description:** New high efficiency membranes for separating gases, used to separate methane and/or carbon monoxide from hydrogen and carbon dioxide for Sabatier or Reverse Water Gas Shift (RWGS) systems, and for separating carbon dioxide and carbon monoxide stream resulting from carbon dioxide ($CO_2$) electrolysis.

**Technology Challenge:** Develop membranes that are optimized specifically for the in-situ resource utilization (ISRU) space applications rather than repurposing membranes adapted for terrestrial use. Need high temperature capability for some separation needs to eliminate need to cool gases before membrane.

**Technology State of the Art:** Commercial-off-the-shelf (COTS) membrane modules (e.g., Air Products Portable Remote Imaging Spectrometer) require large pressure drops (≥ 2 bar) and have limited separation factors, resulting in high recycle ratios (~10) and small losses of hydrogen, when present. They also are not amenable to high temperatures, with operating limits below 55° C because of the polymers used. Ceramic support/molten carbonate membranes for high temperature carbon monoxide (CO)/$CO_2$ separation have been tested in the lab with promising results.

**Parameter, Value:**
Purity of product (e.g., methane ($CH_4$) or CO): 98-99%

**TRL:** 4

**Technology Performance Goal:** Improve purity of product and extend the technology to additional cases (inlet stream compositions). High operating temperatures for CO/$CO_2$ separation downstream of solid oxide electrolyzer.

**Parameter, Value:**
Improve purity to 99.9+% in various cases;
CO/$CO_2$ separation operation temperature up to 800° C

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Gas separation.

**Capability Description:** Support production of oxygen from Mars atmosphere and production of oxygen from lunar regolith by separating mixed gas species for storage of product, recycle of reactants to reactors, and venting of unusable byproducts.

**Capability State of the Art:** Not currently in use in spaceflight.

**Parameter, Value:**
No currently measured value.

**Capability Performance Goal:** Need minimum hourly production rate based on DRM 5.0 propellant needs for Mars human ascent to orbit and mission length. Need minimum operation time. Assuming need 1,000 kilograms of $O_2$ per year on Moon for life support air.

**Parameter, Value:**
Mars: 2.2 kilograms of oxygen ($O_2$) per hour;
Lunar: 0.16 kilograms of $O_2$ per hour;
> 1,200 Mars sols operational life (~30,000 hours)

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 3 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 3 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 3 years |

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## 7.1.3.15 Ionic Liquids for Gas Separation and Co-Electrolysis

### TECHNOLOGY

**Technology Description:** Ionic liquids for separating gas species in a mixed-gas stream, and possibly for co-electrolysis of water and carbon dioxide to produce oxygen for storage and carbon dioxide, carbon monoxide, and hydrogen for conversion to methane in a Sabatier/methanation reactor.

**Technology Challenge:** The same technology used for carbon dioxide ($CO_2$) capture from the atmosphere could be applicable also to separation of $CO_2$ from a mixed carbon monoxide (CO)/$CO_2$ gas stream after solid oxide electrolysis. Co-electrolysis of $CO_2$ and water ($H_2O$) in ionic liquids has not been demonstrated, although existing research shows promise that it will work. The proper electrocatalyst and electrolytic cell design (e.g., maintaining separation of products during operation) are needed.

**Technology State of the Art:** High efficiency electrolysis of $CO_2$ in Ionic Liquids to oxygen ($O_2$) and CO has been demonstrated in a lab scale, but co-electrolysis has not.

**Parameter, Value:**

Purity of product ($CO_2$): 99.9%

**TRL:** 2

**Technology Performance Goal:** For gas separation, need high purity of recycled species ($CO_2$). For co-electrolysis, high conversion of $H_2O$ and $CO_2$ provides better overall product capture and reduced recycling of unreacted species.

**Parameter, Value:**

Conversion of $CO_2$: > 50%

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Gas separation and production of oxygen and fuel from Mars atmosphere.

**Capability Description:** Gas Separation: Support production of oxygen from Mars atmosphere and production of oxygen from lunar regolith by separating mixed gas species for storage of product, recycle of reactants to reactors, and venting of unusable byproducts.Production of oxygen and fuel: Produce oxygen and fuel on Mars by extracting oxygen from atmospheric carbon dioxide and soil water and also creating methane.

**Capability State of the Art:** Not currently in use in spaceflight.

**Parameter, Value:**

Achieve more complete separation of gas streams, reducing the residual of unwanted gas species in each stream.

**Capability Performance Goal:** Need minimum hourly production rate based on Design Reference Mission (DRM) 5.0 propellant needs for human ascent to orbit and mission length. Need minimum operation time.

**Parameter, Value:**

Mars: 2.2 kilograms of $O_2$ per hour;

> 1,200 Mars sols operational life (~30,000 hours).

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 10 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 10 years |

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## 7.1.3.16 Freezers and Condensers

### TECHNOLOGY

**Technology Description:** Separate mixed gas streams by condensing or freezing out higher vapor point species allowing lower vapor species to flow through as a gas. This is primarily for separating water gas out of mixed gas stream.

**Technology Challenge:** Need to expand understanding of variable-g effects on two-phase flow, then translate this knowledge into design of condensors for phase separation. Difficult to do prolonged testing (> 1 minute) in lunar gravity conditions. For water separation, want to chill water as close to freezing as possible to minimize dewpoint of gas phase, while not freezing and clogging plumbing.

**Technology State of the Art:** There is very little knowledge base on behavior of two-phase flows in gravity levels between Earth gravity and zero gravity. Some fundamental studies flown on the variable-gravity aircraft indicate that the behavior with respect to gravity is a non-linear relationship.

| Parameter, Value: | TRL |
|---|---|
| Condensation of water out of mixed gas stream in lunar gravity has not been attempted. | 3 |

**Technology Performance Goal:** Rate of condensing water out of mixed gas stream to send for further processing to produce oxygen and recycle hydrogen back into the process. Want minimum water content in separated gas.

| Parameter, Value: | TRL |
|---|---|
| > 0.20 kilograms of water ($H_2O$) per hour; Water content remaining in hydrogen gas stream < 2% by mole (will cause ~ 8% reduction in oxygen extraction from lunar regolith via hydrogen reduction process). | 6 |

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** Two-phase (gas-liquid) fluid dynamics and separation, and condensation in partial gravity.

### CAPABILITY

**Needed Capability:** Gas separation.

**Capability Description:** Support production of oxygen from Mars atmosphere and production of oxygen from lunar regolith by separating mixed gas species for storage of product, recycle of reactants to reactors, and venting of unusable by-products.

**Capability State of the Art:** Not currently in use in spaceflight.

**Parameter, Value:**

No currently measured value.

**Capability Performance Goal:** Need good purity of remaining gas phase (low moisture content) and certain rate of condensation to match overall oxygen production rate.

**Parameter, Value:**

Water condensation rate: > 0.20 kilograms of $H_2O$ per hour;

Moisture content in gas stream: < 2% by mole (for hydrogen gas in a hydrogen reduction of lunar regolith process).

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 5 years |

7.1 In-Situ Resource Utilization
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# 7.1.3.17 Biological Technology

## TECHNOLOGY

**Technology Description:** Biological processes for extraction or conversion of raw feedstock such as active cultures, enzymes, micro-organisms, and genetically modified synthetic engineered organisms.

**Technology Challenge:** Develop organisms that perform the desired chemical processes.

**Technology State of the Art:** Synthetic biology is being used terrestrially for production of biofuels, but no work has been done on in-situ resource utilization (ISRU) processes needed for space.

**Parameter, Value:**
No currently measured value.

**TRL:** 1

**Technology Performance Goal:** Need minimum hourly production rate based on Design Reference Mission (DRM) 5.0 propellant needs for Mars human ascent to orbit and mission length. Need minimum operation time.

**Parameter, Value:**
2.2 kilograms of oxygen ($O_2$) per hour;
> 1,200 Mars sols operational life (~30,000 hours)

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Production of oxygen and fuel from atmosphere (Mars) or from regolith (lunar).

**Capability Description:** Produce oxygen and fuel on Mars by processing the atmospheric carbon dioxide. Produce oxygen on the Moon by extracting oxygen from the lunar regolith.

**Capability State of the Art:** Not currently used in spaceflight.

**Parameter, Value:**
No currently measured value.

**Capability Performance Goal:** Need minimum hourly production rate based on DRM 5.0 propellant needs for Mars human ascent to orbit and mission length. Need minimum operation time.

**Parameter, Value:**
2.2 kilograms of $O_2$ per hour;
> 1,200 Mars sols operational life (~30,000 hours)

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 7 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 13 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 13 years |

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## 7.1.3.18 Artificial Photosynthesis

### TECHNOLOGY

**Technology Description:** Bio-inspired processes to achieve a net conversion of solar or thermal energy into chemical energy. Create a mimic of photosynthesis to generate oxygen and hydrocarbons from Mars carbon dioxide, light, and water.

**Technology Challenge:** While the mechanism has been studied in great detail, mimicking this process is extremely difficult. Significant challenges remain in catalyst activity, substrate, and life. Natural processes are not particularly efficient, so artificial processes are needed to improve on efficiency of natural process.

**Technology State of the Art:** Cobalt-oxide nano-catalysts have been demonstrated to trigger oxidation of water to molecular oxygen which provides the electrons needed to produce liquid fuels from carbon dioxide and water.

**Parameter, Value:**

Basic temporally resolved observation of two intermediate steps in water oxidation.

**TRL**

2

**Technology Performance Goal:** Hourly production rate of oxygen. Minimum operational life. Mass of hardware, including any solar collectors specific to this process.

**Parameter, Value:**

2.2 kilograms per hour of oxygen production;

Operational life: > 1,200 Mars sols (~30,000 hours);

Mass of hardware: < 15% of oxygen produced in 500 days.

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Production of oxygen and fuel from atmosphere (Mars).

**Capability Description:** Produce oxygen and fuel on Mars by processing the atmospheric carbon dioxide.

**Capability State of the Art:** Not currently in use in spaceflight.

**Parameter, Value:**

No currently measured value.

**Capability Performance Goal:** Need minimum hourly production rate based on DRM 5.0 propellant needs for Mars human ascent to orbit and mission length. Need minimum operation time.

**Parameter, Value:**

2.2 kilograms of oxygen per hour;

> 1,200 Mars sols operational life (~30,000 hours).

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 10 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 10 years |

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7.1.3 Processing and Production

## 7.1.3.19 Integrated Cryocoolers/Radiators

### TECHNOLOGY

**Technology Description:** Integrate cryocoolers and radiators with storage tanks to convert gaseous products into more storable cryogenic liquids.

**Technology Challenge:** Challenges include qualifying commercially-available cryocoolers for spaceflight and developing space-qualified controllers.

**Technology State of the Art:** Integrated cryocoolers/radiators state of the art is addressed in TA 14.1.2.3. Industrial cryocoolers can be modified for space applications.

**Parameter, Value:**

Cooling capacity at 77 K: 16 W

Specific power: 15 W/W

Specific mass: 0.2 kg/W

Percent of Carnot efficiency: 20%

**TRL:** 3

**Technology Performance Goal:** Provide cryocoolers with ability to capture, purify, and compress Martian atmospheric gases for processing.

**Parameter, Value:**

Rate: 12.1 kg $CO_2$/hr to produce 2.2 kg $O_2$/hr.

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Product liquefaction and storage.

**Capability Description:** Liquefy products for long-term storage (1 month to 2 years) at processing plant.

**Capability State of the Art:** Flight-qualified cryocoolers with low capacity. Integrated cryocoolers/radiators state of the art has been addressed in TA 14.1.2.3.

**Parameter, Value:**

Cooling capacity at 77 K: 16 W

Specific power: 15 W/W

Specific mass: 0.2 kg/W

Percent of Carnot efficiency: 20%

**Capability Performance Goal:** Prior to crew arrival, liquefy and store sufficient oxygen ($O_2$) to meet all crew life support needs for the entire mission (lunar and Mars), and liquefy and store $O_2$ for ascent propulsion (Mars). Maintain the stored product for the remainder of the cargo pre-mission and for the duration of the crewed mission.

**Parameter, Value:**

Lunar: Rate: liquefy 0.16 kilograms of $O_2$ per hour; Duration: 1 year.

Mars: Rate: liquefy 2.2 kilograms of $O_2$ per hour; Duration: > 3.5 years from first drop of $O_2$ produced.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 5 years |

7.1 In-Situ Resource Utilization
7.1.4 Manufacturing Products and Infrastructure Emplacement

## 7.1.4.1 Regolith Thermal Mass Formation

### TECHNOLOGY

**Technology Description:** Consolidation of granular regolith using solar thermal, chemical, chemical additive, or resistive heating processing to produce solid mass with improved thermal diffusivity, enabling effective solar thermal energy storage.

**Technology Challenge:** The formation of a continuous (minimally fractured) thermal mass using unconsolidated lunar regolith must be achieved at least semi-autonomously to a depth of approximately 0.5 meters and with a footprint simliar to the size of anticipated lunar suface assets, likely a significant fraction of 1 square meter. The resulting material will conduct incident solar radiation into the depth sufficiently during the lunar day to keep the surface temperature in the vicinity of 270 K throughout a lunar night provided radiative loss to deep space is minimized. Corollary function is such that a thermal mass blocked from incident sun during daytime hours will be chilled by radiative loss to deep space and can provide passive daytime cooling for lunar surface assets.

**Technology State of the Art:** Fusing of regolith simulant using concentrated solar energy, using thermite chemistry, and using resistance heating vitrification have all been demonstrated in laboratories and in the field.

| Parameter, Value: | TRL |
|---|---|
| Laboratory processed samples achieve uniform (+/- 10%) thermal diffusivity similar to that of the basalt rock standard (8.7x10$^{-7}$ m$^2$/s) | 3 |

**Technology Performance Goal:** Achieve uniform thermal diffusivity in thermal mass to evenly distribute solar energy. Want thermal diffusivity equal to or better than that of basalt rock typically used as a standard for rock thermal properties.

| Parameter, Value: | TRL |
|---|---|
| Uniformity: +/- 10%;<br>Thermal diffusivity: > 8.7x10$^{-7}$ m$^2$/s. | 6 |

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Thermal wadi protective infrastructure element.

**Capability Description:** This concept would use fused lunar regolith as a solar thermal energy storage medium to provide heat to keep assets warm during lunar nights. A radiative-loss limiting shield bounds energy storage requirements.

**Capability State of the Art:** Current lunar probes mostly hibernate during lunar night and use nuclear power sources to stay warm.

**Parameter, Value:**

This concept is not currently used in spaceflight

**Capability Performance Goal:** Maintain temperature of lunar surface assets during cold/night periods.

**Parameter, Value:**

Temperature: > 250 K

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 6 years |

7.1 In-Situ Resource Utilization
7.1.4 Manufacturing Products and Infrastructure Emplacement

## 7.1.4.2 Solar Heating of Regolith Thermal Mass

### TECHNOLOGY

**Technology Description:** Depending on location, facilitate or direct unconcentrated solar flux to exposed surface of regolith thermal mass over extended periods to gradually store thermal energy for later retrieval.

**Technology Challenge:** A nominally flat reflector must 'track' the sun and reflect incoming solar irradiation onto the thermal mass surface. In equatorial latitudes that experience the nominal diurnal cycle, sufficient solar heating can be achieved without a reflector provided the radiative loss barrier is deployed in the early and late portions of the daytime hours when the sun angle is oblique to the thermal mass surface. In polar regions sun tracking would be essential, but easier since the sun would always be near the horizon. Reflectors must have intrinsic regolith dust repellant properties.

**Technology State of the Art:** Equatorial regions can use direct solar irradiation, polar regions need sun tracking reflector, not demonstrated.

**Parameter, Value:** | **TRL**
Sun tracking for solar thermal heating is well established in terrestrial applications, not demonstrated for lunar/sun geometry or lunar environment. | 3

**Technology Performance Goal:** Track sun and direct or reflect unconcentrated solar flux onto thermal mass surface.

**Parameter, Value:** | **TRL**
Track sun for at least 80% of solar illuminated periods. | 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Thermal wadi protective infrastructure element.

**Capability Description:** This concept would use fused lunar regolith as a solar thermal energy storage medium to provide heat to keep assets warm during lunar nights. A radiative-loss limiting shield bounds energy storage requirements.

**Capability State of the Art:** Current lunar probes mostly hibernate during lunar night and use nuclear power sources to stay warm.

**Parameter, Value:**
This concept is not currently used in spaceflight.

**Capability Performance Goal:** Maintain temperature of lunar surface assets during cold/night periods.

**Parameter, Value:**
Temperature: > 250 K maintained.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 4 years |

7.1 In-Situ Resource Utilization
7.1.4 Manufacturing Products and Infrastructure Emplacement

## 7.1.4.3 Thermal Mass Interface with Mobile Asset

### TECHNOLOGY

**Technology Description:** Develop standard conductive interface to provide heat to lunar surface asset during cold/night periods.

**Technology Challenge:** The main development effort is to determine broadly acceptable design requirements for a conductive thermal coupling arriving at a standard interface with a potential variety of thermal surface mobile assets.

**Technology State of the Art:** Thermal link concept between rover vehicle and thermal mass has been described but not demonstrated. Heat pipe method can be utilized.

**Parameter, Value:**
Heat Pipe technology is well advanced for a large range of process temperatures for terrestrial and space power applications, but has not been demonstrated for lunar gravity and other environmental conditions.

**TRL:** 3

**Technology Performance Goal:** Need to conduct sufficient thermal energy from warmed thermal mass to lunar surface asset to maintain systems during cold/night periods.

**Parameter, Value:**
Minimum of 25 Wth at 250 K.

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Thermal wadi protective infrastructure element.

**Capability Description:** This concept would use fused lunar regolith as a solar thermal energy storage medium to provide heat to keep assets warm during lunar nights. A radiative-loss limiting shield bounds energy storage requirements.

**Capability State of the Art:** Current lunar probes mostly hibernate during lunar night and use nuclear power sources to stay warm.

**Parameter, Value:**
This concept is not currently used in spaceflight.

**Capability Performance Goal:** Maintain temperature of lunar surface assets during cold/night periods.

**Parameter, Value:**
Temperature: > 250 K maintained.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 5 years |

7.1 In-Situ Resource Utilization
7.1.4 Manufacturing Products and Infrastructure Emplacement

## 7.1.4.4 Radiative Insulation of Regolith Thermal Mass

### TECHNOLOGY

**Technology Description:** Develop deployable radiative barrier to limit radiative heat loss to space from thermal mass and from protected lunar surface asset.

**Technology Challenge:** The main development effort is to devise a deployment mechanism that would not be compromised by exposure to lunar regolith dust.

**Technology State of the Art:** The multi-layer insulation approach is appropriate, but 'umbrella' deployment has not been demonstrated.

**Parameter, Value:** Deployable screens available for terrestrial light barrier applications, not demonstrated in lunar dust environment.

**TRL:** 3

**Technology Performance Goal:** Deploy radiative barrier to cover thermal mass surface and parked lunar surface asset. Objective is to ensure that neither the thermal mass surface area or lunar surface asset have a view factor to the sky, thereby ensuring no heat loss to the cold of space.

**Parameter, Value:** > 97% coverage.

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Thermal wadi protective infrastructure element.

**Capability Description:** This concept would use fused lunar regolith as a solar thermal energy storage medium to provide heat to keep assets warm during lunar nights. A radiative-loss limiting shield bounds energy storage requirements.

**Capability State of the Art:** Current lunar probes mostly hibernate during lunar night and use nuclear power sources to stay warm.

**Parameter, Value:** This concept is not currently used in spaceflight.

**Capability Performance Goal:** Maintain temperature of lunar surface assets during cold/night periods.

**Parameter, Value:** Temperature: > 250 K maintained.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 3 years |

7.1 In-Situ Resource Utilization
7.1.4 Manufacturing Products and Infrastructure Emplacement

## 7.1.4.5 Sintering Regolith

### TECHNOLOGY

**Technology Description:** Heating up of regolith to cause the material to form a hard, solid form.

**Technology Challenge:** Generating enough heat without extensive cost and ensuring consistent quality of sintered products.

**Technology State of the Art:** Some limited experiments with lunar regolith samples and more extensive work with lunar regolith simulants.

**Parameter, Value:** No currently measured value; potential is pretty high using sintering.

**TRL:** 3

**Technology Performance Goal:** Goal is to create solid forms with a minimum of material brought from Earth. Sintering requires no material added to the regolith, but does require mass for the heating process.

**Parameter, Value:** > 95% in-situ material.

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Construction material from regolith.

**Capability Description:** Create materials needed for structures such as bricks, cast basalt, lunar/Mars-crete, glass, composites, and other solid forms out of regolith using ionic liquids, polymers, plastics, composites, curing agents, etc.

**Capability State of the Art:** Never used in space.

**Parameter, Value:** No currently measured value.

**Capability Performance Goal:** Maximize amount of in-situ materials used for structures.

**Parameter, Value:** > 80% of structure mass from regolith.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 7 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 8 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 8 years |

7.1 In-Situ Resource Utilization
7.1.4 Manufacturing Products and Infrastructure Emplacement

# 7.1.4.6 In-Situ Fabrication Using Electron Beam Freeform Fabrication (EBF$^3$)

## TECHNOLOGY

**Technology Description:** Metal additive manufacturing and repair technology using electron beam energy source and wire feed.

**Technology Challenge:** Impurities encapsulated in feedstock may compromise strength of subsequently fabricated parts and imperfections in the feedstock (irregular surface) may result in feedstock feeding mechanism difficulties and entrapped flaws. Additional challenges include: reduce size, mass, power of system; increase precision of fabricated parts; and perform inspection and qualification of parts for entry into service in space.

**Technology State of the Art:** Currently, all EBF$^3$ deposition has been conducted using commercial-off-the-shelf (COTS) wire; some deposition experiments have been performed with ceramic powder encapsulate to assess effects of wire cleanliness on EBF$^3$ process and resulting components.

**Parameter, Value:**

Ability to reliably feed feedstock with increased surface roughness, brittle characteristics (poor handleability), impurities without affecting EBF$^3$ system, quality of resulting deposited materials assessed.

**TRL:** 4

**Technology Performance Goal:** Studies assessing effects of less than pristine feedstock, including chemical, microstructural and mechanical properties; wire feeder evaluation to enable feeding of irregular feedstock forms. Strength of materials produced using in-situ derived feedstock within 75% of COTS materials.

**Parameter, Value:**

Robust feedstock feed capability; quality of resulting parts (chemistry, microstructure, flaws, strength).

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Ability to use recycled feedstock or feedstock generated from locally-sourced (in-situ resource utilization) materials.

**Capability Description:** EBF$^3$ technology development required to assess quality of products fabricated from less than pristine wire supplied from Earth (i.e., recycled or locally produced feedstock, which will include impurities and imperfections in wire).

**Capability State of the Art:** EBF$^3$ feasibility in 0-g demonstrated environment during parabolic flight tests on NASA C-9 in 2007.

**Parameter, Value:**

Precision of parts fabricated, strength of resulting deposited material from recycled or locally-sourced materials.

**Capability Performance Goal:** Reduce size, mass, power of system, increase precision of fabricated parts, and inspection and qualification of parts for entry into service in space.

**Parameter, Value:**

Power: < 1kW;

Robust system design insensitive to regolith or other impurities introduced through unclean feedstock

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enabling | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 5 years |

7.1 In-Situ Resource Utilization
7.1.4 Manufacturing Products and Infrastructure Emplacement

## 7.1.4.7 Microwave Sintering for Dust Passivation and/or Soil Stabilization

### TECHNOLOGY

**Technology Description:** Using microwaves to sinter soil on the surface to create roads, landing pads, or dust-free zones.

**Technology Challenge:** Develop an automated process that can achieve high-quality sinter on the naturally varying terrain while meeting bearing capacity requirements. Optimize the process to achieve high area rate of sintering.

**Technology State of the Art:** Microwave sintering has been tested in laboratory conditions using lunar soil simulants.

**Parameter, Value:**

Bearing capacity failure 310 psi at 6.0 mm thick sintering;

Area rate of sintering: not measured.

**TRL** 3

**Technology Performance Goal:** Test with actual lunar simulant. Develop prototypes that perform automated sintering. Measure area rate of sintering that achieves desired thickness and bearing capacity. Perform field testing and vacuum/thermal testing.

**Parameter, Value:**

Bearing capacity failure 310 psi at 6.0 mm thick sintering;

Area rate of sintering: not measured.

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** Sintering process - Solid phase in liquid matrix, sedimentation rate of solid phase is reduced in partial gravity.

### CAPABILITY

**Needed Capability:** Dust passivation and/or soil stabilization.

**Capability Description:** Passivate upper surface of regolith to reduce dust levitation due to human activity, or passivate/ stabilize soil to greater depth to support rovers and ascent/descent vehicles. Technologies include microwave, solar sintering, etc.

**Capability State of the Art:** Not used in the space environment.

**Parameter, Value:**

No currently measured value.

**Capability Performance Goal:** Bearing capacity to support dynamics loads of landing spacecraft, roving vehicles, and/or human boot traffic.

**Parameter, Value:**

Bearing capacity: depends upon spacecraft or rover mass; study for human boot traffic has not been performed;

Area rate of sintering: depends on architecture-derived requirements on the surface assets' time to perform sintering and the size of the sintered areas.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 5 years |

7.1 In-Situ Resource Utilization
7.1.4 Manufacturing Products and Infrastructure Emplacement

# 7.1.4.8 Solar Concentrator Sintering for Dust Passivation and/or Soil Stabilization

## TECHNOLOGY

**Technology Description:** Using solar concentrator to sinter soil on the surface to create roads, landing pads, or dust-free zones.

**Technology Challenge:** Obtain good sintering that does not crack and that builds up to a satisfactory thickness to have mechanical strength. Sintering to greater depths and widths without melting.

**Technology State of the Art:** Solar concentrator sintering has been tested in laboratory conditions using lunar soil simulants and demonstrated at a field test.

**Parameter, Value:**

Sintered area/depth: ~ 2 cm diameter; 1 to 6 mm depth;

Strength: 85 psi on field-sintered specimen

Sintering rate: not measured

**TRL:** 3

**Technology Performance Goal:** Develop process control to get a better more consistent sinter with desired mechanical performance.

**Parameter, Value:**

Sintered area: 500 $m^2$ (landing pad) or greater (roads);

Sintered depth: calculated from bearing capacity for landed load (see capability goals)

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Dust passivation and/or soil stabilization.

**Capability Description:** Passivate upper surface of regolith to reduce dust levitation due to human activity, or passivate/ stabilize soil to greater depth to support rovers and ascent/descent vehicles. Technologies include microwave, solar sintering, etc.

**Capability State of the Art:** Not used in the space environment.

**Parameter, Value:**

No currently measured value.

**Capability Performance Goal:** Bearing capacity to support dynamics loads of landing spacecraft, roving vehicles, and/or human boot traffic.

**Parameter, Value:**

Bearing capacity: Mars landing pad: ~ 60,000 kg landed mass

Bearing capacity: Lunar landing pad: ~ 45,000 kg landed mass

Area rate of sintering: ~ 3 $m^2$ per day sintered

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 5 years |

7.1 In-Situ Resource Utilization
7.1.4 Manufacturing Products and Infrastructure Emplacement

# 7.1.4.9 Other Methods of Sintering

## TECHNOLOGY

**Technology Description:** Applying heat by various methods (other than solar concentrator) to get the soil to sinter.

**Technology Challenge:** Automate the processes and improve the consistency and strength of the sintering.

**Technology State of the Art:** Convective heater element in additive sintering has been tested in a laboratory and used in field testing. Laser sintering of regolith has been demonstrated on a small scale in the laboratory. The use of combustible additives has been tested in the laboratory. Microwave sintering has been demonstrated in the laboratory.

**Parameter, Value:**

Sintered area/depth:

Microwave: 17 by 17 cm, 4-5 cm depth;

Resistive heater element: 3 by 6 cm, 3-4 mm depth;

Strength: 125 psi (2.5 mm thick) to 600 psi (6 mm thick) for laboratory-prepared speicimens;

Sintering rate: not measured

**TRL** 3

**Technology Performance Goal:** Develop process control to get a better, more consistent sinter with desired mechanical performance.

**Parameter, Value:**

Sintered area: 500 $m^2$ (landing pad) or greater (roads);

Sintered depth: calculated from bearing capacity for landed load (see capability goals).

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** Sintering process - Solid phase in liquid matrix, sedimentation rate of solid phase is reduced in partial gravity.

## CAPABILITY

**Needed Capability:** Dust passivation and/or soil stabilization.

**Capability Description:** Passivate upper surface of regolith to reduce dust levitation due to human activity, or passivate/ stabilize soil to greater depth to support rovers and ascent/descent vehicles. Technologies include microwave, solar sintering, etc.

**Capability State of the Art:** Not used in the space environment.

**Parameter, Value:**

No currently measured value.

**Capability Performance Goal:** Bearing capacity to support dynamics loads of landing spacecraft, roving vehicles, and/or human boot traffic. Mass of consumables and hardware brought from Earth.

**Parameter, Value:**

Bearing capacity: Mars landing pad: ~ 60,000 kg landed mass

Bearing capacity: Lunar landing pad: ~ 45,000 kg landed mass

Area rate of sintering: ~ 3 $m^2$ per day sintered

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 5 years |

7.1 In-Situ Resource Utilization
7.1.4 Manufacturing Products and Infrastructure Emplacement

## 7.1.4.10 Application of Polymers to the Soil for Dust Passivation and/or Soil Stabilization

### TECHNOLOGY

**Technology Description:** Applying polymers to the soil with water evaporation curing, heat curing, ultraviolet curing, or other strategies that avoid use of water.

**Technology Challenge:** Reduce the mass of consumables brought from Earth.

**Technology State of the Art:** Heat-cured polymers have been tested in the laboratory environment. A prototype brick maker and a wide area sprayer have been developed.

**Parameter, Value:**

Bearing capacity: 20-80 psi, for spread rates of 0.08 to 0.31 kg/m$^2$;

Bearing capacity: 1,000 psi, for spread rates of 0.08 to .031 kg/m$^2$;

Bearing capacity: 1,000 psi for 20:1 regolith to binder application.

**TRL:** 3

**Technology Performance Goal:** Reduce consumable mass usage. Automate the process. Build high fidelity prototypes and field test them.

**Parameter, Value:**

Bearing capacity: 20-80 psi, for spread rates of 0.08 to 0.31 kg/m$^2$;

Bearing capacity: 1,000 psi, for spread rates of 0.08 to .031 kg/m$^2$;

Bearing capacity: 1,000 psi for 20:1 regolith to binder application.

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Dust passivation and/or soil stabilization.

**Capability Description:** Passivate upper surface of regolith to reduce dust levitation due to human activity, or passivate/ stabilize soil to greater depth to support rovers and ascent/descent vehicles. Technologies include microwave, solar sintering, etc.

**Capability State of the Art:** Not used in the space environment.

**Parameter, Value:**

No currently measured value.

**Capability Performance Goal:** Bearing capacity to support dynamics loads of landing spacecraft, roving vehicles, and/or human boot traffic. Mass of consumable polymer brought from Earth per surface area treated.

**Parameter, Value:**

Bearing capacity: depends upon spacecraft or rover mass; study for human boot traffic has not been performed)

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 4 years |

7.2 Sustainability and Supportability
7.2.1 Autonomous Logistics Management

## 7.2.1.1 Propellant Scavenging

### TECHNOLOGY

**Technology Description:** Extract residual or ullage propellants from descent tanks, remove any unwanted pressurization gases such as helium or nitrogen, and send to existing fuel cells for power generation. Also generate water either through fuel cells or other means of combining the hydrogen (or methane) and oxygen, and store oxygen directly for life support after purifying.

**Technology Challenge:** Removing inert gas used for pressurization from tank prior to scavenging propellant without losing excessive amounts of resource. Managing over-pressurization of tank due to boil-off of residual cryogenic propellant that can occur faster than propellant can be extracted and used for power or converted to water or life-support oxygen. Capture and transfer of water product in low-mass, vacuum-rated storage bags/containers.

**Technology State of the Art:** Fundamental experimental work on oxygen tank venting and fuel cell operation with high helium concentrations has been conducted. Analytical modeling of spacecraft on lunar surface and internal oxygen and hydrogen tank conditions on touchdown and during venting. No analysis has been done to evaluate feasibility of scavenging methane propellants.

**Parameter, Value:**

No currently measured value.

**TRL**

3

**Technology Performance Goal:** Quantity of propellant residual repurposed for power and/or water or oxygen for life support. Oxygen purity for fuel cell and for life support. Hydrogen purity for fuel cell and/or water generation.

**Parameter, Value:**

90% of remaining propellant;

< 5 mole percent helium in oxygen for life support;

< 10 weight percent helium in combined oxygen and hydrogen stream.

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** Thermodynamic and fluid dynamic behavior (liquid- vapor) of cryogenic fluids in partial or microgravity.

### CAPABILITY

**Needed Capability:** Propellant resource repurposing.

**Capability Description:** Capture residual and ullage propellants from descent tanks for reuse in power generation or consumable production (oxygen, water).

**Capability State of the Art:** Not currently in use in space.

**Parameter, Value:**

No currently measured value.

**Capability Performance Goal:** Quantity of propellant residual repurposed for power and/or water or oxygen for life support. Oxygen purity for fuel cell and for life support. Hydrogen purity for fuel cell and/or water generation.

**Parameter, Value:**

90% of remaining propellant;

< 5 mole percent helium in oxygen for life support;

< 10 weight percent helium in combined oxygen and hydrogen stream.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 5 years |

7.2 Sustainability and Supportability
7.2.1 Autonomous Logistics Management

## 7.2.1.2 Flexible, Vacuum-Rated Liquid Storage Bags

### TECHNOLOGY

**Technology Description:** Water storage bags that can be collapsed/compressed for launch and are vacuum rated and capable of freeze/thaw cycles.

**Technology Challenge:** For propellant scavenging from cargo landers prior to crew arrival and use of the water, water bags may be stored outside the vehicle for long periods. Need flexible materials (for efficient stowage in transit) that are also capable of maintaining integrity at extreme conditions of the lunar surface, and during multiple freeze/thaw cycles – monthly extremes on the lunar surface and daily extremes on the Mars surface.

**Technology State of the Art:** Contingency water containers on Space Shuttle and the International Space Station (ISS) were designed for atmospheric environment rather than for freeze/thaw cycles or any significant delta-pressure across bag walls and seals. Current bags have reasonable ratio of water mass to container empty mass that improves with bag volume. Maximum size that has been developed is limited by internal space in the ISS.

**Parameter, Value:** — **TRL** 3

Freeze/thaw cycles: 0;

External pressure: ~15 psia;

Temperature range: 15-40° C; Ratio of water mass to container empty mass: 25:1;

Minimize ratio of water volume to container empty volume;

Maximum water mass: 45.5 kilograms.

**Technology Performance Goal:** Multiple freeze/thaw cycles. Vacuum capable. Wide temperature range. Ratio of water mass to container empty mass. Ratio of water volume to container empty volume. Water mass in single bag.

**Parameter, Value:** — **TRL** 6

Freeze/thaw cycles: 300 cycles rated to  torr;

Temperature Range: 120 to 400 K;

Ratio of water mass to container empty mass: >100:1;

Maximum water mass: 250+ kilograms.

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Low volume liquid consumable storage.

**Capability Description:** Water produced via in-situ resource utilization, propellant scavenging, or environmental control and life support sytems (ECLSS) needs to be stored in various size bags that require minimal volume when empty.

**Capability State of the Art:** Contingency water containers on the Space Shuttle and ISS are used to capture water from the fuel cells and ECLSS system.

**Parameter, Value:**

~ 45 kilograms of water used at room temperature and pressure.

**Capability Performance Goal:** Capture and store water from propellant scavenging until ready for use over multiple days on lunar or Mars surface.

**Parameter, Value:**

Freeze/thaw cycles: > 300 cycles.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 4 years |

7.2 Sustainability and Supportability
7.2.1 Autonomous Logistics Management

## 7.2.1.3 Power Scavenged Wireless Sensor Tag Systems

### TECHNOLOGY

**Technology Description:** Sensor data is continuously sampled and stored in radio frequency identification (RFID) user memory banks to be gathered by an interrogator via RFID protocols.

**Technology Challenge:** Lower-power sensing technologies required to support higher sampling rates using harvested power; more efficient harvesting and power storage technologies are required to support high rate sensing. More efficient RFID protocols required to support high data rates.

**Technology State of the Art:** Scavenged or battery powered sensing using Enhanced Power Conversion (EPC) Global Class 1 (C1)-Generation 2 (G2) RFID.

**Parameter, Value:**

Temperature, strain, and pressure from several sensor tags at 1 ksample/sec on scavenged or battery power.

**TRL**

3

**Technology Performance Goal:** Interrogators capable of supporting hundreds of tags generating 1 ksample/sec of data each; tags capable of sampling and storing data for < 100 microW power; power harvesting and power storage technologies capable of supporting continuous sensing/data storage.

**Parameter, Value:**

Sample rate;

power consumption;

power generation/storage efficiencies.

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Passive, wireless ubiquitous sensing.

**Capability Description:** Enables situational awareness through ubiquitous, pervasive sensing not otherwise feasible due to high wire mass and battery life. This is applicable to vehicle and crew health monitoring and logistics planning.

**Capability State of the Art:** Not in use in space.

**Parameter, Value:**

No currently measured value.

**Capability Performance Goal:** High rate sensing from hundreds of sensors on scavenged power for multiple sensing modalities.

**Parameter, Value:**

Temperature, strain, pressure at 1 ksamples/sec from hundreds of tags on scavenged power.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 4 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 4 years |

7.2 Sustainability and Supportability
7.2.1 Autonomous Logistics Management

# 7.2.1.4 Dense Zone Technology (Radio Frequency Identification Enclosure)

## TECHNOLOGY

**Technology Description:** Sensing of dense collections of stowed assets for inventory and localization including direct interrogation of tagged items as well as smart containers that infer quantities or levels of contained non-tagged items.

**Technology Challenge:** Finding items onboard the International Space Station (ISS) requires huge amounts of crew time. Providing smart tools that can automatically track where items are and provide that data on demand can significantly reduce crew time and enhance crew safety by enabling the finding of critical items in just minutes instead of hours. Effective logistics management will also enable reduced costs by eliminating unneeded resupply for misplaced items.

**Technology State of the Art:** First radio frequency identification (RFID) Enclosure launched to ISS in 2013; Embedded reader in drawer with 4 ports and radio frequency (RF) cables to 4 antennas. Each drawer requires 4 antennas, each antenna is 0.75 inch thick.

**Parameter, Value:** 95% read accuracy for < 150 items, with antenna 0.75 inch standoff from a drawer surface, requiring 4 reader antenna ports.

**TRL:** 4

**Technology Performance Goal:** Read accuracy for < 150 stored items using minimal antenna ports.

**Parameter, Value:** Read accuracy > 95% for < 150 stored items using only 2 antenna ports.

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Automated tracking and asset localization.

**Capability Description:** Tracking and asset localization system that automatically updates the inventory database without crew or ground intervention. Inventory database is highly accurate. Lost items need to be found quickly when crew assistance is required.

**Capability State of the Art:** Automated capability does not exist. SOA of manually updated inventory database capability: ISS Inventory Management System. Lost items remain lost for months or years. Updates require ground or crew intervention.

**Parameter, Value:**

70 missing items in inventory of 20,000 items;

400 manual database updates per day;

Lost items require multiple crew-hours to find.

**Capability Performance Goal:** Almost all item locations are correctly represented in the database. Items not found by automated means are readily found with crew assistance. All database updates automated.

**Parameter, Value:**

Fewer than 2 lost items per population of 20,000;

< 15 minutes crew time needed to find any given item;

All database updates automated.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 4 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 4 years |

7.2 Sustainability and Supportability
7.2.1 Autonomous Logistics Management

# 7.2.1.5 Sparse Zone Technology

## TECHNOLOGY

**Technology Description:** Radio frequency identification (RFID) based readers mounted in various ways (stationary, mobile, on free flyers) for all habitat areas exclusive of dense zones, including cracks and crevices.

**Technology Challenge:** Finding items onboard the International Space Station (ISS) is requires huge amounts of crew time. Providing smart tools that can automatically track where items are and provide that data on demand can significantly reduce crew time and enhance crew safety by enabling the finding of critical items in just minutes instead of hours. Effective logistics management will also enable reduced costs by eliminating unneeded resupply for misplaced items.

**Technology State of the Art:** Items of moderate size are readable with modest accuracy at modest range. Range accuracy is poor.

**Parameter, Value:**

Not currently used in relevant environment;

In ground analogs 50% read accuracy for items > 100 cm$^2$ on at least 1 surface;

Localization accuracy is +/- 1.5 m.

**TRL** 3

**Technology Performance Goal:** SOA parameters: achievable range assuming 1 W transmission power and < 8 dBi antenna gain

**Parameter, Value:**

80% read accuracy for items > 100 cm$^2$ on at least one surface; Localization accuracy is +/- 10 cm

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Automated tracking and asset localization.

**Capability Description:** Tracking and asset localization system that automatically updates the inventory database without crew or ground intervention. Inventory database is highly accurate. Lost items need to be found quickly when crew assistance is required.

**Capability State of the Art:** Automated capability does not exist. SOA of manually updated inventory database capability: ISS Inventory Management System. Lost items remain lost for months or years. Updates require ground or crew intervention.

**Parameter, Value:**

70 missing items in inventory of 20,000 items;

400 manual database updates per day;

Lost items require multiple crew-hours to find.

**Capability Performance Goal:** Almost all item locations are correctly represented in the database. Items not found by automated means are readily found with crew assistance. All database updates automated.

**Parameter, Value:**

Fewer than 2 lost items per population of 20,000;

< 15 minutes crew time needed to find any given item;

All database updates automated.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 4 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 4 years |

7.2 Sustainability and Supportability
7.2.1 Autonomous Logistics Management

## 7.2.1.6 Logistics Complex Event Processing

### TECHNOLOGY

**Technology Description:** Operational Intelligence software for complex logistics management, including three-dimensional (3D) localization and automated inventory updates. Operational intelligence to aggregate events and establish inferences to enable 3D asset localization in the absence of a complete data set.

**Technology Challenge:** Finding items onboard the International Space Station (ISS) is requires huge amounts of crew time. Providing smart tools that can automatically track where items are and provide that data on demand can significantly reduce crew time and enhance crew safety by enabling the finding of critical items in just minutes instead of hours. Effective logistics management will also enable reduced costs by eliminating unneeded resupply for misplaced items.

**Technology State of the Art:** CEP has been applied in many disciplines, including financial analysis and security. Only simple operational concepts have been demonstrated for radio frequency identification (RFID)-based logistics tracking.

**Parameter, Value:**

Maintain community persistence for populations up to 15 items through 2 RFID portal translations.

**TRL:** 2

**Technology Performance Goal:** Logistics CEP application consumes data events from dense and sparse zone technologies and produces inferences on item location.

**Parameter, Value:**

Maintain community persistence for populations up to 85 items through 3 habitat module transitions;

Properly infer item locations when obscured by other items, or an item was not otherwise observed by an RFID reader;

Anticipated capability performance improvement moves the item-missing rate from 70 out of 20,000 to 2 out of 20,000.

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Automated tracking and asset localization.

**Capability Description:** Tracking and asset localization system that automatically updates the inventory database without crew or ground intervention.Inventory database is highly accurate. Lost items need to be found quickly when crew assistance is required.

**Capability State of the Art:** Automated capability does not exist. SOA of manually updated inventory database capability: ISS Inventory Management System. Lost items remain lost for months or years. Updates require ground or crew intervention.

**Parameter, Value:**

70 missing items in inventory of 20,000 items;

400 manual database updates per day;

Lost items require multiple crew-hours to find.

**Capability Performance Goal:** Almost all item locations are correctly represented in the database. Items not found by automated means are readily found with crew assistance. All database updates automated.

**Parameter, Value:**

Fewer than 2 lost items per population of 20,000;

< 15 minutes crew time needed to find any given item;

All database updates automated.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 6 years |

7.2 Sustainability and Supportability
7.2.1 Autonomous Logistics Management

## 7.2.1.7 Six Degrees of Freedom Logistics Tag System

### TECHNOLOGY

**Technology Description:** Radio frequency identification (RFID) reader infrastructure and passive RFID tag that provides telemetry to the reader system to enable pose estimation. Current RFID technology is insufficient for high accuracy location and orientation.

**Technology Challenge:** Multi-modality tags antennas may be required. Refined localization capability will greatly enhance M-M and M-H interfaces and will enable robotic packing and unpacking of logistics.

**Technology State of the Art:** RFID tags with polarization-based angle discrimination and pulsed ranging.

**Parameter, Value:**

Angle accuracy: 45 degrees;

Localization resolution: 1 $m^3$

**TRL:** 3

**Technology Performance Goal:** RFID-based refined localization and orientation telemetry.

**Parameter, Value:**

Position error: < 10 centimeters;

Angle errors: < 30 degrees

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Autonomous transfer, repackage, and stowage of internal logistics.

**Capability Description:** Robotic transfer, unpackage, and setup of internal logistics for initial habitat setup, followed by disposal of all logistical waste. This enables habitat setup prior to crew arrival, later augmenting crew activities, and culminating in cleanup after crew departure.

**Capability State of the Art:** Not currently in use in relevant environment.

**Parameter, Value:**

No currently measured value.

**Capability Performance Goal:** Accuracy in all 6 DOF for item with at least 1 surface of minimum area.

**Parameter, Value:**

Position error: < 10 centimeters;

Angle errors: < 30 degrees

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enalbing | 2022 | 2022 | 2015-2021 | 3 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enabling | 2027 | 2027 | 2021 | 3 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 3 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 3 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 3 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 3 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 3 years |

7.2 Sustainability and Supportability
7.2.1 Autonomous Logistics Management

## 7.2.1.8 Packaging Foam Additive Printer Feedstock

### TECHNOLOGY

**Technology Description:** Modify packaging foam material to three-dimensional (3D) manufacturing feedstock. Includes processing of foam (melt and extrude fiber or grind and filter) to provide useable feedstock.

**Technology Challenge:** 3D feedstock materials are typically thermoplastics which may not provide required vibration isolation as a foam. Removal of gas voids in foam to produce solid plastic filament.

**Technology State of the Art:** Conceptual discussions between NASA projects.

**Parameter, Value:**

Current foam materials are not suitable for feedstock. Printed parts are melted and extruded in using 1-g environment. No recycling of printed parts on orbit in practice or design.

**TRL** 1

**Technology Performance Goal:** Percent of packaging material suitable for 3D printing feedstock – launched feedstock mass/equivalent system mass of produced feedstock, % of polymer consumables produced by 3D printing.

**Parameter, Value:**

75% of all soft goods are capable of being reprocessed into 3D printing feedstock;

Save at least 5 times the resources by reprocessing materials to feedstock versus bringing new materials;

> 30% of polymer consumables produced by 3D printing.

**TRL** 7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Logistics waste recycling to 3D printing feedstock.

**Capability Description:** Process packaging foam, cargo bags, and other polymers to feedstock for additive manufacturing.

**Capability State of the Art:** Not in use in space.

**Parameter, Value:** No currently measured value.

**Capability Performance Goal:** Heat foam, compact to remove gas volume, and extrude to produce 3D printer filament. Avoids need to fly dedicated feedstock.

**Parameter, Value:**

80% of foam material recovery;

Produced feedstock mass/equivalent system mass of processor mass: > 5;

Produced feedstock strength/virgin feedstock strength: > 90%

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 4 years |

7.2 Sustainability and Supportability
7.2.1 Autonomous Logistics Management

## 7.2.1.9 Multipurpose Cargo Transfer Bag

### TECHNOLOGY

**Technology Description:** A reconfigurable logistics stowage bag that unfolds into a flat panel. Flat panels can be used for outfitting crew structures and reduces stowage volume for empty bags.

**Technology Challenge:** Microgravity fluid distribution limitations in large flat membrane areas.

**Technology State of the Art:** Multipurpose cargo transfer bags (MCTBs) that can be used as crew partitions, acoustic treatments, radio frequency identification (RFID) logistics managment, and forward osmosis water processing.

**Parameter, Value:** No use beyond storage, either for hardware, provisions, or trash.

**TRL** 2

**Technology Performance Goal:** > 50% of cargo transfer bags (CTBs) have capability to be repurposed for crew outfitting.

**Parameter, Value:** > 50% of CTBs repurposed for crew outfitting.

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Repurposing logistics carriers for outfitting crew and crew structures.

**Capability Description:** Light-weight, reconfigurable crew quarters, acoustic reduction for habitable volumes, radiation shielding, water storage and processing.

**Capability State of the Art:** CTBs used for trash storage prior to disposal in visiting vehicle.

**Parameter, Value:** ~ 25% of CTBs used for trash storage.

**Capability Performance Goal:** > 50% of CTBs repurposed for crew outfitting.

**Parameter, Value:** > 50% of CTBs repurposed for crew outfitting (in addition to use for trash storage).

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 3 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 3 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 3 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 3 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 3 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 3 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 3 years |

7.2 Sustainability and Supportability
7.2.2 Maintenance Systems

## 7.2.2.1 Ultrasonics for Electrical Connections

### TECHNOLOGY

**Technology Description:** Ultrasonic sensors integrated into connectors to wirelessly detect and transmit location of loss of electrical connectivity.

**Technology Challenge:** Challenges include size and weight of a system that provides flexibility to operate on a wide range of connection sizes and is also able to recertify connections that have been made previously.

**Technology State of the Art:** Undergoing commercialization for aircraft and ground based applications. Prototype instruments have been demonstrated in several automated and manual configurations.

**Parameter, Value:** Prototype instruments have been demonstrated in several automated and manual configurations.

**TRL:** 4

**Technology Performance Goal:** Detectability of loss of electrical connection through wireless sensors integrated into connectors.

**Parameter, Value:** Effectiveness of sensor in detecting and transmitting connectivity losses in electrical systems.

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Ultrasonic sensor technology that verifies electrical connections.

**Capability Description:** Real-time indication of electrical wire termination and connection quality during contact assembly and while in service.

**Capability State of the Art:** Not currently used in space environment.

**Parameter, Value:** Electrical conductivity/mean time between failure (MTBF)/mean time between replacement (MTBR).

**Capability Performance Goal:** Automated, wireless system development to detect loss of electrical connectivity in connectors.

**Parameter, Value:** Miniaturization, robustness of sensors, incorporation of sensors into variety of electrical connectors, ability to detect loss of connectivity.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 3 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 3 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 3 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 3 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2021 | 3 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2021 | 3 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2021 | 3 years |

7.2 Sustainability and Supportability
7.2.3 Repair Systems

## 7.2.3.1 Multi-Axis Subtractive Machining

### TECHNOLOGY

**Technology Description:** Multi-axis subtractive machining in reduced gravity environment – manufacture of finished parts for repairs.

**Technology Challenge:** Large size and mass of equipment; calibration and maintenance of equipment: tooling wear, replacement or reprocessing of support materials such as cutting oil, coolant, and lubricant.

**Technology State of the Art:** No current in-space machining capability exists. Commercial-off-the-shelf (COTS) capabilities on Earth.

**Parameter, Value:** Ground-based systems are heavy for vibration mitigation, consume large amounts of power, and use consumables (cutting fluids).

**TRL** 6

**Technology Performance Goal:** In-situ computer numerically controlled (CNC) multi-axis mill with the following features: lightweight, portable, modular, reconfigurable, minimal “custom” fixturing, robust, and operates in a reduce gravity environment.

**Parameter, Value:** Part accuracy within +/-0.010 inch or better for parts produced in reduced gravity for repairs.

**TRL** 9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** In-situ CNC multi-axis milling (5+ axis).

**Capability Description:** In-situ manufacturing to enable repairs of “field” hardware and produce new hardware not previously identified.

**Capability State of the Art:** Not demonstrated in reduced or zero gravity environments; limited military and industrial implementation in remote locations in Earth-like environment.

**Parameter, Value:** Part accuracy within +/-0.010 inch or better for parts produced in reduced gravity for repairs.

**Capability Performance Goal:** In-situ CNC multi-axis mill with following features: Lightweight, portable, modular, reconfigurable, minimal “custom” fixturing, robust, and operates in a reduce gravity environment.

**Parameter, Value:** Part accuracy within +/-0.010 inch or better for parts produced in reduced gravity for repairs.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 4 years |

7.2 Sustainability and Supportability
7.2.3 Repair Systems

# 7.2.3.2 Multi-Axis Lathe Machining

## TECHNOLOGY

**Technology Description:** Multi-axis lathe turning operations in reduced gravity; partial gravity required.

**Technology Challenge:** Large size and mass of equipment; calibration and maintenance of equipment: tooling wear, replacement or reprocessing of support materials such as cutting oil, coolant, and lubricant.

**Technology State of the Art:** No current in-space machining capability exists. Commercial-off-the-shelf (COTS) capabilities on Earth.

**Parameter, Value:** (TRL 6)
Ground-based systems are heavy for vibration mitigation, consume large amounts of power, and use consumables (cutting fluids).

**Technology Performance Goal:** In-situ computer numerically controlled (CNC) multi-axis lathe with following features: lightweight, portable, modular, reconfigurable, minimal "custom" fixturing, robust, and operates in a reduce gravity environment.

**Parameter, Value:** (TRL 9)
Part accuracy within +/-0.010 inch or better for parts produced in reduced gravity for repairs.

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** In-situ CNC multi-axis lathe (5+ axis).

**Capability Description:** In-situ manufacturing to enable repairs of "field" hardware and produce new hardware not previously identified.

**Capability State of the Art:** Not demonstrated in reduced or zero gravity environments; limited military and industrial implementation in remote locations in Earth-like environment.

**Parameter, Value:**
Part accuracy within +/-0.010 inch or better for parts produced in reduced gravity for repairs.

**Capability Performance Goal:** In-situ CNC multi-axis lathe with following features: lightweight, portable, modular, reconfigurable, minimal "custom" fixturing, robust, and operates in a reduce gravity environment.

**Parameter, Value:**
Part accuracy within +/-0.010 inch or better for parts produced in reduced gravity for repairs.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 4 years |

7.2 Sustainability and Supportability
7.2.3 Repair Systems

## 7.2.3.3 Machining Fluid and Chip Management

### TECHNOLOGY

**Technology Description:** Management of machining chips and cutting fluids in reduced gravity; partial gravity required.

**Technology Challenge:** Removal and capture of “chips,” “shavings,” coolant, and cutting fluids without the benefit of an Earth-like gravity, use containment chambers and vacuum systems consuming additional volume, mass, and power.

**Technology State of the Art:** No current in-space machining chip capture capability exists. Commercial-off-the-shelf (COTS) capabilities on Earth.

**Parameter, Value:**
Effective capture and containment of all by-products of machining operations for safety of operation and environmental controls.

**TRL**
5

**Technology Performance Goal:** In-situ waste material capture and containment to maintain a “clean” environment during and after machining operations with following features: lightweight, portable, modular, reconfigurable, robust, and operates in a reduce gravity environment.

**Parameter, Value:**
100% capture of all machining chips/ swarf and cooling fluids to avoid contamination of cabin environment.

**TRL**
9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** In-situ machining waste material capture and containment.

**Capability Description:** In-situ manufacturing to enable repairs of “field” hardware produce new hardware not previously identified.

**Capability State of the Art:** Not demonstrated in reduced or zero gravity environments; limited military and industrial implementation in remote locations in Earth-like environment.

**Parameter, Value:**
100% capture of all machining chips/swarf and cooling fluids to avoid contamination of cabin environment.

**Capability Performance Goal:** In-situ waste material capture and containment to maintain a “clean” environment during and after machining operations with following features: lightweight, portable, modular, reconfigurable, robust, and operates in a reduce gravity environment.

**Parameter, Value:**
100% capture of all machining chips/swarf and cooling fluids to avoid contamination of cabin environment.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 3 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 3 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 3 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 3 years |

7.2 Sustainability and Supportability
7.2.3 Repair Systems

## 7.2.3.4 Machining Fluid and Chip Reclamation

### TECHNOLOGY

**Technology Description:** Reclamation and recycling of machining chips and cutting fluids in reduced gravity; partial gravity required.

**Technology Challenge:** Operating without the benefit of an Earth-like gravity; use of additional facilities and/or equipment consuming additional volume, mass, and power.

**Technology State of the Art:** No current in-space machining chip recycling capability exists. Commercial-off-the-shelf (COTS) capabilities on Earth.

**Parameter, Value:** Effective separation, reclamation, and recycling into useable feedstock.

**TRL:** 4

**Technology Performance Goal:** Waste material reclamation and recycle with following features: lightweight, portable, modular, reconfigurable, robust, operates in a reduce gravity environment, and produces minimal quantities of unusable or "environmentally unfriendly" by-product.

**Parameter, Value:** Separation, reclamation, and recycling of machining chips and coolant for reuse in machining cell.

**TRL:** 9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** In-situ machining waste material reclamation and recycle.

**Capability Description:** In-situ manufacturing to enable repairs of "field" hardware produce new hardware not previously identified.

**Capability State of the Art:** Not demonstrated in reduced or zero gravity environments; limited military and industrial implementation in remote locations in Earth-like environment.

**Parameter, Value:** Separation, reclamation, and recycling of machining chips and coolant for reuse in machining cell.

**Capability Performance Goal:** Waste material reclamation and recycle with the following features: lightweight, portable, modular, reconfigurable, robust, operates in a reduce gravity environment, and produces minimal quantities of unusable or "environmentally unfriendly" by-product.

**Parameter, Value:** Separation, reclamation, and recycling of machining chips and coolant for reuse in machining cell.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 7 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 7 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 7 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 7 years |

7.2 Sustainability and Supportability
7.2.3 Repair Systems

## 7.2.3.5 Welding

### TECHNOLOGY

**Technology Description:** Micro-gravity or zero-gravity process for joining of metals using fusion or solid-state welding techniques.

**Technology Challenge:** Lack of current research in the field; many fusion welding processes are dependent on gravity induced convection for proper material consolidation and as such may not produce joints in microgravity with strengths comparable to those created in a terrestrial environment; there is no facility on the ISS currently dedicated to materials joining research.

**Technology State of the Art:** No current in-space welding capability exists. Commercial-off-the-shelf (COTS) capabilities on Earth.

**Parameter, Value:**

Weld quality (minimal defects and high joint strength);
Size of equipment;
Mass of equipment;
Power of equipment.

**TRL:** 4

**Technology Performance Goal:** Performance goal is to develop processes and optimized parameters for each process which will enable assembly and rapid repair of structures in the space environment; overarching goal is to decrease astronaut dependency on Earth by enabling "quick fixes" for damaged components (for instance, in the event of impact with space debris); assembly of structures on orbit using welding technology will also reduce launch mass, lessen payload volume requirements, and improve the rigidity and survivability of space structures. Related performance goal is development of non destructive evaluation (NDE) processes for welds.

**Parameter, Value:**

Ability to produce joints in space with properties comparable to or exceeding joints produced terrestrially for the same configuration/alloy/ process;
Development/maturation of NDE technology to facilitate inspection of joints produced (eliminate need to downmass samples to Earth for evaluation);
NDE must be deployed in a space environment and reliably detect defects at confidence levels which meet or exceed the terrestrial levels associated with the process.

**TRL:** 9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** In-space welding for assembly and repair of future infrastructure.

**Capability Description:** A welding capability enables rapid repair/refurbishment of damaged components and assembly of structures in space without the use of mechanical fasteners or adhesives (compared to these techniques, welding can reduce weight, improve mechanical properties, reduce stress concentrations, and enhance rigidity).

**Capability State of the Art:** No current in-space welding capability exists, although international partners have used an e-beam unit in space.

**Parameter, Value:**

SOA is electron beam unit from– handheld tool, requires about 1 kW of power.

**Capability Performance Goal:** Small, lightweight, low power system that can be automated for safe operations, modified for use in the space environment, and reproducibly produce high quality welds (minimal defects and high joint strength).

**Parameter, Value:**

High quality welds with no leakage and no defects using lightweight, low power equipment.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 5 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 5 years |

7.2 Sustainability and Supportability
7.2.3 Repair Systems

# 7.2.3.6 Friction Stir Welding

## TECHNOLOGY

**Technology Description:** Solid state welding technique that minimizes distortion and thermal input using a high speed rotating tool. Heats and plasticizes metal but does not create a fusion (molten) pool.

**Technology Challenge:** Current lack of technologies that reduce forces to the extent that mobilization is possible; forces and size of equipment make hand held control extremely unlikely (teleoperation required) – may be possible that this technology will emerge first in another sector and can be adapted for space applications.

**Technology State of the Art:** Commercial-off-the-shelf (COTS) on Earth. Large size of equipment and high forces associated with process are limiting factors; some research is being done on mobilization of friction stir welding for use in field repairs for ships and oil and gas pipelines. There are several known techniques to reduce forces (higher rotation rates, pre-heating, tool design), but as of yet none have proved sufficient to enable significant reduction in equipment size and true mobilization of process. The process does not require shielding gas and does not melt material (mixing is mechanical rather than dependent on gravity-driven convective flow), so should in theory be largely unaffected by operation in vacuum and microgravity environment.

| Parameter, Value: | TRL |
|---|---|
| Weld quality (minimal defects and high joint strength) obtainable with portable size, mass, force and power of equipment. | 9 |

**Technology Performance Goal:** Mobile friction stir welding unit for use in the space environment; optimized parameters for joining of various joint configurations/alloys used in space structures; and reliable method of non destructive evaluation (NDE).

| Parameter, Value: | TRL |
|---|---|
| Size and mass consistent with portable use in space while maintaining weld quality in vacuum and low gravity. | 9 |

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Portable size, low mass, low force system.

**Capability Description:** Hull repair; assembly of structures.

**Capability State of the Art:** No in-space capability.

**Parameter, Value:**

No currently measured value.

**Capability Performance Goal:** Small, lightweight, low power system that can be automated for safe operations, modified for use in the space environment, and can produce high quality welds while minimizing forces required (minimal defects and high joint strength).

**Parameter, Value:**

Minimum weight, size, force, and power to obtain high quality welds (pass leak tests and industry standard inspections).

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 7 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 7 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 7 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 7 years |

7.2 Sustainability and Supportability
7.2.3 Repair Systems

# 7.2.3.7 Electron Beam Welding

## TECHNOLOGY

**Technology Description:** Fusion welding technique that uses a focused electron beam in a vacuum environment to create narrow welds with small heat affected zones. Higher power enables deeper penetration in a single pass.

**Technology Challenge:** Hand-held control requires defocused, low penetration beam; high voltage; liquid metal hazards (glove burn-through); and metal vapor contamination.

**Technology State of the Art:** Space Station Mir extravehicular activity (EVA) trials; International Space Welding Experiment; in Earth's atmosphere, this is commercial-off-the-shelf (COTS) technology.

**Parameter, Value:**

Weld quality (minimal defects and high joint strength);

Size of equipment;

Mass of equipment;

Power of equipment.

**TRL** 7

**Technology Performance Goal:** Mobile E-beam unit which is handheld (or teleoperated); optimized parameters for joint/alloy configurations in space structures; non destructive evaluation (NDE) techniques.

**Parameter, Value:**

Minimum weight and power to obtain high quality welds (pass leak tests and industry standard inspections).

**TRL** 9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Portable, low mass, lower power system with safety controls.

**Capability Description:** Gas-tight metal hull repair; assembly of structures; and component-level welding repairs in vacuum environment.

**Capability State of the Art:** Electron beam welder.

**Parameter, Value:**

Power: 1 kW

**Capability Performance Goal:** Small, lightweight, low power system that can be automated for safe operations, modified for use in the space environment, and reproducibly produce high quality welds (minimal defects and high joint strength).

**Parameter, Value:**

Minimum weight and power to obtain high quality welds (pass leak tests and industry standard inspections).

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2021 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2021 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2021 | 4 years |

7.2 Sustainability and Supportability
7.2.3 Repair Systems

# 7.2.3.8 Arc/Plasma Welding

## TECHNOLOGY

**Technology Description:** Fusion welding technique that uses an electrical arc or creates a plasma to couple the workpiece with wire fed in to create the weld bead.

**Technology Challenge:** Sensitive to arcing. Liquid metal hazards (glove burnthrough). Metal vapor contamination. Many systems require inert gas (Argon) consumable.

**Technology State of the Art:** Vacuum chamber trials in lab; in Earth's atmosphere, this is commercial-off-the-shelf (COTS ) technology.

| Parameter, Value: | TRL |
|---|---|
| Weld quality (minimal defects and high joint strength);<br>Size of equipment;<br>Mass of equipment;<br>Power of equipment. | 4 |

**Technology Performance Goal:** Arc welding unit; optimized parameters for joint/alloy configurations in space structures; and non destructive evaluation (NDE) techniques.

| Parameter, Value: | TRL |
|---|---|
| Weld quality (minimal defects and high joint strength);<br>Size of equipment;<br>Mass of equipment;<br>Power of equipment. | 9 |

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Portable, low mass, lower power system with safety controls.

**Capability Description:** Gas-tight metal hull repair; assembly of structures.

**Capability State of the Art:** Hollow cathode welder.

**Parameter, Value:**

Minimal shield/arc transfer gas flow;

Power: 1 kW

**Capability Performance Goal:** Small, lightweight, low power system that can be automated for safe operations, modified for use in the space environment, and produce high quality welds (minimal defects and high joint strength).

**Parameter, Value:**

Minimum weight and power to obtain high quality welds (pass leak tests and industry standard inspections).

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 3 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 3 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 3 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 3 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 3 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 3 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 3 years |

7.2 Sustainability and Supportability
7.2.3 Repair Systems

## 7.2.3.9 Additive Manufacturing (Three-Dimensional (3D) Printing)

### TECHNOLOGY

**Technology Description:** Freeform deposits plastic, elastomeric, or semiconductor components by extrusion or inkjet.

**Technology Challenge:** Scaleup past glovebox size, structural materials development.

**Technology State of the Art:** First plastic printer used on the International Space Station (ISS) in 2014; variety of systems available commercial-off-the-shelf (COTS) on Earth.

**Parameter, Value:**

System limited in size and complexity to fit into Microgravity Science Glovebox (MSG) on the ISS; initial experiments planned are technology demonstration only (not meeting inspection and qualification standards).

**TRL**: 6

**Technology Performance Goal:** To enable fabrication and/or recycling of plastic, elastomeric, or electronic components in space and on other planets.

**Parameter, Value:**

Part precision with usable surface finish and mechanical properties to meet service requirements for original parts being replaced.

**TRL**: 9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Additive manufacturing hardware capable of producing a variety of small (less than approximately 10 x 10 x 10 inch) components direct from computer assisted design (CAD) drawings.

**Capability Description:** Ability to build plastic, elastomeric, or multi-material components directly from CAD as repair or replacement parts for in-space supportability.

**Capability State of the Art:** First plastic printer on ISS in 2014. Project using extruded plastic filament (Fused Deposition Modeling technology) in glovebox.

**Parameter, Value:**

Part precision with usable surface finish and mechanical properties to meet service requirements for original parts being replaced.

**Capability Performance Goal:** To enable fabrication and/or recycling of plastic, elastomeric, or electronic components in space and on other planets.

**Parameter, Value:**

Hardware safe and compatible with reduced gravity environment; resulting parts must satisfy part qualification standards equivalent to those manufactured on Earth.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 5 years |

7.2 Sustainability and Supportability
7.2.3 Repair Systems

## 7.2.3.10 Three-Dimensional (3D) Scanning

### TECHNOLOGY

**Technology Description:** Lightweight, low power surface precision measurements of parts requiring repair or modification and verification of repairs made in space for certification of quality.

**Technology Challenge:** Automated scanning and identification of areas requiring repair; scale down to smaller system, and integration with manufacturing/machining capability for inspection of parts after manufacturing in space; ease of use/autonomous operation.

**Technology State of the Art:** 3D white light scanner has been deployed on Space Shuttle and International Space Station (ISS) robotic arms for imaging, inspection, and measurements; commercial-off-the-shelf (COTS).

**Parameter, Value:**

Resolution: 5 µm;

Repeatability: 12 µm with 100 W halogen lamp;

Packaged into small, lightweight system with ease of use/autonomy.

**TRL** 9

**Technology Performance Goal:** Small, lightweight system, autonomous operation, precision and accuracy to qualify parts built in space for entering into service.

**Parameter, Value:**

Resolution: 5 µm;

Repeatability: 12 µm with 100 W halogen lamp;

Packaged into small, lightweight system with ease of use/autonomy.

**TRL** 9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** 3D white light scanner.

**Capability Description:** High precision scanner that can be automated for measuring surfaces of components/structures requiring repairs and inspection and quality control measurements of repairs and parts built in space for supportability.

**Capability State of the Art:** 3D white light scanner has been deployed on Space Shuttle and ISS robotic arms for imaging, inspection, and measurements.

**Parameter, Value:**

3D surface measurement accuracy and ease of use/autonomy.

**Capability Performance Goal:** Small, lightweight system, autonomous operation, precision and accuracy to qualify parts built in space for entering into service.

**Parameter, Value:**

Resolution: 5 µm;

Repeatability: 12 µm with 100 W halogen lamp.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 5 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 5 years |

7.2 Sustainability and Supportability
7.2.3 Repair Systems

## 7.2.3.11 Electron Beam Freeform Fabrication (EBF$^3$)

### TECHNOLOGY

**Technology Description:** Metal additive manufacturing and repair technology using electron beam energy source and wire feed.

**Technology Challenge:** Scanning and programming for conducting repairs, reduce size, mass, power of system, increase precision of fabricated parts, inspection and qualification of parts for entry into service in space.

**Technology State of the Art:** EBF$^3$ technology still under development but being qualified for components on manned and unmanned aerospace structures. Current positioning system is gantry-style; small, low power system under development at NASA's Langley Research Center (LaRC) appropriate for deployment to space and use for repairs on irregular surface conditions. Ground-based systems are currently manually intensive to program and operate. EBF$^3$ feasibility in 0-g demonstrated environment during parabolic flight tests on NASA C-9 in 2007.

**Parameter, Value:**
Small, low power, and low mass system appropriate for deployment to space and use for repairs on irregular surface conditions, producing materials with sufficient strength, inspectability and certifiable for intended applications.

**TRL** 5

**Technology Performance Goal:** Precision of deposition to meet form, fit, and function of required repairs at strength required for original structure; and programming required to autonomously identify surface condition, program repair, and perform repair (or enable hand-held use for manual repairs). Minimize size, mass, and power of hardware.

**Parameter, Value:**
Small, low power, and low mass system appropriate for deployment to space and use for repairs on irregular surface conditions, producing materials with sufficient strength, inspectability and certifiable for intended applications.

**TRL** 9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Multi-scale additive manufacturing/repair capability for use in space.

**Capability Description:** Structural repairs, fill/patch holes from wear or micrometeorite strikes on hull, fabrication of replacement parts, and refurbishment of worn or broken parts.

**Capability State of the Art:** No current capability in space.

**Parameter, Value:**
No currently measured value.

**Capability Performance Goal:** Reduce size, mass, power of system, increase precision of fabricated parts, inspection and qualification of parts for entry into service in space.

**Parameter, Value:**
Part tracking for repairs, power < 1kW, system design on repositionable robotic arm enabling repairs on larger scale than size of deposition hardware.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 5 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 5 years |

7.2 Sustainability and Supportability
7.2.3 Repair Systems

## 7.2.3.12 Laser Powder Systems

### TECHNOLOGY

**Technology Description:** Melt metal powder with laser beam to form objects.

**Technology Challenge:** Large power, volume, mass; many systems require gravity.

**Technology State of the Art:** Earth-based systems are commercial-off-the-shelf (COTS) but need to be modified to operate in reduced gravity environment.

**Parameter, Value:**

Minimize mass, volume, and power of hardware. Precision of parts fabricated, material usage metrics (powder capture efficiency in parts), powder handling in reduced gravity.

**TRL** 3

**Technology Performance Goal:** Reduce size and power of equipment, improve metal powder capture efficiency and handling of unfused metal powder particles to enable metallic repairs and fabrication of component near net shapes in space and on other planets.

**Parameter, Value:**

Minimize mass, volume, and power of hardware. Precision of parts fabricated, material usage metrics (powder capture efficiency in parts), powder handling in reduced gravity. Values vary with application.

**TRL** 9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Directed energy deposition, also called Laser Engineered Net Shaping.

**Capability Description:** Melt metal powder with laser beam to form objects.

**Capability State of the Art:** None to date in space or in relevant reduced gravity environment.

**Parameter, Value:**

No currently measured value.

**Capability Performance Goal:** To enable metallic repairs and fabrication of component near net shapes in space and on other planets.

**Parameter, Value:**

Precision of parts fabricated, material usage metrics (powder capture efficiency in parts), powder handling in reduced gravity.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 4 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 4 years |

7.2 Sustainability and Supportability
7.2.3 Repair Systems

## 7.2.3.13 Ultrasonic Consolidation

### TECHNOLOGY

**Technology Description:** Low thermal input bonding technology with integrated machining capability for fabrication and repair of metal parts.

**Technology Challenge:** Generates high vibrations and waste material; large mass, volume.

**Technology State of the Art:** Still needs development on Earth; being used in research and development environments but not mature enough for transition to industry on Earth. Low heat input, low forces enabling bonding with minimal distortion; machining after deposition allows embedded sensors.

**Parameter, Value:**
Not developed enough to measure.

**TRL**
1

**Technology Performance Goal:** Increased tensile strength of materials bonded (especially across bond layers), reduced size, mass and vibrations of equipment to enable metallic repairs and fabrication of component near net shapes in space and on other planets.

**Parameter, Value:**
Mobile ultrasonic consolidation unit for use in the space environment; optimized parameters for depositing alloys used in space structures; reliable method of non destructive evaluation (NDE).

**TRL**
9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Solid state metal foil bonding using ultrasonic consolidation of thin metal foils.

**Capability Description:** Low thermal input bonding technology with integrated machining capability for fabrication and repair of metal parts.

**Capability State of the Art:** None to date in reduced gravity environment.

**Parameter, Value:**
No currently measured value.

**Capability Performance Goal:** Enable metallic repairs and fabrication of component near net shapes in space and on other planets.

**Parameter, Value:**
Minimum weight and power to obtain high quality deposits (pass certification requirements and industry standard inspections).

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 7 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 7 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 7 years |

7.2 Sustainability and Supportability
7.2.3 Repair Systems

# 7.2.3.14 Friction Stir Additive Process

## TECHNOLOGY

**Technology Description:** Low thermal input metal additive process based on friction stir welding technology with integrated machining capability for fabrication and repair of metal parts.

**Technology Challenge:** Current lack of technologies that reduce forces to the extent that mobilization is possible; forces and size of equipment make hand held control extremely unlikely (teleoperation required) – may be possible that this technology will emerge first in another sector and can be adapted for space applications.

**Technology State of the Art:** New technology under development enabling multi-material and dissimilar material additive manufacturing with low heat input (minimizes distortion and enables metal matrix composite fabrication).

| Parameter, Value: | TRL |
|---|---|
| Weld quality (minimal defects and high joint strength);<br>Size of equipment;<br>Mass of equipment;<br>Power of equipment. | 1 |

**Technology Performance Goal:** Maturation of technology to enable high strength material deposition with minimal thermal residual stresses and distortion.

| Parameter, Value: | TRL |
|---|---|
| Mobile additive friction stir unit for use in the space environment; optimized parameters for depositing alloys used in space structures; reliable method of non destructive evaluation (NDE). | 9 |

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Additive friction stir processing.

**Capability Description:** Low thermal input metal additive process based on friction stir welding technology with integrated machining capability for fabrication and repair of metal parts. None to date in reduced gravity environment.

**Capability State of the Art:** None to date in reduced gravity environment.

**Parameter, Value:**

No currently measured value.

**Capability Performance Goal:** Small, lightweight, low power system that can be automated for safe operations, modified for use in the space environment, and produce high quality deposits (with minimal defects and high joint strength).

**Parameter, Value:**

Minimum weight and power to obtain high quality deposits (pass certification requirements and industry standard inspections).

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 7 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 7 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 7 years |

7.2 Sustainability and Supportability
7.2.3 Repair Systems

## 7.2.3.15 In-Situ Manufactured Parts/Components Verification and Certification

### TECHNOLOGY

**Technology Description:** Lightweight, low power through-thickness non destructive evaluation (NDE) of parts fabricated in space for certification of quality.

**Technology Challenge:** Wireless encoder or movement tracking technology is used in gaming and other applications but needs to be integrated in a NDE scanner which works with commercial-off-the-shelf (COTS) NDE instruments.

**Technology State of the Art:** The phased array ultrasonic instrument scanning application for micrometeoroid and orbital debris (MMOD) damage assessment has been demonstrated to astronauts.

| Parameter, Value: | TRL |
|---|---|
| Integration of wireless encoder in phased array instrument, minimizing mass, volume, and ease of use for single-operator or robotic operations. | 4 |

**Technology Performance Goal:** Need to eliminate the mechanical encoder and replace it with wireless encoder to make it practical for one crew member to complete the scan (manually or robotically).

| Parameter, Value: | TRL |
|---|---|
| Integration of wireless encoder in phased array instrument, minimizing mass, volume, and ease of use for single-operator or robotic operations. | 9 |

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** NDE: phased array ultrasonic scanning from intravehicular activity (IVA).

**Capability Description:** Ultrasonic scanning can map suspect space vehicle pressure wall damage region in areas accessible from IVA and can be demonstrated on the International Space Station (ISS) for MMOD impact damage.

**Capability State of the Art:** Current inspections on the ISS are visual-only, detecting external damage but not measuring damage below the surface of the structure.

**Parameter, Value:**

No currently measured value.

**Capability Performance Goal:** Need to eliminate the mechanical encoder and replace it with wireless encoder to make it practical for one crew member to complete the scan.

**Parameter, Value:**

Integration of wireless encoder in phased array instrument, minimize mass, volume, and ease of use for single-operator or robotic operations.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 6 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 6 years |

7.2 Sustainability and Supportability
7.2.4 Food Production, Processing, and Preservation

## 7.2.4.1 Bioregenerative Food System

### TECHNOLOGY

**Technology Description:** A food system that grows plants and stores until use.

**Technology Challenge:** A food system that is safe, nutritious, and acceptable is not available for all Design Reference Missions (DRMs) due to shelf life and delivery limitations.

**Technology State of the Art:** A portable pop-up greenhouse was taken to the International Space Station (ISS) in April. The system will grow lettuces to prove system concept; however, the vegetables will be flown to ground for testing to determine if they are safe to eat.

**Parameter, Value:**
Percentage of crew food intake derived from foods grown onboard: 0%

**TRL** 5

**Technology Performance Goal:** Development of a bioregenerative food system that meets the requirements for ingredient functionality/nutrition, bulk storage, equipment, processing and preparation procedures, and resource use.

**Parameter, Value:**
Percentage of crew food intake derived from foods grown onboard: > 10%

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** The kinetics of vitamin losses through processing and storage of the food items and the amount of remaining nutrition at the end of five years is unknown. The effect of ingredient interactions and food matrices on nutrient stability in the food system is also unknown.

### CAPABILITY

**Needed Capability:** Bioregenerative food system.

**Capability Description:** Ability to grow food to supplement stored food supplies.

**Capability State of the Art:** A flight demonstration test article is on the ISS to grow lettuces to prove system concept, including whether the lettuce is safe to eat.

**Parameter, Value:**
Percentage of crew food intake derived from foods grown onboard: 0%

**Capability Performance Goal:** Development of a bioregenerative food system that meets the requirements for ingredient functionality/nutrition, bulk storage, equipment, processing and preparation procedures, and resource use.

**Parameter, Value:**
Percentage of crew food intake derived from foods grown onboard: > 10%

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enabling | 2027 | 2027 | 2021 | 7 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 7 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 7 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 7 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 7 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 7 years |

7.3 Human Mobility Systems
7.3.1 EVA Mobility

## 7.3.1.1 Exoskeletons

### TECHNOLOGY

**Technology Description:** Electro/mechanical assistive elements to augment human capability.

**Technology Challenge:** Key challenges in this area are how to enable space based systems that will work for very long spans of time, how to make the systems safe for human use over long spans of time, integration into extravehicular activity (EVA) suits, and effect of these technologies in different gravity environments.

**Technology State of the Art:** Lower extremety exoskeletons for assisted mobility of handicapped (Rewalk). The human universal load carrier device in military trials.

**Parameter, Value:** 10-30% increase in work done (raw estimates).

**TRL** 4

**Technology Performance Goal:** Kinematically couple devices to a user that increase efficacy of human operators.

**Parameter, Value:** 10-30% increase in work done (raw estimates).

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** Verification and validation of exoskeleton performance in variable gravity environments using motion based test systems.

### CAPABILITY

**Needed Capability:** Wearable robotic systems.

**Capability Description:** Electro/mechanical assistive elements to augment human capability. Components worn by humans to augment, monitor and/or assist crew activities.

**Capability State of the Art:** Not in use in space today.

**Parameter, Value:** No currently measured value.

**Capability Performance Goal:** The best measure may be to gauge human effectiveness measures compared to metabolic costs. We want to enhance effectiveness without raising the metabolic cost.

**Parameter, Value:** Increase work done by 50% at the same metabolic cost.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 7 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 7 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 7 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 7 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 6-8 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6-8 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 6-8 years |

7.3 Human Mobility Systems
7.3.1 EVA Mobility

## 7.3.1.2 Suitport

### TECHNOLOGY

**Technology Description:** A piece of hardware that replaces an airlock and allows a spacesuit to be mated to the side of a vehicle. The crew dons the suit through a rear entry hatch. In a suitport system, the dustiest parts of the suit (gloves, arms, boots, etc.) remain outside the pressurized cabin and reduce the possibility of dust from those components from entering the cabin. The suitport can be used by itself or in conjunction with an airlock (often referred to as a "hybrid" or suitport-airlock). Suitport technology is most enabling for mobile assets such as pressurized rovers.

**Technology Challenge:** Development of a suitport is a unique piece of hardware that requires integration between the hardware under development and the Advanced Extravehicular Mobility Unit (EMU). Operating this hardware in a dusty environment is expected to be a challenge. For surface operations, suit restraints and an environment cover will be needed to protect the exposed suit against vibration loads. Tackling the thermal aspects of this hardware will likely also be a challenge. Initial testing in limited chamber activities, while demonstrating feasibility has also demonstrated issues with repeated donning of pressurized suits, with multiple subjects stuck in an intermediate position, unable to complete donning and unable to complete doffing. Vehicle (suitport) changes as well as suit changes are needed to correct this problem. Confidence must be developed that no subjects will experience this event in the final design. Suitports are likely to operate at a lower atmospheric pressure to gain full advantage of lower prebreathe times.

**Technology State of the Art:** Suitport has been demonstrated as feasible in limited chamber.

| Parameter, Value: | TRL |
|---|---|
| 10-15 minutes in a 1g environment. | 3 |

**Technology Performance Goal:** Develop suitport maturity to demonstrate the capability in the relevant environment and ensure feasibility in a dusty environment.

| Parameter, Value: | TRL |
|---|---|
| Durability: operate for a minimum of 500 extravehicular activities (EVAs) in a dusty environment; Ease of repeated ingress: to be determined;<br>Total Free Gas Volume beyond portable life support system (PLSS) out mold life (OML): 3 $ft^3$. | 6 |

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Enhanced extravehicular activity (EVA) access.

**Capability Description:** Future exploration architectures will require frequent/rapid EVA while also providing significant dust mitigation and reduction in usage of consumables.

**Capability State of the Art:** International Space Station (ISS) and Space Shuttle both have airlocks to enable EVA.

**Parameter, Value:**

Approximately three hours are needed to get ready for an EVA;

Over 100 $ft^3$ of airlock volume to either vent or expend power to recapture the atmosphere

**Capability Performance Goal:** Want to enable crew members to be outside within minutes while reducing vehicle consumables (gas and power) and reducing dust introduction into the cabin.

**Parameter, Value:**

10 minutes to get ready for EVA in a low gravity environment;

Total Free Gas Volume beyond PLSS OML: 3 $ft^3$

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 6 years |

7.3 Human Mobility Systems
7.3.1 EVA Mobility

# 7.3.1.3 Advanced Tools Development for Extravehicular Activity (EVA)

## TECHNOLOGY

**Technology Description:** Tools used by crew member during extravehicular activity that enable collection and analysis of geology samples.

**Technology Challenge:** Building a complete set of microgravity EVA tools that enable safe EVA operations and collection of geology samples worthy of returning while minimizing mass, power, and volume is a significant challenge given the broad array of planetary geology science objectives and the competing vehicle limitations.

**Technology State of the Art:** Micro-g EVA body stabilization techniques assume engineered structure exists to attach to. Geology tasks have never been done in micro-g EVA, only in partial gravity on the lunar surface. Sample collection, where the greatest challenge lies in obtaining the samples without contamination and not losing them as the float away (the geology samples don't come with "tether points"). Hard rock drilling in 0-g thermal vac has not been tested.

| Parameter, Value: | TRL |
|---|---|
| No currently measured value. | 2 |

**Technology Performance Goal:** High-resolution imagery with near-infrared (IR) and ultraviolet (UV) capability. Develop an EVA operable X-ray fluorescent spectrometer. Develop a one meter-capable EVA operable core drill unit capable of obtaining samples in less than four hours from hard rock without liquid cooling of the drill bits. Develop an EVA deployable/operable geophone system. Develop an EVA deployed retroreflector.

| Parameter, Value: | TRL |
|---|---|
| Microgravity operation;<br>Parameters vary with application. | 6 |

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Advanced tools development for EVA.

**Capability Description:** EVA tools have been successfully used for planetary (lunar) surface science operations in the Apollo Program as well as microgravity construction and maintenance tasks (low-Earth orbit) in the Skylab, Space Shuttle, and International Space Station (ISS) Programs. However, the blending of natural sciences such as geology with the microgravity environment has yet to be done. This is applicable to Near Earth Asteroids and Mars Moon operations as those surfaces represent natural bodies for scientific investigation but do not have the benefit of significant gravity levels. This should include microgravity anchoring, stability, and translation on non-engineered surfaces, sample collection for loosely adhered surface particles, sample collection and containment for break chips of larger geology samples in micro-g, subsurface (core) sampling, and in-situ high-grading instrumentation.

**Capability State of the Art:** Current EVA tools primarily focus on ISS construction and maintenance tasks in microgravity, most recently on as-required vehicle maintenance when failures occur. Geologic sampling to date has only been done in 1g or partial gravity environments; sample capture systems have not been developed that contain samples in micro-g. Core drilling for subsurface samples was successfully done on the lunar surface but only in compacted regolith (soil) so the drill bits did not require active cooling. Active (flush) cooling is commonly done on Earth's surface with liquid water which would not be acceptable for a thermal vacuum, all other known fluids would be difficult to manage in micro-g.

**Parameter, Value:**

Apollo lunar surface tools relied upon gravity. Core drills did not use active cooling and were for loose soil only.

**Capability Performance Goal:** Assessment of textural and mineralogical heterogeneity of the sampled body will be critically important for site and sample selection. EVA operable high-resolution cameras with in-situ highgrading instruments. Collection of at least 1,000 grams of material from two sites. Collection of 5 centimeter diameter core samples from at least 4 centimeters in depth, preferably 1 meter depth. Measurement of porosity and internal structure of an near-Earth asteroid (NEA). Apply surveying tools to track deformation of the asteroid.

**Parameter, Value:**

High-resolution imagery with near-IR and UV capability. Develop an EVA operable X-ray fluorescent spectrometer. Develop a one meter-capable EVA operable core drill unit capable of obtaining samples in less than four hours from hard rock without liquid cooling of the drill bits. Develop an EVA deployable/operable geophone system. Develop an EVA deployed retroreflector.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enabling | 2022 | 2022 | 2015-2021 | 5 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enabling | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 5 years |

7.3 Human Mobility Systems
7.3.1 EVA Mobility

# 7.3.1.4 Sample Storage and Curation, Low Mass, Low Power

## TECHNOLOGY

**Technology Description:** System to store sample at needed environment parameters.

**Technology Challenge:** Controlling the samples after collection is highly important to maximize the scientific data that can be collected.

**Technology State of the Art:** Current International Space Station (ISS) "cold stowage" hardware is capable of reaching temperatures in the range for volatile preservation, though active systems require power through all phases of flight from sample obtainment to return. Passive systems are time-limited and do not meet most Design Reference Mission (DRM) timelines.

**Parameter, Value:**

Power: depends on application;

Storage volume: depends on application;

Operating temperature: depends on application;

Passive storage duration: depends on application.

**TRL:** 2

**Technology Performance Goal:** Maintain samples at required temperature and environment with reduced power and storage volume.

**Parameter, Value:**

Power: values vary with application;

Storage volume: values vary with application;

Operating temperature: values vary with application;

Vacuum or inert gas purge level: values vary with application;

Storage duration: values vary with application.

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Sample storage and curation, low mass, low power.

**Capability Description:** Design, development, test, and evaluation (DDT&E) for sample curation, packaging, and labeling. Some samples may be considered volatile or require special handling, including storage at vacuum and refrigerated conditions. Development and evaluation to be conducted with detailed scientific community input.

**Capability State of the Art:** Apollo had limited sample collection and storage capability. Samples collected during Apollo experienced ambient thermal conditions after collection and return. Sealed containers protected samples from the intravehicular activity (IVA) environment, though issues with materials, construction, and post-return processing techniques limited scientific investigations. On the Space Shuttle and ISS, cold stowage solutions exist for microbiology samples and have been successfully utilized with vehicles having large down/upmass and powered return for short duration (single-digit days).

**Parameter, Value:**

Samples remained at ambient temperature and pressure; in some cases specialized sealed containers prevented contact between the samples and the IVA environment. On the Space Shuttle and ISS, specialized containers were used to protect crew from health impacts of biological samples.

**Capability Performance Goal:** Maintain samples at required temperature and environment with reduced power and storage volume.

**Parameter, Value:**

Power: values vary with application;

Storage volume: values vary with application;

Operating temperature: values vary with application;

Vacuum or inert gas purge level: values vary with application;

Storage duration: values vary with application.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enabling | 2022 | 2022 | 2015-2021 | 6 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enabling | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 6 years |

7.3 Human Mobility Systems
7.3.1 EVA Mobility

## 7.3.1.5 Anchoring

### TECHNOLOGY

**Technology Description:** Restraint for human exploration of bodies and destinations where minimal gravity exist to support extravehicular activity (EVA) of in-space assets like asteroids to safely acquire samples or perform in-place analysis of indigenous materials.

**Technology Challenge:** Designing solutions that provide safe restraint to crew while allowing free range of motion in a spacesuit.

**Technology State of the Art:** Portable handholds while executing operations on the International Space Station (ISS). Circumferential rope tether for terrestrial applications. Applications utilized for the ISS can be mimicked for similar conditions on man-made elements. Circular rope concepts or similar netting concepts that enable crew to scale and examine small bodies.

**Parameter, Value:**

Installation time: many hours typical on the ISS;

Attachment force: varies based on tools being used;

Compatibility with some irregular interfaces.

**TRL** 4

**Technology Performance Goal:** Lightweight, relocatable, adjustable restraint requiring minimal force that is within the human factors limits for crew, and provides freedom of movement.

**Parameter, Value:**

EVA Crew-deployed/installed anchor point(s) that do not require continuous vehicle thrust or station keeping to maintain attachment to a natural micro-g surface such as an near-Earth asteroid (NEA);

Setup time of 5 minutes per installation for single attachment points, less than 2.27 kilograms per individual “left-behind” attachment interface;

Compatible with irregular interfaces.

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Low-gravity body anchoring systems for crew restraint/placement and positioning during EVA. Enables anchoring of tethers or surface components on low-gravity bodies.

**Capability Description:** Temporary restraint and support allowing crew to translate or suspend from objects during EVA at small bodies and on maintenance/crew operations missions in micro-g or partial-g conditions. This includes portable restraints, grappling aids, and ‘assemble/deploy in place’ solutions that enable or enhance exploration of unique characteristics under varying conditions.

**Capability State of the Art:** Portable handholds to facilitate crew movement during maintenance missions or for use as restraints exists for known operations on the ISS. The ISS uses well-defined interfaces such as hand rails as opposed to unknown rocky surfaces.

**Parameter, Value:**

Compatible with well-defined interfaces.

**Capability Performance Goal:** Lightweight, relocatable, adjustable restraint requiring minimal force that is within the human factors limits for crew, and provides freedom of movement. Clamping force to safely facilitate crew operations. Grappling with or without the aid of mechanized inflatable, helical, or harpoon anchor is covered in TA 4.

**Parameter, Value:**

EVA crew-deployed/installed anchor point(s) that do not require continuous vehicle thrust or station keeping to maintain attachment to a natural micro-g surface such as an NEA;

Setup time of 5 minutes per installation for single attachment points, less than 2.27 kilograms per individual “left-behind” attachment interface;

Compatible with irregular interfaces.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enabling | 2022 | 2022 | 2015-2021 | 6 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enabling | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 6 years |

7.3 Human Mobility Systems
7.3.1 EVA Mobility

# 7.3.1.6 Advanced Airlock/Suitlock

## TECHNOLOGY

**Technology Description:** A device that permits the passage of people and objects between a pressure vessel and its surroundings while minimizing the changes in pressure in the vessel and loss of air from it.

**Technology Challenge:** Provide airlock capability that reduces vehicle mass, decreases egress and ingress times, extends suit life, and provides increased environmental protection.

**Technology State of the Art:** The International Space Station (ISS) airlock is the SOA. Dust mitigation technologies are commercially available and are commonly applied on Earth for handling hazardous materials. These technologies have been demonstrated on the ground as part of the Desert Research and Technology Studies (RATS) test.

**Parameter, Value:**

Gas loss: 10's of pounds of gas each EVA;

Dust intrusion: not measured

**TRL**

3

**Technology Performance Goal:** Depending on approach chosen, reductions in lost gases of at least 20 to 30%. Extending suit life is harder to measure. Minimize dust entrance to maximum extent possible compared to Apollo.

**Parameter, Value:**

Gas loss: 20-30% lower;

Dust intrusion: minimized to maintain surface systems within operating requirements

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Enhanced EVA access.

**Capability Description:** Future exploration architectures will require frequent/rapid EVA, employing systems that allow crews to doff and don spacesuits outside of habitable volumes, while also providing significant dust mitigation and reduction in usage of consumables. All missions will have launch mass and volume limitations that relate to airlocks primarily through the structure and pressurizing gas.

**Capability State of the Art:** The ISS and Space Shuttle both have airlocks to enable EVA. Orion plans to depressurize the entire cabin, as was done in Gemini and Apollo.

**Parameter, Value:**

Approximately 3 hours needed to get ready for an EVA. Over 100 $ft^3$ of airlock volume to either vent or expend power to recapture the atmosphere. Advanced airlock systems may have to operate at reduced pressures to reduce prebreathe time.

**Capability Performance Goal:** Reduce EVA consumables (gas and power) by at least 20% compared to the ISS. Minimize/ eliminate dust entry to habitable volumes.

**Parameter, Value:**

Maintain surface systems within operating requirements in a dusty environment for 3 EVAs per week for 500 days or 214 EVAs over a 500-day mission.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 6 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 6 years |

7.3 Human Mobility Systems
7.3.1 EVA Mobility

## 7.3.1.7 Incapacitated Extravehicular Activity (EVA) Crew Rescue Devices

### TECHNOLOGY

**Technology Description:** Hardware and techniques for rescue of incapacitated extravehicular activity (EVA) crew in partial gravity environments.

**Technology Challenge:** Flight hardware and techniques for rescue of incapacitated crew over rough terrain in a partial gravity environment.

**Technology State of the Art:** Commercially available equipment for avalanche recovery and other types of terrestrial rescue equipment.

| **Parameter, Value:** | **TRL** |
|---|---|
| Designed for terrestrial use in 1g with one or more operators. | 4 |

**Technology Performance Goal:** Volume and masses appropriate for delivery to partial gravity destinations such as the surface of Earth's Moon or Mars.

| **Parameter, Value:** | **TRL** |
|---|---|
| Minimal hardware capable over diverse terrain. Components must make physical contact with incapacitated crew member. Crew member to be carried by rescuing crew in a single traverse, either attached to a suit of rescuing crew member or carried in one hand across undulating terrain, inclusive of traverse across changes in elevation. | 6 |

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** Design Reference Mission (DRM) Concept of Operations and development/advancement of the EVA Systems (see TA 6.2)

### CAPABILITY

**Needed Capability:** Incapacitated EVA crew rescue.

**Capability Description:** Design, development, test, and evaluation (DDT&E) of incapacitated EVA crew rescue device(s) that is operable in partial gravity destinations without regard to anthropometric differences among crew members and taking into account physical debilitation resulting from reduced gravity exposure. Development needs to be integrated with the EVA suit development efforts (see TA 6.2).

**Capability State of the Art:** Conventional rescue methods for EVA are limited to microgravity where the weightless environment works to the advantage of the rescuing crew member.

**Parameter, Value:**

No additional hardware required for rescue, clear translation paths on pre-engineered surfaces such as International Space Station (ISS) modules.

**Capability Performance Goal:** Single-crew deployment and operation in the partial gravity environment, with recovery of an incapacitated crew member over a 200-meter separation distance, over undulating surfaces in 30 minutes. The distance is measured from the location of the incapacitated crew to the location of a designated recovery point.

**Parameter, Value:**

Compatible with a suited but incapacitated EVA crew member, operable by any crew member without regard to anthropometric differences, and compatible with the partial gravity environment and accompanying crew member's physical debilitation resulting from microgravity transit and partial gravity destination exposure.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crew to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 5 years |

7.3 Human Mobility Systems
7.3.2 Surface Mobility

## 7.3.2.1 Strontium Aluminate (Photoluminescent) Markers for Exterior Markings

### TECHNOLOGY

**Technology Description:** A photo-luminescent material that can be formed into decals for labeling items outside a vehicle, spaceflight system, or path traveled. It is currently used on the International Space Station (ISS) habitable environment for emergency egress guidance. It is "charged" by the ambient lighting environment, and when exposed to enough light, can hold its charge and be visible for at least eight hours. It is currently only used for interior marking, but could be made very useful for external non-powered lighting where it is charged by sunlight and then available for crew safety when portions of the spacecraft are in shadow due to operations.

**Technology Challenge:** The material has not been certified for extravehicular activity (EVA) or the external spacecraft environment.

**Technology State of the Art:** Used for emergency egress markings when ISS lighting/power is disrupted.

**Parameter, Value:** Internal use.

**TRL** 6

**Technology Performance Goal:** Certify for external spacecraft use and apply technology for safety/passage marking for robotics and crew EVA.

**Parameter, Value:** External use.

**TRL** 9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Mark spacecraft with markers that are visible without artificial light sources to increase visibility of the spacecraft for rendezvous, proximity operations, and docking (RPOD) operations and to increase safety of crew when they are performing external operations without sunlight.

**Capability Description:** RPOD and EVA require a strong sense of situational awareness to reduce stress on crew and increase safety during spacecraft operations.

**Capability State of the Art:** Used for emergency egress marking inside spacecraft.

**Parameter, Value:** Internal use.

**Capability Performance Goal:** Material is certified for usage. Human factors testing to determine best usage of markers for RPOD and EVA safety improvements.

**Parameter, Value:** External use.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 2 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 2 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 2 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 2 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 2 years |

7.3 Human Mobility Systems
7.3.2 Surface Mobility

## 7.3.2.2 Light Emitting Plasma (LEP) Technology

### TECHNOLOGY

**Technology Description:** A solid-state lighting technology that generates high quality broad-spectrum lighting at high lumen intensities at much lower power levels than other technologies such as High Intensity Discharge (HID).

**Technology Challenge:** LEP uses a waveguide to deliver high power radio frequencies to the LEP gas capsule, which is the size of a grain of rice. The gas inside the capsule excites and emits plasma (much similar to the glow of a lightning bolt). The challenge is that NASA has strict requirements on radio emissions and this technology has not been tested to NASA environmental standards to determine survivability and usability.

**Technology State of the Art:** Commercially available roadway light sources and high intensity lamps for fiber optic remote lighting solutions.

**Parameter, Value:**
Lumens: values vary with application;
Power: values vary with application.

**TRL** 3

**Technology Performance Goal:** Reduce weight, power, and the need to ship fragile glass HID bulbs.

**Parameter, Value:**
Lumens: values vary with application;
Power: values vary with application.

**TRL** 5

**Technology Development Dependent Upon Basic Research or Other Technology Candidate: LEP research and market for LEP. NASA acceptance of a light source that contains a radio frequency (RF) source that is not used for communications.**

### CAPABILITY

**Needed Capability:** External spacecraft lighting.

**Capability Description:** External lighting is used for extravehicular activity (EVA), docking, and robotics tasks for spacecraft.

**Capability State of the Art:** HID lighting.

**Parameter, Value:**
Lumens: values vary with application;
Power: values vary with application.

**Capability Performance Goal:** Reduce maintenance, fragility, weight, and power usage of vehicle external light sources while maintaining or improving light quality in intensity, spectrum, and visual acuity of crew and equipment that use the lighting.

**Parameter, Value:**
Lumens: values vary with application;
Power: values vary with application.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 4 years |

7.3 Human Mobility Systems
7.3.3 Off-Surface Mobility

# 7.3.3.1 Advanced Extravehicular Activity (EVA) Jetpacks

## TECHNOLOGY

**Technology Description:** System that provides extravehicular mobility for incapacitated crew members with hands-free or voice control.

**Technology Challenge:** The key challenges for improving these systems are to incorporate much longer mission times and delta V into smaller packages. There is also a significant need to improve the human interface and reduce the amount of direction from the human.

**Technology State of the Art:** Manned Maneuvering Unit (MMU) and Simplified Aid for EVA Rescue (SAFER) have flown in space. Tridyne has been tested in a laboratory. Li-ion batteries have been used in space. Autonomy and size/mass reduction possibilities demonstrated in Mini-autonomous extravehicular robotic camera (AERCam) ground demo unit. Hands-free control technologies demonstrated with virtual reality. SAFER simulation and flat floor demonstration prototype have been demonstrated on the ground.

**Parameter, Value:**

Fault tolerance/Controllability: values vary;
Delta V/unit mass amp-hours/unit mass: values vary;
Autonomy: values vary;
Size: values vary;
Mass: values vary;
Reliability: values vary

**TRL:** 3

**Technology Performance Goal:** Reduced mass, greater autonomy, incresed fault tolerance, and longer operating time.

**Parameter, Value:**

Mass: < 75 pounds;
Delta V: > 40 feet per second;
Propellant: Tri-dyne;
Operating time: 8 hours;
Fault tolerant: > Single;
Recharageable on orbit: yes;
Autonomy:
- Attitude hold,
- Position hold,
- Obstacle avoidance,
- Hands-free control,
- Destination commanding,
- Remote commanding for incapacitated crew and/or mobility for humanoid robot.

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** Verification and validation of jetpack performance using motion based test systems.

## CAPABILITY

**Needed Capability:** Advanced extravehicular activity (EVA) jetpacks.

**Capability Description:** Advanced EVA jetpacks will be semi-autonomous and fault-tolerant, allowing them to be used as a primary mode of EVA mobility and to provide rescue capability for incapacitated EVA crew members. The system will be capable of being controlled either manually or via voice command by the EVA crew member, being teleoperated in either mode by an IVA crew member, and performing pre-defined tasks such as “translate to worksite A” or “emergency return to airlock.” These capabilities will be enabled by navigation sensors and a communications system. If multiple spacewalks are to be performed on a given flight, the ability to replenish propellant and power will be required.

**Capability State of the Art:** The Space Shuttle MMU and International Space Station (ISS) SAFER.

**Capability Performance Goal:** Reduced mass, greater autonomy, incresed fault tolerance, and longer operating time.

| CAPABILITY - CONTINUED | |
|---|---|
| **Parameter, Value:**<br>The Space Shuttle MMU had these characteristics:<br>Mass: 340 pounds;<br>Delta V: 75 feet per second;<br>Propellant: Gaseous Nitrogen;<br>Operating time: 6 hours;<br>Fault tolerant: Single;<br>Recharageable on orbit: yes;<br>Autonomy: Attitude hold.<br>The ISS SAFER is the most recent tool that fits in these categories and has these characteristics:<br>Mass: 80 pounds;<br>Delta V: 10 feet per second;<br>Propellant: Gaseous Nitrogen;<br>Operating time: 75 minutes;<br>Fault tolerant: zero;<br>Recharageable on orbit: no;<br>Autonomy: Attitude hold | **Parameter, Value:**<br>Mass: < 75 pounds;<br>Delta V: > 40 feet per second;<br>Propellant: Tri-dyne;<br>Operating time: 8 hours;<br>Fault tolerant: > Single;<br>Recharageable on orbit: yes;<br>Autonomy:<br>Attitude hold,<br>Position hold,<br>Obstacle avoidance,<br>Hands-free control,<br>Destination commanding,<br>Remote commanding for incapacitated crew and/or mobility for humanoid robot. |

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 6 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 6 years |

7.4 Habitat Systems
7.4.1 Integrated Habitat Systems

## 7.4.1.1 Low-Toxicity, Fire-Retardant Textiles

### TECHNOLOGY

**Technology Description:** Textile materials that operate in a low pressure, high oxygen environment to enable crew psychological well-being and safe operations of human exploration spacecraft and habitats.

**Technology Challenge:** Technology challenges include developing non-toxic, flame retardant, multi-color, easy cleaning (or self-cleaning) textile fabrics that can be human-rated certified for operational use in a 8.2 psia and high oxygen (32-34%) enclosed spacecraft environment. Safety and functionality are of the utmost importance for the selection and development of new fabrics. This means that aside from toxicity and flammability other characteristics must be present such as durability, dimensional stability, and retention of aesthetic quality.

**Technology State of the Art:** High-tech fabric and bio-coating wall coverings are used in architecture and smart homes. “Nano,” environmentally friendly, and low toxicity flame retardant protects fabric.

| **Parameter, Value:** | **TRL** |
|---|---|
| Many colors, Bio-self cleaning, Low toxicity, Low flammability. | 4 |

**Technology Performance Goal:** Multiple colored fabrics with less mass, very low toxicity, and flame retardant materials to be used in spacecraft operating environment with pressure of 8.2 psia and 32-34% oxygen.

| **Parameter, Value:** | **TRL** |
|---|---|
| Toxicity level: 50% less mass (50% less than current Nomex ppm);<br>Off gassing levels: 50% less;<br>Flame spread rating: 4 Cal/cm$^2$; Available in 8 colors with unrestricted use per volume. | 6 |

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** Material flammability and flame propagation characteristics.

### CAPABILITY

**Needed Capability:** Fabric wall coverings, fabric walls, close-out panels, and crew systems.

**Capability Description:** Provide human spaceflight qualified multi-color fabric wall coverings, fabric walls, close-out panels, and crew systems to enable crew psychological well-being and safe operations of human exploration spacecraft and habitats. Also could be used for cargo transfer bags and then repurposed for other uses.

**Capability State of the Art:** International Space Station (ISS): Nomex (white and blue):

White: no limits in spacecraft volume;

Blue: spacecraft volume limited to 10 square feet per 100 cubic feet of volume.

**Parameter, Value:**

White with limited use of blue in spacecraft volume;

Toxicity level: unavailable ppm;

Off gassing levels: unavailable ppml;

Flame spread rating: unavailable per square foot

**Capability Performance Goal:** Provide low-toxicity, fire-retardant textiles in multiple colors for use in a spacecraft and exploration habitat.

**Parameter, Value:**

Toxicity level: 50% less mass (75% less than current Nomex ppm)

Off gassing levels: 75% less;

Flame spread rating: 4 Cal/cm$^2$;

Available in 8 colors: unrestricted use per volume;

Consider Pressure: 8.2 psia;

High oxygen: 32-34% environment

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 6 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 6 years |

7.4 Habitat Systems
7.4.1 Integrated Habitat Systems

## 7.4.1.2 Anti-Microbial Coatings

### TECHNOLOGY

**Technology Description:** A thin layer covering a surface that deters microbial growth harmful to humans, filters, pipes, and mechanisms in a high oxygen ($O_2$) environment.

**Technology Challenge:** Technology challenges include developing non-toxic anti-microbial coating that will result in a reduction in harmful microbial bacteria and fungi growth in a spacecraft. Other challenges include longevity degradation of the coating, non-harmful off-gassing, and human-rating the coating.

**Technology State of the Art:** Antimicrobial surfaces are functionalized in a variety of different processes. A coating may be applied to a surface that has a chemical compound which is toxic to microorganisms. Other surfaces may be functionalized by attaching a polymer, or polypeptide, to its surface.

| Parameter, Value: | TRL |
|---|---|
| Reduction in harmful microbial bacteria and fungi growth in pipe lines, waste systems, etc. | 3 |

**Technology Performance Goal:** Provide reduction of harmful microbial bacteria and fungi growth within a human spacecraft.

| Parameter, Value: | TRL |
|---|---|
| Maximum for Bacteria:<br>Air: 1000 CFU/m$^3$;<br>Internal Surfaces: 10,000 CFU/100 cm$^2$<br>Maximum for Fungi:<br>Air: 100 CFU/m$^3$;<br>Internal Surfaces: 100 CFU/100 cm$^2$ | 6 |

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 6.1.4 Habitation; 6.4.1 Sensors: Air, Water, Microbial, and Acoustic; 8.1 Remote Sensing Instruments and Sensors; 8.3 In-Situ Instruments and Sensors; 12.1.5 Special Materials

### CAPABILITY

**Needed Capability:** Antimicrobial bio-coatings for surfaces and textiles.

**Capability Description:** Prevent harmful (to humans and subsystems/components) microbial growth on surfaces, filters, pipes, and mechanisms.

**Capability State of the Art:** ISS: sanitary wipes and biocides. Manual crew cleaning. Effects crew time, trash disposal, toxins into waste recycling stream.

Extravehicular Mobility Unit (EMU): the EMU program has adopted TCHDE for antimicrobial coating many textiles including those utilized on the inside of the EMU.

**Parameter, Value:**

Maximum for Bacteria:
Air: 1000 CFU/m$^3$;
Internal Surfaces: 10,000 CFU/100 cm$^2$
Maximum for Fungi:
Air: 100 CFU/m$^3$;
Internal Surfaces: 100 CFU/100 cm$^2$

**Capability Performance Goal:** Provide reduction of harmful microbial bacteria and fungi growth within a human spacecraft.

**Parameter, Value:**

Pressure: 8.3 psia, 841 kilopascal;
High oxygen: 30-34% environment;
Non-toxic

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 6 years |

7.4 Habitat Systems
7.4.1 Integrated Habitat Systems

## 7.4.1.3 Exploration Habitat Performance Monitoring Embedded Sensors

### TECHNOLOGY

**Technology Description:** Subsystem performance sensors to monitor and provide real-time feedback wirelessly to the Intelligent Habitat (iHab) operating system.

**Technology Challenge:** Technology challenges include providing reliable wireless sensors; low power; long battery life; and integrated operating systems with high data rates that will be incorporated into fabrics, floors, walls, surfaces, mechanisms, subsystems, and components to monitor performance and link wirelessly to the intelligent operating system. The iHab operating system provides autonomous monitoring, automated failure isolation and recovery, and situational awareness to the crew.

**Technology State of the Art:** Other government agencies are embedding sensors. High-reliability, low data-rate wireless protocols currently deployed in process control (e.g., ISA100.11a, WirelessHART).

**Parameter, Value:**
Mass, volume, battery life, reliability, mean time between failure (MTBF).

**TRL**
4

**Technology Performance Goal:** Enable to monitor performance of spacecraft mechanisms, subsystems, and components which will link wirelessly to the intelligent operating system.

**Parameter, Value:**
Sample rate: 2x;
Data storage: 3x;
Battery life: 10 years

**TRL**
6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 8.1 Remote Sensing Instruments and Sensors; 8.3 In-Situ Instruments and Sensors; 12.1.5 Special Materials; 11.2.3 Human-Systems Performance Modeling; 11.3.2 Integrated System Lifecycle Simulation; 11.3.3 Simulation-Based Systems Engineering; 6.4.1 Sensors: Air, Water, Microbial, and Acoustic.

### CAPABILITY

**Needed Capability:** iHab, autonomous operations, human-tended quiescent mode operations.

**Capability Description:** Provide long-life, reliable, battery operated wireless sensors that will be incorporated into fabrics, floors, walls, surfaces, mechanisms, subsystems, and components to monitor performance and link wirelessly to the intelligent operating system. The iHab operating system provides autonomous monitoring, automated failure isolation and recovery, and situational awareness to the crew.

**Capability State of the Art:** Orbiter Wing Leading Edge: wireless sensors have been embedded into the Space Shuttle/Orbiter wing leading edge to detect heating and failures on the International Space Station (ISS).

**Parameter, Value:**
Sample rate: 20,000 Hz;
Data storage: 256 Mb;
Battery life: 80 hours w/ 5 year sleep mode;
Sensor: Piezoelectric

**Capability Performance Goal:** Monitor performance of spacecraft mechanisms, subsystems, and components which will link wirelessly to the iHab operating system.

**Parameter, Value:**
Spacecraft Coverage: 100%;
Integration into iHab: 100%;
75% reduction crew time to monitor and check systems, subsystems, assemblies, and components.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 6 years |

7.4 Habitat Systems
7.4.1 Integrated Habitat Systems

## 7.4.1.4 Bio-Illumination

### TECHNOLOGY

**Technology Description:** Non-powered biotechnology coating for spacecraft interior and exterior illumination.

**Technology Challenge:** Technology challenges include developing natural or bio-engineered agents that will provide non-powered spacecraft ambient lighting. Other challenges include longevity degradation of the agent, non-harmful off-gassing, and reliability of the illumination.

**Technology State of the Art:** Bioluminescence is the production and emission of light by a living organism. Bioluminescence occurs widely in marine vertebrates and invertebrates, as well as in some fungi, microorganisms and terrestrial invertebrates. Some symbiotic organisms carried within larger organisms produce light.

**Parameter, Value:** 150 lux; 5 foot candles; 0.2 kg/m$^2$

**TRL:** 3

**Technology Performance Goal:** Enable ambient illumination of the spacecraft without the use of power while reducing mass and spares.

**Parameter, Value:** 100% coverage for ambient lighting; 66% reduction of spare's mass and volume.

**TRL:** 7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 6.1.4 Habitation; 6.3.3 Behavioral Health; 6.3.4 Human Factors; 8.1 Remote Sensing Instruments and Sensors; 12.1.5 Special Materials; 11.3.2 Integrated System Lifecycle Simulation; 6.4.1 Sensors: Air, Water, Microbial, and Acoustic.

### CAPABILITY

**Needed Capability:** Powerless illumination/lighting spacecraft interior and exterior illumination.

**Capability Description:** Provide natural bio-coatings that will provide natural ambient lighting without the use of power.

**Capability State of the Art:** Not currently in use for human spaceflight. The International Space Station (ISS) uses fluorescent lighting and light emitting diode (LED) solid-state lighting module (SSLM) lighting. ISS-SSLM measures 26.5" x 6.6" x 3.9" and has a mass of approximately 7.5 pounds.

**Parameter, Value:**

ISS current values:

Ambient: 100-200 lux;

Task: 1,500-3,000 lux;

SSLM: 7.5 pounds, 30 watts

**Capability Performance Goal:** Provide non-powered ambient lighting (illumination) within the human spacecraft thus reducing mass and power needs.

**Parameter, Value:**

Ambient: 100-200 lux;

Task: 1,500-3,000 lux;

SSLM: 7.5 pounds, 30 watts

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 6 years |

7.4 Habitat Systems
7.4.1 Integrated Habitat Systems

## 7.4.1.5 Self-Cleaning Biotechnology Surface Coatings

### TECHNOLOGY

**Technology Description:** Biotechnology coatings that will enable self-cleaning of spacecraft internal surfaces. Consider "visibly clean" as well as the microbial clean parameter in assessing this techology, as microbial requirements may not cover particulates, greases, etc.

**Technology Challenge:** Technology challenges include providing agents that will perform self-cleaning of surfaces, pipes, wiring, mechanisms, and components. Other challenges include longevity degradation of the self-cleaning agent, non-harmful off-gassing, and reliability of the agent.

**Technology State of the Art:** The lotus effect refers to the very high water repellence (superhydrophobicity) resulting in self-cleaning properties, as exhibited by the leaves of the lotus flower (Nelumbo). Dirt particles are picked up by water droplets due to a complex micro- and nano-scopic architecture on the surface, which minimizes the droplet's adhesion to said surface.

**Parameter, Value:**

Maximum for Bacteria:

Air: 1000 CFU/$m^3$

Internal Surfaces: 10,000 CFU/100 $cm^2$

Maximum for Fungi:

Air: 100 CFU/$m^3$

Internal Surfaces: 100 CFU/100 $cm^2$

**TRL** 2

**Technology Performance Goal:** Enable the capability of keeping the internal spacecraft clean without requiring the crew to perform housekeeping duties such as wiping down and washing the surfaces.

**Parameter, Value:**

75% reduction in housekeeping (manual cleaning) crew time;

66% reduction in mass and volume of cleaning supplies and waste.

**TRL** 7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 6.1.4 Habitation; 8.1 Remote Sensing Instruments and Sensors; 8.3 In-Situ Instruments and Sensors; 12.1.5 Special Materials; 6.4.1 Sensors: Air, Water, Microbial, and Acoustic.

### CAPABILITY

**Needed Capability:** Self-cleaning of human spacecraft internal surfaces.

**Capability Description:** Provide bio and nano coatings and agents that will perform self-cleaning of surfaces, pipes, wiring, mechanisms, and components.

**Capability State of the Art:** International Space Station (ISS): specialized antifungal agents, such as cleansing wipes for surfaces. Self-cleaning Biotechnology Surface Coatings are currently not used for human spaceflight.

**Parameter, Value:**

Design requirement limits:

Maximum for Bacteria:

Air: 1000 CFU/$m^3$

Internal Surfaces: 10,000 CFU/100 $cm^2$

Maximum for Fungi:

Air: 100 CFU/$m^3$

Internal Surfaces: 100 CFU/100 $cm^2$

**Capability Performance Goal:** Provide the ability to self-clean within the human spacecraft thus reducing mass, power, cleaning supplies, and trash.

**Parameter, Value:**

75% reduction in housekeeping (manual cleaning) crew time;

66% reduction in mass and volume of cleaning supplies and waste.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 6 years |

7.4 Habitat Systems
7.4.1 Integrated Habitat Systems

# 7.4.1.6 Thin Flexible Visualization Display

## TECHNOLOGY

**Technology Description:** Visual displays for situational awareness and sensory stimulation that can be mounted onto pressure vessel walls and internal wall coverings that will change color or imagery depending on human occupants –intelligent awareness.

**Technology Challenge:** Technology challenges include providing integrated sensors and visual displays (for example Organic Light Emitting Diodes (OLED)), onto a pressure vessel wall and internal wall coverings that will change color or imagery depending on human occupants – intelligent awareness. Other challenges include radiation hardened Graphics Processing Units (GPUs), longevity degradation of the display, low-power usage, non-harmful off-gassing, and reliability the display.

**Technology State of the Art:** Integrated wall systems with sensor activated detection.

**Parameter, Value:**

Lightweight, thin film;
Wireless;
Low power;
Size: 6 feet by 12 feet

**TRL** 2

**Technology Performance Goal:** Enable visual displays within a habitat that can be used for habitat system situational awareness and systems evaluation, as well as changing of wall colors and/or scenery internal to the spacecraft that will increase crew productivity and psychological well-being while reducing the mass and power required doing so. Radiation hard GPU.

**Parameter, Value:**

Resolution: 5K, 6000 x 4500;
Refresh rate: 150 Htz
50% wall interchangeability of color and images;
70% increase in crew productivity;
66% reduction in crew fatigue/stress

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 6.1.4 Habitation; 6.3.3 Behavioral Health; 6.3.4 Human Factors; 8.1 Remote Sensing Instruments and Sensors; 8.3 In-Situ Instruments and Sensors; 12.1.5 Special Materials; 11.2.6 Analysis Tools for Mission Design

## CAPABILITY

**Needed Capability:** Situational awareness, sensory stimulation, and automated color/image changeability.

**Capability Description:** Visual displays for the crew. Intelligent awareness sensory stimulation: pressure vessel wall and internal wall coverings that will change color or imagery depending on human occupants.

**Capability State of the Art:** Not currently used for human spaceflight. The International Space Station (ISS) uses a laptop computer or projected images/movies onto wall area.

**Parameter, Value:**

High definition 5K, 6000 x 4500;
Refresh rate: 150 htz;
50% reduction of mass;
50% reduction of power;
Size: 6 feet by 12 feet;
Flexibility

**Capability Performance Goal:** Provide visualization through lightweight, low-power, flexible displays for situational awareness and sensory stimulation.

**Parameter, Value:**

High definition 5K, 6000 x 4500;
Refresh rate: 150 htz;
50% reduction of mass;
50% reduction of power;
Size: 6 feet by 12 feet;
Flexibility

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 6 years |

7.4 Habitat Systems
7.4.1 Integrated Habitat Systems

## 7.4.1.7 Inlet Optics

### TECHNOLOGY

**Technology Description:** Micro-reflector cone array (or microlens matrix) that injects the concentrated solar radiation into individual optical fiber for transmission. Transmitted solar radiation can be used for thermal, thermochemical, or photosynthetically active radiation (PAR) for growing plants or lighting interior of a spacecraft or habitat.

**Technology Challenge:** Technology challenges include providing low-mass, highly-reliable solar concentrators; transformer system; and fiber optics to deliver natural light and thermal heat for uses inside the habitat for food growth, heating food or shell heaters, natural, ambient, and task lighting. Other challenges include longevity degradation of the concentrators; wavelength conversion; fiber optic cable efficiencies and lengths; light and heat distribution; and reliability the system.

**Technology State of the Art:** Solar fiber optic lighting and thermal heating solar optic lighting is currently being used in “green” architecture approaches to reduce the environmental impacts from carbon emissions created by turbine generator fossil fuel plants.

**Parameter, Value:**

Fiber cable length: 100 meters; Transmission efficiency: 77%, 400 W (~1,800 μmole/s);

Solar Spectra (color):  Visible Blue- Red, λ: 400-700 nm;

Thermal Heating Solar Spectra (color): ultraviolet/ infrared (UV/IR);

Mass: 5.8 kilograms per kW of solar power;

Volume: 0.53 m3 per kW of solar power;

Mean time between failure (MTBF)/(mean time between replacement (MTBR): not specified

**TRL:** 4

**Technology Performance Goal:** Enable natural solar lighting to the interior of the spacecraft by using fiber optics, thus reducing dependence on artificial lighting (mass, power, volume, and spares). Use solar light to grow plants inside habitat or spacecraft for food (wheat, lettuce, tomato, potato, etc.). Use solar power for thermochemical material processing such as oxygen production from lunar regolith. Use solar power for thermal production of construction materials such as bricks, or making tools by using three-dimensional (3D) printer technology.

**Parameter, Value:**

Fiber cable length: 100 meters; Transmission efficiency: 77%, 400 W (~1,800 μmole/s);

Solar Spectra (color):  Visible Blue- Red, λ: 400-700 nm;

Thermal Heating Solar Spectra (color): UV/IR;

Mass: 5.8 kilograms per kW of solar power;

Volume: 0.53 $m^3$ per kW of solar power;

MTBF / MTBR: not specified

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** Solar collectors or concentrators are covered by TA 3; 6.1.4 Habitation; 8.1 Remote Sensing Instruments and Sensors; 8.3 In-Situ Instruments and Sensors; 12.1.5 Special Materials; 11.3.2 Integrated System Lifecycle Simulation; 6.4.1 Sensors: Air, Water, Microbial, and Acoustic.; 12.3.3 Electro-Mechanical, Mechanical, and Micromechanisms

### CAPABILITY

**Needed Capability:** Solar collector, fiber optic system, spacecraft and habitat lighting, thermal heating, and thermochemical material processing or plant growing on habitat. Examples include: making construction material or tools with three-dimensional (3D) printing, producing oxygen from lunar soil, or growing plants for food.

**Capability Description:** Provide solar collected fiber optic natural lighting by using solar collectors, transformer system, and fiber optics to deliver natural light and thermal and heat for uses inside the habitat such as food growth, heating food or pressure vessel shell heaters, and natural, ambient, and task lighting.

**Capability State of the Art:** Solar optic lighting used by architectural/ engineering industry to light basements and interior spaces.

**Parameter, Value:**

Fiber cable length: 100 meters;

Transmission efficiency: 77%, 400 W (~1,800 μmole/s);

Solar Spectra (color): Visible Blue- Red, λ: 400-700 nm;

Thermal Heating Solar Spectra (color): UV/IR;

Mass: 5.8 kilograms per kW of solar power;

Volume: 0.53 $m^3$ per kW of solar power;

MTBF / MTBR: not specified

**Capability Performance Goal:** Provide thermal heat and solar lighting to the interior of a spacecraft and habitat. 50% reduction of artificial lighting, 50% reduction of mass, and 100% reduction of lighting logistics mass and volume.

**Parameter, Value:**

Fiber cable length: 100 meters; Transmission efficiency: 77%, 400 W (~1,800 μmole/s);

Solar Spectra (color):  Visible Blue- Red, λ: 400-700 nm;

Thermal Heating Solar Spectra (color): UV/IR;

Mass: 5.8 kilograms per kW of solar power;

Volume: 0.53 $m^3$ per kW of solar power;

MTBF / MTBR: not specified

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 6 years |

7.4 Habitat Systems
7.4.1 Integrated Habitat Systems

## 7.4.1.8 Optical Waveguide Solar Power Transmission System

### TECHNOLOGY

**Technology Description:** Optical waveguide transmission photosynthetically active radiation (PAR) to grow plants and illuminate the habitat via fiber optic transmission of solar radiation.

**Technology Challenge:** Technology challenges include providing low mass highly reliable solar concentrators; transformer system; and fiber optics to deliver natural light and thermal heat for uses inside the habitat such as food growth, heating food or shell heaters, natural, ambient, and task lighting. Other challenges include longevity degradation of the concentrators; wavelength conversion; fiber optic cable efficiencies and lengths; light and heat distribution; and reliability the system.

**Technology State of the Art:** Solar fiber optic lighting and thermal heating.

**Parameter, Value:** — **TRL** 4

Fiber cable length: 100 meters;
Transmission efficiency: 77%, 400 W (~1,800 μmole/s);
Solar Spectra (color): Visible Blue- Red, λ: 400-700 nm;
Thermal Heating Solar Spectra (color): ultraviolet (UV) or infrared (IR);
Mass: 5.8 kilograms per kW of solar power;
Volume: 0.53 $m^3$ per kW of solar power;
Mean time between failure (MTBF) /mean time between replacement (MTBR): not specified

**Technology Performance Goal:** Enable natural solar lighting to the interior of the spacecraft by using fiber optics, thus reducing dependence on artificial lighting (mass, power, volume, and spares). Use solar light to grow plants inside habitat or spacecraft for food (wheat, lettuce, tomato, potato, etc.). Use solar power for thermochemical material processing such as oxygen production from lunar regolith. Use solar power for thermal production of construction materials such as bricks, or making tools by using three-dimensional (3D) printer technology.

**Parameter, Value:** — **TRL** 6

Fiber cable length: 100 meters;
Transmission efficiency: 77%, 400 W (~1,800 μmole/s);
Solar Spectra (color): Visible Blue- Red, λ: 400-700 nm;
Thermal Heating Solar Spectra (color): UV/IR;
Mass: 5.8 kilograms per kW of solar power;
Volume: 0.53 $m^3$ per kW of solar power;
MTBF / MTBR: not specified

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** Solar collectors or concentrators are covered by TA 3; 6.1.4 Habitation; 8.1 Remote Sensing Instruments and Sensors; 8.3 In-Situ Instruments and Sensors; 12.1.5 Special Materials; 11.3.2 Integrated System Lifecycle Simulation; 6.4.1 Sensors: Air, Water, Microbial, and Acoustic.; 12.3.3 Electro-Mechanical, Mechanical, and Micromechanisms

### CAPABILITY

**Needed Capability:** Optical waveguide solar power transmission system. Spacecraft and habitat lighting for plant growth, and illumination for human activity. Also, thermal and thermochemical material processing.

**Capability Description:** Provide solar lighting by using solar collectors, optical waveguide transmission line to deliver natural light and thermal heat for uses inside the habitat such as food growth, heating food or shell heaters, natural ambient and task lighting. Provide thermal power for thermo/chemical materials processing such as tool making via 3D printing, production of oxygen by thermochemical processing, and production of construction materials by thermal sintering.

**Capability State of the Art:** Solar optic lighting used by architectural/ engineering industry to light basements and interior spaces.

**Parameter, Value:**

Fiber cable length: 100 meters;
Transmission efficiency: 77%, 400 W (~1,800 μmole/s);
Solar Spectra (color): Visible Blue- Red, λ: 400-700 nm;
Thermal Heating Solar Spectra (color): UV/IR;
Mass: 5.8 kilograms per kW of solar power;
Volume: 0.53 $m^3$ per kW of solar power;
MTBF / MTBR: not specified.

**Capability Performance Goal:** Provide thermal heat and solar (natural) lighting to the interior of a spacecraft and habitat. 50% reduction of artificial lighting, 50% reduction of mass, and 100% reduction of lighting logistics mass and volume.

**Parameter, Value:**

Fiber cable length: 100 meters;
Transmission efficiency: 77%, 400 W (~1,800 μmole/s);
Solar Spectra (color): Visible Blue- Red, λ: 400-700 nm;
Thermal Heating Solar Spectra (color): UV/IR;
Mass: 5.8 kilograms per kW of solar power;
Volume: 0.53 $m^3$ per kW of solar power;
MTBF / MTBR: not specified.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 6 years |

7.4 Habitat Systems
7.4.1 Integrated Habitat Systems

# 7.4.1.9 Optical Fiber Cables with Thermal Power Delivery Component

## TECHNOLOGY

**Technology Description:** Transmit solar radiation for thermal and thermochemical applications (such as oxygen production, making construction materials, and tool making by three-dimensional (3D) printing).

**Technology Challenge:** Technology challenges include providing low mass highly reliable solar concentrators; transformer system; and fiber optics to deliver natural light and thermal heat for uses inside the habitat such as food growth, heating food or shell heaters, and natural, ambient, and task lighting. Other challenges include longevity degradation of the concentrators; wavelength conversion; fiber optic cable efficiencies and lengths; light and heat distribution; and reliability of the system.

**Technology State of the Art:** Optical fiber cables: hard polymer-clad fused silica fibers.

**Parameter, Value:** (TRL 4)

Fiber cable length: 100 meters;

Transmission efficiency: 77%, 400 W (~1,800 $\mu$mole/s);

Solar Spectra (color): Visible Blue- Red, λ: 400-700 nm;

Thermal Heating Solar Spectra (color): ultraviolet (UV) and infrared (IR);

Mass: 5.8 kilograms per kW of solar power;

Volume: 0.53 $m^3$ per kW of solar power;

Mean time between failure (MTBF) /mean time between replacement (MTBR): not specified

**Technology Performance Goal:** Enable natural solar lighting to the interior of the spacecraft by using fiber optics, thus reducing dependence on artificial lighting (mass, power, volume, and spares). The system can also transmit the thermal energy for high temperature material processing such as 3D printing of mechanical components.

**Parameter, Value:** (TRL 6)

Fiber cable length: 100 meters;

Transmission efficiency: 77%, 400 W (~1,800 $\mu$mole/s);

Solar Spectra (color): Visible Blue- Red, λ: 400-700 nm;

Thermal Heating Solar Spectra (color): UV/IR;

Mass: 5.8 kilograms per kW of solar power;

Volume: 0.53 $m^3$ per kW of solar power;

MTBF / MTBR: not specified

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** Solar collectors or concentrators are covered by TA 3; 6.1.4 Habitation; 8.1 Remote Sensing Instruments and Sensors; 8.3 In-Situ Instruments and Sensors; 12.1.5 Special Materials; 11.3.2 Integrated System Lifecycle Simulation; 6.4.1 Sensors: Air, Water, Microbial, and Acoustic; 12.3.3 Electro-Mechanical, Mechanical, and Micromechanisms

## CAPABILITY

**Needed Capability:** Optical waveguide solar power transmission system for spacecraft and habitat for thermal and thermochemical material processing. Providing heat inside of spacecraft and habitat (such as oxygen production, making construction materials, and tool making by 3D printing).

**Capability Description:** Provide solar collected fiber optic natural lighting by using solar collectors, transformer system, and fiber optics to deliver natural light and for thermal and thermochemical materials processing such as tool making via 3D printing, production of oxygen by thermochemical processing, and production of construction materials by thermal sintering.

**Capability State of the Art:** Solar optic lighting used by architectural/ engineering industry to light basements and interior spaces.

**Parameter, Value:**

Fiber cable length: 100 meters;

Transmission efficiency: 77%, 400 W (~1,800 $\mu$mole/s);

Solar Spectra (color): Visible Blue- Red, λ: 400-700 nm;

Thermal Heating Solar Spectra (color): UV/IR;

Mass: 5.8 kilograms per kW of solar power;

Volume: 0.53 $m^3$ per kW of solar power;

MTBF / MTBR: not specified

**Capability Performance Goal:** Provide thermal heat and solar (natural) lighting to the interior of a spacecraft and habitat. 50% reduction of artificial lighting, 50% reduction of mass, 100% reduction of lighting logistics mass and volume.

**Parameter, Value:**

Fiber cable length: 100 meters;

Transmission efficiency: 77%, 400 W (~1,800 $\mu$mole/s);

Solar Spectra (color): Visible Blue- Red, λ: 400-700 nm;

Thermal Heating Solar Spectra (color): UV/IR;

Mass: 5.8 kilograms per kW of solar power;

Volume: 0.53 $m^3$ per kW of solar power;

MTBF / MTBR: not specified

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 6 years |

7.4 Habitat Systems
7.4.1 Integrated Habitat Systems

# 7.4.1.10 Optical Lighting Panel

## TECHNOLOGY

**Technology Description:** Optical lighting panel for distribution of the photosynthetically active radiation (PAR) via fiber optic transmission of thermal heat and solar lighting to the interior of a spacecraft and habitat.

**Technology Challenge:** Technology challenges include providing low mass highly reliable solar concentrators; transformer system; and fiber optics to deliver natural light and thermal heat for uses inside the habitat such as food growth, heating food or shell heaters, and natural, ambient, and task lighting. Other challenges include longevity degradation of the concentrators; wavelength conversion; fiber optic cable efficiencies and lengths; light and heat distribution; and reliability of the system.

**Technology State of the Art:** Optical lighting panel as demonstrated in a plant growth experiment at Kennedy Space Center (KSC).

**Parameter, Value:**

**TRL** 4

Fiber cable length: 100 meters;

Cable transmission efficiency: 90%;

System transmission efficiency: 77%, 400 W (~1,800 $\mu$mole/s);

Solar Spectra (color): Visible Blue- Red, λ: 400-700 nm;

Thermal Heating Solar Spectra (color): ultraviolet (UV) and infrared (IR);

Mass: 5.7 kilograms per kW of solar power;

Volume: 0.53 $m^3$ per kW of solar power;

Mean time between failure (MTBF) /mean time between replacement (MTBR): not specified

**Technology Performance Goal:** Enable natural solar lighting to the interior of the spacecraft by using fiber optics, thus reducing dependence on artificial lighting (mass, power, volume, and spares). 100% ambient light, 66% reduction of artificial lighting (mass, power, volume and spares), and 50% increase in crew well-being and circadian rhythm.

**Parameter, Value:**

**TRL** 6

Fiber cable length: 100 meters;

Cable transmission efficiency: 90%;

System transmission efficiency: 77%, 400 W (~1,800 $\mu$mole/s);

Solar Spectra (color): Visible Blue- Red, λ: 400-700 nm;

Thermal Heating Solar Spectra (color): UV/IR;

Mass: 5.7 kilograms per kW of solar power;

Volume: 0.53 $m^3$ per kW of solar power;

MTBF / MTBR: not specified

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** Solar collectors or concentrators are covered by TA 3; 6.1.4 Habitation; 6.3.3 Behavioral Health; 6.3.4 Human Factors; 8.1 Remote Sensing Instruments and Sensors; 8.3 In-Situ Instruments and Sensors; 12.1.5 Special Materials; 11.3.2 Integrated System Lifecycle Simulation; 6.4.1Sensors: Air, Water, Microbial, and Acoustic; 12.3.3 Electro-Mechanical, Mechanical, and Micromechanisms

## CAPABILITY

**Needed Capability:** Solar collector, fiber optic system, spacecraft and habitat lighting, and thermal heating. Optical waveguide, solar power transmission system. Spacecraft and habitat lighting for plant growth, and illumination for human activity. Also, thermal and thermochemical material processing.

**Capability Description:** Provide solar collected fiber optic natural lighting by using solar collectors, transformer system and fiber optics to deliver natural light and thermal/heat for uses inside the habitat such as food growth, heating food or shell heaters, natural, ambient, and task lighting.

**Capability State of the Art:** Solar optic lighting used by architectural/ engineering industry to light basements and interior spaces.

**Parameter, Value:**

Fiber cable length: 100 meters;

Cable transmission efficiency: 90%;

System transmission efficiency: 77%, 400 W (~1,800 $\mu$mole/s);

Solar Spectra (color): Visible Blue- Red, λ: 400-700 nm;

Thermal Heating Solar Spectra (color): UV/IR;

Mass: 5.7 kilograms per kW of solar power;

Volume: 0.53 $m^3$ per kW of solar power;

MTBF / MTBR: not specified

**Capability Performance Goal:** Provide thermal heat and solar (natural) lighting to the interior of a spacecraft and habitat. 50% reduction of artificial lighting. 50% reduction of mass. 100% reduction of lighting logistics mass and volume.

**Parameter, Value:**

Fiber cable length: 100 meters;

Cable transmission efficiency: 90%;

System transmission efficiency: 77%, 400 W (~1,800 $\mu$mole/s);

Solar Spectra (color): Visible Blue- Red, λ: 400-700 nm;

Thermal Heating Solar Spectra (color): UV/IR;

Mass: 5.7 kilograms per kW of solar power;

Volume: 0.53 $m^3$ per kW of solar power;

MTBF / MTBR: not specified

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 6 years |

7.4 Habitat Systems
7.4.1 Integrated Habitat Systems

## 7.4.1.11 Bioregenerative Resources

### TECHNOLOGY

**Technology Description:** Bioregenerative engineered resources and materials (construction materials) to be used by crew and spacecraft.

**Technology Challenge:** Technology challenges include providing the ability to grow, harvest, and prepare products for use within a habitat that will enable self-sufficiency from Earth logistics supply. Other challenges include useable feed stock (seeds); longevity degradation of the feed stock and growth material; non-harmful off-gassing processing; and reliability of the processing.

**Technology State of the Art:** The International Space Station (ISS) is testing a veggie unit, which is the first step in development of bio-reg resources. Bioregenerative engineering is an emerging discipline based on applying engineering principles and technologies to regenerative medicine. It induces, modulates, enhances, and/or controls regenerative processes by using engineering approaches to improve the restoration of the structure and function of disordered or lost molecules, cells, tissues, and organs. This reference systematically summarizes Bioregenerative engineering principles, technologies, and current research to help scientists understand biological regeneration and design new therapeutic strategies.

**Parameter, Value:**
10 kilograms of product per year.

**TRL**
3

**Technology Performance Goal:** Enable the growth of renewable resources such as bamboo for use to construct internal spacecraft/habitat floor, walls, furniture, etc. thus reducing the dependency of bringing these materials and supplies from earth. Self-sustaining.

50% increase in growing renewable resources for sustainable use, 75% reduction of crew supplies and spares.

**Parameter, Value:**
250 kilograms of product per year.

**TRL**
6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 6.1.4 Habitation; 8.1 Remote Sensing Instruments and Sensors; 8.3 In-Situ Instruments and Sensors; 12.1.5 Special Materials; 11.3.2 Integrated System Lifecycle Simulation; 6.4.1 Sensors: Air, Water, Microbial, and Acoustic

### CAPABILITY

**Needed Capability:** Bioregenerative engineered resources and materials.

**Capability Description:** Provide bioregenerative engineered resources and materials to be used by crew and spacecraft. For example growing bamboo in-situ to enable a sustainable campaign.

**Capability State of the Art:** The ISS is testing a veggie unit, which is the first step in development of bio-regenerative resources.

**Parameter, Value:**
10 kilograms of product per year.

**Capability Performance Goal:** Provide bioregenerative engineered resources and materials to be used by crew and spacecraft. For example growing bamboo or medicines in-situ to enable a sustainable campaign. 50% reduction in logistics supplies for long-duration missions.

**Parameter, Value:**
250 kilograms of product per year.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6 years |

7.4 Habitat Systems
7.4.1 Integrated Habitat Systems

## 7.4.1.12 Acoustical Treatments

### TECHNOLOGY

**Technology Description:** Human spaceflight qualified materials and lay-ups that are lightweight and provide the following acoustic functions: sound blocking, sound absorption, vibration isolation, and vibration damping. Materials also need to be cleanable, water-resistant, and contain particulates, depending on the application.

**Technology Challenge:** Technology challenges include providing low toxicity flame retardant sound absorbent treatments; offgassing; low mass, low volume; and longevity degradation of materials.

**Technology State of the Art:** Current acoustic blanket layups consist of: a blocker, a Heat Treated Nomex batting, absorber, and fabric (to contain particulates, provide flame resistance, and allows acoustic waves to penetrate).

| Parameter, Value: | TRL |
|---|---|
| dBA sound absorption coefficient NC-40. | 1 |

**Technology Performance Goal:** Enable acoustical treatments that will absorb sound from components and subsystems down to meet noise criterion (NC)-40 or lower.

| Parameter, Value: | TRL |
|---|---|
| 50% reduction in Acoustical Treatments mass;<br>10 dB improvement in Insertion Loss with weight similar or lighter than honeycomb closeout panels;<br>Vehicle environments that meet NC-50 for work and NC-40 for sleep. | 6 |

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** Material flammability and flame propagation characteristics.

### CAPABILITY

**Needed Capability:** Acoustic flight materials and blankets, acoustical treatments and closeout panels, acoustic blankets to reduce reverberation, acoustic partitions to quiet sleep stations, isolators, and damping to reduce structure-borne noise.

**Capability Description:** Provide materials and coatings that will absorb, block, or isolate sound from components and subsystems. Can be used to quiet hardware, isolate compartments, and reduce reverberation.

**Capability State of the Art:** International Space Station (ISS): Sound attenuation foams, mufflers, blankets, and other noise controls.

**Parameter, Value:**

Delta dB, Insertion Loss for barriers, Delta lbm, weight reduction for closeout panels and barriers, Sound absorption coefficient for sound absorbers, NC-40 acoustic emission limit for individual hardware items.

**Capability Performance Goal:** 10 dB improvement in Insertion Loss with weight similar or lighter than honeycomb closeout panels. Vehicle environments that meet NC-50 for work and NC-40 for sleep.

**Parameter, Value:**

Delta dB: 10 dB for barriers;

Sound absorption coefficient improved by 10% over broad frequency range;

20% increase in low-frequency absorption without increasing thickness;

NC-50 (work) NC-40 (sleep).

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 6 years |

7.4 Habitat Systems
7.4.1 Integrated Habitat Systems

# 7.4.1.13 Sound Blocking

## TECHNOLOGY

**Technology Description:** Human spaceflight qualified materials, close-out panels, locker designs, and lay-ups that are lightweight and provide significant sound blocking. Materials may also need to be cleanable and water-resistant.

**Technology Challenge:** Technology challenges include providing low toxicity flame retardant sound absorbent treatments; off-gassing; low mass, low volume; and longevity degradation of materials.

**Technology State of the Art:** Blocking material, aluminum panels, and honeycomb panels (sometimes with fiberglass inside the honeycomb).

**Parameter, Value:**
Varies depending on materials

**TRL**
1

**Technology Performance Goal:** 10 dB better Insertion Loss for same weight.

**Parameter, Value:**
Insertion loss, delta dB

**TRL**
6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** Material flammability and flame propagation characteristics.

## CAPABILITY

**Needed Capability:** Acoustic flight materials and blankets.

**Capability Description:** To contain or block acoustic noise propagation.

**Capability State of the Art:** Varies as a function of acoustic frequency. Honeycomb panels tend to have very low transmission loss capability in important frequency range because of reduced coincidence frequency, where airborne and structure born speeds of sound are equal.

**Parameter, Value:**
Delta dB transmission loss as a function of frequency per unit mass.

**Capability Performance Goal:** Higher transmission loss with lower mass/weight.

**Parameter, Value:**
Higher delta dB transmission loss as a function of frequency per unit mass.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enabling | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 6 years |

7.4 Habitat Systems
7.4.1 Integrated Habitat Systems

# 7.4.1.14 Sound Absorption

## TECHNOLOGY

**Technology Description:** Human spaceflight qualified materials and lay-ups that are lightweight and provide significant sound absorption. Materials also need to be cleanable, water-resistant, and contain particulates, depending on the application.

**Technology Challenge:** Technology challenges include providing low toxicity flame retardant sound absorbent treatments; off-gassing; low mass, low volume; and longevity degradation of materials.

**Technology State of the Art:** Feltmetal metal foams Helmholtz resonators (for tones).

**Parameter, Value:**
Varies depending on materials.

**TRL:** 1

**Technology Performance Goal:** Same absorption per frequency, at half of thickness.

**Parameter, Value:**
Absorption coefficient, non-dimensional.

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** Material flammability and flame propagation characteristics.

## CAPABILITY

**Needed Capability:** Acoustic flight materials and blankets.

**Capability Description:** To absorb acoustic noise and reduce reverberation.

**Capability State of the Art:** Varies as a function of acoustic frequency.  Absorption frequency varies with increasing absorber depth.

**Parameter, Value:**
Sound absorption coefficient as a function of frequency.

**Capability Performance Goal:** Higher absorption coefficient with reduced material depth.

**Parameter, Value:**
Sound absorption coefficient improved by 10-20% over broad frequency range for same material depth.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enabling | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 6 years |

7.4 Habitat Systems
7.4.1 Integrated Habitat Systems

# 7.4.1.15 Vibration Isolation

## TECHNOLOGY

**Technology Description:** Human spaceflight qualified materials that are lightweight and provide vibration isolation for rotating equipment.

**Technology Challenge:** Technology challenges include providing low toxicity flame retardant sound absorbent treatments; off-gassing; low mass, low volume; and longevity degradation of materials.

**Technology State of the Art:** Chorolastic, blocking material, and various rubber isolators.

**Parameter, Value:**
Varies depending on materials.

**TRL:** 1

**Technology Performance Goal:** Same isolation performance, but can be activated remotely (after launch/launch loads), or Is designed to be used in microgravity (does not oscillate about compressed state).

**Parameter, Value:**
Delta dB

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** Material flammability and flame propagation characteristics.

## CAPABILITY

**Needed Capability:** Acoustic flight materials and blankets.

**Capability Description:** Isolates structure and panels from vibrating components.

**Capability State of the Art:** Passive isolators.

**Parameter, Value:**
Delta dB vibration transmission loss as a function of frequency.

**Capability Performance Goal:** Need vibration isolators that can be remotely disabled to support launch loads. Need active vibration isolation. Need vibration isolators designed for microgravity (with no weight/gravity pre-load).

**Parameter, Value:**
Higher delta dB vibration transmission loss as a function of frequency.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 6 years |

7.4 Habitat Systems
7.4.1 Integrated Habitat Systems

## 7.4.1.16 Acoustic Blanket Lay-Ups

### TECHNOLOGY

**Technology Description:** Human spaceflight qualified materials lay-ups that are lightweight and provide sound blocking and sound absorption. Materials also need to be cleanable, water-resistant, and contain particulates, depending on the application.

**Technology Challenge:** Technology challenges include providing low toxicity flame retardant sound absorbent treatments; off-gassing; low mass, low volume; and longevity degradation of materials.

**Technology State of the Art:** Blocking material, cloth for particulate containment.

**Parameter, Value:**

Varies depending on materials.

**TRL**

1

**Technology Performance Goal:** Enable acoustical treatments that will absorb sound from components and subsystems down to meet noise criterion (NC)-40 or lower.

**Parameter, Value:**

50% reduction in Acoustical Treatments mass;

Vehicle environments that meet NC-50 for work and NC-40 for sleep.

**TRL**

6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** Material flammability and flame propagation characteristics.

### CAPABILITY

**Needed Capability:** Acoustic flight materials and blankets.

**Capability Description:** Blocks and absorbs acoustic noise, and reduces reverberation. To build quiet sleep stations.

**Capability State of the Art:** Consists of sound blockers, absorbers, and particulate containment (also fire-retardant).

**Parameter, Value:**

Sound absorption coefficient as a function of frequency. Delta dB transmission loss as a function of frequency per unit mass.

**Capability Performance Goal:** Higher absorption coefficient with reduced material depth.

**Parameter, Value:**

Higher delta dB transmission loss as a function of frequency per unit mass sound absorption coefficient improved by 10-20% over broad frequency range for same material depth.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enabling | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 6 years |

7.4 Habitat Systems
7.4.1 Integrated Habitat Systems

# 7.4.1.17 Fiber Optic Paneling for Remote Diffuse Lighting Applications

## TECHNOLOGY

**Technology Description:** Woven fiber optic paneling is a material that can be formed into any flat shape and be connected to any point source light. The result is a uniquely sized panel that provides diffuse lighting for the intended application.

**Technology Challenge:** Material may be in some NASA backlit consoles on commercial-off-the-shelf (COTS) products, but is not widely used as a solution for signage and diffuse lighting implementation. The fiber optic material needs certification.

**Technology State of the Art:** Medical devices and tooling with built-in diffuse lighting. Marking of military vehicles, backlit control consoles. Commercially available for terrestrial uses.

**Parameter, Value:**
Ambient: 50-200 lux;
Remote light source offers 10,000 to 100,000 hours.

**TRL**
3

**Technology Performance Goal:** Integration of custom diffuse lighting solutions for NASA tooling. Diffuse wall lighting for space constrained applications. Remotely lit light panels for heat sensitive applications that require task lighting.

**Parameter, Value:**
Ambient: 50-200 lux;
Remote light source 100,000 hours.

**TRL**
6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Diffuse light source where the main lighting component is remote, making the “lit material” a non-heating source of light.

**Capability Description:** Provide a way to increase task visibility when direct light sources are not feasible.

**Capability State of the Art:** Medical devices and tooling with built-in diffuse lighting. Marking of military vehicles, backlit control consoles.

**Parameter, Value:**
Ambient: 50-200 lux;
Remote light source offers 10,000 to 100,000 hours.

**Capability Performance Goal:** Spacecraft wall panels are internally lit; medical devices and tooling for access behind racks have internal lighting. Diffuse light sources where the “hot” lamp is remote to the light source.

**Parameter, Value:**
Ambient: 50- 200 lux;
Remote light source 100,000 hours.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 6 years |

7.4 Habitat Systems
7.4.2 Habitat Evolution

# 7.4.2.1 Exploration Habitat Systems Concurrent Engineering Modeling and Simulation

## TECHNOLOGY

**Technology Description:** Provide a fully integrated parametrically based habitat design tool for Exploration Habitat modelling and simulation.

**Technology Challenge:** Technology challenges include developing a fully integrated flight hardware data-based habitat design simulator that combines system requirements, computer assisted design (CAD), cost estimating, algorithms, multi-domain modeling (MDM), virtual reality (VR), simulation "caves," organic light emitting diodes (OLED) curved large format displays and rooms, and high data-rate processors for Habitat Modelling and Simulation. Additional challenges include being able to link a data base system infrastructure; being able to run on multiple desktop platforms; and validating the models and simulations.

**Technology State of the Art:** Partially integrated cross-linking sizing, analysis and design tools.

**Parameter, Value:**

50% cross-linkage of design and analysis tools;

5 years of design, development, test, and evaluation (DDT&E) development time;

Months of redesign time to accommodate changes.

**TRL:** 3

**Technology Performance Goal:** Enable a fully integrated parametrically-driven modeling, sizing, and data integration into a three-dimensional (3D) VR modeling simulation and performance characterization for designing exploration habitats with optimized mass, power, fluidic, and thermal aspects.

**Parameter, Value:**

100% integrated tools and parametric and system modeling;

50% reduction in person-hours required for conceptual and preliminary design.

**TRL:** 9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** TA 4 Robotics and Autonomous Systems; TA11 Modeling and Simulation; 6.1.4 Habitation; 6.3.4 Human Factors; 11.2.3 Human-System Performance Modeling; 11.3.2 Integrated System Lifecycle Simulation; 11.3.3 Simulation-Based Systems Engineering; 6.4.1 Sensors: Air, Water, Microbial, and Acoustic; 11.2.6 Analysis Tools for Mission Design

## CAPABILITY

**Needed Capability:** Exploration habitat modelling and simulation analysis tools.

**Capability Description:** Provide a fully integrated and linked parametrically based exploration habitat design and analysis simulator that combines system model language requirements, CAD/computer aided manufacturing (CAM), Building Information Modeling (BIM), MDM, cost estimating, algorithms, event simulations, VR, simulation "caves," OLED curved large format displays and rooms, and high data-rate processors that will be used to perform Exploration Habitat element DDT&E throughout its project life-cycle—with emphasis on the early project life cycle rapid prototyping environment.

**Capability State of the Art:** Individual and separate excel parametric sizing tools, modeling advanced exploration systems (AES), International Space Station (ISS), CAD/CAM, System-based Modeling Language (SysML), DOORS, CERES/Asteroid redirect mission (ARM) Validation Experiment (CAVE) simulators.

**Parameter, Value:**

Months and years for habitat design and analysis;

Traceability of functional and performance requirements and analysis of design impacts due to changing requirements or parameters

**Capability Performance Goal:** Provide a fully integrated and linked parametrically based exploration habitat design and analysis simulator that combines system model language requirements, CAD/CAM, BIM, MDM, cost estimating, algorithms, event simulations, VR, simulation "caves," OLED curved large format displays and rooms, and high data-rate processors that will be used to perform Exploration Habitat element DDT&E throughout its project life-cycle—with emphasis on the early project life cycle rapid prototyping environment.

**Parameter, Value:**

100% cross-linkage of design and analysis tools; 50% reduction of DDT&E development time;

75% reduction of redesign time to accommodate changes.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 2 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 2 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 2 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 2 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 2 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 2 years |

7.4 Habitat Systems
7.4.3 “Smart” Habitats

## 7.4.3.1 Auto-Lighting Control

### TECHNOLOGY

**Technology Description:** Context-aware, task-aware environments that automatically and responsively provide appropriate lighting to support crew activity and health, and preserve resources.

**Technology Challenge:** Technology challenges include developing combined human space flight (HSF) qualified sensors, algorithms and lighting systems to perform crew recognition, identify crew movements and task recognition with auto-control of lighting levels in order to optimize lighting levels and performance while conserving energy and resources. Additional challenges include incorporation of fault detection, isolation, and recovery (FDIR); longevity material degradation; and reliability of the software, sensors, and components.

**Technology State of the Art:** Responsive architectures distinguish themselves from other forms of interactive design by incorporating intelligent and responsive technologies into the core elements of a building’s fabric.

**Parameter, Value:** Watt-hours, time to effect, number of commands, source lines of code.

**TRL:** 4

**Technology Performance Goal:** Enable the crews’ environment to automatically adjust lighting, etc. to conserve resources.

**Parameter, Value:** Reduce power/wattage consumption by 66%

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 4.1.5 Force and Tactile Sensing; 4.4 Human-System Interaction; 4.5.1 System Health Management; 4.5.2 Activity Planning, Scheduling, and Execution; 4.5.4 Multi-Agent Coordination; 4.5.5 Adjustable Autonomy; 4.5.8 Automated Data Analysis for Decision Making; 4.6.4 Mission and System Managers for Autonomy and Automation; 6.1.4 Habitation; 6.3.3 Behavioral Health; 6.3.4 Human Factors; 8.1 Remote Sensing Instruments and Sensors; 8.1.2 Electronics; 8.3 In-Situ Instruments and Sensors; 12.1.5 Special Materials; 11.3.2 Integrated System Lifecycle Simulation; 6.4.1 Sensors: Air, Water, Microbial, and Acoustic; 12.3.3 Electro-Mechanical, Mechanical, and Micromechanisms

### CAPABILITY

**Needed Capability:** Responsive automated lighting environment.

**Capability Description:** Provide embedded lighting software control algorithms and sensors into exploration habitat systems to automate and monitor lighting performance (including auto-dimming, crew recognition, and diurnal cycling), crew task awareness for appropriate lighting levels, fixture fatigue, failure, impacts and links wirelessly to the Intelligent Habitat (iHab) operating system and Integrated System Health Management (ISHM).

**Capability State of the Art:** Not currently used for human spaceflight.

**Parameter, Value:** Watt-hours, time to effect, number of commands, software lines of code (SLoC).

**Capability Performance Goal:** Provide a habitat lighting environment that supports the crew’s movement and activities adjusting the lighting levels accordingly while preserving resources.

**Parameter, Value:**
50% less power usage;
50% reduction of spares due to efficient use of lighting hours;
100% accuracy in predictive crew tasking usage.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 5 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 5 years |

7.4 Habitat Systems
7.4.3 “Smart” Habitats

# 7.4.3.2 Auto-Responsive Environment Control

## TECHNOLOGY

**Technology Description:** Crew context-aware, task-aware environments that automatically and responsively provide appropriate crew environment (air flow, temperature, etc.) to support crew activity and health, and preserve resources.

**Technology Challenge:** Technology challenges include developing crew context-aware, task-aware integrated habitat environments that support crew activity, health, etc., while conserving resources. Additional challenges include incorporation of fault detection, isolation, and recovery (FDIR); longevity material degradation; and reliability of the software, sensors, and components.

**Technology State of the Art:** Responsive architectures distinguish themselves from other forms of interactive design by incorporating intelligent and responsive technologies into the core elements of a building's fabric.

**Parameter, Value:**
Reduction of 66% in the number of ground commands; telemetry, planning, failures, displays.

**TRL**
5

**Technology Performance Goal:** Enable context-aware, task-aware environments that support crew activity, health, etc., and conserve resources.

**Parameter, Value:**
Reduction of 66% in the number of ground commands; telemetry, planning, failures, displays.

**TRL**
7

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 4.1.5 Force and Tactile Sensing; 4.4 Human-System Interaction; 4.5.1 System Health Management; 4.5.2 Activity Planning, Scheduling, and Execution; 4.5.4 Multi-Agent Coordination; 4.5.5 Adjustable Autonomy; 4.5.8 Automated Data Analysis for Decision Making; 4.6.4 Mission and System Managers for Autonomy and Automation; 6.1.4 Habitation; 6.3.3 Behavioral Health; 6.3.4 Human Factors; 8.1 Remote Sensing Instruments and Sensors; 8.1.2 Electronics; 8.3 In-Situ Instruments and Sensors; 12.1.5 Special Materials; 11.3.2 Integrated System Lifecycle Simulation; 6.4.1 Sensors: Air, Water, Microbial, and Acoustic; 12.3.3 Electro-Mechanical, Mechanical, and Micromechanisms

## CAPABILITY

**Needed Capability:** Automated Systems Control Responsive Environments.

**Capability Description:** Provide embedded software control algorithms and sensors into exploration habitat systems (inflatable fabrics, floors, walls, surfaces, mechanisms, subsystems, and components) to automate and monitor performance, fatigue, failure, impacts and links wirelessly to the Intelligent Habitat (iHab) operating system and Integrated System Health Management (ISHM).

**Capability State of the Art:** International Space Station (ISS) ground based Mission Controllers.

**Parameter, Value:**
Number of ground commands, telemetry, planning, failures, and displays.

**Capability Performance Goal:** Provide a crew-aware environment that supports crew activities, crew well-being, crew health, and habitat systems health while preserving resources.

**Parameter, Value:**
50% reduction of system resources (power, thermal, mass of consumables).

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 5 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 5 years |

7.4 Habitat Systems
7.4.3 "Smart" Habitats

## 7.4.3.3 Crew Recognition

### TECHNOLOGY

**Technology Description:** Crew recognition and context-aware, task-aware environments that automatically and responsively provides appropriate crew well-being support environments that supports crew activity and health, while preserving resources.

**Technology Challenge:** Technology challenges include developing crew recognition combined with Intelligent Habitat (iHab) to enable an environment that supports crew activities, crew well-being, crew health, and habitat systems health, while preserving resources. Additional challenges include incorporation of fault detection, isolation, and recovery (FDIR); crew awareness capability; and reliability of the software, sensors, and components.

**Technology State of the Art:** Facial and person recognition. Also done by wearing an radio frequency identification (RFID) badge. A facial recognition system is a computer application for automatically identifying or verifying a person from a digital image or a video frame from a video source.

| Parameter, Value: | TRL |
|---|---|
| Increase in employee productivity;<br>Reduction of employee errors. | 4 |

**Technology Performance Goal:** Enable the efficient use of crew time, their awareness to situations and dangers, and to conserve resources by enabling the spacecraft central operating system the ability to interact with the crew by anticipating needs and resources.

| Parameter, Value: | TRL |
|---|---|
| 30% increase in crew productivity;<br>50% reduction in crew errors. | 6 |

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 4.1.5 Force and Tactile Sensing; 4.4 Human-System Interaction; 4.5.1 System Health Management; 4.5.2 Activity Planning, Scheduling, and Execution; 4.5.4 Multi-Agent Coordination; 4.5.5 Adjustable Autonomy; 4.5.8 Automated Data Analysis for Decision Making; 4.6.4 Mission and System Managers for Autonomy and Automation; 6.1.4 Habitation; 6.3.3 Behavioral Health; 6.3.4 Human Factors; 8.1 Remote Sensing Instruments and Sensors; 8.1.2 Electronics; 8.3 In-Situ Instruments and Sensors; 12.1.5 Special Materials; 11.3.2 Integrated System Lifecycle Simulation; 6.4.1 Sensors: Air, Water, Microbial, and Acoustic; 12.3.3 Electro-Mechanical, Mechanical, and Micromechanisms

### CAPABILITY

**Needed Capability:** Crew Recognition Responsive Environments.

**Capability Description:** Provide embedded crew recognition software control algorithms and sensors into exploration habitat systems to automate and monitor crew awareness and performance (including crew recognition, crew health, and well-being), fatigue, error impacts, and links wirelessly to the iHab operating system and Integrated System Health Management (ISHM).

**Capability State of the Art:** Not currently used for human spaceflight.

**Parameter, Value:**

dB, watts, mb data, software lines of code (SLoC), and crew errors.

**Capability Performance Goal:** Provide a crew-recognition environment that supports crew activities, crew well-being, crew health, and habitat systems health, while preserving resources.

**Parameter, Value:**

Increase in crew productivity;

Reduction in crew errors.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 5 years |

7.4 Habitat Systems
7.4.4 Artificial Gravity

# 7.4.4.1 Off-Center of Gravity (CG) Thrust Technology

## TECHNOLOGY

**Technology Description:** Provides steering, control, and course correction of artificial gravity rotating and spinning spacecraft.

**Technology Challenge:** Technology challenges include developing thrust vector navigation, course correction of a rotating spacecraft, managing the CG of the spacecraft, adjusting the plane of rotation without affecting trajectory, momentum exchange, and reducing propellant needs.

**Technology State of the Art:** This technology is not currently used for human spacecraft. The gyroscopic effects of helicopter control uses this technology. It is also used for robot control of aircraft. Robust reactive collision avoidance method is present taking into account the mobile robot kinematic and dynamic constraints.

**Parameter, Value:**

In-flight maneuvering without de-spinning the spacecraft; accuracy of course correction. Thrust vector navigation course correction. Accuracy 0.5 arc degrees.

**TRL:** 2

**Technology Performance Goal:** Enable thrust vector course correction.

**Parameter, Value:**

In-flight maneuvering without de-spinning the spacecraft; accuracy of course correction. Thrust vector navigation course correction. Accuracy 0.5 arc degrees.

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 4.1.5 Force and Tactile Sensing; 4.4 Human-System Interaction; 4.5.1 System Health Management; 4.5.2 Activity Planning, Scheduling, and Execution; 4.5.4 Multi-Agent Coordination; 4.5.5 Adjustable Autonomy; 4.5.8 Automated Data Analysis for Decision Making; 4.6.4 Mission and System Managers for Autonomy and Automation; 5.4.2 On-Board Auto Navigation and Maneuver; 6.1.4 Habitation; 6.3.3 Behavioral Health; 6.3.4 Human Factors; 8.1 Remote Sensing Instruments and Sensors; 8.1.2 Electronics; 8.3 In-Situ Instruments and Sensors; 12.1.5 Special Materials; 11.3.2 Integrated System Lifecycle Simulation; 6.4.1 Sensors: Air, Water, Microbial, and Acoustic; 12.3.3 Electro-Mechanical, Mechanical, and Micromechanisms

## CAPABILITY

**Needed Capability:** Guidance, navigation, and control (GN&C) of an artificial gravity (spinning) spacecraft.

**Capability Description:** Provide off-CG thrust approaches for steering and control algorithms and mechanisms to vector course correct, or steer/direct, an artificial gravity rotating/spinning spacecraft.

**Capability State of the Art:** International Space Station (ISS) maneuvering and control to avoid orbital debris not currently used for an artificial gravity (AG) rotating spacecraft.

**Parameter, Value:**

Reliability of off-CG thrust vectoring of 0.5 arc degrees.

**Capability Performance Goal:** Provide GN&C off-CG thrust for steering and control to perform a vector course correction and steer or redirect an artificial gravity rotating/ spinning spacecraft.

**Parameter, Value:**

Reliability of off-CG thrust vectoring of 0.5 arc degrees.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 6 years |

7.4 Habitat Systems
7.4.4 Artificial Gravity

## 7.4.4.2 Controlled Energy Release Mechanisms

### TECHNOLOGY

**Technology Description:** Controlled energy release mechanisms for deployable and retracting mechanism.

**Technology Challenge:** Technology challenges include developing mechanisms and control devices to control energy release for deploying and retracting spacecraft mechanisms that enable artificial gravity (AG) spin-up and spin-down.

**Technology State of the Art:** Several innovative technologies have been developed for the James Webb Space Telescope (JWST). These include a folding, segmented primary mirror, adjusted to shape after launch; ultra-lightweight beryllium optics; detectors able to record extremely weak signals, microshutters that enable programmable object selection for the spectrograph; and a cryocoolers for cooling the mid-IR detectors to 7K.

**Parameter, Value:**
Newton-force pounds: 100 pound force.

**TRL** 3

**Technology Performance Goal:** Release of 100 pound force (newton-force lbs) while maintain control.

**Parameter, Value:**
Newton-force pounds: 100 pound force.

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 4.1.5 Force and Tactile Sensing; 4.4 Human-System Interaction; 4.5.1 System Health Management; 4.5.2 Activity Planning, Scheduling, and Execution; 4.5.4 Multi-Agent Coordination; 4.5.5 Adjustable Autonomy; 4.5.8 Automated Data Analysis for Decision Making; 4.6.4 Mission and System Managers for Autonomy and Automation; 5.4.2 On-Board Auto Navigation and Maneuver; 6.1.4 Habitation; 6.3.3 Behavioral Health; 6.3.4 Human Factors; 8.1 Remote Sensing Instruments and Sensors; 8.1.2 Electronics; 8.3 In-Situ Instruments and Sensors; 12.1.5 Special Materials; 11.3.2 Integrated System Lifecycle Simulation; 6.4.1 Sensors: Air, Water, Microbial, and Acoustic; 12.3.3 Electro-Mechanical, Mechanical, and Micromechanisms

### CAPABILITY

**Needed Capability:** Controlled energy release mechanisms for deployable and retracting mechanism for AG spin-up and spin-down in zero-G.

**Capability Description:** Provide materials, software control algorithms, and sensors that will enable controlled energy release for a deployable and retracting mechanism that enables AG spin-up and spin-down.

**Capability State of the Art:** JWST and other similar deployable telescopes have performed deployment operations. Parameters of these systems include, but are not limited to, mass of the deployment system, power to perform the deployment, complexity of the system (risk of deployment), efficiency of packaging volume, and probability of success.

**Parameter, Value:**
Mass, volume, power, packaging efficiency, mean time between failure (MTBF)/mean time between replacement (MTBR)

**Capability Performance Goal:** Provide controlled energy release that allows the safe deployment and retraction of mechanical systems for AG spacecraft spin-up and spin-down operations.

**Parameter, Value:**
Newton-force pounds: 100 pound force.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 6 years |

7.5 Mission Operations and Safety
7.5.2 Planetary Protection

## 7.5.2.1 Active Sterilization

### TECHNOLOGY

**Technology Description:** Advanced, compact, and efficient sterilization of spacecraft and space operations bioburden through application of heat, ultraviolet (UV), plasma, radiation, reactive gas-phase processes, and other means.

**Technology Challenge:** Achieve a bioload log reduction of at least $10^{-12}$ with a portable device capable of use during crewed planetary surface operations.

**Technology State of the Art:** Current technologies in-use include: dry heat sterilization, electron beam and gamma ray radiation, UV light, plasma, vapor hydrogen peroxide, ethylene dioxide, and hydrazine. Not all have been used on space hardware. Technologies have also been demonstrated in the medical industry.

**Parameter, Value:** Sterility Assurance Level (SAL)/log reduction ranging from $10^{-4}$ to $10^{-12}$ depending on the specific technology

**TRL:** 1

**Technology Performance Goal:** Development of low mass and volume sterilization technologies which require little to no consumables and produce little to no waste by-products for the purpose of sterilizing spacecraft and operational hardware in a space or planetary surface environment.

**Parameter, Value:** Consistent SAL/log reduction of at least $10^{-12}$.

**TRL:** 9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Reduction of bioburden through treatment application.

**Capability Description:** Bioload reduction and maintenance through active sterilization systems during all mission phases, including ground processing and in-space operations.

**Capability State of the Art:** Heat application, irradiation, and gas-phase processes technologies used in ground-based environments for robotic missions. No in-space sterilization capability is available beyond utilization of space environment effects.

**Parameter, Value:** Log reduction/ SAL of bioload.

**Capability Performance Goal:** Evaluate and advance sterilization technologies for development in space applications and/or advanced ground processing.

**Parameter, Value:** Consistent SAL/log reduction of at least $10^{-12}$ provided in a space and planetary surface environment by a compact, minimal mass, waste, and consumable technology.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 6 years |

7.5 Mission Operations and Safety
7.5.2 Planetary Protection

## 7.5.2.2 Cleanable Adhesive Surfaces for Variable Gravity

### TECHNOLOGY

**Technology Description:** Advanced, reusable surfaces which capture particulate contamination that may also host molecular organic/microbial material.

**Technology Challenge:** Minimize the mass and waste products of a system that captures and retains particulate contamination which might host molecular organic/microbial material.

**Technology State of the Art:** Cleanroom sticky mats are adhesive surfaces that can sometimes be cleaned and reused, and are designed to capture particulate contamination.

**Parameter, Value:** Retainment of 98-100% of particulate contamination.

**TRL:** 1

**Technology Performance Goal:** Prevent release of 100% of captured particulate contamination when transitioning between gravity and non-gravity environments while minimizing any waste by-products resulting from cleaning and reuse of such surfaces.

**Parameter, Value:** Percentage of particulate contamination retained.

**TRL:** 9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Cleanable adhesive surfaces for variable gravity environments.

**Capability Description:** Minimize/control the transport of particulate contamination that may host molecular organic/microbial contamination between crew habitation environments (e.g., lander, surface habitat, ascent vehicle, etc.).

**Capability State of the Art:** Not in use in space today.

**Parameter, Value:** Percentage of particulate contamination retained

**Capability Performance Goal:** Analysis and evaluation needed (engineering activity) of existing technology and requisite modification for variable gravity/transitionary environments.

**Parameter, Value:** Reduce liberation of planetary surface materials (dust) during transition to microgravity operations so as to achieve retention of 100% particulate contamination.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 6 years |

7.5 Mission Operations and Safety
7.5.2 Planetary Protection

## 7.5.2.3 Cleaning Systems

### TECHNOLOGY

**Technology Description:** Processes, chemicals, and treatments that require few consumables and produce negligible waste byproducts to clean spacecraft hardware to sterility.

**Technology Challenge:** The challenge will be development of low/no-waste cleaning systems and processes compatible with spacecraft, spacesuits, and tool materials, spacecraft environmental recycling processes, and the in-space environment, potentially suitable for use in low pressure environments. A candidate technology includes "pyro/ablative" paint. Development should target portable systems that can achieve a bioload log reduction of at least $10^{-12}$ capable of use during crewed planetary surface operations.

**Technology State of the Art:** Technologies include: alcohol wipes/other forms of mechanical "washing/removal," high-efficiency particulate air (HEPA) filtration, $CO_2$ snow, and many of the reactive gas phase methods identified in "Sterilization" technology. Cleaning is achieved through continual application of the gas phase methods.

**Parameter, Value:** | **TRL**

Log reduction ranging from $10^{-4}$ to $10^{-12}$ depending on the specific technology.

**Technology Performance Goal:** Development of low mass and volume cleaning technologies that require little to no consumables and produce little to no waste by-products for the purpose of cleaning spacecraft, spacesuits, extravehicular activity (EVA )tools, and operational hardware in a space or planetary surface environment.

**Parameter, Value:** | **TRL** 7

Consistent log reduction of at least $10^{-12}$.

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Reduction of bioburden through bioload removal.

**Capability Description:** Ability to clean spacecraft hardware (including crewed mission operational systems – e.g., EVA tools, spacesuits) to remove bioburden.

**Capability State of the Art:** Ground-based methods include mechanical removal, entrapment, and reactive gas phase methods. In-space methods have only been demonstrated in pressurized low-Earth orbit (LEO) environments (mechanical removal and HEPA filtration).

**Parameter, Value:**

Log reduction of bioload.

**Capability Performance Goal:** Achieve minimal consumable and waste by-product cleaning methodologies for in-space use.

**Parameter, Value:**

Consistent log reduction of at least $10^{-12}$ provided in a space and planetary surface environment by a compact, minimal mass, waste, and consumable technology.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 6 years |

7.5 Mission Operations and Safety
7.5.2 Planetary Protection

# 7.5.2.4 Microbial Burden Identification and Monitoring

## TECHNOLOGY

**Technology Description:** Reliable assay techniques for spacecraft, spacecraft subsystems, and planetary environments which identify and monitor the specific microbiology present (microbial burden).

**Technology Challenge:** Develop a reduced mass, volume, and minimal consumable (i.e., "handheld") capability to characterize microbial bioburden and assess changes in the bioload before and during spaceflight operations, including monitoring of markers/organisms of terrestrial origin due to human-associated activities in an unpressurized environment.

**Technology State of the Art:** Laboratory assays including culturable/growth (8 hours to 48 hours) and wet-lab rapid assay (~minutes) techniques such as: adenosine triphosphate (ATP), limulus amebocyte lysate (LAL), and Polymerase Chain Reaction. Field-deployable systems such as: Lab-on-a-Chip Application Development - Portable Test System (LOCAD-PTS) (portable wet-lab), deep ultraviolet (UV)/native fluoresence, and other optical and spectorophotometric assay methods.

**Parameter, Value:** — **TRL** 2

Ability to provide characterization of 99% of known microbial life and markers in a laboratory (ground-based) environment.

**Technology Performance Goal:** Mass and volume reduction of ground-based assay technologies resulting in compact, minimal waste/consumable assay techniques suited to long-duration exploration missions. Includes advancement of optical, spectrophotometric, deoxyribonucleic acid (DNA), or other biomolecule-based assay technologies including ion mobility spectroscopy and Bioluminescent Bioreported Integrated Circuits (BBICS).

**Parameter, Value:** — **TRL** 9

Ability to provide characterization of > 99% of known microbial life and markers in an exploration (space and planetary surface) environment.

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Identification and monitoring of microbial burden.

**Capability Description:** Microbial burden analysis capable of actively identifying and monitoring viruses, prions, prokaryotic and eukaryotic cells, and associated markers/organisms of terrestrial origin and ability to differentiate from potential extraterrestrial organisms.

**Capability State of the Art:** Lab-based culturable assays and limited in-space rapid-assay techniques such as Lab-on-a-Chip Application Development - Portable Test System (LOCAD-PTS), which does not provide microbe characterization.

**Parameter, Value:**

Percentage of identified cells/biomarkers

**Capability Performance Goal:** Selection and development of terrestrial technologies for in-space application which provide complete identification and monitoring of bioburden on spacecraft surfaces and/or the planetary surface environment with in reduced volume and mass. Need to also understand the impact of PP monitoring technologies on hardware design (design for doing PP).

**Parameter, Value:**

> 99% characterization of microbial burden including presence and density of terrestrial contamination

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 5 years |

7.5 Mission Operations and Safety
7.5.2 Planetary Protection

## 7.5.2.5 Recontamination Prevention

### TECHNOLOGY

**Technology Description:** Biobarrier materials.

**Technology Challenge:** Create lighting materials that provide appropriate level of prevention and methodologies to ensure prevention of recontamination of surfaces cleaned or sterilized in-situ (in-space and planetary surface).

**Technology State of the Art:** Thin-film sleeves or 'shields' and similar medical packaging techniques, hot gas purges, high-efficiency particulate air (HEPA) filtration, and system overpressurization.

**Parameter, Value:**
Effectiveness of biobarrier through maintenance of cleaning/ sterilization log reduction (ranging from $10^{-4}$ to $10^{-12}$ depending on the approach utilized).

**TRL**
2

**Technology Performance Goal:** Advancement of materials and techniques that provide lightweight, easily removable protection of sterilized surfaces from re-contamination while maintaining the logarithmic reduction value (LRV) achieved through cleaning/ sterilization.

**Parameter, Value:**
Effectiveness of biobarrier through maintenance of cleaning/sterilization log reduction (up to $10^{-12}$) in both in-space, planetary surface, and transitionary environments.

**TRL**
9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Prevention of recontamination.

**Capability Description:** Lightweight physical protection of cleaned/sterilized surfaces from being re-exposed to biological contamination.

**Capability State of the Art:** Encapsulation, purges, filtration, and over-pressurization are leveraged capabilities for ground processing of spacecraft. Encapsulation and over-pressurization utilized on robotic missions, no such capabilities used on human missions thus far.

**Parameter, Value:**
Barrier effectiveness in terms of logarithmic reduction value.

**Capability Performance Goal:** Lightweight materials and techniques (i.e., purges and overpressurization) to protect cleaned and sterilized surfaces from re-contamination in in-space and planetary surface environments.

**Parameter, Value:**
Biobarrier effectiveness in terms of logarithmic reduction value in relevant environment (in-space or planetary surface environment).

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 5 years |

7.5 Mission Operations and Safety
7.5.2 Planetary Protection

# 7.5.2.6 Debris Quantification for Planetary Material Containment

## TECHNOLOGY

**Technology Description:** Modeling and simulation tools to quantify risks posed by orbital and in-space debris to planetary material containment systems.

**Technology Challenge:** Develop modeling tools with a high level of validated accuracy (> 99%) to quantify the risks of in-space micrometeroid and orbital debris (MMOD) to containment of returned planetary material.

**Technology State of the Art:** Orbital debris analysis code utilized in Monte Carlo runs of micrometeoroid and orbital debris (MMOD) risk to low-Earth orbit (LEO) assets. Historical MMOD impact data.

**Parameter, Value:**
Probability of PNI/CI.

**TRL** 3

**Technology Performance Goal:** 99.7% accuracy in determining the Probability of Non-Critical and Critical Impacts (PNI/CI).

**Parameter, Value:**
Probability of PNI/CI.

**TRL** 9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Risk quantification of in-space debris to planetary material containment.

**Capability Description:** Quantify the risks posed by in-space and orbital debris to planetary material containment and provide verification of predictive models.

**Capability State of the Art:** Monte Carlo MMOD simulations for LEO.

**Parameter, Value:**
Probability of debris strike over orbital lifetime.

**Capability Performance Goal:** Analysis and evaluation needed (engineering activity) to perform validation of models for planetary material containment systems.

**Parameter, Value:**
Ability to quantify orbital and in-space debris events during Mars-transit and in Mars orbit to 99.7% (three sigma) certainty.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 7 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 7 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 7 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 7 years |

7.5 Mission Operations and Safety
7.5.2 Planetary Protection

## 7.5.2.7 Particle Transport Modeling

### TECHNOLOGY

**Technology Description:** Monte Carlo, discrete event, and human-in-the-loop simulations to predict particle transport in a Mars environment.

**Technology Challenge:** Validation of transport models that depict transport of Mars material as well as microbial (forward) contamination.

**Technology State of the Art:** Particle transport models (also applicable to Mars Environment Characterization).

**Parameter, Value:** Percent error not yet determined.

**TRL:** 3

**Technology Performance Goal:** Develop an accurate model that can depict the effects of human exploration systems on the Mars environment (forward contamination) and vice versa.

**Parameter, Value:** 99.7% certainty (three sigma) in particle distribution and transport as a result of crewed mission activities on a planetary surface.

**TRL:** 9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Particle transport modeling.

**Capability Description:** Capability to model particle transport under varying environmental conditions (Mars and in-space).

**Capability State of the Art:** Monte Carlo simulations.

**Parameter, Value:** Percent error in models compared to scientific observations.

**Capability Performance Goal:** Analysis and evaluation needed (engineering activity).

**Parameter, Value:** Ability to quantify particle transport and settling in a variety of gravity environments with > 99% certainty (three sigma).

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 4 years |

7.5 Mission Operations and Safety
7.5.2 Planetary Protection

## 7.5.2.8 Dust Analyzer

### TECHNOLOGY

**Technology Description:** Mars environmental monitoring system measuring dust density, distribution, composition, and behavior.

**Technology Challenge:** Mars dust contains a lot of unknowns, difficult to design technology to assess dust when its characteristics and behavior is unknown.

**Technology State of the Art:** Dust characterization, Risk assessment and Environment Analyzer on Martian Surface (DREAMS) instrument to fly on ExoMars 2016.

| Parameter, Value: | TRL |
|---|---|
| Characterization (composition, distribution, and transportation) of Mars dust. | 3 |

**Technology Performance Goal:** Ability to rapidly assess dust composition, dispersion, adhesion qualities, and local environment effects on dust composition, distribution, and transportation. By characterizing dust, may be able to shape planetary protection policy for crewed surface operations.

| Parameter, Value: | TRL |
|---|---|
| Characterization (composition, distribution, and transportation) of Mars dust. | 9 |

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Dust characterization of Mars surface.

**Capability Description:** Ability to characterize Mars landing site environments (particularly dust composition). This data needs to be captured during robotic precursor missions because it will be used to design eventual human missions.

**Capability State of the Art:** Mass spectrometer, surface weather stations, etc. on current Mars robotic landers. No fully integrated system with the sole purpose of dust characterization exists.

**Parameter, Value:**

Characterization (composition, distribution, and transportation) of Mars dust.

**Capability Performance Goal:** Ability to rapidly assess dust composition, dispersion, adhesion qualities, and local environment effects on dust composition, distribution, and transportation.

**Parameter, Value:**

Identify dust composition (toxicity, chemical composition, reactivity, water content, etc.).

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 5 years |

7.5 Mission Operations and Safety
7.5.2 Planetary Protection

## 7.5.2.9 Containment Sensors

### TECHNOLOGY

**Technology Description:** Systems that allow instantaneous verification of containment integrity.

**Technology Challenge:** Development of robust, non-invasive, low mass and volume containment verification methodologies to provide assured sample containment prior to Earth return.

**Technology State of the Art:** Early development of wireless sensor technology and ion trap mass spectrometer for carbon dioxide ($CO_2$) leak detection.

**Parameter, Value:** No currently measured value

**TRL:** 1

**Technology Performance Goal:** Non-invasively determine that sample containment is achieved and maintained throughout transport (e.g., verification post micrometeoroid and orbital debris (MMOD) event).

**Parameter, Value:** Ability to verify positive containment that meets $10^{-6}$ probability of the release of a particle < 50 nanometers in size.

**TRL:** 9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Ability to verify proper containment of returned planetary material.

**Capability Description:** Systems for analysis and verification of sample containment.

**Capability State of the Art:** Use of wirelessly transmitting transducers.

**Parameter, Value:** No currently measured value.

**Capability Performance Goal:** Evaluation of technology and performance of sensor technology for verifying containment systems.

**Parameter, Value:** Ability to verify 100% containment.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 7 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 8 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 8 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 8 years |

7.5 Mission Operations and Safety
7.5.2 Planetary Protection

## 7.5.2.10 Post-Return Sample Containment

### TECHNOLOGY

**Technology Description:** Biosafety Level (BSL) 4 or greater laboratories which offer effective sample containment while preserving the cleanliness of the sample.

**Technology Challenge:** Ability to retain attributes of both positive pressure (containment) and negative pressure (sample cleanliness) simultaneously during sample transfer and storage.

**Technology State of the Art:** Current BSL-4 laboratories, which handle dangerous and exotic agents.

**Parameter, Value:** Protect for 1 x $10^{-6}$ potential for contaminant release/hazard to general public.

**TRL:** 4

**Technology Performance Goal:** Provide assured containment of extraterrestrial sample material from return throughout curation, while also maintaining sample purity/cleanliness. Considered to be accomplished through modified BSL-4 laboratories or construction of a facility with both BSL-4 and current astromaterial curation criteria properties.

**Parameter, Value:** Protect for 1 x $10^{-6}$ potential for contaminant release/hazard to general public while maintaining sample cleanliness/purity (zero terrestrial contamination).

**TRL:** 9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Contamination control during post-return sample handling.

**Capability Description:** Facilities for transfer of collected samples under appropriate contamination control (both sample containment and maintenance of sample cleanliness).

**Capability State of the Art:** This is an Earth-based technology development required to support future space missions. Capabilities currently fulfilled by high biosafety level laboratories (BSL-4), but have not had to additionally protect for sample cleanliness.

**Parameter, Value:** Protect for 1 x $10^{-6}$ potential for contaminant release/hazard to general public.

**Capability Performance Goal:** Technology needs to protect samples from terrestrial contaminants as well as humans from exposure to samples (usually the protection is only one-way).

**Parameter, Value:** Suggested operation at BSL 4 while preventing forward terrestrial contamination of the sample.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 4 years |

7.5 Mission Operations and Safety
7.5.2 Planetary Protection

## 7.5.2.11 Sample Containment Systems

### TECHNOLOGY

**Technology Description:** Hermetically sealed containers.

**Technology Challenge:** Achieving sample containment is the cornerstone of "breaking the chain of contact" with extraterrestrial material and is necessary to ensure the safety of Earth's biosphere. As measurement capabilities improve, the containment requirements will likely become increasingly stringent.

**Technology State of the Art:** Hermetic sealing containers and redundant sealing technologies used in laboratory environment and unrestricted planetary sample return.

**Parameter, Value:**
Hermetic sealing containers and redundant sealing technologies used in laboratory environment and unrestricted planetary sample return.

**TRL:** 2

**Technology Performance Goal:** Provide the demonstrated ability to contain extraterrestrial material returned to Earth either through robotic Mars Sample Return (MSR) or human missions until delivered to a designated processing facility for analysis.

**Parameter, Value:**
Need to provide containment against the release of a single self-replicating particle.

**TRL:** 9

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Containment of returned samples (extraterrestrial material).

**Capability Description:** Assured containment of returned sample containers.

**Capability State of the Art:** Hermetic sealing methods used primarily in ground-based laboratories or other containment measures for unrestricted planetary sample return.

**Parameter, Value:**
Most current systems evaluated by sccm leakage rates.

**Capability Performance Goal:** Develop sample containment technology that prevents the release of the smallest known self-replicating particles at the current limits of detection.

**Parameter, Value:**
Protection against $10^{-6}$ probability of the release of a particle 10 nm or larger in size.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 5 years |
| Planetary Flagship: Mars Sample Return | Enabling | -- | 2026* | 2023 | 5 years |

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

7.5 Mission Operations and Safety
7.5.3 Integrated Flight Operations Systems

## 7.5.3.1 Autonomous Crew Operations

### TECHNOLOGY

**Technology Description:** Ability for the crew to monitor information, manage faults, modify plans, and execute procedures with limited interaction with the ground.

**Technology Challenge:** Extending autonomy capability requires: transitioning responsibility from ground to crew (e.g., autonomous procedure execution); automating functions done by people (e.g., procedure automation); expanding autonomy from simple to complex tasks (e.g., from single procedures to managing entire system); scaling autonomy from smaller to larger systems (e.g., one power bus to four); and expanding autonomy to more types of systems (e.g., power, environmental control and life support system (ECLSS), and thermal).

**Technology State of the Art:** Current work at International Space Station (ISS) has examined: communication delay characterization; observe impact of time delay on team interaction; autonomous procedures; revise existing procedures for ISS crew execution without ground assistance; ISS texting; develop texting protocols; demonstrate texting to and from the ISS; crew self-scheduling; and compare multiple crew self-scheduling technologies.

**Parameter, Value:**

All parameters currently represent manual activities. Automated activities are being developed.

**TRL:** 2

**Technology Performance Goal:** Extending the number, range, and diversity of functions that can be performed without direct support from the ground operations infrastructure.

**Parameter, Value:**

Issue commands autonomously: 28,000;
Monitor data autonomously: 72,000 data items;
Displays: 1,200;
Autonomously manage operational constraints: 100;
Perform procedures: 1,600;
Manage plans: 100 activities per day;
Manage fault conditions: 9,000

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** Autonomous Crew Operations will rely upon key building block technologies described in TA 4.

### CAPABILITY

**Needed Capability:** Autonomous mission operations.

**Capability Description:** The capability of flight controllers and crews to manage a crewed mission with minimal reliance on Earth-based mission control. Autonomy is accomplished by automating vehicle functions, and by transitioning responsibilities from mission control to crew.

**Capability State of the Art:** ISS Mission Operations and limited experiments onboard the ISS that demonstrate advancement of some key underlying capabilities.

**Parameter, Value:**

Less than 1% of current commands on ISS executed autonomously.

**Capability Performance Goal:** Crew will have to execute thousands of procedures during a mission, and hundreds of activities a day. Crew works toward a predetermined timeline with less mission control oversight. Requires systems to detect, isolate, and recover from faults.

**Parameter, Value:**

Issue commands autonomously: 28,000;
Monitor data autonomously: 72,000 data items;
Displays: 1,200;
Autonomously manage operational constraints: 100;
Perform procedures: 1,600;
Manage plans: 100 activities per day;
Manage fault conditions: 9,000

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enabling | 2027 | 2027 | 2021 | 7 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 7 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 8 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 8 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 8 years |

7.5 Mission Operations and Safety
7.5.3 Integrated Flight Operations Systems

## 7.5.3.2 Autonomous Ground Operations

### TECHNOLOGY

**Technology Description:** Enable effective ground support of increasingly autonomous crew activities as mission duration and distance increase, by providing capability to manage operational constraints, perform procedures, and manage plans without contact with Earth-based mission control.

**Technology Challenge:** Extending autonomy capability requires: transitioning responsibility from ground to crew (e.g., autonomous procedure execution); automating functions done by people (e.g., procedure automation); expanding autonomy from simple to complex tasks (e.g., from single procedures to managing entire system); assist ground controls in identifying slowly developing trends of data towards off-nominal (or out of family) performance; scaling autonomy from smaller to larger systems (e.g., one power bus to four); clearly displaying and drawing attention to the right things given an extremely large amount of data available; and expanding autonomy to more types of systems (e.g., power, environmental control and life support system (ECLSS), and thermal).

**Technology State of the Art:** Extended series of mission operation advancements and software developments have reduced ground support workloads but have not significantly changed interactions with onboard crew.

**Parameter, Value:**

Less than 1% of current commands on the International Space Station (ISS) are executed autonomously.

**TRL:** 3

**Technology Performance Goal:** Protocols and technology to accurately transmit tens of thousands of commands and telemetry items with delays of up to eight minutes (1 way).

**Parameter, Value:**

Transmit commands with time delay: 35,000;

Monitor telemetry with a time delay: 90,000 telemetry items;

Displays: 750;

Manage operational constraints: 500;

Perform procedures: 2,000;

Mange plans: 100 activities per day;

Manage fault conditions: 9,000

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** Autonomous Ground Operations will rely upon key building block technologies described in TA 4.

### CAPABILITY

**Needed Capability:** Autonomous mission operations.

**Capability Description:** The capability of flight controllers and crews to manage a crewed mission with minimal reliance on Earth-based mission control. Autonomy is accomplished by automating vehicle functions, and by transitioning responsibilities from mission control to crew.

**Capability State of the Art:** ISS mission operations.

**Parameter, Value:**

Less than 1% of current commands on the ISS are executed autonomously.

**Capability Performance Goal:** Protocols and technology to accurately transmit tens of thousands of commands and telemetry items with delays of up to eight minutes (1 way).

**Parameter, Value:**

Transmit commands with time delay: 35,000;

Monitor telemetry with a time delay: 90,000 telemetry items;

Displays: 750;

Manage operational constraints: 500;

Perform procedures: 2,000;

Mange plans: 100 activities per day;

Manage fault conditions: 9,000

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enabling | 2027 | 2027 | 2021 | 7 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 7 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 8 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 8 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 8 years |

7.6 Cross-Cutting Systems
7.6.1 Particulate Contamination Prevention and Mitigation

## 7.6.1.1 “Tunnels” to Minimize Regolith Transfer During Extravehicular Activities (EVAs)

### TECHNOLOGY

**Technology Description:** Passageways that incorporate technologies such as active-active mating adapter and articulating jet ways to reduce the amount of dust transported during extravehicular activity (EVA) operations.

**Technology Challenge:** Create lightweight pressurized (intravehicular activity( and/or unpressurized passageways (EVA) for crew members that reduce the amount of dust transport while traversing between surface assets.

**Technology State of the Art:** Active-active mating adapter tested in field tests and articulating jet ways widely used in airport operation.

**Parameter, Value:** No currently measured value.

**TRL** 3

**Technology Performance Goal:** Develop passageways and mating adaptors that minimize dust intrusion into habitable volumes.

**Parameter, Value:** Mass of dust transported (will depend on mission architectures).

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Dust prevention.

**Capability Description:** The ability to prevent dust from contaminating hardware surfaces, soft surfaces such as spacesuits, mechanisms, and habitat/spacecraft interiors.

**Capability State of the Art:** Not previously used in planetary/surface systems.

**Parameter, Value:** No currently measured value.

**Capability Performance Goal:** Minimize dust intrusion into habitable volumes.

**Parameter, Value:** Amount of dust around a component and/or amount of time dust is present before the component must be cleaned of dust or repaired/replaced. Parameter value dependent on type of component and the performance tolerance to dust build-up.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 4 years |

7.6 Cross-Cutting Systems
7.6.1 Particulate Contamination Prevention and Mitigation

# 7.6.1.2 Air and Airlock Cleaning

## TECHNOLOGY

**Technology Description:** Spacesuit, tools, and other system cleaning within suitlock or airlock to prevent dust from entering habitable volumes and create a clean environment for suit maintenance and repair. Possible technologies include low power/mass air shower, low power/mass air handler, low power/mass vent hood, electrostatic precipitator, electrospray, and water shower.

**Technology Challenge:** Develop systems that clean dusty surfaces within the airlock and contain dust when items must be brought into habitable volumes with a minimum amount of mass and power required.

**Technology State of the Art:** These technologies are available for a wide range of commercial applications on Earth, but have not been demonstrated in a relevant environment for space applications.

**Parameter, Value:**

Cleanrooms range from Class 1 (35 maximum particles per cubic foot for >= .1 micron to 1 particle per cubic foot for >= .5 microns) to Class 100,000 (100,000 particles per cubic foot for .5 microns to 5 particles per cubic foot for >= 700 particles per square foot).

**TRL:** 3

**Technology Performance Goal:** Cleaning techniques that improve air quality, lower mass and power requirements.

**Parameter, Value:**

Cleanrooms range from Class 1 (35 maximum particles per cubic foot for >= .1 micron to 1 particle per cubic foot for >= .5 microns) to Class 100,000 (100,000 particles per cubic foot for .5 microns to 5 particles per cubic foot for >= 700 particles per square foot).

Parameter values may be modified for specific missions.

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Dust prevention.

**Capability Description:** The ability to prevent dust from contaminating hardware surfaces, and soft surfaces such as spacesuits, mechanisms, and habitat/spacecraft interiors.

**Capability State of the Art:** Not previously used in planetary/surface systems.

**Parameter, Value:**

No currently measured value.

**Capability Performance Goal:** Minimize dust on interior components and systems.

**Parameter, Value:**

Amount of dust around a component and/or amount of time dust is present before the component must be cleaned of dust or repaired/replaced. Parameter value dependent on type of component and the performance tolerance to dust build-up.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 7 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 7 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 10 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 10 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 10 years |

7.6 Cross-Cutting Systems
7.6.1 Particulate Contamination Prevention and Mitigation

## 7.6.1.3 Sample Handling

### TECHNOLOGY

**Technology Description:** A sealed container with exterior ports that enables a person to manipulate objects, where a separate atmosphere is desired.

**Technology Challenge:** Technology challenges are minimizing the mass and power requirements of the container.

**Technology State of the Art:** Glove box technology is widely used in Earth applications for protective handling and transfer of materials. Prototype tested in the Habitat Demonstration Unit in Desert Research and Technologies Studies (DRATS).

**Parameter, Value:**
Earth based glovebox technology consume ~ 1 kilowatt typically move 10 to 100 cfm and weigh around 400 to 600 pounds.

**TRL** 5

**Technology Performance Goal:** Contain dust during sample handling with minimal mass and power requirements.

**Parameter, Value:**
100% containment of dust with low power and mass. Power/mass values will be mission dependent.

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Dust prevention.

**Capability Description:** The ability to prevent dust from contaminating hardware surfaces, and soft surfaces such as spacesuits, mechanisms, and habitat/spacecraft interiors.

**Capability State of the Art:** Not previously used in planetary/surface systems.

**Parameter, Value:**
No currently measured value.

**Capability Performance Goal:** Performance measure is the amount of dust around a component and/or amount of time dust is present before the component must be cleaned of dust or repaired/replaced.

**Parameter, Value:**
Parameter value dependent on type of component and the performance tolerance to dust build-up.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 5 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 5 years |

7.6 Cross-Cutting Systems
7.6.1 Particulate Contamination Prevention and Mitigation

## 7.6.1.4 Dust Covers

### TECHNOLOGY

**Technology Description:** Umbilical dust covers, modular suit cover system, strippable coatings that minimize dust intrusion.

**Technology Challenge:** Technology challenges are minimizing dust contamination with minimal mass required.

**Technology State of the Art:** These technologies are widely applied for commercial applications on Earth. Booties were developed for Apollo; however, they were not used. Lens covers are used on camera lenses.

**Parameter, Value:** Dust exclusion, abrasion prevention. Dependent on application, e.g., electrical connectors, optical systems, clothing systems, etc.

**TRL:** 4

**Technology Performance Goal:** Develop covers that prevent or minimize dust contamination with minimal mass required.

**Parameter, Value:** Dust exclusion, abrasion prevention. Dependent on application, e.g., electrical connectors, optical systems, clothing systems, etc.

**TRL:** 8

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Dust prevention.

**Capability Description:** The ability to prevent dust from contaminating hardware surfaces, and soft surfaces such as spacesuits, mechanisms, and habitat/spacecraft interiors.

**Capability State of the Art:** Dust covers were used during Apollo on camera lenses.

**Parameter, Value:** No currently measured value.

**Capability Performance Goal:** Performance measure is the amount of dust around a component and/or amount of time dust is present before the component must be cleaned of dust or repaired/replaced.

**Parameter, Value:** Parameter value dependent on type of component and the performance tolerance to dust build-up.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 4 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 4 years |
| Strategic Missions: Mars 2020 | Enhancing | -- | 2020 | 2017 | 3 years |
| Planetary Flagship: Mars Sample Return | Enhancing | -- | 2026* | 2023 | 4 years |

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

7.6 Cross-Cutting Systems
7.6.1 Particulate Contamination Prevention and Mitigation

## 7.6.1.5 Dissipation, Reduction, and/or Elimination of Triboelectric Charge Build-Up

### TECHNOLOGY

**Technology Description:** Systems to eliminate internal spacecraft triboelectric charging.

**Technology Challenge:** May be difficult to dissipate charge in a dusty environment without good electrical grounding, in harsh ultraviolet (UV) environment, in charged space plasmas.

**Technology State of the Art:** No systems have been developed for use in planetary surface environments but many technologies are mature for terrestrial applications. NASA has established guidelines and design practices to minimize spacecraft internal charging due to interactions between the in-flight plasma environment and spacecraft electronics systems. The technologies used in design are off-the-shelf surface and volume resistance meters, non-contact voltmeters, dielectric constant meters and the like. Because of these design practices, damage to onboard electronic instruments is now rare. However, interference with scientific instruments is still a problem. Measurement of the electrostatic potential of spacecraft relative to the space plasma is measured in flight with Langmuir probes, retarding potential analyzers, floating probes, and charged particle energy analyzers.

**Parameter, Value:** Voltage measurements arbitrarily accurate for terrestrial applications. No standard method to measure spacecraft charge has been developed.

**TRL** 3

**Technology Performance Goal:** Eliminate risk to onboard electronics due to triboelectric charge.

**Parameter, Value:** Voltage measurements arbitrarily accurate for terrestrial applications. No standard method to measure spacecraft charge has been developed.

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Dust prevention.

**Capability Description:** The ability to prevent dust from contaminating hardware surfaces, and soft surfaces such as spacesuits, mechanisms, and habitat/spacecraft interiors.

**Capability State of the Art:** Not previously used in planetary/surface systems.

**Parameter, Value:** No currently measured value.

**Capability Performance Goal:** Performance measure is the amount of dust around a component and/or amount of time dust is present before the component must be cleaned of dust or repaired/replaced.

**Parameter, Value:** Parameter value dependent on type of component and the performance tolerance to dust build-up.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enabling | 2027 | 2027 | 2021 | 7 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 7 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 7 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 10 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 10 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 10 years |

7.6 Cross-Cutting Systems
7.6.1 Particulate Contamination Prevention and Mitigation

## 7.6.1.6 Passive Cleaning

### TECHNOLOGY

**Technology Description:** Lotus and gecko coatings.

**Technology Challenge:** Developing dust shedding coatings that do not degrade when subjected to abrasive dust, radiation, and thermal swings.

**Technology State of the Art:** Lotus and gecko coating are commercially available for applications on Earth. Lab-scale and field testing has been performed on Lotus coatings.

**Parameter, Value:**

Amount of dust adhering to surface. Dependent upon application, e.g., power, thermal, optical, etc.

**TRL** 3

**Technology Performance Goal:** Surfaces that shed dust in the presence of dust, vacuum, and solar and thermal radiation.

**Parameter, Value:**

Amount of dust adhering to surface. Dependent upon application, e.g., power, thermal, optical, etc.

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Dust tolerant, dust phobic, and/or dust shedding materials.

**Capability Description:** Coatings and surface materials that maintain integrity and minimize the amount of dust accumulated on hard and soft good surfaces and/or enable easy removal of accumulated dust.

**Capability State of the Art:** Not actively used in planetary/surface systems.

**Parameter, Value:**

Amount of dust adhering to surface. Dependent upon application, e.g., power, thermal, optical, etc. Not demonstrated in space applications.

**Capability Performance Goal:** Surfaces that shed dust in the presence of dust, vacuum, and solar and thermal radiation.

**Parameter, Value:**

Surface systems abrasion upon cleaning: values pending further study in relevant environments;

Performance degradation: values pending further study in relevant environments;

Dust rejection: values pending further study in relevant environments.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 4 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 4 years |

7.6 Cross-Cutting Systems
7.6.1 Particulate Contamination Prevention and Mitigation

## 7.6.1.7 Dust Repellant, Dust Shedding Materials, and Coatings for Thermal Control Surfaces

### TECHNOLOGY

**Technology Description:** Functional surface treatments or coatings that prevent dust adhesion or enables effective dust removal from thermal control surfaces.

**Technology Challenge:** Materials that can be applied and functional on structures made of different materials with large surface areas and complex geometry. Full size radiators need to be tested under simulated conditions. Amount of gas and gas force required for effective cleaning needs to be minimized.

**Technology State of the Art:** Work function matching coatings on metallized Teflon exhibited reduced dust adhesion.

**Parameter, Value:**
Solar absorptance restored to 0.2 when coupon-sized coated metallized Teflon was cleared of a lunar dust simulant in high vacuum with short gas burst.

**TRL** 3

**Technology Performance Goal:** Thermal control surfaces must maintain low solar absorptance, defined as fraction of solar energy absorbed. Large area application of coatings. Gas force and quantity.

**Parameter, Value:**
Solar absorptance: ≤ 0.2 in the presence of dust;
Surface area: > 5 $m^2$;
Gas force and quantity: dependent on analysis of effects on thermal control surfaces

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Dust tolerant, dust phobic, and/or dust shedding materials.

**Capability Description:** Coatings and surface materials that maintain integrity and minimize the amount of dust accumulated on hard and soft good surfaces and/or enable easy removal of accumulated dust.

**Capability State of the Art:** Not actively used in planetary/surface systems.

**Parameter, Value:**
No currently measured value.

**Capability Performance Goal:** Surfaces that shed dust in the presence of dust, vacuum, and solar and thermal radiation.

**Parameter, Value:**
Surface systems abrasion upon cleaning: values pending further study in relevant environments;
Performance degradation: values pending further study in relevant environments;
Dust rejection: values pending further study in relevant environments.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 3 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 3 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 3 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 3 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 3 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 3 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 3 years |
| Strategic Missions: Mars 2020 | Enhancing | -- | 2020 | 2017 | 3 years |
| Planetary Flagship: Mars Sample Return | Enhancing | -- | 2026* | 2023 | 3 years |

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

7.6 Cross-Cutting Systems
7.6.1 Particulate Contamination Prevention and Mitigation

## 7.6.1.8 Dust Repellant, Dust Shedding Materials, and Coatings for Photovoltaic Surfaces

### TECHNOLOGY

**Technology Description:** Functional surface treatments or coatings that prevent dust adhesion or enables effective dust removal from photovoltaic surfaces.

**Technology Challenge:** Developing surface treatment process and/or coating material that has the required transmittance properties for high-energy photovoltaics application and can be applied to large surface areas and complex geometry. Amount of gas and gas force required for effective cleaning needs to be minimized.

**Technology State of the Art:** Work function matching coatings have shown promise to reduce dust adhesion in other applications.

**Parameter, Value:**

Solar transmittance: > to be determined when dust-covered glass cleared with a short burst of gas (value needs to be measured in relevant environment).

**TRL:** 2

**Technology Performance Goal:** Photovoltaic surfaces must maintain high solar transparency and/or have solar transmittance restored when dust cleared. Large area application of coatings. Gas force and quantity.

**Parameter, Value:**

Solar transmittance: > to be determined in the presence of dust;

Surface area: > 5 m$^2$;

Gas force and quantity: dependent on analysis of effects on photovoltaic surfaces.

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Dust tolerant, dust phobic, and/or dust shedding materials.

**Capability Description:** Coatings and surface materials that maintain integrity and minimize the amount of dust accumulated on hard and soft good surfaces and/or enable easy removal of accumulated dust.

**Capability State of the Art:** Not actively used in planetary/surface systems.

**Parameter, Value:**

No currently measured value.

**Capability Performance Goal:** Surfaces that shed dust in the presence of dust, vacuum, and solar and thermal radiation.

**Parameter, Value:**

Surface systems abrasion upon cleaning: values pending further study in relevant environments;

Performance degradation: values pending further study in relevant environments;

Dust rejection: values pending further study in relevant environments

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 4 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 4 years |
| Strategic Missions: Mars 2020 | Enhancing | -- | 2020 | 2017 | 3 years |
| Planetary Flagship: Mars Sample Return | Enhancing | -- | 2026* | 2023 | 4 years |

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

7.6 Cross-Cutting Systems
7.6.1 Particulate Contamination Prevention and Mitigation

## 7.6.1.9 Dust Repellant, Dust Shedding Materials, and Coatings for Wear Surfaces

### TECHNOLOGY

**Technology Description:** Abrasion protective coatings for exposed wear surfaces.

**Technology Challenge:** Coating that is able to be applied to different material surfaces with complete geometry. The coating must maintain it optical, thermal, and mechanical properties during its service life.

**Technology State of the Art:** Plasma deposited tungsten carbide and aluminum oxide coated stainless steel.

**Parameter, Value:**
Not specified.

**TRL** 3

**Technology Performance Goal:** Wear surfaces must not abrade beyond the coating thickness in the presence of dust during operational lifetime.

**Parameter, Value:**
Abrasion depth: < coating thickness (~100 $\mu$m);
Service life: > 10 years

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Dust tolerant, dust phobic, and/or dust shedding materials.

**Capability Description:** Coatings and surface materials that maintain integrity and minimize the amount of dust accumulated on hard and soft good surfaces and/or enable easy removal of accumulated dust.

**Capability State of the Art:** Not actively used in planetary/surface systems.

**Parameter, Value:**
No currently measured value.

**Capability Performance Goal:** Surfaces that shed dust in the presence of dust, vacuum, and solar and thermal radiation.

**Parameter, Value:**
Surface systems abrasion upon cleaning: values pending further study in relevant environments;
Performance degradation: values pending further study in relevant environments;
Dust rejection: values pending further study in relevant environments.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 4 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 4 years |
| Strategic Missions: Mars 2020 | Enhancing | -- | 2020 | 2017 | 3 years |
| Planetary Flagship: Mars Sample Return | Enhancing | -- | 2026* | 2023 | 4 years |

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

7.6 Cross-Cutting Systems
7.6.1 Particulate Contamination Prevention and Mitigation

## 7.6.1.10 Electrodynamic Removal

### TECHNOLOGY

**Technology Description:** A multi-phase alternating current (AC) signal applied to sets of electrodes embedded in a substrate generate a dynamic electric field that carries along electrostatically charged dust particles (metallic or non-metallic).

**Technology Challenge:** Developing materials for application on fabrics and developing tight geometries for application inside connectors.

**Technology State of the Art:** Electrodynamic dust shield at the development stage.

**Parameter, Value:**

Amount of dust removed: 99.90%

**TRL** 4

**Technology Performance Goal:** Remove nearly all dust. Increase range of applications (surfaces, materials, geometries) where it can be applied.

**Parameter, Value:**

Amount of dust removed: Near 100% for extraterrestrial environments.

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Dust removal.

**Capability Description:** Remove dust from equipment, suits, tools, etc. to prevent it from contaminating living environments and/or to ensure proper operation of systems. Remove dust from spacecraft surfaces, optical systems, solar panels, thermal radiators, spacesuits, viewports, and other instruments to prevent damage to equipment, degrading of camera lenses, reduced performance of thermal radiators and solar panels, and contamination of habitats.

**Capability State of the Art:** Apollo lunar missions had limited capability for removing dust. More recent robotic missions to Mars, the Moon, and asteroids have tested some mechanisms for removing dust but not at the level needed for human habitation environments.

**Parameter, Value:**

Not measured in Apollo, but anecdotal evidence suggests it was low. Obscuration of surfaces during Pathfinder was measured at 0.3% per sol. Measurements with the Microscopic Imager on the Mars Exploration Rovers showed that suspended dust in the Martian atmosphere has a diameter of 2 to 4 micrometers.

**Capability Performance Goal:** Maximize the amount and size of dust particles that are removed. Minimize time required for removal process if manually performed by astronauts.

**Parameter, Value:**

Amount of dust removed: 95%;

Size range of dust particles removed;

Time (if manual) for dust removal: dependent on mission location and timelines.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 4 years |

7.6 Cross-Cutting Systems
7.6.1 Particulate Contamination Prevention and Mitigation

## 7.6.1.11 Electron Discharge and Bombardment

### TECHNOLOGY

**Technology Description:** Electron gun provides current at surface to cause particles to repel one another.

**Technology Challenge:** Developing applications for spacesuits and connectors.

**Technology State of the Art:** Electron gun at the development stage.

**Parameter, Value:**

Amount of dust removed: 99.90%

**TRL** 4

**Technology Performance Goal:** Increase range of applications (surfaces, materials, geometries) where it can be applied.

**Parameter, Value:**

Amount of dust removed: near 100% for extraterrestrial environments.

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Dust removal.

**Capability Description:** Remove dust from equipment, suits, tools, etc. to prevent it from contaminating living environments and/or to ensure proper operation of systems. Remove dust from spacecraft surfaces, optical systems, solar panels, thermal radiators, spacesuits, viewports, and other instruments to prevent damage to equipment, degrading of camera lenses, reduced performance of thermal radiators and solar panels, and contamination of habitats.

**Capability State of the Art:** Apollo lunar missions had limited capability for removing dust. More recent robotic missions to Mars, the Moon, and asteroids have tested some mechanisms for removing dust but not at the level needed for human habitation environments.

**Parameter, Value:**

Not measured in Apollo, but anecdotal evidence suggests it was low. Obscuration of surfaces during Pathfinder was measured at 0.3% per sol. Measurements with the Microscopic Imager on the Mars Exploration Rovers showed that suspended dust in the Martian atmosphere has a diameter of 2 to 4 micrometers.

**Capability Performance Goal:** Maximize the amount and size of dust particles that are removed. Minimize time required for removal process if manually performed by astronauts.

**Parameter, Value:**

Amount of dust removed: 95%;

Size range of dust particles removed;

Time (if manual) for dust removal: dependent on mission location and timelines.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 4 years |

7.6 Cross-Cutting Systems
7.6.1 Particulate Contamination Prevention and Mitigation

## 7.6.1.12 Magnetic Brush

### TECHNOLOGY

**Technology Description:** Bar that is moved over a surface or spacesuit to attract and remove the dust.

**Technology Challenge:** Move dust from magnetized components into storage container without losing the dust.

**Technology State of the Art:** A prototype magnetic roller has been developed and tested in the laboratory.

**Parameter, Value:**

Dust lifting from surface, 90%;

Dust capture (prevent falling back onto surface) only 40%

**TRL**: 3

**Technology Performance Goal:** Improve the dust capture rate as well as the dust lifting rate.

**Parameter, Value:**

> 95% dust capture.

**TRL**: 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Dust removal.

**Capability Description:** Remove dust from equipment, suits, tools, etc. to prevent it from contaminating living environments and/or to ensure proper operation of systems. Remove dust from spacecraft surfaces, optical systems, solar panels, thermal radiators, spacesuits, viewports, and other instruments to prevent damage to equipment, degrading of camera lenses, reduced performance of thermal radiators and solar panels, and contamination of habitats.

**Capability State of the Art:** Apollo lunar missions had limited capability for removing dust. More recent robotic missions to Mars, the Moon, and asteroids have tested some mechanisms for removing dust but not at the level needed for human habitation environments.

**Parameter, Value:**

Not measured in Apollo, but anecdotal evidence suggests it was low. Obscuration of surfaces during Pathfinder was measured at 0.3% per sol. Measurements with the Microscopic Imager on the Mars Exploration Rovers showed that suspended dust in the Martian atmosphere has a diameter of 2 to 4 micrometers.

**Capability Performance Goal:** Maximize the amount and size of dust particles that are removed. Minimize time required for removal process if manually performed by astronauts.

**Parameter, Value:**

Amount of dust removed: 95%;

Size range of dust particles removed;

Time (if manual) for dust removal: dependent on mission location and timelines.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enabling | 2027 | 2027 | 2021 | 3 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 3 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 3 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 3 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 3 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 3 years |

7.6 Cross-Cutting Systems
7.6.1 Particulate Contamination Prevention and Mitigation

## 7.6.1.13 Dust Removal Brushes

### TECHNOLOGY

**Technology Description:** Brushes with bristles optimized for dust removal for each destination.

**Technology Challenge:** Creating reusable brushes that will remove dust without damaging surfaces being cleaned, and will not create a condition that could attract additional dust to surface or interfere with hardware operations. Brush should minimize cross contamination if used on multiple components.

**Technology State of the Art:** Preliminary work has been done to quantify the parameters that make a brush effective for removing lunar simulant from thermal control surfaces in a simulated lunar environment.

**Parameter, Value:**

Restoration of solar absorptance and thermal emittance of thermal control surfaces dusted with lunar simulant has been demonstrated in a simulated lunar environment.

**TRL** 3

**Technology Performance Goal:** Remove sufficient dust to restore the key performance parameter (i.e., solar absorptance, transmittance, thermal emittance) of the component to an acceptable level.

**Parameter, Value:**

Dependent on surface to be cleaned. Need to remove all loose dust from spacesuits; for hardware surfaces, need to remove enough dust to restore the key performance parameter to an acceptable level.

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Dust removal.

**Capability Description:** Remove dust from equipment, suits, tools, etc. to prevent it from contaminating living environments and/or to ensure proper operation of systems. Remove dust from spacecraft surfaces, optical systems, solar panels, thermal radiators, spacesuits, viewports, and other instruments to prevent damage to equipment, degrading of camera lenses, reduced performance of thermal radiators and solar panels, and contamination of habitats.

**Capability State of the Art:** Apollo lunar missions had limited capability for removing dust. More recent robotic missions to Mars, the Moon, and asteroids have tested some mechanisms for removing dust but not at the level needed for human habitation environments.

**Parameter, Value:**

Not measured in Apollo, but anecdotal evidence suggests it was low. Obscuration of surfaces during Pathfinder was measured at 0.3% per sol. Measurements with the Microscopic Imager on the Mars Exploration Rovers showed that suspended dust in the Martian atmosphere has a diameter of 2 to 4 micrometers.

**Capability Performance Goal:** Maximize the amount and size of dust particles that are removed. Minimize time required for removal process if manually performed by astronauts.

**Parameter, Value:**

Amount of dust removed: 95%;

Size range of dust particles removed;

Time (if manual) for dust removal: dependent on mission location and timelines.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 4 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 4 years |

7.6 Cross-Cutting Systems
7.6.1 Particulate Contamination Prevention and Mitigation

## 7.6.1.14 Self-Cleaning Connectors

### TECHNOLOGY

**Technology Description:** Various types of connectors (electrical, fluid, optical, etc.) that actively prevent dust from getting inside or passively or actively remove dust after it gets inside the vehicle or suit.

**Technology Challenge:** Fluid connectors may be more difficult because the need to maintain extremely low leak rates across sealing surfaces.

**Technology State of the Art:** Several prototypes of electrical connectors or connector housings have been developed, employing different strategies to prevent or remove dust. One strategy mechanically wipes the electrical pins using self-healing membranes or other materials. Another strategy uses interlocking connector caps to keep dust out of the connectors and the caps.

**Parameter, Value:**

Percent dust removed not measured, but reported anecdotally as “only a very small quantity” got past the cleaning mechanism. “No change in electrical resistance.” Changes in mechanical force to mate/demate was not measured, but no increase in force was noted in the testing.

**TRL** 5

**Technology Performance Goal:** Build prototypes with liquid and gas connectors and fiber optics. Demonstrate fluid seals are dust tolerant. Perform more complete environmental testing including at vacuum. Perform more mate/demate cycles to determine lifespan of the connectors.

**Parameter, Value:**

Dust removed: ~99%;

Increased resistance: ~ 0 ohms

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Dust removal.

**Capability Description:** Remove dust from equipment, suits, tools, etc. to prevent it from contaminating living environments and/or to ensure proper operation of systems. Remove dust from spacecraft surfaces, optical systems, solar panels, thermal radiators, spacesuits, viewports, and other instruments to prevent damage to equipment, degrading of camera lenses, reduced performance of thermal radiators and solar panels, and contamination of habitats.

**Capability State of the Art:** Apollo lunar missions had limited capability for removing dust. More recent robotic missions to Mars, the Moon, and asteroids have tested some mechanisms for removing dust but not at the level needed for human habitation environments.

**Parameter, Value:**

Not measured in Apollo, but anecdotal evidence suggests it was low. Obscuration of surfaces during Pathfinder was measured at 0.3% per sol. Measurements with the Microscopic Imager on the Mars Exploration Rovers showed that suspended dust in the Martian atmosphere has a diameter of 2 to 4 micrometers.

**Capability Performance Goal:** Maximize the amount and size of dust particles that are removed. Minimize time required for removal process if manually performed by astronauts.

**Parameter, Value:**

Amount of dust removed: 95%;

Size range of dust particles removed;

Time (if manual) for dust removal: dependent on mission location and timelines.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enabling | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 5 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 5 years |

7.6 Cross-Cutting Systems
7.6.1 Particulate Contamination Prevention and Mitigation

## 7.6.1.15 Forced Gas Showers

### TECHNOLOGY

**Technology Description:** Use gas (air, carbon dioxide, nitrogen) showers to decontaminant astronauts prior to entering the habitat by forcibly blowing it off the suit or item.

**Technology Challenge:** The concept of forced gas showers is relatively easy to implement. However, doing this on the Moon or Mars is much more complex because of the amount of consumables required and the inability to vent the end product to the 'atmosphere.' These capabilities have to be designed and implemented in a way to reduce power, mass, and consumable quantities for space applications while also preserving planetary protection requirements. Spacesuit materials, helmet visor, seals, and bearings must be evaluated to determine impacts on design of suit.

**Technology State of the Art:** Forced gas showers are routinely used in terrestrial applications such as clean rooms.

**Parameter, Value:**

Amount of dust removed: near 100%

**TRL** 3

**Technology Performance Goal:** Remove nearly 100% of dust from spacesuits. Gas force required to remove dust does not damage suits.

**Parameter, Value:**

Amount of dust removed: > 99%;

Gas force: dependent on analysis of effects on spacesuits.

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Dust removal.

**Capability Description:** Remove dust from equipment, suits, tools, etc. to prevent it from contaminating living environments and/or to ensure proper operation of systems. Remove dust from spacecraft surfaces, optical systems, solar panels, thermal radiators, spacesuits, viewports, and other instruments to prevent damage to equipment, degrading of camera lenses, reduced performance of thermal radiators and solar panels, and contamination of habitats.

**Capability State of the Art:** Apollo lunar missions had limited capability for removing dust. More recent robotic missions to Mars, the Moon, and asteroids have tested some mechanisms for removing dust but not at the level needed for human habitation environments.

**Parameter, Value:**

Not measured in Apollo, but anecdotal evidence suggests it was low. Obscuration of surfaces during Pathfinder was measured at 0.3% per sol. Measurements with the Microscopic Imager on the Mars Exploration Rovers showed that suspended dust in the Martian atmosphere has a diameter of 2 to 4 micrometers.

**Capability Performance Goal:** Maximize the amount and size of dust particles that are removed. Minimize time required for removal process if manually performed by astronauts.

**Parameter, Value:**

Amount of dust removed: 95%;

Size range of dust particles removed;

Time (if manual) for dust removal: dependent on mission location and timelines.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enabling | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 4 years |

7.6 Cross-Cutting Systems
7.6.1 Particulate Contamination Prevention and Mitigation

# 7.6.1.16 Forced Gas Cleaning of Hard Surfaces

## TECHNOLOGY

**Technology Description:** Use jets of (pulsed, steady, vortices, etc.) to remove dust that is adhered onto solid surfaces by creating sufficient shear stress or turbulent kinetic energy in the gas at the bottom of the boundary layer to overcome dust adhesion.

**Technology Challenge:** Creating enough shear stress to overcome adhesion (van der waals force, etc.) from the micron and submicron sized dust particles, which lie deep in the viscous sublayer of a gas flow's boundary layer.

**Technology State of the Art:** Forced air is used for cleaning on Earth routinely, but not with the focus on micron and submicron fines. Concepts using vortices to enhance shear stress have been studied analytically.

**Parameter, Value:**

Amount of dust removed: near 100%

**TRL** 2

**Technology Performance Goal:** Remove near 100% of dust for extraterrestrial environments.

**Parameter, Value:**

Amount of dust removed: 99%

**TRL** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Dust removal.

**Capability Description:** Remove dust from equipment, suits, tools, etc. to prevent it from contaminating living environments and/or to ensure proper operation of systems. Remove dust from spacecraft surfaces, optical systems, solar panels, thermal radiators, spacesuits, viewports, and other instruments to prevent damage to equipment, degrading of camera lenses, reduced performance of thermal radiators and solar panels, and contamination of habitats.

**Capability State of the Art:** Apollo lunar missions had limited capability for removing dust. More recent robotic missions to Mars, the Moon, and asteroids have tested some mechanisms for removing dust but not at the level needed for human habitation environments.

**Parameter, Value:**

Not measured in Apollo, but anecdotal evidence suggests it was low. Obscuration of surfaces during Pathfinder was measured at 0.3% per sol. Measurements with the Microscopic Imager on the Mars Exploration Rovers showed that suspended dust in the Martian atmosphere has a diameter of 2 to 4 micrometers.

**Capability Performance Goal:** Maximize the amount and size of dust particles that are removed. Minimize time required for removal process if manually performed by astronauts.

**Parameter, Value:**

Amount of dust removed: 95%;

Size range of dust particles removed;

Time (if manual) for dust removal: dependent on mission location and timelines.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enabling | 2027 | 2027 | 2021 | 2 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 2 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enabling | 2027 | 2027 | 2021 | 2 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 2 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 2 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 2 years |

7.6 Cross-Cutting Systems
7.6.1 Particulate Contamination Prevention and Mitigation

## 7.6.1.17 Failure Isolation, Detection, and Recovery (FIDR)

### TECHNOLOGY

**Technology Description:** Dust detector and dust alarm to alert crew when dust exposure limits are exceeded. This system can measure particles as defined in the exposure limit for dust and an alarm system that alerts crew when dust in air exceeds those limits.

**Technology Challenge:** Detection of small dust particles from moons, planets, asteroids, and smoke.

**Technology State of the Art:** Particle detection and monitoring are commonly employed in clean room and other applications on Earth. Particle detectors have also been demonstrated on the International Space Station (ISS).

**Parameter, Value:**

Number of particles in air;

Class 1 cleanroom sizes and concentrations.

**TRL:** 7

**Technology Performance Goal:** Develop prototypes, perform performance testing, field-testing, and environmental testing.

**Parameter, Value:**

Number of lunar, Mars, asteroid dust particles in air. Concentration will be determined based on standard to be developed by relevant industry/academia team.

**TRL:** 1

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Fault detection, isolation, and recovery.

**Capability Description:** System that alerts crew members when airborne dust exceeds Spacecraft Maximum Allowable Concentrations (SMAC).

**Capability State of the Art:** Particle detectors are on orbit in the ISS, however, the technology to distinguish very tiny dust particles from smoke particles needs to be developed.

**Parameter, Value:**

Number of particles in the air. Particle counters that distinguish very small dust particles from smoke particles do not exist.

**Capability Performance Goal:** Alert crew when SMAC limits are exceeded.

**Parameter, Value:**

Dust particle detection – as defined by exposure limits.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO | Enhancing | 2022 | 2022 | 2015-2021 | 4 years |
| Exploring Other Worlds: DRM 6 Crewed to NEA | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Exploring Other Worlds: DRM 8 Crewed to Mars Moons | Enhancing | 2027 | 2027 | 2021 | 4 years |
| Planetary Exploration: DRM 8a Crewed Mars Orbital | Enabling | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 4 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 4 years |

7.6 Cross-Cutting Systems
7.6.1 Particulate Contamination Prevention and Mitigation

## 7.6.1.18 Plume Mitigation

### TECHNOLOGY

**Technology Description:** Technologies to mitigate the plume blast effects from landing spacecraft on planetary surfaces.

**Technology Challenge:** No technical challenges identified .

**Technology State of the Art:** Prototype rovers with attachments for site grading and berm-building have been field tested. Several soil stabilization technologies have been tested in the laboratory and in limited field tests. There has been only one test of a concept for a fence or blast burner. Spacecraft coatings to mitigate high impact ejecta damage by prevention or self-repair have not been reported in the literature.

**Parameter, Value:** No technologies have been developed to the point of demonstrating performance values.

**TRL:** 2

**Technology Performance Goal:** Prevent damage to surface systems from blowing ejecta and stabilize surface for landing spacecraft.

**Parameter, Value:** Performance values dependent on mission architecture.

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Plume mitigation.

**Capability Description:** Preventing the blowing of regolith ejecta; preventing deep cratering and fluidization and instability of regolith beneath a landing spacecraft; preventing regolith debris strikes on a spacecraft or spoofing of sensors or contamination or other damage of vehicle; stopping blown ejecta prior to impact upon surrounding hardware. This category does not include spacecraft technologies designed to mitigate plume blast effects, as those technologies are in TA 9.

**Capability State of the Art:** Not used in the space environment.

**Parameter, Value:** No currently measured value.

**Capability Performance Goal:** Prevent damage to surface systems from blowing ejecta and stabilize surface for landing spacecraft.

**Parameter, Value:** Reduce hardware damage from ejecta to levels determined acceptable per mission or architecture analysis. Reduce dust obscuration of landing site to acceptable levels. Reduce depth and volume of destabilized soil beneath the lander. Decrease probability of lander tilting > 11 degrees.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 7 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 10 years |
| Planetary Flagship: Mars Sample Return | Enhancing | -- | 2026* | 2023 | 9 years |

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

7.6 Cross-Cutting Systems
7.6.1 Particulate Contamination Prevention and Mitigation

# 7.6.1.19 Deployable Landing Surfaces

## TECHNOLOGY

**Technology Description:** Material that can be used as a landing pad on an asteroid, moon, or planetary surface.

**Technology Challenge:** No low-mass, deployable materials known to meet thermal and mechanical needs have been demonstrated.

**Technology State of the Art:** No technology development known.

**Parameter, Value:**
No technologies have been developed to the point of demonstrating performance values.

**TRL**
1

**Technology Performance Goal:** Develop high-temperature, high-strength, low-mass materials and deployment methods to prevent damage to surface systems from blowing ejecta and stabilize surface for landing spacecraft.

**Parameter, Value:**
Mass: values dependent on mission and application;
Temperature: up to 3,700 K at the center, less for peripheral regions; Shear strength: depends on lander footpad dynamics.

**TRL**
6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Plume mitigation.

**Capability Description:** Preventing the blowing of regolith ejecta; preventing deep cratering and fluidization and instability of regolith beneath a landing spacecraft; preventing regolith debris strikes on a spacecraft or spoofing of sensors or contamination or other damage of vehicle; stopping blown ejecta prior to impact upon surrounding hardware. This category does not include spacecraft technologies designed to mitigate plume blast effects, as those technologies are in TA 9.

**Capability State of the Art:** Not used in the space environment.

**Parameter, Value:**
No currently measured value.

**Capability Performance Goal:** Prevent damage to surface systems from blowing ejecta and stabilize surface for landing spacecraft.

**Parameter, Value:**
Mass: values dependent on mission and application;
Temperature: up to 3,700 K at the center, less for peripheral regions;
Shear strength: depends on lander footpad dynamics.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enabling | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enabling | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enabling | 2033 | -- | 2027 | 5 years |

7.6 Cross-Cutting Systems
7.6.1 Particulate Contamination Prevention and Mitigation

## 7.6.1.20 Deployable/Erectable Blast Curtain Around Landing Site

### TECHNOLOGY

**Technology Description:** Lightweight, withstand ultraviolet (UV), self-healing, and anchored.

**Technology Challenge:** Minimize the mass of material required while maintaining adequate material strength to stop high velocity particulate ejecta and to prevent the plume gas from ripping the material. Develop concept of operations for easy deployment.

**Technology State of the Art:** One concept for an inflatable barrier has been prototyped at a low-fidelity level but not performance tested.

**Parameter, Value:**
No currently measured value.

**TRL**
2

**Technology Performance Goal:** Develop low-mass materials that are self-healing or resistant to ejecta or UV damage, easy to erect, and anchoring so that it will not be blown over by the plume. Further, to reduce gas pressure from the lander it needs to be taller to block ejecta and thus more massive.

**Parameter, Value:**
Mass requirement depends on mission architectural decisions. Requirement for reduction of plume damage to surrounding hardware has not been determined.

**TRL**
6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Plume mitigation.

**Capability Description:** Preventing the blowing of regolith ejecta; preventing deep cratering and fluidization and instability of regolith beneath a landing spacecraft; preventing regolith debris strikes on a spacecraft or spoofing of sensors or contamination or other damage of vehicle; stopping blown ejecta prior to impact upon surrounding hardware. This category does not include spacecraft technologies designed to mitigate plume blast effects, as those technologies are in TA 9.

**Capability State of the Art:** Not used in the space environment.

**Parameter, Value:**
No currently measured value.

**Capability Performance Goal:** Prevent damage to surface systems from blowing ejecta and stabilize surface for landing spacecraft.

**Parameter, Value:**
Mass: to be determined kilograms;

Ejecta mass flux going over fence: < to be determined kilograms;

Volume of pitting from particulate impacts per $cm^2$ of surface material;

< to be determined cubic microns eroded material per $cm^2$ surface area;

Mass of lander it can withstand: 60 tonnes.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 5 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 5 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 5 years |

7.6 Cross-Cutting Systems
7.6.1 Particulate Contamination Prevention and Mitigation

## 7.6.1.21 Plume Resistant Concrete

### TECHNOLOGY

**Technology Description:** Repeated use landing and launch pads.

**Technology Challenge:** Binders to make cement/concrete are not readily available on planetary surfaces. Sintering avoids the need for binders but the process to obtain good mechanical properties is difficult to control especially when the mineralogy, particle sizes, and non-homogeneities of realistic regolith are taking into account.

**Technology State of the Art:** Polymer binders have been tested for regolith but these fail and burn through at high temperature. Several sintering methods have been tested with varying success, but high temperature plume exposure tests have not been performed.

**Parameter, Value:**

Mass brought from Earth = ~186 kg/m$^3$ for polymer landing pad material or 0 kg/m$^3$ for sintering methods. Not currently measured for other methods. Temperatures material can withstand and has not been measured. Mass of spallation and ablation has not been measured.

**TRL**
3

**Technology Performance Goal:** Reduce mass of consumable material brought from Earth (water, binder, etc.). Withstand high exhaust temperatures without spalling or other mechanical failure. Minimize mass of spalling and ablating of surface.

**Parameter, Value:**

Ideally, 0 kilograms of consumable material brought from Earth; Temperature: > 3,700 K without failure;

Ideally, 0 grams of spallation per landing and minimal ablation.

**TRL**
6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

### CAPABILITY

**Needed Capability:** Plume mitigation.

**Capability Description:** Preventing the blowing of regolith ejecta; preventing deep cratering and fluidization and instability of regolith beneath a landing spacecraft; preventing regolith debris strikes on a spacecraft or spoofing of sensors or contamination or other damage of vehicle; stopping blown ejecta prior to impact upon surrounding hardware. This category does not include spacecraft technologies designed to mitigate plume blast effects, as those technologies are in TA 9.

**Capability State of the Art:** Not used in the space environment.

**Parameter, Value:**

No currently measured value.

**Capability Performance Goal:** Prevent damage to surface systems from blowing ejecta and stabilize surface for landing spacecraft.

**Parameter, Value:**

Mass: < to be determined kilograms

Temperature: up to 3,700 K at the center, less for peripheral regions;

Mass of spallation and ablation per landing: < to be determined grams.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6 years |

7.6 Cross-Cutting Systems
7.6.1 Particulate Contamination Prevention and Mitigation

# 7.6.1.22 High Fidelity Two-Phase Flow Modeling for Plume-Soil Interaction

## TECHNOLOGY

**Technology Description:** Plume flow software capable of predicting the interaction of high velocity gas with regolith in the planetary environment. For the Mars case, the plume will dig deep into the regolith and fluidize a large volume, causing chaotic flow behavior and leaving a deep/wide region of soil in an unstable mechanical state. For the lunar case, the plume primarily scours the surface and throws ejecta outward at high velocity. Asteroidal cases are still to be determined.

**Technology Challenge:** Incorporating the complexities of granular physics to accurately predict transitions between the many flow regimes and to accurately capture the variety of phenomenology. Making the model predictive while extrapolating into planetary environments where very little empirical data are available for these extreme flow regimes. Using terrestrial data sets that cannot mimic all the correct environmental parameters at the same time (gravity, vacuum, size scale of the cratering phenomenon, etc.), knowing that inaccurately copying the parameters will cause behaviors to occur in the wrong flow regimes.

**Technology State of the Art:** Discrete Element method has been two-way coupled with gas but not with realistic particle size distributions. Eulerian constitutives for soil have been developed and integrated into gas flow codes for continuum conditions but not tested for the space environment. One-way coupling of collisionless particles has been integrated with gas flow code that handles vacuum to continuum conditions.

**Parameter, Value:**

Prediction of mass blown by lunar module is estimated to be accurate to within a factor of 3. Depth of hole dug into regolith for Mars is not yet accurate to within an order of magnitude.

**TRL:** 2

**Technology Performance Goal:** Develop particle ejection algorithms with 2-way coupling for lunar-case erosion models. Integrate particle shape behavior and wide particle size distributions in Garzo, Hrenya, and Dufty (GHD) Granular Kinetic Theory into eulerian constitutives for regolith. Develop flow code architecture to handle the transitions between solid-like, fluidized, aggregation and dispersion, and collisional transport of regolith material. Obtain high quality data sets for benchmarking of the flow codes.

**Parameter, Value:**

Mass blown in lunar landing accurate to within 20%. Agreement with experimental cases in reduced gravity aircraft, vacuum chambers, and terrestrial conditions at field tests, percent error in each measureable parameter, % error accuracy requirement has not been determined. Agreement with data from planetary landings (volume of observed plume crater on Mars, optical density of blowing soil in Apollo landing videos, etc.), % error requirement has not been determined.

**TRL:** 6

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** None

## CAPABILITY

**Needed Capability:** Plume effects prediction.

**Capability Description:** Predict ejecta mass rate, velocity, particle sizes (including rocks), angle, and distance as a function of plume and lander conditions. Predict damage to surrounding hardware. Predict damage to the landing spacecraft. Predict loss of visibility during landing. Predict fluidization and loss of stability of regolith beneath and around the lander during landing and after engine shuts off, including depth, volume, mechanical strength of soil, settling dynamics, etc., as a function of plume conditions and regolith properties.

**Capability State of the Art:** Flow codes that only handle the gas phase are used to predict plume conditions acting on regolith, without the dynamics of the regolith. One-way coupling has been used to estimate ejecta velocities and distances.

**Parameter, Value:**

Prediction of mass blown by lunar module is estimated to be accurate to within a factor of 3. Depth of hole dug into regolith for Mars is not yet accurate to within an order of magnitude.

**Capability Performance Goal:** Develop physics-based algorithms for erosion of regolith in lunar cases with two-way coupling (mass loading of plume provides feedback) that agrees with empirical data sets. Develop fluid modeling methods that predict soil transitions from solid to fluidized (including chaotic aggregative flow) to dispersed ejecta (including collisional transport) that accurately predicts growth of crater and disturbed region and regolith mechanical properties under lander.

**Parameter, Value:**

Mass blown in lunar landing accurate to within 20%. Agreement with experimental cases in reduced gravity aircraft, vacuum chambers, and terrestrial conditions at field tests, percent error in each measureable parameter, % error accuracy requirement has not been determined. Agreement with data from planetary landings (volume of observed plume crater on Mars, optical density of blowing soil in Apollo landing videos, etc.), % error requirement has not been determined.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 7 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 10 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 10 years |

7.6 Cross-Cutting Systems
7.6.2 Construction and Assembly

# 7.6.2.1 Shaped Charges and Explosives

## TECHNOLOGY

**Technology Description:** Explosives to create holes of the required depth and size in the planetary surface to provide natural radiation shielding for outpost infrastructure.

**Technology Challenge:** Lower gravity, minimal or total lack of atmosphere, and differences in surface structural characteristics present the primary challenges. Other challenges include minimizing blast ejecta and getting it in the right place, as well as safe storage of explosive charges, safe handling of the explosive materials, and safe detonation of the devices.

**Technology State of the Art:** A shaped charge is an explosive charge shaped to focus the effect of the explosive's energy. Various types are used to cut and form metal, penetrate armor, and "complete" wells in the oil and gas industry. A typical modern lined shaped charge can penetrate armor steel to a depth of 7 or more times the diameter of the charge (charge diameters, CD), though greater depths of 10 CD and above have been achieved. The shaped charge does not depend in any way on heating or melting for its effectiveness; that is, the jet from a shaped charge does not melt its way through armor, as its effect is purely kinetic in nature.

**Parameter, Value:** — **TRL** 3

Mass: 50% lighter;

Stability and shelf life: 10 years;

Effectiveness: 2x more effective (trinitrotoluene (TNT) equivalent explosive power)

**Technology Performance Goal:** High-strength, long-life, lightweight, durable, flexible, radiation tolerant shape charges and explosives.

**Parameter, Value:** — **TRL** 6

Mass: 50% lighter;

Stability and shelf life: 10 years;

Effectiveness: 2x more effective (TNT equivalent explosive power)

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 4.1.1 3D Sensing; 4.1.2 State Estimation; 4.1.3 Onboard Mapping; 4.1.5 Force and Tactile Sensing; 4.4 Human-System Interaction; 4.5.1 System Health Management; 4.5.2 Activity Planning, Scheduling, and Execution; 4.5.4 Multi-Agent Coordination; 4.5.5 Adjustable Autonomy; 4.5.8 Automated Data Analysis for Decision Making; 6.1.4 Habitation; 6.3.3 Behavioral Health; 6.3.4 Human Factors; 6.4.1 Sensors: Air, Water, Microbial, and Acoustic; 8.1 Remote Sensing Instruments and Sensors; 8.1.2 Electronics; 8.3 In-Situ Instruments and Sensors; 12.1.5 Special Materials; 11.3.2 Integrated System Lifecycle Simulation; 12.3.3 Electro-Mechanical, Mechanical, and Micromechanisms

## CAPABILITY

**Needed Capability:** Planetary excavation and site infrastructure preparation.

**Capability Description:** Construction and assembly on planetary surfaces. Primarily providing natural shielding for surface assets, such as nuclear power systems or habitats, to protect the crew from both man-made and natural radiation sources.

**Capability State of the Art:** Aerospace Pyros and explosive bolts. Standard pyrotechnic mixtures used by NASA: Manganese / barium chromate / lead chromate: Time-delay mix, used for sequencing. Gasless burning. Research Department Explosive (RDX) / nitrocellulose: Gas generator, unsuitable for deep space missions, burn rate dependent on pressure. Boron / potassium nitrate: Gas generator and rocket-motor igniter, thermally stable, stable in vacuum, burn rate independent of pressure. Zirconium / potassium perchlorate: NASA standard initiator (NSI). Rapid pressure rise, little gas but emits hot particles, thermally stable, vacuum stable, long shelf life. Sensitive to static electricity. Known to cause circuit damage during ground testing. Lead azide: Used in detonators. Sensitive to impact, friction, and static electricity. Thermally and vacuum stable, if dextrin is not used for desensitizing. Long shelf life. Hexanitrostilbene: Used in detonators, linear shaped charges, and bulk explosives. Insensitive to stimuli other than explosion. Thermally stable. Vacuum stable. Detonates at 22,000 feet per second.

**Parameter, Value:**

"Ton of TNT" is a unit of energy equal to 4.184 gigajoules (1 gigacalorie)

**Capability Performance Goal:** Provide the ability to prepare, excavate, and emplace planetary outpost infrastructure.

**Parameter, Value:**

TNT equivalent explosive power.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 10 years |

7.6 Cross-Cutting Systems
7.6.2 Construction and Assembly

## 7.6.2.2 Ballistic Fabric Barriers

### TECHNOLOGY

**Technology Description:** Deployable and erectable blast shield barriers using tensile fabrics.

**Technology Challenge:** Challenges include minimizing out-gassing into the lunar or Martian environment, reducing the long-term material degradation caused by the hostile space environment, and reducing the mass and volume for transport and deployment of the blast barriers.

**Technology State of the Art:** Military fuel depots and airports. Developed by other government agencies.

| Parameter, Value: | TRL |
|---|---|
| 80% stoppage of lander blast debris;<br>High no-penetration ballistic value to mass ratio;<br>10 kilograms per square meter;<br>2:1 packaging ration to deployed protection. | 3 |

**Technology Performance Goal:** High-strength, long-life, lightweight, durable, flexible, radiation tolerant blast debris control.

| Parameter, Value: | TRL |
|---|---|
| 100% stoppage of lander blast debris;<br>High no-penetration ballistic value to mass ratio;<br>< 2 kilograms per square meter;<br>< 4:1 packaging ration to deployed protection. | 6 |

**Technology Development Dependent Upon Basic Research or Other Technology Candidate:** 4.1.1 3D Sensing; 4.1.2 State Estimation; 4.1.3 Onboard Mapping; 4.1.5 Force and Tactile Sensing; 4.4 Human-System Interaction; 4.5.1 System Health Management; 4.5.2 Activity Planning, Scheduling, and Execution; 4.5.4 Multi-Agent Coordination; 4.5.5 Adjustable Autonomy; 4.5.8 Automated Data Analysis for Decision Making; 6.1.4 Habitation; 6.3.3 Behavioral Health; 6.3.4 Human Factors; 6.4.1 Sensors: Air, Water, Microbial, and Acoustic; 8.1 Remote Sensing Instruments and Sensors; 8.1.2 Electronics; 8.3 In-Situ Instruments and Sensors; 12.1.5 Special Materials; 11.3.2 Integrated System Lifecycle Simulation; 12.3.3 Electro-Mechanical, Mechanical, and Micromechanisms

### CAPABILITY

**Needed Capability:** Blast debris control.

**Capability Description:** Controlling blast debris during in-situe construction and assembly using embedded bio-engineered, nano compounds, materials, software control algorithms, and sensors.

**Capability State of the Art:** Kennedy Space Center (KSC) Launch Pads. The pad was recently refurbished and any possible debris left behind must be removed from the area prior to launch. Foreign objects that are alien to flight systems may cause material damage or may make the system or equipment inoperable, unsafe or less efficient. Apollo landings blasted the Surveyor lander. Many of these craters were on the side of the Surveyor facing the Lunar Module. It is likely that these are the result of a sand-blasting effect from dust that was blown away from the Apollo landing site by rocket exhaust.

**Parameter, Value:**

No barriers have been used in spaceflight.

**Capability Performance Goal:** Barriers that are robotically deployable with 50% less mass (lightweight).

**Parameter, Value:**

100% stoppage of lander blast debris;
High no-penetration ballistic value to mass ratio;
< 2 kilograms per square meter;
< 4:1 packaging ration to deployed protection.

| Technology Needed for the Following NASA Mission Class and Design Reference Mission | Enabling or Enhancing | Mission Class Date | Launch Date | Technology Need Date | Minimum Time to Mature Technology |
|---|---|---|---|---|---|
| Exploring Other Worlds: DRM 7 Crewed to Lunar Surface | Enhancing | 2027 | 2027 | 2021 | 6 years |
| Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0) | Enhancing | 2033 | -- | 2027 | 6 years |
| Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal) | Enhancing | 2033 | -- | 2027 | 10 years |