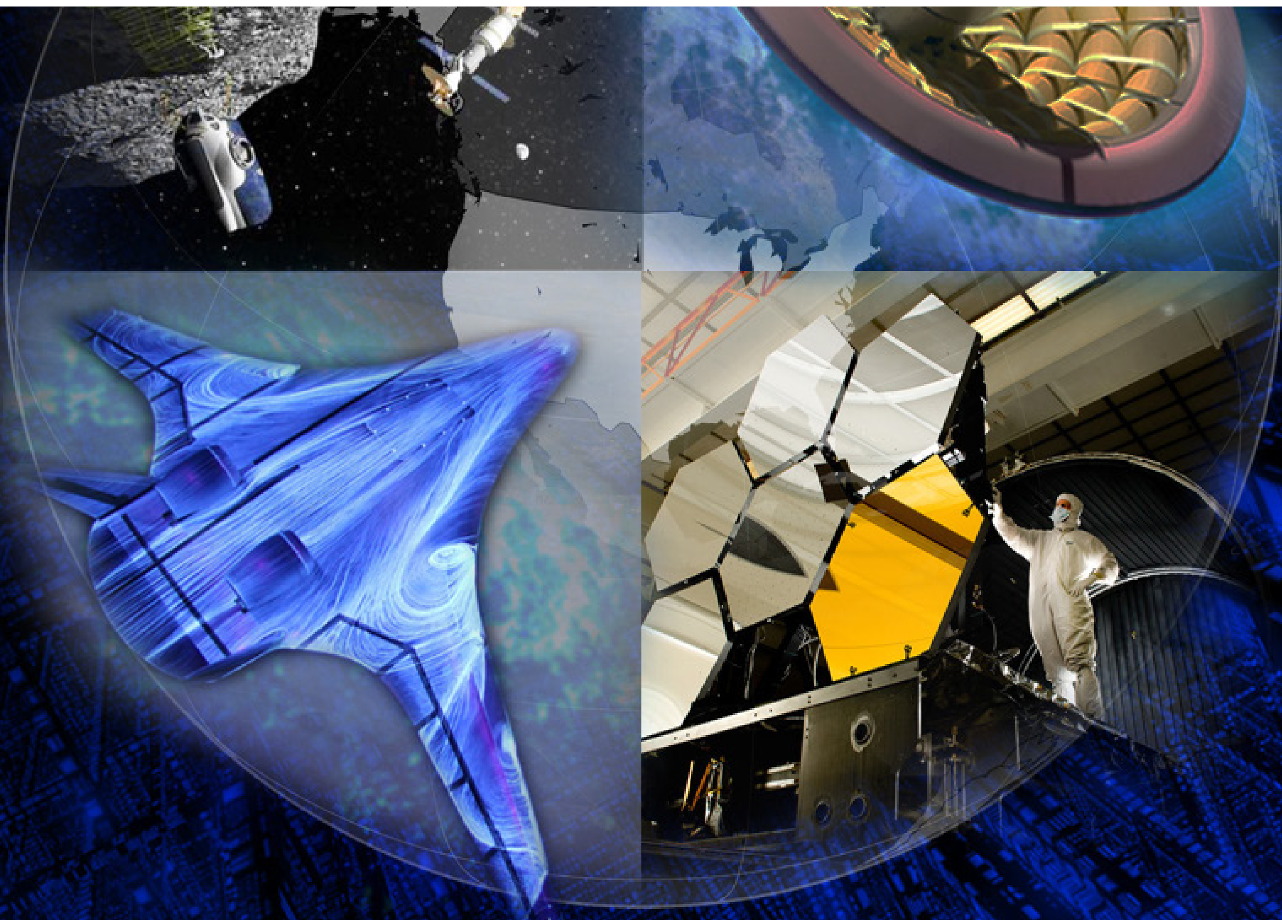
National Aeronautics and Space Administration

NASA Technology Roadmaps

TA 6: Human Health, Life Support, and Habitation Systems

The 2015 NASA Technology Roadmaps have been replaced with the 2020 NASA Technology Taxonomy and the NASA Strategic Technology Integration Framework.

Note: The 2015 NASA Technology Roadmaps will be archived and remain accessible via their current Internet address as well as via the new 2020 NASA Technology Taxonomy Internet page. Please visit https://www.nasa.gov/offices/oct/home/taxonomy to see the Taxonomy.



July 2015

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) 6: Human Health, Life Support, and Habitation 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.

This roadmap provides a summary of key capabilities and technologies for the Human Health, Life Support, and Habitation Systems TA, which include game-changing or breakthrough items. These capabilities and technologies are deemed necessary to achieve predicted national and Agency goals in space over the next few decades. The sub-TAs included in the roadmap are Environmental Control and Life Support Systems (ECLSS) and Habitation Systems; Extravehicular Activity (EVA) Systems; Human Health and Performance (HHP); Environmental Monitoring, Safety, and Emergency Response (EMSER); and Radiation.

Goals

For future crewed missions beyond low-Earth orbit (LEO) and into the solar system, regular resupply of consumables and emergency or quick-return options will not be feasible, and spacecraft will experience a more challenging radiation environment in deep space than in LEO. Therefore, TA 6 focuses on developing technologies that enable long-duration, deep-space human exploration with minimal resupply consumables and increased independence from Earth, within permissible space radiation exposure limits. Planetary protection for Mars missions is managed under NPI 8020.7 and although detailed requirements are still being developed, it needs to be considered at the TA 6 level.

Overarching sub-goals include: transitioning from partially-closed life support systems on the International Space Station (ISS) to a more fully-closed integrated system; developing advanced technologies for spacesuits that enable more frequent and rapid EVAs in both microgravity and surface environments (e.g., exposure to dust); significantly improving in-space crew health diagnostics, treatments, and countermeasures; and enabling real-time analysis of a broad range of compounds and microbial organisms in the vehicle. In addition, the radiation effort is focused on developing technologies that increase crewed mission duration (100 to 1,000 days, depending on the mission) in the free-space radiation environment while remaining below the space radiation permissible exposure limits (PELs). Technology snapshots with more detailed performance metrics for various Design Reference Missions are provided in the Appendix of TA 6.

Table 1. Summary of Level 2 TAs

6.0 Human Health, Life Support, and Habitation Systems	Goals:	Enable long-duration, deep-space human exploration within permissible space radiation exposure limits, minimal resupply consumables, and increased Earth independence.
6.1 Environmental Control and Life Support Systems and Habitation Systems	Sub-Goals:	Maintain an environment suitable for sustaining human life throughout the duration of a mission.
6.2 Extravehicular Activity Systems	Sub-Goals:	Enable crew operations outside the vehicle or habitat in all mission environments. Protect the crew during launch, entry, and landing, and for the potential events of cabin contamination or depressurization. Protect the crew during ascent/decent transition for planetary excursions.
6.3 Human Health and Performance	Sub-Goals:	Maintain the health of the crew and support optimal and sustained performance throughout the duration of a mission as well as terrestrial life, thereafter.

Table 1. Summary of Level 2 TAs - Continued

6.0 Human Health, Life Support, and Habitation Systems	**Goals:**	**Enable long-duration, deep-space human exploration within permissible space radiation exposure limits, minimal resupply consumables, and increased Earth independence.**
6.4 Environmental Monitoring, Safety, and Emergency Response	Sub-Goals:	Ensure crew health and safety by providing the crew early warnings of potentially hazardous conditions and to provide the crew time for effective response should an accident occur.
6.5 Radiation	Sub-Goals:	Increase crew mission duration in the free-space radiation environment while remaining below the space radiation permissible exposure limits.

Benefits

The primary benefit of developing technology for the Human Health, Life Support and Habitation Systems TA is the ability to successfully achieve affordable crewed space missions to LEO and beyond. As a unique, human-tended test platform in the space environment, continued operations and missions on the ISS will directly contribute to the knowledge base and spur advances in these areas in the coming decade. Developing long-duration ground test capabilities and either extending ISS operations or using an alternative permanent or semi-permanent in-space facility would facilitate sustained testing and associated advancements into the following decade as well, in preparation for missions beyond LEO. Ground and in-space test beds will be crucial to the development and validation of technologies (including mission operations and automation, human habitation advancements, human mobility tools, and improvements in sustainability) needed for those bold space missions.

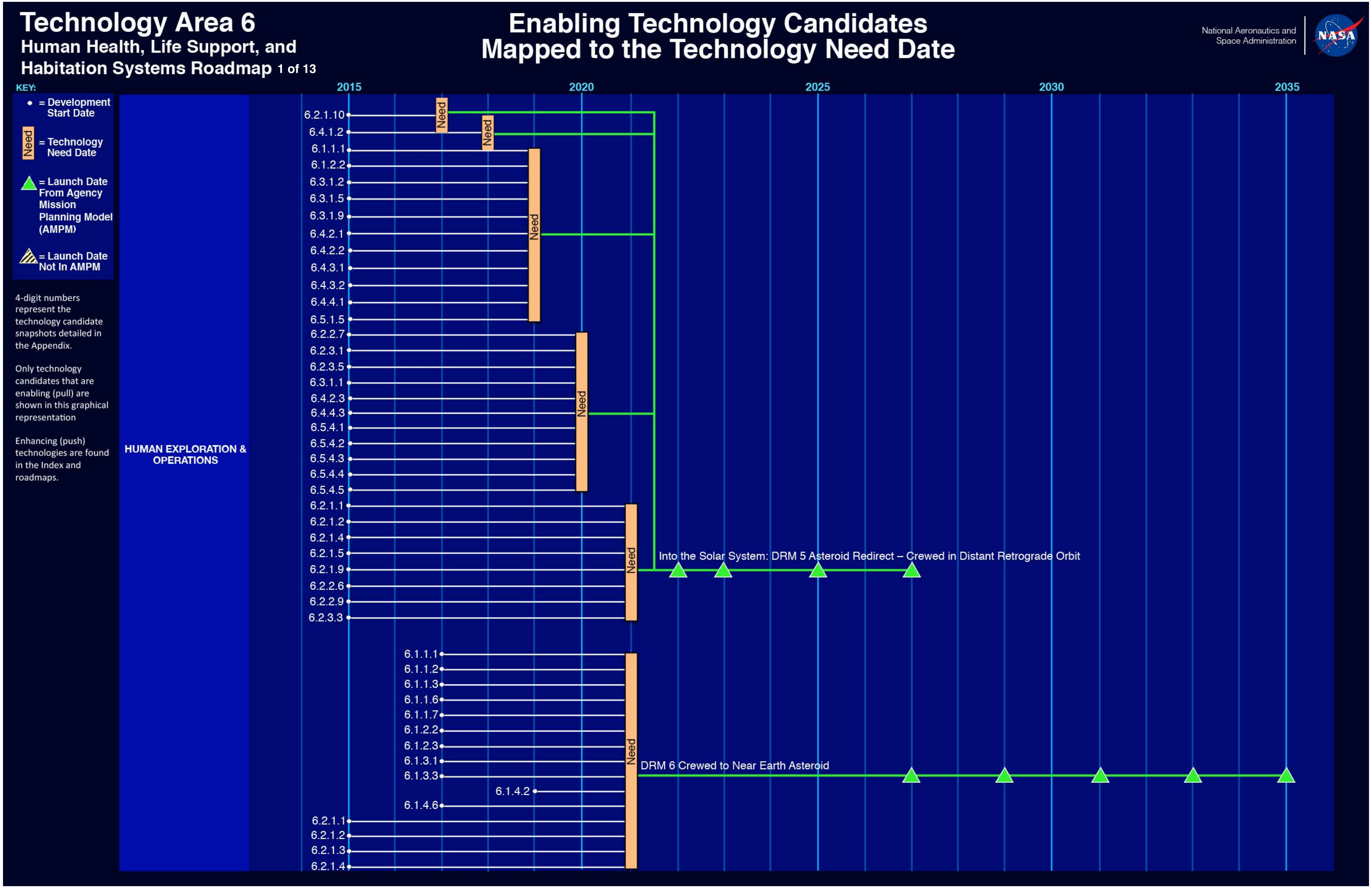

Figure 1. Technology Area Strategic Roadmap

Technology Area 6
Human Health, Life Support, and Habitation Systems Roadmap 2 of 13

Enabling Technology Candidates Mapped to the Technology Need Date

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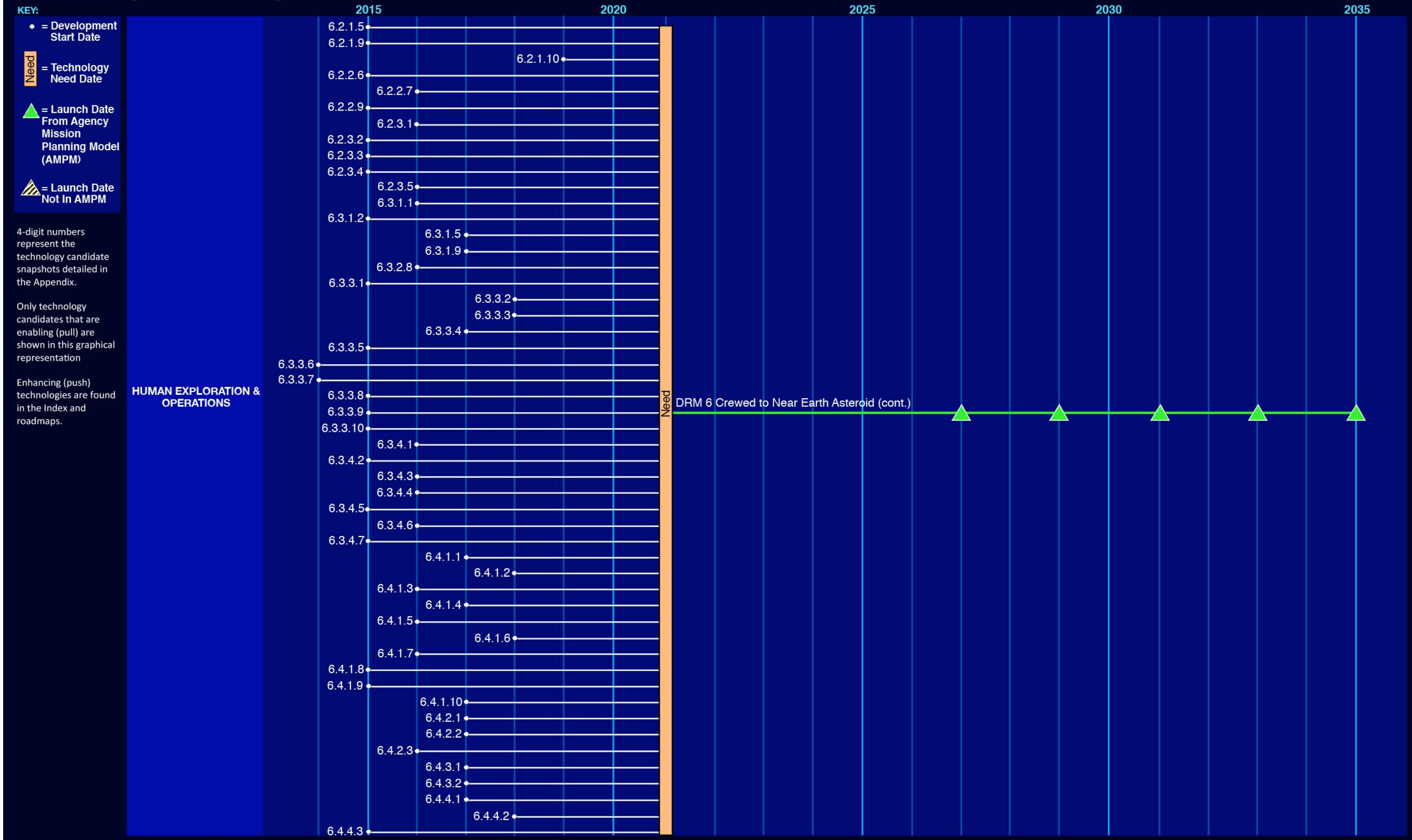

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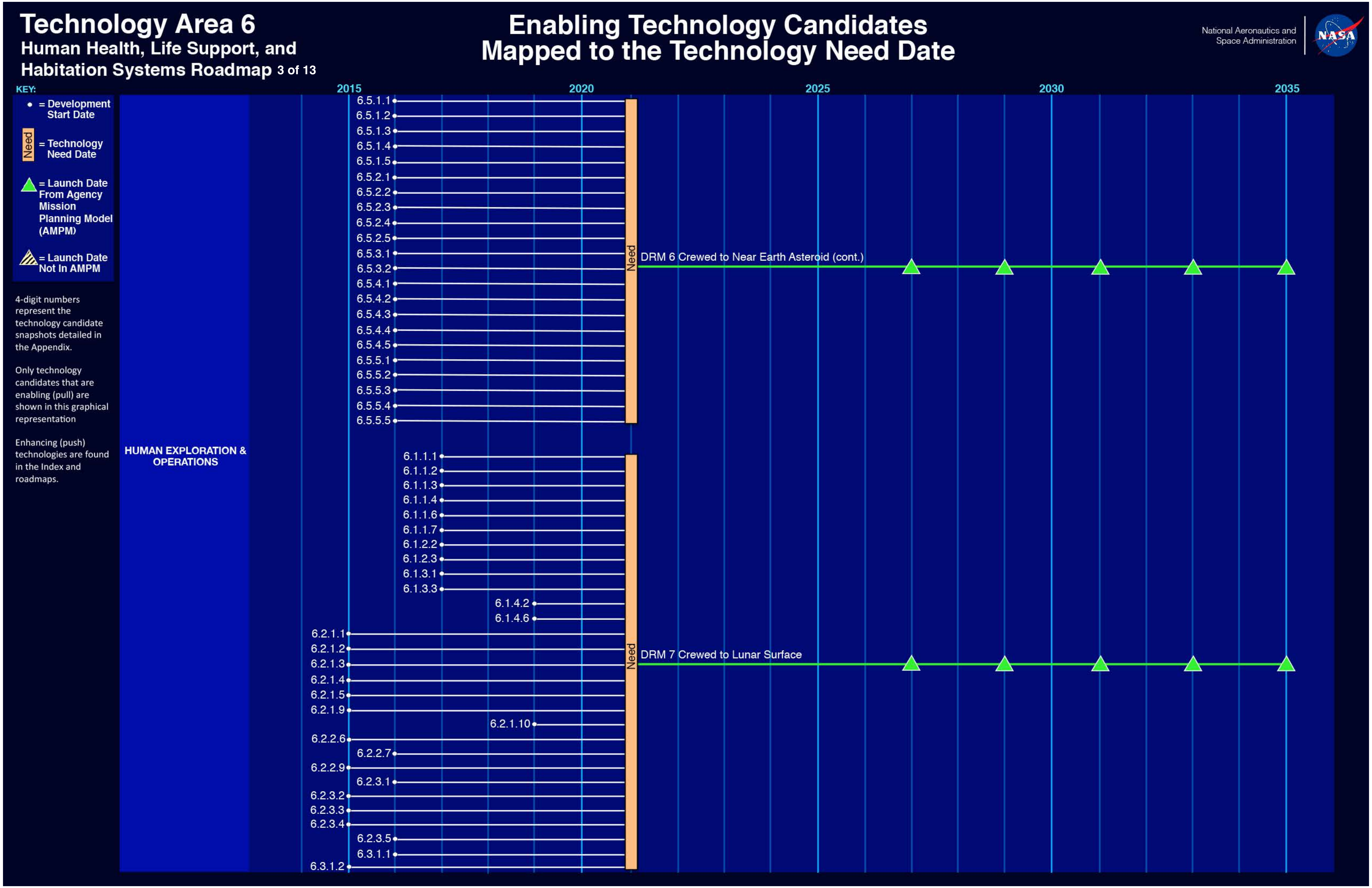


Figure 1. Technology Area Strategic Roadmap (Continued)

Technology Area 6
Human Health, Life Support, and Habitation Systems Roadmap 4 of 13

Enabling Technology Candidates Mapped to the Technology Need Date

National Aeronautics and Space Administration

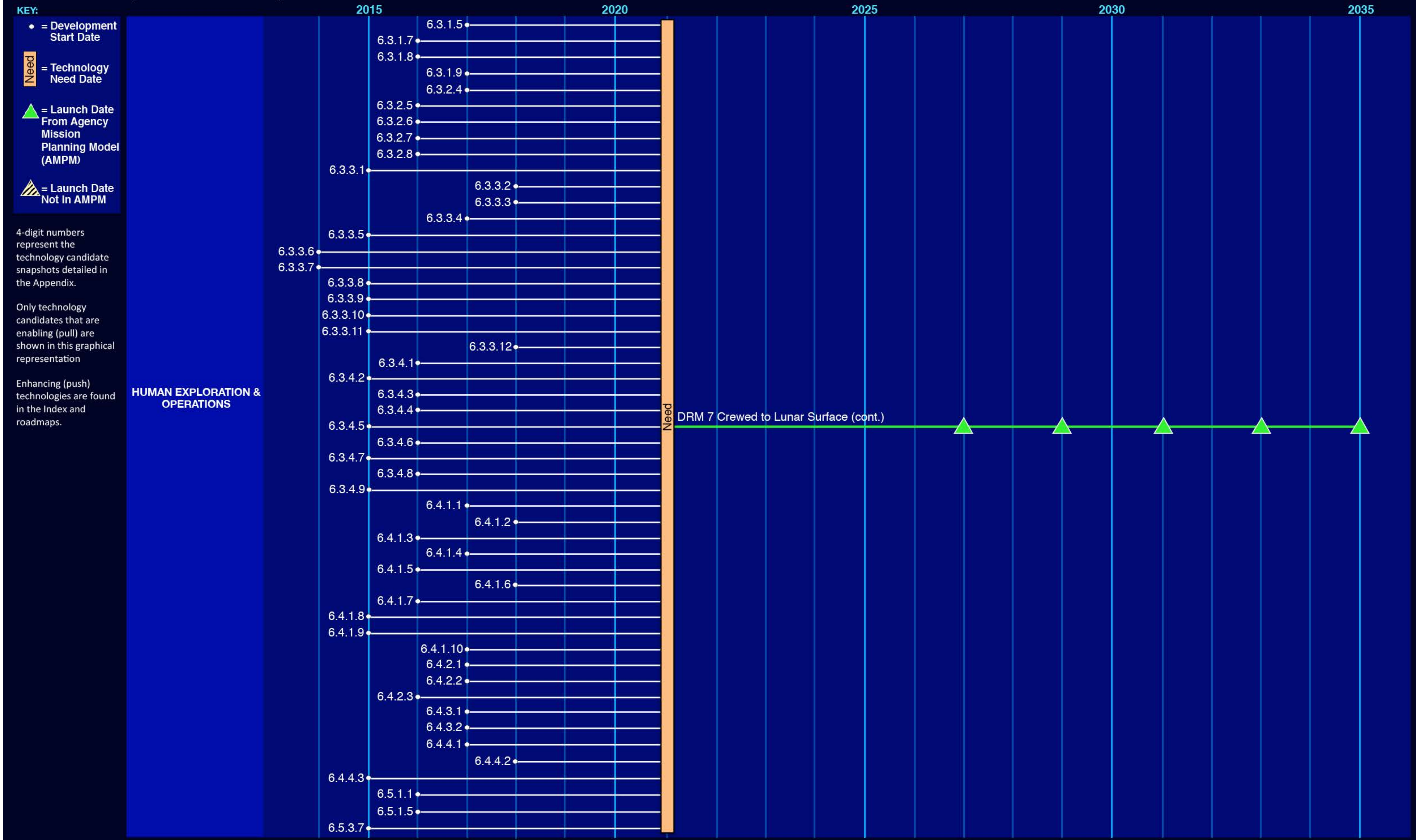
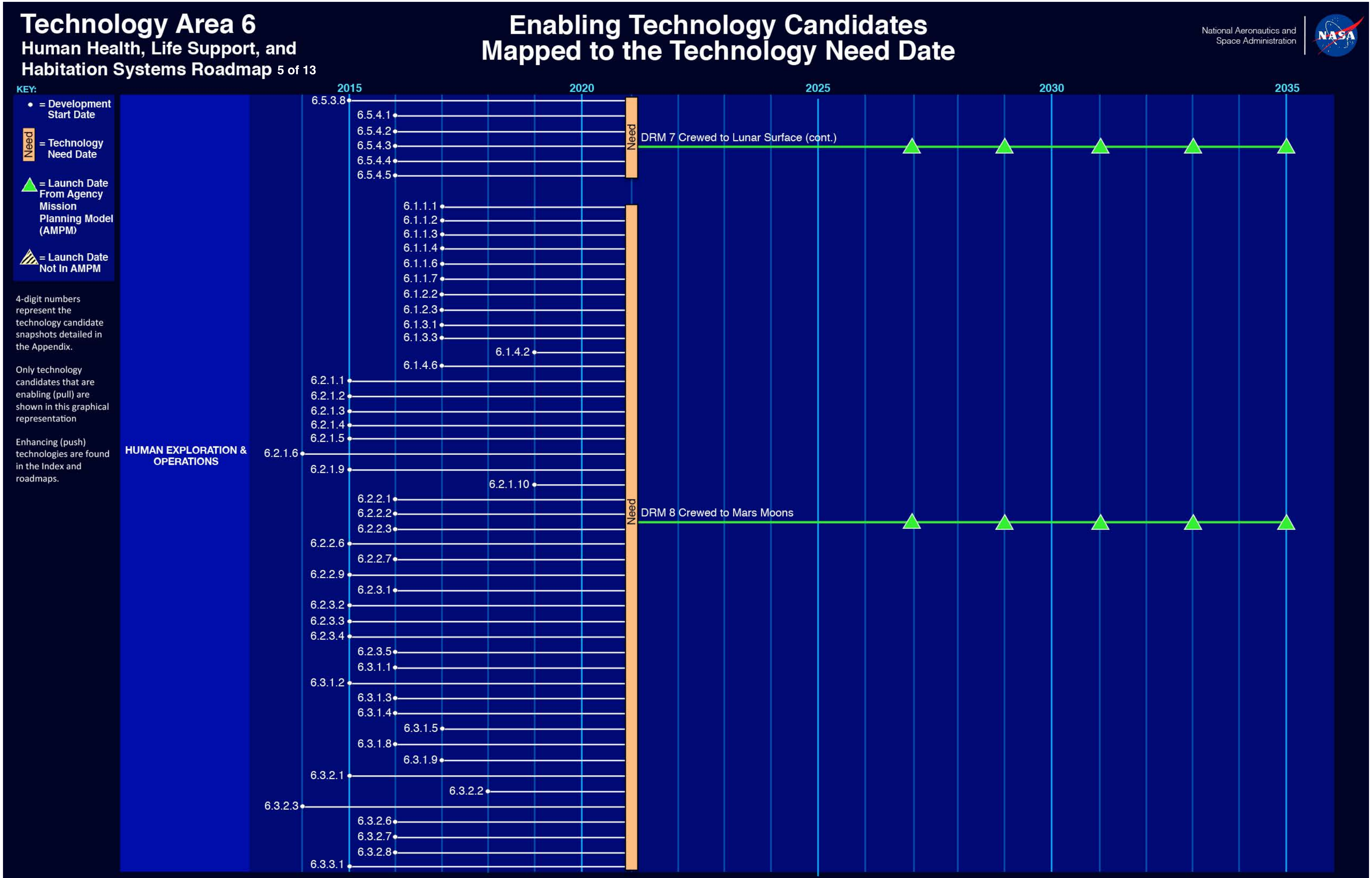


Figure 1. Technology Area Strategic Roadmap (Continued)



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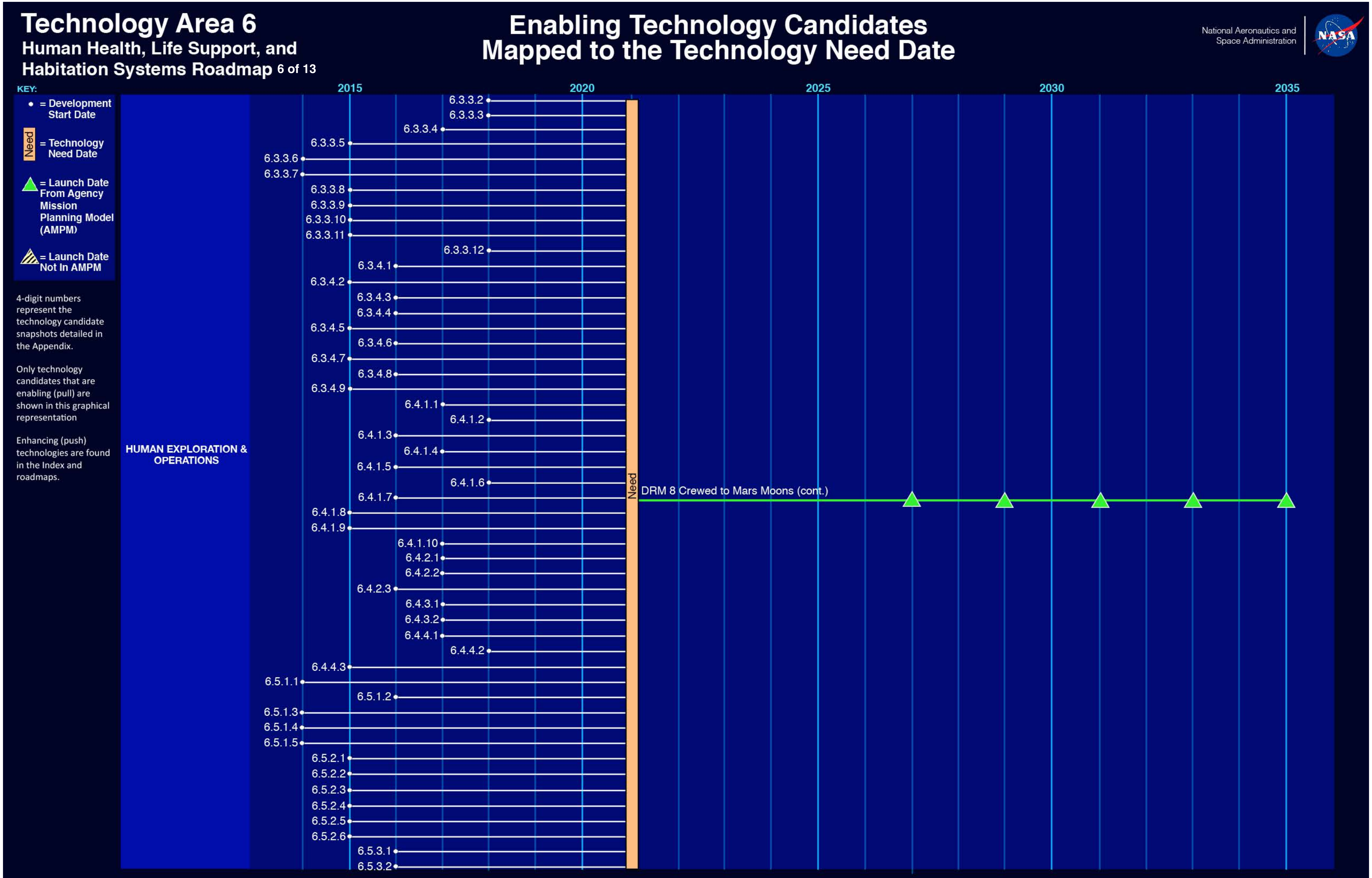

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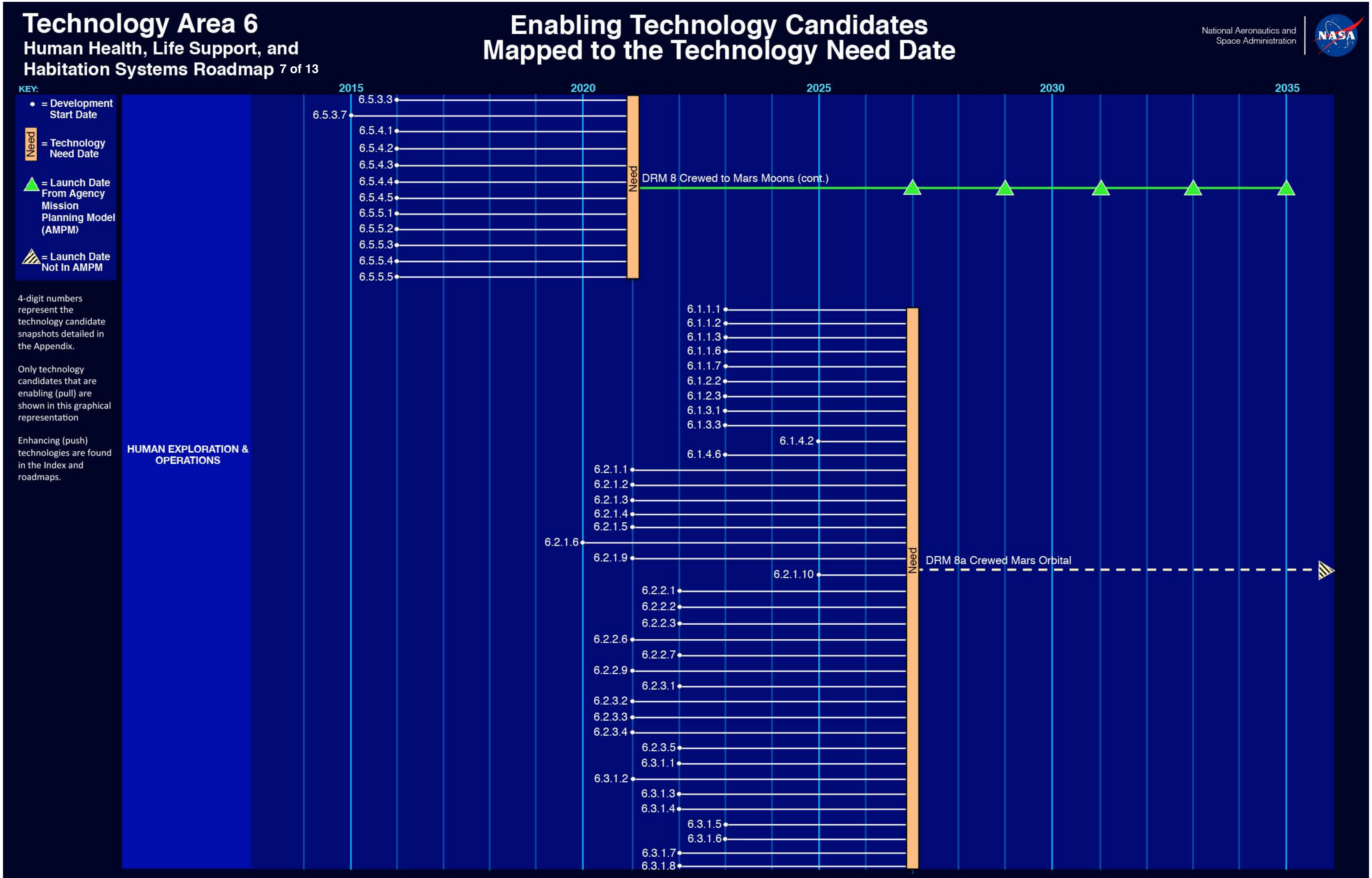

Figure 1. Technology Area Strategic Roadmap (Continued)

Technology Area 6
Human Health, Life Support, and Habitation Systems Roadmap 8 of 13

Enabling Technology Candidates Mapped to the Technology Need Date

National Aeronautics and Space Administration

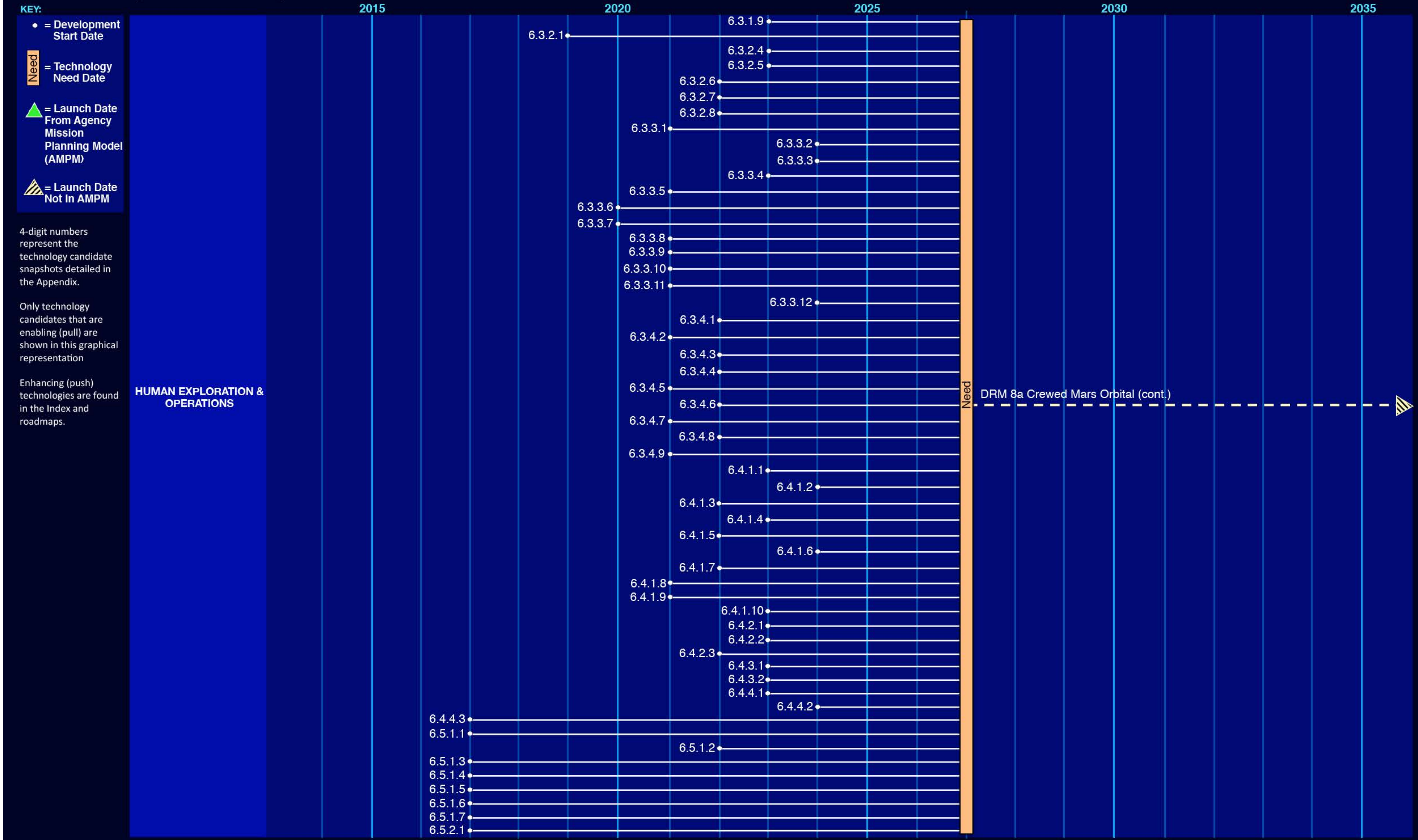

Figure 1. Technology Area Strategic Roadmap (Continued)

Technology Area 6

Human Health, Life Support, and Habitation Systems Roadmap 9 of 13

Enabling Technology Candidates Mapped to the Technology Need Date

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KEY:
- • = Development Start Date
- Need = Technology Need Date
- = Launch Date From Agency Mission Planning Model (AMPM)
- = Launch Date Not In AMPM

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.

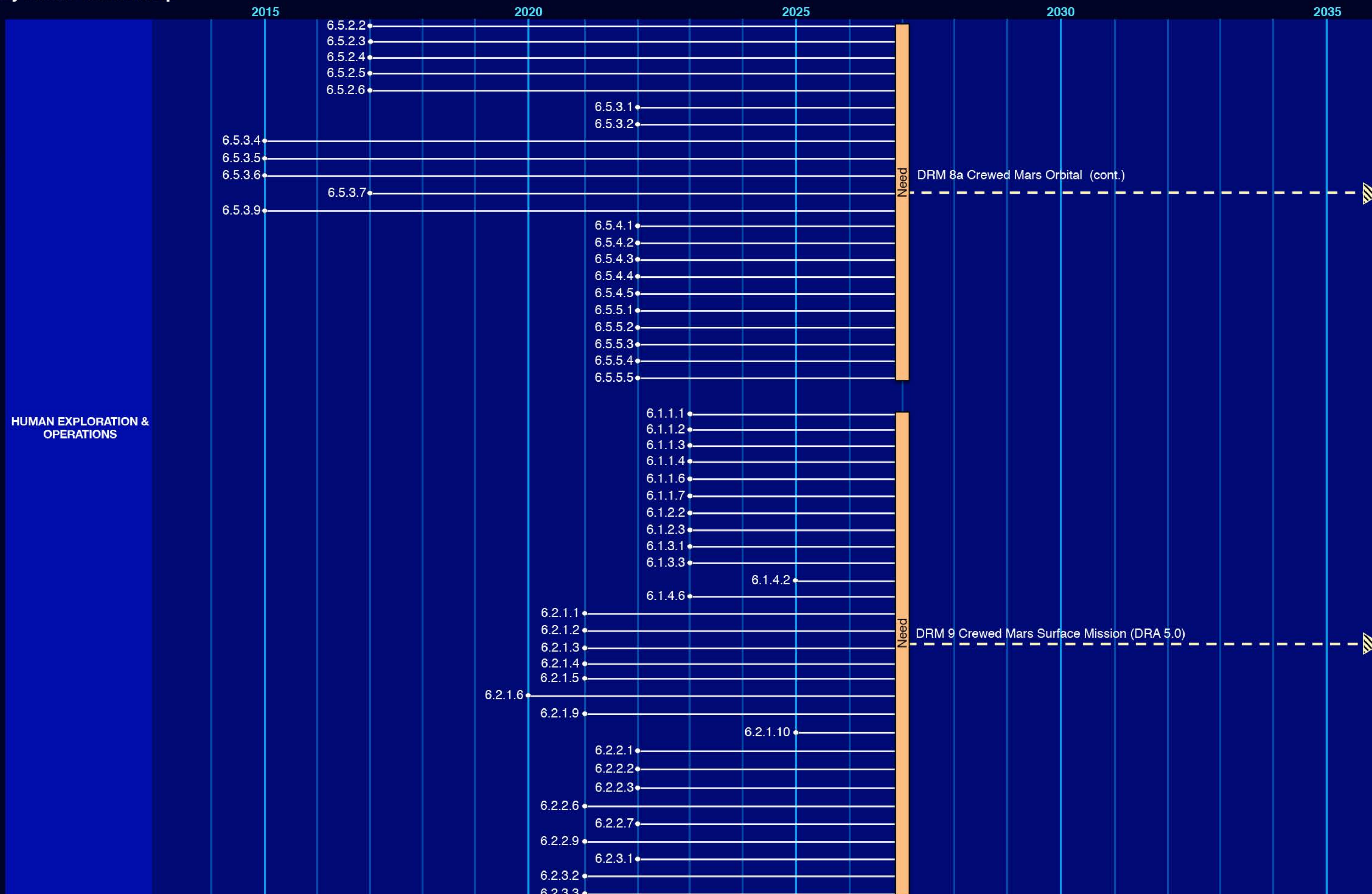
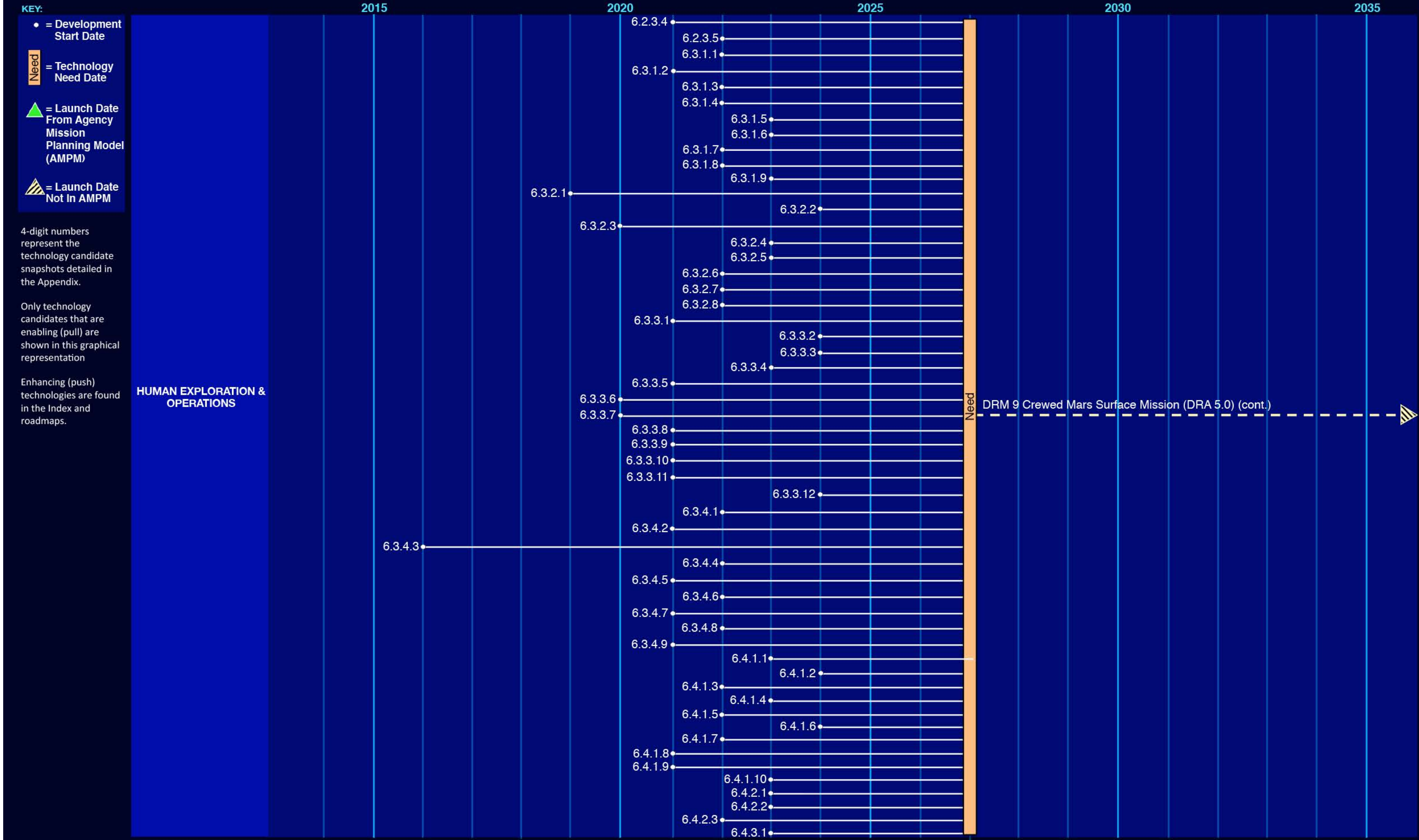


Figure 1. Technology Area Strategic Roadmap (Continued)

Technology Area 6
Human Health, Life Support, and Habitation Systems Roadmap 10 of 13

Enabling Technology Candidates Mapped to the Technology Need Date

National Aeronautics and Space Administration



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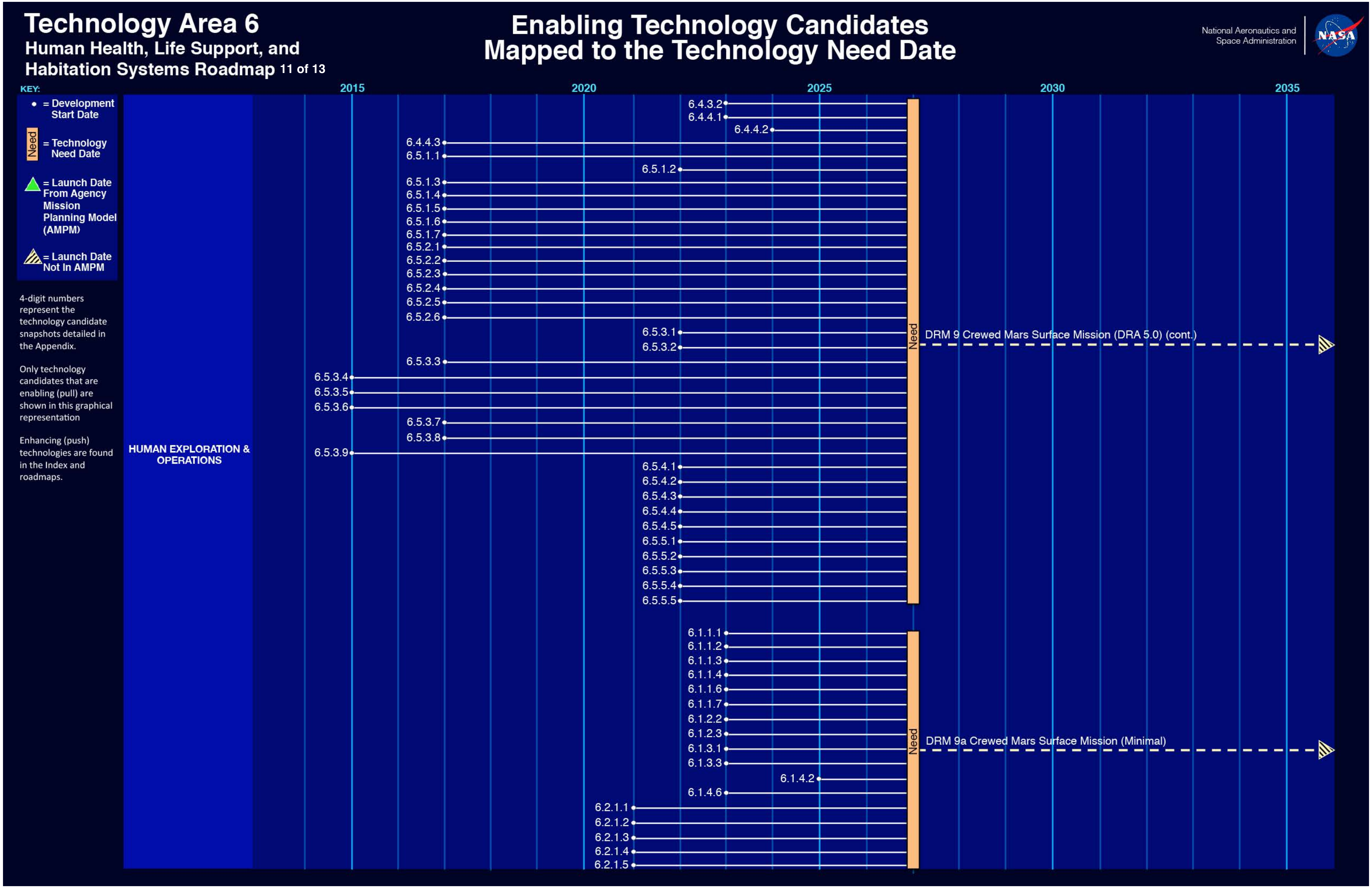

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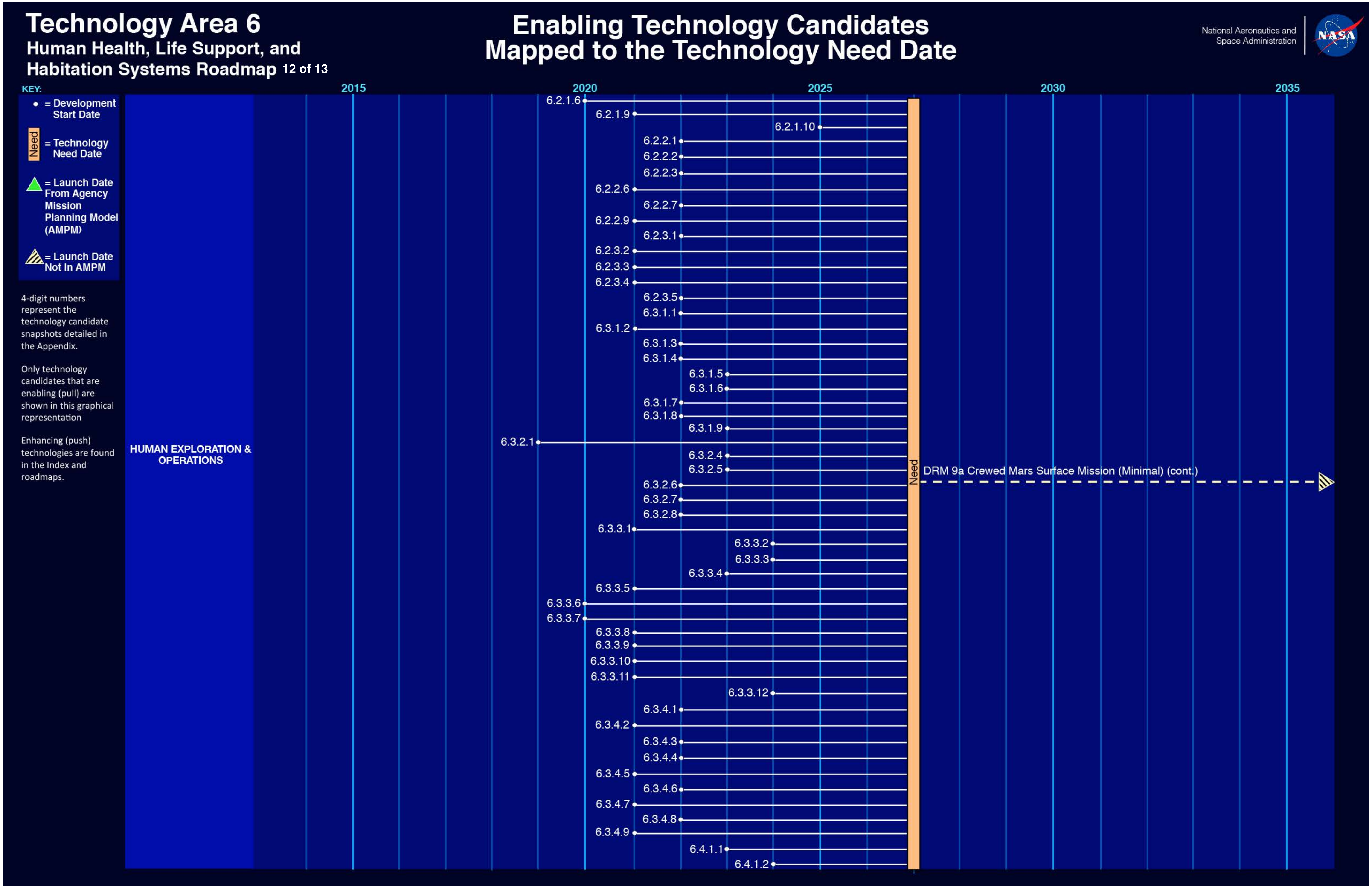


Figure 1. Technology Area Strategic Roadmap (Continued)

Technology Area 6
Human Health, Life Support, and Habitation Systems Roadmap 13 of 13

Enabling Technology Candidates Mapped to the Technology Need Date

National Aeronautics and Space Administration

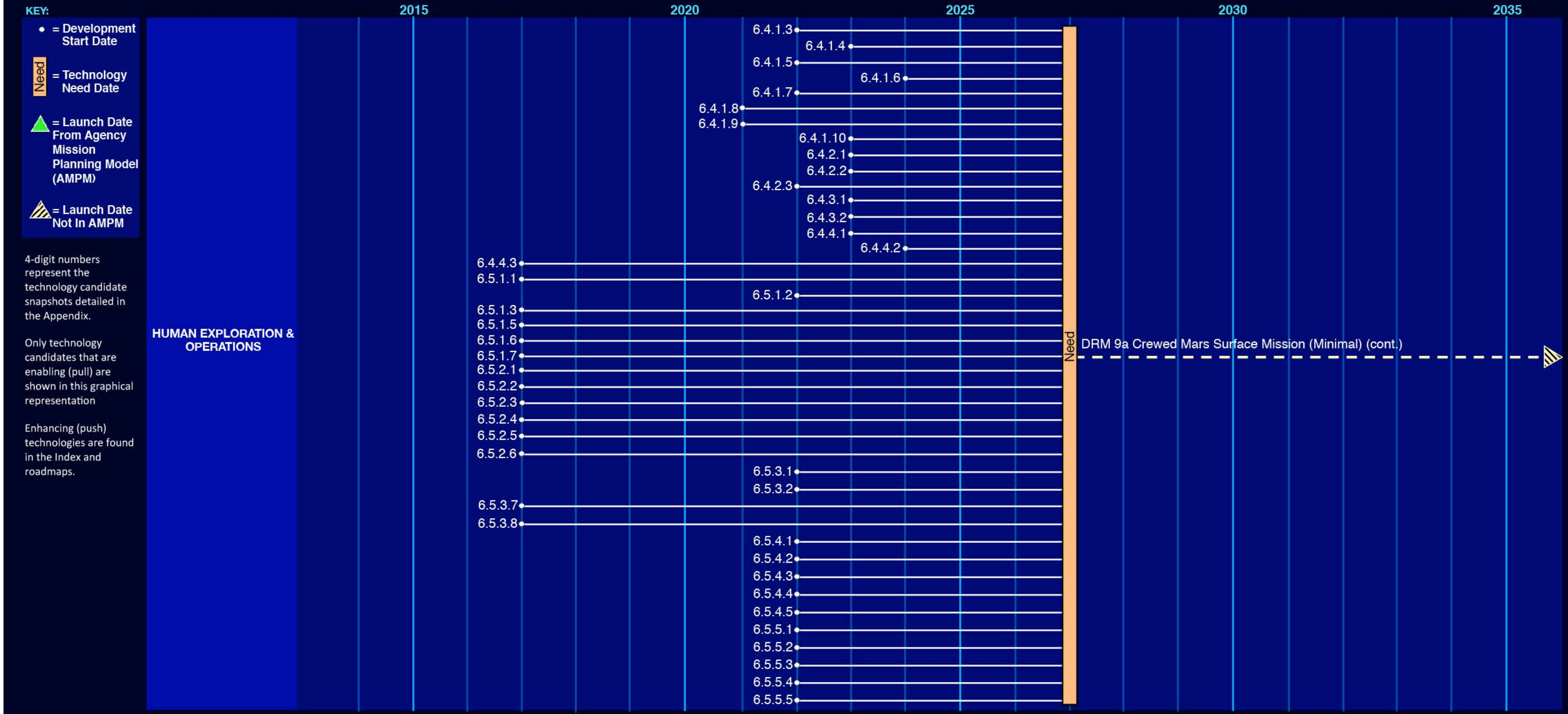


Figure 1. Technology Area Strategic Roadmap (Continued)

Introduction

This roadmap provides a summary of key capabilities necessary to achieve national and Agency goals in human space exploration over the next few decades in the Human Health, Life Support and Habitation Systems technology area (TA). As an example, crewed missions venturing beyond low-Earth orbit (LEO) will require technologies with improved reliability and radiation protection, reduced mass, improved self-sufficiency, and minimal logistical needs, since an emergency or quick-return option will not be feasible. As shown in Figure 2, the sub-TAs included in the roadmap are: Environmental Control and Life Support Systems (ECLSS) and Habitation Systems; Extravehicular Activity (EVA) Systems; Human Health and Performance (HHP); Environmental Monitoring, Safety, and Emergency Response (EMSER); and Radiation.

TA 6 Human Health, Life Support, and Habitation Systems

6.1 Environmental Control and Life Support Systems and Habitation Systems
- 6.1.1 Air Revitalization
- 6.1.2 Water Recovery and Management
- 6.1.3 Waste Management
- 6.1.4 Habitation

6.2 Extravehicular Activity Systems
- 6.2.1 Pressure Garment
- 6.2.2 Portable Life Support System
- 6.2.3 Power, Avionics, and Software

6.3 Human Health and Performance
- 6.3.1 Medical Diagnosis and Prognosis
- 6.3.2 Long-Duration Health
- 6.3.3 Behavioral Health
- 6.3.4 Human Factors

6.4 Environmental Monitoring, Safety, and Emergency Response
- 6.4.1 Sensors: Air, Water, Microbial, and Acoustic
- 6.4.2 Fire: Detection, Suppression, and Recovery
- 6.4.3 Protective Clothing and Breathing
- 6.4.4 Remediation

6.5 Radiation
- 6.5.1 Risk Assessment Modeling
- 6.5.2 Radiation Mitigation and Biological Countermeasures
- 6.5.3 Protection Systems
- 6.5.4 Space Weather Prediction
- 6.5.5 Monitoring Technology

Figure 2. Technology Area Breakdown Structure for Human Health, Life Support, and Habitation Systems

TA 6 technologies are specific to the human element and include those that directly affect crew needs for survival and well-being, as well as the environment to which the crew is exposed and interfaces that crew members encounter. For example, water recovery technologies are needed not only for allowing direct human consumption, but also for hygiene and controlling the humidity of the crew's environment. In addition to shared applications, each sub-TA has unique technological challenges, which will be discussed below.

6.1 Environmental Control and Life Support Systems and Habitation Systems

The main sub-goal of spacecraft life support and habitation systems is to maintain an environment suitable for sustaining human life throughout the duration of a mission. The ECLSS and Habitation System area is typically described as serving four primary functions:

- **6.1.1 Air Revitalization:** The overarching function of this area is to maintain a safe and habitable atmosphere within a spacecraft, surface vehicle, or habitat.
- **6.1.2 Water Recovery and Management:** This area provides a safe and reliable supply of potable water to meet crew consumption and operational needs.
- **6.1.3 Waste Management:** The objective of this area is to safeguard crew health, increase safety and performance, recover resources, and protect planetary surfaces, all while decreasing mission costs.
- **6.1.4 Habitation:** This area focuses on habitation functions that closely interface with life-support systems, including food preparation and production, hygiene, metabolic waste collection, clothing/laundry, and the conversion of logistics trash to resources.

While this functional decomposition is helpful for describing ECLSS and habitation systems, it is important to recognize opportunities where combining lower-level functions or applying technology solutions to multiple functions may offer attractive benefits.

6.2 Extravehicular Activity Systems

EVA systems are critical to every foreseeable human exploration mission, from in-space microgravity missions in LEO to planetary surface exploration. In addition, a launch, entry, and abort (LEA) suit system is needed to protect the crew during launch, landing, and cabin contamination/depressurization events, as well as the ascent/decent transition for planetary excursions.

An EVA system includes hardware and software that spans multiple assets in a given mission architecture and interfaces with many vehicle systems, such as life support, power, communications, avionics, robotics, materials, pressure systems, and thermal systems. The roadmap for TA 7 (Human Exploration Destination Systems), addresses tools that are included with the EVA system. For the purpose of this document, the EVA system includes three subsystems:

- **6.2.1 Pressure Garment:** The suit, or pressure garment, is the set of components a crew member wears and uses. It includes the torso, arms, legs, gloves, joint bearings, helmet, and boots. The suit employs a complex system of soft-goods and mobility elements in the shoulders, arms, hips, legs, torso, boots, and gloves to optimize performance while pressurized without inhibiting unpressurized operations. The LEA suit also contains provisions to protect the crew member from both nominal and off-nominal environments (e.g., gravitational, sound, chemical) encountered during launch, entry, and landing, as well as potential descent/ascent to planetary surfaces.
- **6.2.2 Portable Life Support System (PLSS):** The PLSS performs functions required to keep a crew member alive during an EVA. These functions include maintaining thermal control of the astronaut, providing a pressurized oxygen (O_2) environment, and removing products of metabolic output such as carbon dioxide (CO_2) and water (H_2O).
- **6.2.3 Power, Avionics, and Software (PAS):** The PAS system is responsible for the EVA system's power supply and distribution, collecting and transferring several types of data to and from other mission assets, providing avionics hardware to perform numerous data display and in-suit processing functions, and furnishing information systems to supply data that enables crew members to perform their tasks with more autonomy and efficiency.

6.3 Human Health and Performance

The main sub-goal of the HHP technologies is to maintain the health of the crew and support optimal and sustained performance throughout the duration of a mission. The HHP domain includes four functional focus areas:

- **6.3.1 Medical Diagnosis and Prognosis:** This functional area provides a suite of medical technologies, knowledge, and procedures that minimize the likelihood and consequence of off-nominal medical events during exploration missions. Efforts are also focused on developing novel screening, diagnosis, and treatment technologies for conditions that drive medical risk, as well as developing the appropriate infrastructure to match the level of care required for exploration Design Reference Missions (DRMs).
- **6.3.2 Long-Duration Health:** This area focuses on providing validated technologies for medical practice to address the effects of the space environment on human systems and countermeasures to maintain crew physical health, behavioral health, and sustained performance on extended-duration missions.
- **6.3.3 Behavioral Health:** The objective in this area is to provide countermeasures and conduct monitoring to reduce the psychosocial, neurobehavioral, and performance risk associated with extended space travel and return to Earth. Technology advancements are needed to identify, characterize, and prevent or reduce risks associated with space travel, exploration, and return to terrestrial life on astronauts' behavioral health and performance
- **6.3.4 Human Factors:** This area focuses on technologies that support the crew's ability to effectively, reliably, and safely interact within mission environments. Elements include physical accommodation, fit, ergonomics of crew hardware interfaces, physical and cognitive augmentation, training, and Human-Systems Integration (HSI) tools, metrics, methods, and standards.

6.4 Environmental Monitoring, Safety, and Emergency Response

The sub-goals of the EMSER effort are to develop technologies that ensure crew health and safety by protecting against spacecraft hazards and to ensure effective response should an accident occur. This area includes four functions:

- **6.4.1 Sensors: Air, Water, Microbial, and Acoustic:** The objective of this area is to provide future spacecraft with advanced, networks of integrated sensors to monitor environmental health and accurately determine and control the physical, chemical, and biological environments of crew living areas and their environmental control systems.
- **6.4.2 Fire: Detection, Suppression, and Recovery:** The objective of spacecraft fire safety is to develop technologies that ensure crew health and safety by reducing the likelihood of a fire, or, if one does occur, minimizing the risk to the crew, mission, and/or system.
- **6.4.3 Protective Clothing and Breathing:** The objective of this area is to provide the crew with sufficient capability to address off-nominal situations within the habitable compartments of the spacecraft. Off-nominal events include fire, chemical release, microbial contamination, and unexpected depressurization.
- **6.4.4 Remediation:** The focus of remediation is to provide the crew with the ability to clean the habitable environment of the spacecraft in the event of an off-nominal situation. Off-nominal events include fire, an inadvertent chemical release, or microbial contamination.

6.5 Radiation

The radiation area is focused on developing technologies to increase crew mission duration (100 to 1,000 days, depending on the mission) in the free-space radiation environment while remaining below the space radiation permissible exposure limits (PELs). It is generally accepted that to meet the sub-goal of extending crew mission duration, an integrated, optimized approach utilizing shielding options, biological countermeasures, improved understanding of the risks, and the ability to better predict and monitor the radiation environment will be required. The primary radiation technologies requiring advancement to meet this sub-goal include:

- **6.5.1 Risk Assessment Modeling:** The focus of this area is to develop tools that enable, quantify, and reduce uncertainty in assessing astronaut risk due to space radiation exposure, as well as to improve mission operations, mission planning, and system design for LEO, deep-space, lunar, and Mars missions.
- **6.5.2 Radiation Mitigation and Biological Countermeasures (BCM):** The focus of this area is to develop BCMs that can minimize or prevent physical, cognitive, and behavioral disorders due to space radiation without adverse side effects and loss of life.
- **6.5.3 Protection Systems:** The focus of this area is to advance the design of integrated radiation protection shielding technologies that extend the duration of missions beyond LEO by more than 60 days, within the scope of reasonable vehicle design and mass. The focus is to provide passive or active shielding through design advances, advanced materials, lightweight structures, and in-situ resources.
- **6.5.4 Space Weather Prediction:** The focus of this area is to advance improvements in solar particle event (SPE) forecasting and alert systems to minimize operational constraints for missions outside the protection of the Earth's geo-magnetic field.
- **6.5.5 Monitoring Technology:** The focus of this area is to prototype and mature advanced, miniaturized radiation measurement technologies, and to demonstrate these technologies as integrated vehicle systems using available platforms.

TA 6.1: Environmental Control and Life Support Systems and Habitation Systems

In short-duration missions lasting days or weeks, open-loop life-support systems, in which stored consumables like water and oxygen are used once by the crew and discarded in various forms of metabolic wastes, typically offer the best combination of simplicity, reliability, and mission mass. As mission durations increase to months and years, the mass of consumables grows until, depending on specific mission parameters, it becomes more advantageous from a life-cycle cost perspective to recover water and oxygen from metabolic byproducts for subsequent re-utilization by the crew. Onboard the International Space Station (ISS), water is recovered from wastewater and oxygen is recovered indirectly from carbon dioxide. The physical-chemical processes that are employed provide safe water and oxygen that meet the metabolic and basic hygiene needs of the crew. However, less than 90% of the available water and less than half of the potential oxygen that could be is actually recovered. Furthermore, the reliance on expendable items like filters and sorbent beds, and the complexities of the systems themselves, create a dependence on the re-supply of equipment and materials from Earth. In LEO, where the ISS operates, equipment and material re-supply can be sustained through the logistics contributions of international partners and United States (U.S.) commercial cargo transportation providers. However, in missions beyond LEO, such re-supply chains will become stretched to the point of limiting the potential for extended-duration human space exploration. It is critically important to evolve and supplement today's Earth-reliant systems and prove their readiness to extend humanity's reach to Mars and other deep-space destinations.

Improvements to life support and habitation capabilities are expected to be achieved through a combination of evolutionary improvements to the state of the art (SOA) technologies and system architectures, supplemented with new capabilities and paradigms that have yet to be proven. Demonstration that these improvements have been achieved will require testing in a flight environment for at least two years to prepare for a likely Mars round-trip transit mission duration. The ISS will be an important part of such a proving ground, providing opportunities to integrate and operate technologies within existing systems, independently as separate stand-alone payloads, as part of complete new systems operated independently in a dedicated location or module, or some combination of each strategy. Once proven on the ISS, the suite of technologies will be ready for integration with other systems, such as power and thermal control, for a vehicle-level demonstration of the readiness to proceed on to Mars.

The ECLSS and Habitation Systems Technical sub-TA has technologies that crosscut with other sub-TAs in TA 6, as well as with other TAs. Within TA 6, the technologies that require maturation to support Air Revitalization (6.1.1), Water Recovery and Management (6.1.2), and Waste Management (6.1.3) are also relevant to Extravehicular Activity Systems (6.2), albeit on a different scale. Habitation (6.1.4) benefits from technology advances in TA 7 Human Exploration Destination Systems, and TA 12 Materials, Structure, Mechanical Systems and Manufacturing, and all of TA 6.1 can benefit from advances made in TA 10, Nanotechnology.

Sub-Goals

The overarching sub-goal for environmental control, life support, and habitation is to develop and demonstrate highly reliable capabilities needed to sustain humans for long periods of time in deep space with minimal reliance on Earth-supplied consumables, expendables, replacement equipment, and crew intervention and maintenance, coupled with capabilities to efficiently use in-situ resources and recycle, reuse, and repurpose consumable and expendables. The ISS or other suitable platforms in the relative vicinity of Earth will serve as the proving ground to demonstrate readiness to support missions to Mars and deep-space destinations over mission lengths measured in years.

Increasing closure of water and oxygen loops can pay significant dividends to deep-space missions, but only if the systems involved have the demonstrated reliability needed to avoid mission costs associated with large stored reserves; large, redundant systems; and large inventories of replacement hardware. Overall system reliability and potential reductions in spare equipment should be addressed at both the subsystem (hardware) and complete system levels, Design and operational simplicity, combined with process robustness to unforeseen circumstances and conditions, need to be regarded among the most important measures of "goodness" as candidate technologies are developed and compared.

Table 2. Summary of Level 6.1 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
6.0 Human Health, Life Support, and Habitation Systems	Goals:	Enable long-duration, deep-space human exploration within permissible space radiation exposure limits, minimal resupply consumables, and increased Earth independence.
Level 2		
6.1 Environmental Control and Life Support Systems and Habitation Systems	Sub-Goals:	Maintain an environment suitable for sustaining human life throughout the duration of a mission.
Level 3		
6.1.1 Air Revitalization	Objectives:	Reliably and efficiently condition and revitalize spacecraft and habitat atmospheres to provide safe and comfortable environments within which crewmembers may live and work.
	Challenges:	Simplify and increase the robustness of systems involved with controlling carbon dioxide to safe levels and recovering oxygen from it. High-capacity sorbents and high-efficiency oxidizing catalysts to limit the accumulation of volatile organic contaminants. Durable and chemically-inert hydrophilic surfaces with antimicrobial properties suitable for long-term use in condensing heat exchangers. High-capacity, high-efficiency filtration media that reduce crew time dedicated to routine filter cleaning and keep airborne particulates and microorganisms at safe levels.
	Benefits:	Reduces resources needed to limit carbon dioxide to low concentrations that mitigate long-term health and cognition risks to crew members. Enables reliable and efficient recovery and recycling of oxygen to meet crew member metabolic needs. Reduces the amount of crew time dedicated to maintaining systems and allows more compact packaging of systems. Reduces crew time dedicated to filter cleaning and maintenance and mitigates allergenic responses in crew members. Simplifies system architectures and reduces resource demands.
6.1.2 Water Recovery and Management	Objectives:	Reliably and efficiently manage the collection, storage, and distribution of waste and potable water and increase the percentage of re-useable water recovered from waste water sources.
	Challenges:	Long-term stabilization and preservation of waste and potable water with methods and materials that are non-toxic and compatible with processing systems. Long-duration, reliable production of safe water with minimal expendables usage and crew maintenance. Tolerance to dormancy between operational periods. Recovery of water from solutions (brines) that are nearly saturated with a complex mixture of inorganic and organic chemical species.
	Benefits:	Reduces resources needed to provide safe and dependable supplies of water to crew members.

Table 2. Summary of Level 6.1 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
6.1.3 Waste Management	Objectives:	Reliably and efficiently enable the hygienic collection, stabilization, and disposal or re-utilization of solid and liquid metabolic wastes and trash.
	Challenges:	Effective, hygienic separation and containment of metabolic liquid and solid wastes from male and female crew members in microgravity environment. Stabilizing, compacting, and containing trash for long term storage or recovering/repurposing materials for alternative uses.
	Benefits:	Provides sanitary conditions to sustain crew health and a clean and pleasant living environment. Reduces the accumulated volume of discarded materials onboard a spacecraft or within a habitat and stabilizes the material to minimize its potential environmental hazard to the crew.
6.1.4 Habitation	Objectives:	Provide safe, comfortable, and adaptable living and working spaces within the confines of space exploration vehicles and habitats.
	Challenges:	Enabling crew members to engage in routine daily hygiene in privacy without impacting the overall habitable environment. Adapting items and containers so that they may be repurposed or reutilized to meet multiple needs. Protecting crew members from the adverse effects of long-term exposure to harmful levels of ambient noise. Minimizing the logistical burden associated with things like clothing, linens, wipes, etc. Minimizing the logistical burden associated with providing safe, palatable, and nutritional food supplies over mission durations lasting years.
	Benefits:	Maximizes the utility of space within spacecraft and habitats that are typically constrained volumetrically due to launch and transportation limitations. Reduces the logistical burdens associated with long-duration human space missions. Sustains crew member health and morale by providing fresh and enjoyable foods.

TA 6.1.1 Air Revitalization

Technical Capability Objectives and Challenges

Open-loop air revitalization architectures typically utilize stored oxygen to meet the daily metabolic consumption needs of the crew. Exhaled carbon dioxide is scrubbed from the cabin atmosphere with either expendable media, such as lithium hydroxide, or regenerable media, such as solid amines, from which the carbon dioxide is then vented overboard. Respired and perspired water vapor is also vented overboard, either with the carbon dioxide or separately. Volatile organic compounds emitted by the crew or off-gassed from spacecraft equipment are cleansed from the cabin atmosphere using suitable sorbents and catalytic oxidizers. Fans circulate air through ducting to and from points in the cabin selected to ensure uniform mixing for safety and comfort. Filters mounted at duct inlets capture airborne particulates and microbiological contaminants. Heat exchangers, operated at temperatures above the cabin dew point, collect waste heat from circulated cabin air and transfer it to coolant loops.

Closed-loop air revitalization architectures perform the same primary functions as do open-loop architectures, but they do so in a manner specifically designed to preserve precious oxygen and water for re-utilization. This requires additional equipment and operational complexity and, therefore, is not typically implemented unless mission durations are of sufficient length to make it worthwhile. In a closed-loop architecture, rather than venting carbon dioxide overboard, it is adsorbed onto regenerable media, from which it can then be desorbed and delivered to systems designed to recover the oxygen component of the molecule. On the ISS, this is done by reacting the carbon dioxide with hydrogen to produce water and methane in what is referred to as the Sabatier process. The methane is vented overboard while the water, once polished, becomes part of the ISS's water supply. A portion of this water supply is used to generate oxygen for the crew through electrolysis, a process that dissociates water into oxygen and hydrogen. Because the amount of hydrogen produced is proportional to the amount of oxygen needed by the crew, its supply is limited, which then limits the maximum amount of oxygen recoverable from carbon dioxide to no more than half of what's available. Closed-loop air revitalization systems also are distinguished from open-loop systems in that cabin heat exchangers are operated at temperatures below the cabin dew point so that water vapor may be condensed, collected, and delivered to water processing equipment for purification and re-use.

Air Revitalization Test Articles

The primary air revitalization capability objective is the reliable and efficient recovery of oxygen from carbon dioxide exhaled by crew members. This capability depends on a number of inter-dependent functions, beginning with the removal of carbon dioxide from a spacecraft cabin atmosphere and culminating with the liberation of re-useable oxygen either directly from carbon dioxide or, more typically, from water that is generated as a by-product of carbon dioxide reduction reactions. Durable, robust materials are needed that are suitable for removing carbon dioxide from cabin atmospheres and delivering it to downstream processes for oxygen recovery. The capacity to control carbon dioxide partial pressures to levels measured at less than 2 millimeters of mercury (mmHg) without substantially impacting equipment size and power consumption may be needed to alleviate crew member health issues. Increasing the percentage of oxygen recoverable from carbon dioxide from 50 percent today, to 75 percent initially, and ultimately more than 90 percent, could enable or enhance deep-space exploration, depending on the specific duration and constraints of the missions. Means are needed to simplify the integrated complexity of the SOA water electrolysis system to increase reliability and operational robustness, as is the capability to recharge oxygen storage tanks to pressures up to 3,600 pounds per square inch absolute (psia) with oxygen generated onboard. High-capacity sorbents and high-efficiency oxidizing catalysts are needed to replace obsolete materials in spacecraft trace contaminant control applications. Durable and chemically-inert hydrophilic surfaces with antimicrobial properties are needed to avoid periodically drying out condensing heat exchangers, as well as the problematic conversion of airborne silica-containing compounds into refractory compounds, which are difficult to subsequently extract from recycled water supplies. High-capacity, high-efficiency filtration media that reduce crew time dedicated to routine filter cleaning are needed, as are media and methods suitable for capturing planetary dust particles that may be carried into habitable elements on the suits and equipment of crew members following EVAs on planetary surfaces.

Benefits of Technology

Improving the reliability of air revitalization capabilities will most directly benefit future long-duration human missions beyond LEO by reducing the amount of spare equipment and emergency supplies of oxygen that must be launched from Earth to ensure crew survival and mission success. Secondary benefits can include reducing the amount of crew time dedicated to maintaining systems and allowing more compact packaging of systems which don't require frequent access for maintenance. Reducing the resources needed to maintain carbon-dioxide partial pressures in cabin atmospheres by developing higher-efficiency materials and processes might reduce the incidence of headaches and mitigate cognitive decline among crew members during both short- and long-duration missions. Increasing the percentage of oxygen recoverable from crew member carbon dioxide can reduce the dependence on Earth-based oxygen re-supply and build up oxygen reserves that can subsequently be used to support EVAs and short-duration vehicular excursions away from a primary habitat. Improving the efficiency and capacities of systems that remove particulates from cabin atmospheres can reduce crew time dedicated to filter cleaning and maintenance and can mitigate allergic responses in crew members caused by exposure to particulate-laden air. Dust inadvertently transferred into habitable cabins from planetary bodies, such as the Moon or asteroids, may pose unique risks to crew health due to the absence of Earth-like weathering processes. Processes that take advantage of metabolic pathways available in organisms like algae and bacteria may also provide benefits for carbon dioxide removal, oxygen production, and air purification. A highly reliable system that could remove carbon dioxide from the air and generate oxygen directly from it, while safely and efficiently managing the formation and handling of problematic by-products like carbon monoxide and solid carbon, could offer opportunities to simplify system architectures and reduce resources.

Table 3. TA 6.1.1 Technology Candidates – not in priority order

TA	Technology Name	Description
6.1.1.1	Carbon Dioxide (CO_2) Removal (Closed-Loop)	Systems that remove metabolically-generated carbon dioxide from the spacecraft atmosphere to safe levels for the crew, and deliver the carbon dioxide to onboard processes dedicated to the recovery of oxygen.
6.1.1.2	Carbon Dioxide (CO_2) Reduction	Systems that recover oxygen from carbon dioxide removed from the spacecraft atmosphere through chemical reactions to reduce the carbon dioxide to other products.
6.1.1.3	Trace Contaminant Control	Systems that remove toxins from the spacecraft cabin atmosphere to below the spacecraft maximum allowable concentrations. Contaminants may be either metabolically generated or off-gassed from equipment and materials over time.
6.1.1.4	Particulate and Microbial Control	System that removes particulates (generated from crew, clothing, etc.) and microbial contamination from the spacecraft cabin atmosphere.
6.1.1.5	Temperature and Humidity Control	Systems that control the temperature and humidity levels within a spacecraft cabin and can collect humidity water for recovery.
6.1.1.6	Oxygen (O_2) Supply	Systems that provide oxygen from stored supplies or onboard generation systems to meet crew metabolic needs and makeup for cabin atmosphere leakage or re-pressurization makeup.
6.1.1.7	High-Pressure Oxygen (O_2) Supply	Systems that supply oxygen at high pressure to recharge storage tanks for use during extravehicular activities or short-duration crewed vehicles or spacecraft.

TA 6.1.2 Water Recovery and Management

Technical Capability Objectives and Challenges

Open-loop water management systems meet daily crew needs by delivering water stored in onboard tanks. The tanks are loaded prior to launch and typically contain a residual biocide to maintain microbial cleanliness throughout the mission. Water vapor perspired and respired by the crew is scrubbed from the cabin atmosphere and vented overboard. Urine is collected and discarded overboard.

Closed-loop water recovery and management systems purify cabin humidity condensate and crew member urine so that the resulting potable water can be re-used by the crew. On the ISS, chemicals are added to the urine upon collection in order to stabilize it. The stabilized urine is distilled via a vapor compression distillation process. The resulting distillate is combined with cabin humidity condensate and processed through a sequence of operations including degassing, filtration, adsorption, ion exchange, and catalytic oxidation. Iodine is added to the finished water to maintain microbial control; health risks associated with long-term consumption of iodine dictate that the iodine be removed at the delivery point of use. The combination of stabilization chemicals with the constituents of urine, including elevated levels of calcium induced by crew members' physiological responses to the micro-gravity environment, limits the amount of water recoverable from urine today to about 75 percent, beyond which problematic precipitation of solids begins to occur. Even with changes that are currently being made to the formulation of urine-stabilizing solutions, water recovery from urine will likely remain limited to no more than 85 percent without supplemental processing in a solids-tolerant system.

Also of interest are means to reduce the usage rate of expendable media like filters, adsorbents, and ion-exchange resins.

Water recovery and management objectives include reliably increasing the percentage of water recovered from urine beyond 85 percent and potentially broadening the types of wastewaters that can be processed. A challenge to achieving water recovery efficiencies of 90 percent or greater is having systems that are resilient to the formation of complex precipitants, which form as water is extracted from increasingly concentrated brine. Reducing reliance on expendable media, such as filtration media, sorbents, and ion-exchange resins is an important capability enhancement as well. Any additional equipment mass required to achieve higher water recovery efficiencies must be substantially less than the water re-supply mass savings to justify the added complexity and risk involved. Other objectives include developing biocides, which are microbiologically effective at concentrations that are safe for long-term human consumption, or alternative microbial control techniques that can assure the long-term safety of stored water supplies. These biocides must be dosed, preferably by passive means, into recycled water supplies within specific target ranges and would preferably be able to maintain anti-microbial effectiveness in stored water reserves for several years. Non-toxic urine pretreatment solutions that effectively prevent microbial growth and the precipitation of solids can reduce potential hazards and simplify system design and operations. Some exploration mission scenarios may also require water recovery and management systems to be tolerant of intermittent periods of dormancy, measured in months and years, between periods of extended operation; having technologies and system architectures that don't require substantial effort to "safe" and then reactivate after long periods of dormancy will be required.

Benefits of Technology

Improving the reliability of water recovery capabilities will most directly benefit future long-duration human missions beyond LEO by reducing the amount of spare equipment and emergency supplemental supplies of water that must be launched from Earth to ensure crew survival and mission success. A secondary benefit of increasing water recovery is the reduction in volume of residual brine (which may be toxic) that must be stored or somehow disposed of. In long-duration missions into deep space, the retention of water mass within a transit or habitation vehicle can provide secondary benefits, like radiation shielding. Highly reliable water-recovery technologies and architectures that depend minimally on expendable media can substantially reduce the stowage volume needed for spare equipment and fresh expendable items. Biocides that are safe for prolonged human consumption at concentrations that effectively prevent microbial growth can simplify system architectures and operations by eliminating the need to strip the biocide out of water prior to its consumption by the crew. By remaining effective over periods of years, such biocides can enable exploration scenarios in which stored water supplies remain safe for immediate use for a year or more prior to or between crew visits. Non-toxic urine pretreatment solutions can reduce the hazard potential associated with fluid leaks and can also enable a greater degree of invasive crew maintenance within systems than would otherwise be safe with more toxic fluids.

Table 4. TA 6.1.2 Technology Candidates – not in priority order

TA	Technology Name	Description
6.1.2.1	Wastewater Collection	Systems that collect wastewater, including condensate and urine, stabilize it (if necessary), and store it prior to disposal or processing.
6.1.2.2	Wastewater Processing	Systems that process urine, humidity condensate, hygiene, CO_2 reduction product, and other sources of water generated on orbit that cannot be considered potable without some processing for purification.
6.1.2.3	Brine Processing	Systems that recover water from concentrated by-product solutions ("brines") that remain after primary wastewater processing. Such systems must be tolerant of the formation of, and facilitate the efficient disposal of, precipitated solids.
6.1.2.4	Potable Water Microbial Control	Systems that ensure that potable water meets microbial limits for consumption by the crew. This can include biocides, point-of-use filters, or other means.

TA 6.1.3 Waste Management

Technical Capability Objectives and Challenges

Today, waste management encompasses the collection, containment, and ultimate disposal of solid waste, including crew fecal material (and associated wipes) and wet and dry trash generated by the crew through their daily activities. On the ISS, airflow entrains crew fecal waste and associated wipes into a fixed canister outfitted with individual porous bags. No compaction other than that achieved by the forces of airflow, which draw the bag and its contents to the bottom of the container, is done. Full canisters are removed, capped, and disposed of in departing logistics vehicles. Urine is collected separately and is drawn by airflow into a funnel and hose assembly by a centrifugal device that separates the air from entrained urine. Separation and containment is imperfect, resulting in frequent escapes of urine and fecal materials. Trash is deposited into bags and manually compacted by crew members to minimize volume.

Waste management objectives include developing a universal metabolic-waste management system that can be effectively integrated and operated within any type of exploration spacecraft or habitat. Simplicity of use and the effectiveness of material capture and containment are key aspects of this system. Compatibility with potential resource recovery processes, including pretreatment of urine for subsequent water recovery or compaction of solid waste to reduce volume, are required. In the event of a waste management system failure, contingency devices based on passive, capillary-driven fluid containment are needed to enable the continued collection and overboard disposal of crew member urine. The ability to effectively compact and stabilize trash enables long-duration missions and the ability to repurpose trash material to serve other purposes, such as provide radiation protection or alternative fuels, may enhance missions to deep space.

Benefits of Technology

Universal metabolic waste management systems suitable for integration and used throughout a fleet of various exploration spacecraft, habitats, or excursion vehicles will reduce exploration life-cycle costs and enhance crew effectiveness by facilitating common usage and maintenance procedures. These metabolic waste management systems must be designed to support system architectures and mission concepts in which wastes are simply collected and contained for disposal or for processing to recover reusable resources, such as water, minerals, or gases. Trash management technologies can substantially reduce the accumulated volume of discarded materials onboard a spacecraft or within a habitat and can stabilize the material to minimize its potential environmental hazard to the crew. In missions where planetary protection safeguards must be adhered to, compacting and inerting trash may be required at levels beyond those required for spacecraft habitation needs.

Table 5. TA 6.1.3 Technology Candidates – not in priority order

TA	Technology Name	Description
6.1.3.1	Metabolic Waste Management	System that collects, contains, and stores or processes metabolically-generated solid waste.
6.1.3.2	Contingency Urine Collection	Device, with no moving parts, that collects and temporarily contains urine for overboard disposal.
6.1.3.3	Trash Management System	A device that reduces the volume of trash (paper and plastic products, residual foods, beverages, and containers, used housekeeping and hygiene wipes, etc.) and stabilizes it for safe storage and/or disposal.
6.1.3.4	Trash-to-Gas (TtG)	System that uses trash as feedstock to produce gases (methane) for propulsion. Venting of gas is also a possible disposal means.

TA 6.1.4 Habitation

Technical Capability Objectives and Challenges

On the ISS, habitation systems include crew quarters, a galley and food systems, hygiene supplies, clothing and linens, and cargo transfer bags. Crew quarters provide a private space for sleep and relaxation. Dehydrated foods and beverages constitute the bulk of crew member dietary intake, supplemented with fresh foods made available from periodic resupply missions. Limited refrigerated and frozen storage is available for foods that are not shelf-stabilized. Laundering of clothing and linens is limited and rudimentary, involving substantial manual effort by crew members. Clothing and linen items contribute substantially to airborne particulate loads that require crew to periodically clean cabin air filters. Cargo transfer bags and packaging materials provide little to no functionality beyond their initial usage for protecting equipment, and are not conducive to efficient inventory management.

Habitation objectives include maximizing mass and volume efficiency by developing multi-functional capabilities. For example, volumes dedicated to crew quarters could serve the additional purpose of enabling crew hygiene with the development of liners that protect crew-quarters equipment and prevent the uncontrolled escape of liquid water into other habitable areas. Lightweight, multi-functional cargo transfer bags and packing materials that can be re-purposed for other functions once stored contents are removed could reduce the launch mass of logistics vehicles, as well as internal stowage volumes. Other habitation objectives include reducing ambient noise levels in the cabin by developing quiet fans and adaptive, intelligent noise control systems to enhance crew comfort and well-being. Lint-free, extended-wear clothing, linens, and surface wipes that can be repeatedly laundered by means that are compatible with other onboard life support systems can enhance long-duration missions by reducing launch mass dedicated to clothing, personal hygiene, and general housekeeping, particularly on long-duration missions. Long-duration missions will require that the nutritional stability of food be maintained for periods of up to five years without refrigeration. The ability to efficiently grow fresh vegetables may be required to fully address nutritional needs.

Benefits of Technology

Multi-functional materials and devices can reduce the mass and volume of equipment and supplies that need to be launched from Earth, and may also be re-purposed to meet needs that might not have been anticipated in mission planning. The internal habitable volume of spacecraft and habitats will likely be at a premium. As such, the innovative, multi-functional use of materials, equipment, and spaces can maximize the level of functionality achievable within very confined habitable volumes. Spacecraft cabins have historically been noisy environments, with acoustic emissions from fans, pumps, and air flowing through ducts and diffusers impacting crew communication and comfort. These emissions are partially attenuated now by bulky insulation and mufflers. Quiet components, such as fans, would reduce emissions at the source, reducing the need to add mass and volume for attenuating materials. Active, intelligent noise-cancellation technologies could also attenuate the acoustics effect on crew members, particularly as emissions change over time when equipment ages or as crew operations change.

Understanding the kinetics of vitamin loss that occurs during food processing and storage and the nutritional content that remains over extended periods of storage will provide the tools necessary to optimize the processing, packaging, and storage of food items needed for multi-year missions. Reliable and efficient food production systems in which fresh vegetables are grown in-situ within a deep-space habitat can provide a nutritionally important supplement to stored foods while also providing a psychological benefit to crew members. Food crops may also provide benefits for carbon dioxide removal, oxygen production, and water purification. Multi-functional lighting systems that provide efficient ambient illumination, aid circadian management, and sustain plant growth may provide multiple benefits.

Table 6. TA 6.1.4 Technology Candidates – not in priority order

TA	Technology Name	Description
6.1.4.1	Free-Water Shower for Full Body Cleansing	Private enclosure with water system for full-body cleansing. Limits or prevents water escapes and collects wastewater for ECLSS reclamation. Provides ventilation and lighting.
6.1.4.2	Multi-Purpose Cargo Transfer Bag (MCTB)	Reconfigurable logistics stowage bag that unfolds into a flat sheet used for outfitting crew structures. Reduces stowage volume for empty bags.
6.1.4.3	Adaptive Intelligent Noise Control System	Active system to reduce acoustic levels. Detects noise levels and emits anti-noise.
6.1.4.4	Quiet Fans	Lightweight, efficient fans and ducting for ventilation systems in human vehicles or modules. Fans and ducting with reduced and lower acoustic noise levels.
6.1.4.5	Long-Wear Clothing (Advanced Clothing)	Lightweight, antimicrobial clothing for extended wear. Reduces mass, volume, and disposal rate of clothing. Non-cotton-based clothing reduces lint.
6.1.4.6	Laundry Freshening System (Simple Laundry)	Freshening system to extend clothing life. Removes odors from clothing and restores hygienic cleanliness.
6.1.4.7	Lightweight Crew Quarters	Minimal mass crew quarters for sleeping and privacy. Constructed from MCTBs to provide acoustic mitigation and radiation shielding (compacted trash). Integrated active noise cancellation system.
6.1.4.8	Reusable Wet Wipes (Housekeeping Only)	Wet wipes that can be laundered for multiple uses. Includes generating wetting solution for wet wipes.
6.1.4.9	Packaged Food Mass Reduction	Packaged food mass reduction technology development.
6.1.4.10	Vegetable Cleaning and Safety Verification	Cleaning vegetables in-flight such that they are safe for consumption.
6.1.4.11	Stabilized Foods	Development of innovative packaging, innovative processing, and stable nutrient content and acceptability.

TA 6.2: Extravehicular Activity Systems

Spacesuits have been and are expected to be included on every human exploration space mission, as they provide the capability for EVAs outside of a pressurized space vehicle, as well as crew protection for nominal and off-nominal operations or events. Existing suits in operation today are designed for Earth-orbital missions with infrequent and short-duration EVAs in a relatively clean environment. Additionally, a LEA suit provides for crew survivability and occupant protection during contingency and post-landing mission events, and may be used for ascent from and descent to planetary surfaces.

A new generation of suits and technologies is required to support national and Agency goals and projected missions over the next few decades, including the development of technologies to extend EVA capability and to be tested on the ISS beyond 2020. An example is the current Modified Advanced Crew Escape Suit (MACES), which is a derivative of LEA suits utilized for Shuttle. The MACES can be enhanced to support short-duration EVA tasks. Another example is the Z-2 suit, which will provide key advances over the first generation Z-1 suit, the most significant being a hard composite upper torso, to provide long-term durability for planetary EVAs. The critical technology needs are those that enable the proposed future missions, due to the difference in the environments, frequency and duration of EVAs, and remote exploration mission locations. Some identified technologies include those that may significantly impact mission implementation (e.g., decreased mass, enhanced mobility, and dust protection) and those that are critical to human safety and well-being (e.g., in-suit waste management).

MACES is the current LEA suit for the Orion spacecraft

Extravehicular Activity Systems has technologies that crosscut with other areas of TA 6, as well as with other TAs. Within TA 6, the technologies that require maturation to support Portable Life Support System (6.2.2) are also relevant to Air Revitalization (6.1.1), Water Recovery and Management (6.1.2) and Waste Management (6.1.3), albeit on differing level of scale. EVA applications will require additional miniaturization and integration in the suit's form factor. Pressure Garments (6.2.1) will benefit from technology advances in TA 12 Materials, Structure, Mechanical Systems and Manufacturing; similarly, EVA PAS (6.2.3) will benefit from advances in TA 5 Communication, Navigation, and Orbital Debris Tracking and Characterization Systems. Likewise, all of TA 6.2 can benefit from advances made in TA 10 Nanotechnology and several sub-areas of TA 7 Human Exploration Destination Systems.

Sub-Goals

EVA systems are critical to every foreseeable human exploration mission, from in-space microgravity EVAs in LEO to planetary surface exploration. In addition, a LEA suit system is needed to protect the crew during launch, entry, and landing, and for the potential events of cabin contamination or depressurization. The overarching sub-goal is to develop new suit designs and technologies that are enabling to proposed future missions into the solar system, due to the difference in the environments, frequency and duration of EVAs, and remote exploration mission locations versus current suit systems for Earth orbital missions.

Table 7. Summary of Level 6.2 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
6.0 Human Health, Life Support, and Habitation Systems	Goals:	Enable long-duration, deep-space human exploration within permissible space radiation exposure limits, minimal resupply consumables, and increased Earth independence.
Level 2		
6.2 Extravehicular Activity Systems	Sub-Goals:	Enable crew operations outside the vehicle or habitat in all mission environments. Protect the crew during launch, entry, and landing, and for the potential events of cabin contamination or depressurization. Protect the crew during ascent/decent transition for planetary excursions.
Level 3		
6.2.1 Pressure Garment	Objectives:	Enable long-duration, frequent, and efficient suited operations in both space and planetary environs. Accommodate advanced mission operations (e.g., pressurized don or doff).
	Challenges:	Provide donning or doffing suits up to approximately nine pounds per square inch differential (psid) while maintaining other features of pressure suits. Quantified structural suit stresses in different loading conditions. Ability to fit a diverse set of occupants in any or all of the critical dimensions. Ability to incorporate new and innovative technologies for human-centered design, including for prediction and prevention of injuries. Managing in-suit human waste during a depressurized or contaminated vehicle scenario. Meeting planetary protection requirements, as applicable. Enabling modifications to suit material layup and components, such as gloves, helmets, and mobility joints. Providing in-suit hydration and nutrition. Providing micrometeoroid and orbital debris (MMOD) protection.
	Benefits:	Provides the ability for unassisted pressurized don or doff for future space vehicle architectures; the ability to change out components; capability for long-duration performance with durability in both space and planetary environs; significant mass reduction over the current extravehicular mobility unit (EMU) with increased capability (e.g., abrasion resistance, self-healing); capability for frequent EVAs to support mission needs without extensive servicing, maintenance, or need for ground support; improvements in crew comfort, sizing, and fit level; and ease of use.
6.2.2 Portable Life Support System	Objectives:	Reduce or eliminate consumables, improve reliability, increase efficiency to support crew performance and mission needs and constraints, and meet planetary protection requirements.
	Challenges:	Heat rejection to the spectrum of thermal environments of expected exploration-class missions. Meeting planetary protection requirements, as applicable. Developing efficient system and component design(s) that can be effectively packaged with minimal mass. Improving on the CO_2 and H_2O membrane technologies.
	Benefits:	Reduces or eliminates consumables. Significantly reduces suit mass. Enables technologies to meet planetary protection requirements. Significantly increases suit performance and reliability.

Table 7. Summary of Level 6.2 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
6.2.3 Power, Avionics, and Software	Objectives:	Integrate advances in radio and avionics technologies; user-friendly, minimally-invasive crew member information displays; and technologies for in-helmet communications. Increase the specific energy of suit power systems.
	Challenges:	Improved power density for suit battery packages. Development of new technologies or modification of Earth-based systems that can be effectively integrated into a spacesuit. Automated checkouts of suit systems.
	Benefits:	Enables long-duration EVAs with reduction in mass. Improves crew comfort and the reliability of the communications system. Provides crew-health diagnostics, coupled with advanced informatics, speech recognition, voice commanding, computing, and display systems. Offers a wealth of information on crew state, external environment, mission tasks, and other mission-critical information to maximize crew performance and safety.

TA 6.2.1 Pressure Garment

Technical Capability Objectives and Challenges

The pressure garment system (PGS) is the set of components (torso, arms, legs, gloves, and helmet) that a crew member wears and uses for operations external to the space vehicle. The PGS also contains provisions to protect crew members from both nominal and off-nominal conditions during launch, entry, and landing. The current Extravehicular Mobility Unit (EMU) on the ISS has a PGS design and associated components for orbital, short-duration EVAs in a relatively clean environment. The Advanced Crew Escape Suit (ACES) was the LEA suit used for the Space Shuttle, but it was not designed with adequate mobility to support EVA tasks.

Future suits require a PGS that can accommodate new environments such as Mars' and advanced mission operations (pressurized don or doff). Other PGS advancements include advanced and multi-functional suit materials and fabrication techniques; suit configurations and architectures with decreased mass; components with increased capability (e.g., mobility); sizing to accommodate a wide range of crew members; dust-resistance technologies; and increased durability or life.

Advances in the pressure garment for future spacesuits are sought to allow efficient donning or doffing, enable long-duration and high-performance suited operations in both space and planetary environs, provide scaling across a range of anthropometric sizes, and provide crew support, such as safe in-suit waste management and provision of water. The majority of these technological advances and an overall new suit design(s) are needed to support near-term design reference missions (DRMs) (e.g., EM-2, DRM 5) and for testing aboard the ISS in a relevant space environment, including microgravity and radiation. For those technologies identified for test or demonstration on the ISS, the need date for integration into a prototype and operational suit is as early as 2021, but no later than 2023 (prior to the end of operations on the ISS in 2024).

The Z-1 is the state of the art ground test demonstration suit

Numerous technical challenges exist for the PGS. For future missions, one challenge is to provide donning or doffing suits up to approximately 9 pounds per square inch differential (psid) while maintaining other features of pressure suits (low mass, sizing, long-life, mobility, and environmental protection).This capability does not currently exist, as all suits to date have been or are donned or doffed at cabin pressure. Also, to support future suit design and implementation, quantified structural suit stresses in different loading conditions (e.g., satellite capture or picking up a rock) are needed, including the effects of crew. Additionally, future suits must be capable of fitting an occupant per NASA-STD-3001, NASA Space Flight Human-System Standard. As stated in Volume 2, Space Flight Human-System Standard, "each program shall identify or develop an anthropometry, biomechanics, aerobic capacity, and strength data set for the crew member population to be accommodated." While program requirements may vary based on the mission and other pertinent requirements or constraints, the current practice is to design to the fifth to 95th percentile American in any or all of the critical dimensions. Future exploration-class suits should incorporate new and innovative technologies for human-centered design to meet challenges like requiring no more than 10 percent of an individual's strength to articulate the suit. Future missions will also include gravitational environments and mission limitations for overall vehicle or systems mass; for future suits, a significant reduction in mass is needed (i.e., less than 100 pounds total mass).

Managing in-suit waste poses significant challenges to preclude human waste leakage, allow for extended days in suit (vehicle contingency) without causing occupant injury or death, and increase the capacity of the SOA for both liquid and solid content. Advances are required for the PGS material layup for both space and planet environments, and can include material exposure to dust, abrasion, punctures, cuts, hypervelocity impacts (micrometeoroids and secondary ejecta), plasma and shock, general vehicle materials compatibility (such as ammonia), and Mars thermal environment (including seasonal variation), without compromising existing suit mobility. New suit materials should continually be identified, evaluated in coupon-level testing, and integrated into the suit PGS and components. Game-changing advances would include materials that combine two or more of the following functions: power generation, heat rejection, communication, dust protection, injury protection, reduced risk of electrical shock hazards (e.g., due to plasma charging), radiation protection, fire protection, and enhanced crew survivability. Other advances should address limitations in current helmets by providing permanent anti-fogging, being durable (anti-scratch), and providing visor assemblies (to allow change-out when damage does occur). Advancements necessary for an exploration-class glove include mobility of the complete assembly, reduced injury potential during use, reduced system mass, increased thermal operational range, and increased life in the lunar or Martian dirt environment. Also needed for future missions is a long-life, high-use, reusable in-suit drink or nutrition bag. Future suits should also incorporate automatically activated distress and geo-locating systems.

Benefits of Technology

Advancements in suit technologies is enabling to all planned future missions. Specific benefits include the ability to perform unassisted pressurized don or doff for future space vehicle architectures (e.g., suitport - which is discussed in TA 7.3); the ability to change out components; long-duration performance with durability (e.g., in-suit waste management, dust); significant mass reduction over the current EMU with increased capability (e.g., abrasion resistance, self-healing); the ability to perform frequent EVAs to support mission needs without extensive servicing, maintenance, or need for ground support; improvements in crew comfort, sizing, and fit level; and ease of use.

Table 8. TA 6.2.1 Technology Candidates – not in priority order

TA	Technology Name	Description
6.2.1.1	Launch, Entry, and Abort (LEA) Arm Mobility via Soft Disconnect	A soft disconnect, which would allow change-out of components on a LEA suit. Includes modification of an existing LEA suit with soft disconnect at the arm joint and development of a more mobile LEA arm utilizing a soft disconnect.
6.2.1.2	Launch, Entry, and Abort (LEA), In-Suit Waste Containment	In-suit waste management system, which will allow the crew to spend long durations in a pressurized suit (days) without access to a pressurized cabin volume (such as during a contingency Orion depressurization).
6.2.1.3	Pressurized Suit Ingress Systems	Technologies or systems for donning and doffing pressurized suits, such as with a suitport.

Table 8. TA 6.2.1 Technology Candidates – not in priority order - Continued

TA	Technology Name	Description
6.2.1.4	Dust Protectant Mobility Bearings	Develop dust proof seals and/or bearings. Prove long-duration performance after extended exposure to dusty environment.
6.2.1.5	Pressure Garment System (PGS) Materials Layup – Vacuum	PGS material layup that accounts for material exposure to dust, abrasion, punctures, cuts, hypervelocity impacts (micrometeoroids and secondary ejecta), plasma and shock, and general vehicle materials compatibility (such as ammonia) without compromising existing suit mobility. Layup may include developing self-healing materials.
6.2.1.6	Mars Pressure Garment System (PGS) Layup	PGS material layup accounting for material exposure to dust, abrasion, punctures, cuts, hypervelocity impacts (micrometeoroids and secondary ejecta), plasma and shock, general vehicle materials compatibility (such as ammonia), and Mars thermal environment (including seasonal variation) without compromising existing suit mobility. Develop and evaluate flexible aerogel materials to increase durability of the material when used as a thermal insulator within the suit.
6.2.1.7	Pressure Garment System (PGS) for 5th to 95th Percentile American	A suit capable of fitting an occupant who is the 5th to 95th percentile American in any or all of the critical dimensions. Understand the system implications and break-over points for designing a pressure garment system, which can be utilized by occupants with 5th to 95th percentile American dimensions in any or all of the identified critical dimensions.
6.2.1.8	Advanced Helmet Systems	Advanced helmet technologies to be developed include permanent anti-fogging, more durable (anti-scratch) helmet approaches, and Orbital Replacement Unit (ORU) visor assemblies (to allow changeout when damage does occur).
6.2.1.9	High-Performance Extravehicular Activity (EVA) Gloves	Advancements necessary for an exploration-class glove for use on the pressure garment. Areas requiring improvement include: mobility of the complete assembly, reducing injury potential during use, reducing system mass, increasing thermal operational range, and increasing durability for longer life in the lunar or Martian dust environment.
6.2.1.10	Reusable Drink/Nutrition Bag	Long-life, high-use, and reusable in-suit drink or nutrition bag.
6.2.1.11	Launch, Entry, and Abort (LEA) Occupant Protection Materials, Analytical Tools, and Technologies	Products, materials, and analytical tools leading to enhanced occupant protection in the capsule landing loads environment.

TA 6.2.2 Portable Life Support System

Technical Capability Objectives and Challenges

The PLSS is used with EVA suits to perform functions required to keep a crew member alive during an excursion from the space vehicle. The functions include maintaining thermal control of the crew member, providing a pressurized oxygen environment, and removing products of metabolic output, such as carbon dioxide, water, trace contaminants, and heat.

Advancements in the PLSS are necessary to enable future missions, such as to planetary environments. An example is the sublimator currently utilized as a part of the ISS EMU to reject heat (metabolic heat plus system-generated heat); it sublimates water and the vapor is released into space. Sublimation is a physical mechanism requiring a hard vacuum environment, and thus cannot be used for Mars surface missions. Another example is the current ISS EMU, which uses either a lithium hydroxide (LiOH) or silver oxide (MetOx) single-sorbent bed to absorb CO_2 during an EVA. The LiOH is relatively light but not reusable and therefore has a significant logistical and system mass impact for longer missions. The MetOx is regenerable between EVAs but has a mass greater than 18 kilograms (kg) when scaled for surface exploration metabolic loading, and also requires significant power and vehicle space for the hardware used for regeneration. For Mars missions, the PLSS design will be pursued as closed-loop to function in the Mars atmosphere and be compliant with planetary protection guidelines and policy.

EVA suit with PLSS

The PLSS is a prime candidate for infusion of new technologies to significantly reduce or eliminate consumables, improve reliability, and increase crew performance. Significant (order of magnitude) increase in heat rejection performance and provision for closed-loop operations (no venting to environment) are some key advances that would enable future missions. For most technological advances and for an overall new suit design, the objective is to test aboard the ISS in a relevant space environment. This drives a need date for the technologies integrated into a prototype suit no later than 2023, to allow testing prior to the end of the ISS program in 2024.

Technical challenges for the PLSS include the development of hardware that can reject heat in a Martian atmosphere while fitting within a small enough mass and volume box to be carried by an astronaut. Radiator approaches seem to hold the most promise, but a radiator must allow adjustment of the heat removal rate, without penalty against other parameters compared to the SOA. The radiator would also need to be dust tolerant (degradation of emissivity) and impact tolerant (for example, falling or hitting a rock). In addition, developing closed-loop CO_2 removal is necessary if stringent planetary protection requirements are implemented. Current technology requires a separate large oven, which would have a large impact on pressurized mobile assets. For in-suit atmospheric constituent sensors, three different technology approaches exist at this time, each with their own challenges: Nondispersive Infrared (NDIR), phase-resolved luminescence, and wavelength modulation spectroscopy. Two of them are sensitive to liquid water and the other is at a low Technology Readiness Level (TRL). Suits will also need accurate pressure sensors, and the increased accuracy can be obtained from precision-matched resistors and active compensation circuits. However, this approach draws more power, increases the size, and makes the sensor more susceptible to radiation effects. Using an alternate sorbent is highly desirable for suit life support, but obtaining a sorbent that has the affinity to adsorb compounds at trace levels without adding considerable energy release, and then releasing those compounds with a relatively minor pressure swing to vacuum is a challenge. Another example sorbent technology is the amine swingbed, which can meet many of the functional requirements but also releases ammonia (NH_3) into the ventilation loop and concentrates it during storage periods.

Another suit challenge is to improve on the CO_2 and H_2O membrane technologies, but early versions require heating to high temperatures, which in an EVA application would be prohibitive from a power perspective and would increase the flammability risk from an oxygen compatibility perspective. Optimizing PLSS components, such as the fan, is also sought. Current centrifugal blower designs achieve high aero efficiency but with very tight tolerances (< 0.003 inch (in.)) and high shaft speeds (over 20 thousand revolutions per minute (krpm+)). Advanced technology would seek to open the tolerances and increase the head-rise, while lowering the shaft speed and keeping the volume approximately the same as the current technology.

Benefits of Technology

A benefit of advancing suit technologies is that advanced regenerable technologies for removing moisture and CO_2 from the suit lead to reduced consumables and mass. In addition, the ability to capture CO_2 and moisture from the suit and deliver them back to the vehicle without incurring significant mass, volume, or power penalties would help close the loop for water and oxygen on a mission level. Non-venting heat rejection technologies would lead to significant reduction in mission consumables as well. Compact, low-mass, reliable, and efficient technologies and advanced suit components need to be developed to enable heat rejection to the spectrum of thermal environments and ensure crew performance for the expected exploration missions.

Table 9. TA 6.2.2 Technology Candidates – not in priority order

TA	Technology Name	Description
6.2.2.1	Closed-Loop Heat Rejection System with Zero Consumables; Spacesuit Water Membrane Evaporator (SWME)-Radiator Hybrid	Heat rejection components are used to reject metabolic heat from the suit occupant and internal components.
6.2.2.2	Closed-Loop Heat Rejection System with Zero Consumables; Heat Pump Radiator Hybrid	Heat-rejection components are used to reject metabolic heat from the suit occupant and internal components. Goal is to develop hardware that can be utilized to reject heat in a Martian atmosphere, does not vent, works with potable water, and is appropriate volume and mass to package into a PLSS.
6.2.2.3	Closed-Loop Heat Rejection System with Zero Consumables; Portable LIfe Support System (PLSS) Radiator	Heat-rejection components are used to reject metabolic heat from the suit occupant and internal components. Goal is to develop hardware that can be utilized to reject heat in a Martian atmosphere, does not vent, works with potable water, and is appropriate volume and mass to package into a PLSS.
6.2.2.4	Portable Life Support System (PLSS) Fan	PLSS fan is responsible for circulating the gas in the ventilation loop. Needs to provide adequate head rise to circulate 6 actual cubic feet per minute (ACFM) through the Advanced Extravehicular Mobility Unit (AEMU) ventilation loop.
6.2.2.5	Portable Life Support System (PLSS) Pressure Sensor	Pressure sensor that is a small form factor, high reliability, radiation hardened, and consumes little power.
6.2.2.6	Closed-loop On-Back Regenerable Carbon Dioxide (CO_2) and Humidity Control	Concepts for CO_2 and H_2O removal system that is compatible with the development of PLSS architectures. Need an on-back, regenerable solution, which requires significant vehicle power.
6.2.2.7	Closed-Loop Consumable Carbon Dioxide (CO_2) Removal, Low Mass	Concepts for CO_2 and H_2O removal system that is compatible with the development of PLSS architectures. Need a lightweight, non-regenerable CO_2 and H_2O removal system that is compatible with in-development PLSS architectures.
6.2.2.8	Alternate Carbon Dioxide (CO_2) Sorbent	Alternate CO_2 sorbent systems used within the rapid cycle amine (RCA). Alternate chemistries may provide a greater capacity and efficiency in removing CO_2 and provide a lower preference for removing water and therefore result in less loop drying.
6.2.2.9	Atmospheric Constituent Sensor	Modular sensor that is sized appropriately for inclusion in a PLSS, not susceptible to humidity, has accurate readings in 3 psia to 23 psia range, and has low time between each sample collection and its associated reporting. Sensor should be a common sensor and avionics package to be used by EVA, ECLSS, and others; that is, capable of sensing a variety of gas constituents (e.g., ammonia, CO_2, water vapor, and O_2).
6.2.2.10	Alternate Contaminant Control Cartridge (CCC) Sorbent	Alternate sorbent for CCC function.
6.2.2.11	Carbon Dioxide (CO_2) and Water (H_2O) Membrane	Membrane-based systems to remove CO_2 and water vapor from the vent loop without requiring moving parts.

TA 6.2.3 Power, Avionics, and Software

Technical Capability Objectives and Challenges

The PAS system is responsible for supplying and distributing power to the overall EVA system, collecting and transferring several types of data both to and from other mission assets, providing avionics hardware to perform numerous data display and in-suit processing functions, and furnishing information systems to supply data that enables crew members to perform their tasks with autonomy and efficiency. Current space suits are equipped with radio transmitters and receivers so that spacewalking astronauts can talk with ground controllers and other astronauts. The astronauts wear headsets with microphones and earphones. The transmitters and receivers are located in the backpacks worn by the astronauts and operate only in the ultra-high frequency (UHF) band.

Advances in PAS technologies can dramatically increase capabilities over the SOA. Examples include advances in radio and avionics technologies, such as antennas, tunable radiofrequency (RF) front-ends, and power amplifiers; low-power cameras; user-friendly, minimally-invasive crew member information displays; and technologies that provide improvements in speech quality, auditory quality, and listening effort for in-helmet vocal communications. Another advancement would be a radio with networking capabilities and data rates that support the transmission of high-definition (HD) video. Integrating components like speakers and microphones into the suit will improve crew comfort and the reliability of the communications system. Also, dramatic increases in the specific energy of future suit power systems are needed. Similar to the PLSS, these advances should be tested aboard the ISS in a relevant space environment, especially for radiation-hardened components. For those technologies identified for test or demonstration on the ISS, a need date for integration into a prototype and operational suit is as early as 2021, but no later than 2023 (prior to the end of operations on the ISS in 2024).

Also needed are technologies for space field geology, which has not been conducted since the Apollo missions. An example would be where the EVA informatics system would record suited-crew position relative to a known point (such as a rover); record audio (such as spoken field notes), record HD video from a camera to mark the position of the geological sample, and provide real-time access to the astronaut to review findings while still conducting the EVA. Only analog space missions are currently active in this field and are limited to standard Earth-based techniques (e.g., manual logging and photography), which cannot support future missions. Advanced EVA informatics (to include field geology) and other advanced suit PAS should be in place by 2027 to be viable for implementation on planetary exploration missions.

For PAS, key hardware constraints include mass, power, volume, and performance of existing radiation-hardened electronics. The primary challenge for suit battery packages is improved power density (100 percent increase). Lithium ion cells do not have adequate power density to meet the needs of future portable life support systems. One primary focus for radio systems is improving the interface between the crew member, the acoustic pickup (microphones), and communications and generation (speaker) systems.

Benefits of Technology

For suit radio and audio systems, integrating speakers and microphones into the suit will improve crew comfort as well as the reliability of the communications system. Information systems and displays have tremendous possibilities for improving crew autonomy and efficiency and advancing the SOA. An integrated sensor suite that includes crew-health diagnostics, coupled with advanced informatics, speech recognition, voice commanding, computing, and display systems, can offer a wealth of information on crew state, external environment, mission tasks, and other mission-critical information to maximize crew performance and safety. Advanced batteries can support long-duration EVAs with minimal servicing or maintenance.

Table 10. TA 6.2.3 Technology Candidates – not in priority order

TA	Technology Name	Description
6.2.3.1	Battery Package	A new battery chemistry with a form factor that is usable in an Advanced Extravehicular Mobility Unit (AEMU) portable life support system (PLSS) battery volume and other AEMU systems. Includes vehicle support hardware, such as battery rechargers, as required.
6.2.3.2	Extravehicular Activity (EVA) Informatics	EVA informatics system (to include field geology) that accurately records the position of the AEMU relative to a known point such as a rover; records audio from the AEMU (such as spoken field notes); records HD video from a camera; and provides real time access to the astronaut to review findings while still EVA and for situational awareness.
6.2.3.3	Integrated Radio/Audio System	Radiation-hardened, integrated radio and audio system that is small enough to package into a PLSS and can operate simultaneously on ultra-high frequency (UHF) and second frequency with high data throughput, and that does not use a communications cap or other head-worn equipment. The system should be tolerant of noise internal to the suit and a wide pressure regime. Communications data transfer and networking, such as via the Deep Space Network and associated accessibility, are addressed in the roadmap for TA 5 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems.
6.2.3.4	Autonomous Checkout	An autonomous suit checkout system to confirm readiness of the EVA suit system to perform an EVA. Checkout system will operate with minimal crew time investment and screen the EVA system for relevant failure modes. Development needs to be integrated with EVA suit and PLSS development efforts.
6.2.3.5	Suit-Integrated Personal Locating Technologies	System that automatically (without crew intervention) provides search and rescue assets in the event of contingency cabin egress.

TA 6.3: Human Health and Performance

Astronauts are selected, in part, for their ability to live and perform in a challenging environment. Equally important to the crew's physical health is their behavioral health and their ability to function effectively throughout the mission and upon their return to Earth. Advanced "omics" technologies, which screen astronaut candidates to ascertain their susceptibility to various effects of space missions, could be used to recruit the astronaut corps. Sophisticated methodologies could be used to select a team for a particular mission. Additionally, personalized prescriptions (pharmaceutical, exercise, sensorimotor, psychological, etc.) could be developed and implemented during the mission.

The physical and mental health of crew members should be optimal to maximize performance throughout the mission. Based on the personalized rehabilitation regimens, long-term physical and mental health of the crew members can be achieved. If environmental conditions can compromise the physical and mental health of the crew, the performance of the crew will be suboptimal. This requires the design and maintenance of operational environments and scenarios that support appropriate life and work behaviors (e.g., restful sleep, reasonable stress and workload levels), as well as a safe and efficient environment (i.e., human-centered tools and automation; adequate space for privacy and crew cooperation). Additionally, it is important to understand human health and performance in the exploration atmosphere (8.2 psi/34 percent oxygen, microgravity, elevated carbon dioxide), since the effects of the exploration atmosphere could drive countermeasure procedures, protocols, and technologies.

Human-centered design of onboard systems with effective interfaces and information architectures is critical for mission success. Appropriate allocation of tasks, coupled with proper integration of humans with automation and robotics, will minimize errors and maximize efficiency. Training technologies that support initial, recurrent, and just-in-time instruction will ensure that crew members can apply the proper knowledge and skills to both nominal and off-nominal situations. These technologies will prove increasingly critical as mission durations and distances from Earth increase, since the crews will be required to function without timely support from Earth.

Technologies for Human Health and Performance (TA 6.3) crosscut with other areas in TA 6, as well as with other TAs. Within TA 6, the technologies that require maturation to support Medical Diagnosis and Prognosis (6.3.1) and Long-Duration Health (6.3.2) are also relevant to Radiation Monitoring Technology (6.5.5) and Risk Assessment Modeling (6.5.1). Tools for monitoring cognitive state, as well as training technologies developed for behavioral health (6.3.3) can be leveraged to support long-duration mission needs for human factors (6.3.4). Human Factors (6.3.4) will also benefit from and contribute to advances within TA 4 Robotics and Autonomous Systems, especially with regards to ensuring effective teaming of humans with automation and robots.

Sub-Goals

Future human spaceflight exploration objectives will present significant new challenges to crew health, including hazards created by traversing the terrain of planetary surfaces during exploration and the physiological effects of variable-gravity environments. The limited communications with ground-based personnel for diagnosis and consultation of medical events will create additional challenges. Providing healthcare capabilities for exploration missions will require definition of new medical requirements and development of technologies. These capabilities will help to ensure exploration crew health and mission safety and success before, during, and after flight.

Table 11. Summary of Level 6.3 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
6.0 Human Health, Life Support, and Habitation Systems	Goals:	Enable long-duration, deep-space human exploration within permissible space radiation exposure limits, minimal resupply consumables, and increased Earth independence.
Level 2		
6.3 Human Health and Performance	Sub-Goals:	Maintain the health of the crew and support optimal and sustained performance throughout the duration of a mission.
Level 3		
6.3.1 Medical Diagnosis and Prognosis	Objectives:	Develop medical hardware that can operate in microgravity and that has reduced resource and logistics needs. Develop screening technologies to personalize in-flight medical planning and care.
	Challenges:	Effective countermeasure to minimize vision impairment during space missions. More medical hardware and increased crew training for long-duration missions.
	Benefits:	A number of proposed technologies can be transitioned to commercial medical practices: enriched oxygen generator, generation of medical-grade water, other miniaturized imaging technologies, and biosample analytical methodologies could be used in home health care and remote conditions, namely, rural, battlefield, and wilderness medicine.
6.3.2 Long-Duration Health	Objectives:	Provide countermeasures to maintain crew physical health, behavioral health, and sustained performance on extended-duration missions.
	Challenges:	Providing a system that combines both resistive and cardiovascular exercise. Providing vibration isolation and stabilization systems. Developing monitoring capabilities that can be used for long-term missions. Ensuring the stability of pharmaceuticals, and improving the shelf life of consumables used for biosample analysis. Providing crew members with a multi-spectral, controllable suite that enables quality sleep.
	Benefits:	Provides specialized exercise hardware and safe exercise prescriptions with equivalent or improved benefits that reduce the time dedicated to daily physical exercise.
6.3.3 Behavioral Health	Objectives:	Identify, characterize, and prevent or reduce risks associated with space travel, exploration, and return to terrestrial life on astronauts' behavioral health and performance.
	Challenges:	Approaches that are feasible in spaceflight, have high user acceptability, are individualized (where applicable), and provide real-time feedback to crew members.
	Benefits:	Identifies individual, team, and environmental factors that increase the likelihood and consequence of adverse outcomes, and increases the efficacy of prevention and treatment in missions to come. Provides the ability to detect when countermeasures in the exploration context may be needed. Provides preventive mitigations, including virtual worlds for sensory stimulation and connection to family and friends back home; just-in-time training to facilitate team coordination and performance skills throughout the mission; and dynamic lighting systems to support a day-night cycle for optimal physiological and psychological health.
6.3.4 Human Factors	Objectives:	Integrate human factors principles into the environmental and architectural design of hardware, software, vehicles, and habitats.
	Challenges:	Technologies must be designed to elicit appropriate inputs from the operator. Clearly defined roles and responsibilities for accomplishing tasks to not exist. Robust training technologies, pre and in-flight.
	Benefits:	Preserves the safety of the crew, promotes human performance, and increases efficiency during all phases of the mission.

TA 6.3.1 Medical Diagnosis/Prognosis

Technical Capability Objectives and Challenges

NASA has generated a stochastic, statistical, predictive health risk model to identify medical conditions for each exploration DRM that have a high likelihood of occurring and high crew health consequences. Efforts have been made to develop and select technologies to screen, diagnose, and treat these medical conditions, as well as provide efficient infrastructure support for a particular level of care. In large part, NASA relies on commercial medical hardware and practices to screen, diagnose, and treat medical conditions. However, these technologies are often incompatible with microgravity, primarily because they depend on gravity in order to operate, resulting in altered performance in space. Additionally, resource constraints (mass, volume, and power; limited resupply; lack of refrigeration and limited training time) and logistical concerns often complicate and constrain the efficient use of devices in microgravity. Optical Coherence Tomography (OCT), Fundoscope, ultrasound, and Tonometer are currently available onboard the ISS to measure the eye structure and function of crew members in a microgravity environment. The vision impairment noted during space missions is potentially due to elevation of Intracranial Pressure (ICP), sodium ion intake through food, and higher carbon dioxide levels in the habitable environment. Developing an effective countermeasure to minimize this vision impairment during space mission is one of the challenges of this TA. The current ultrasound imaging platform on the ISS will be enhanced with additional infrared and other fluorescence-based image modalities.

For long-term missions, the approach to address microgravity-induced physiological challenges and isolation-induced performance issues will be radically different compared to LEO missions. Astronaut corps selection, followed by selection of the team for long-term missions, could be addressed based on personalized medicine principles. Vision impairment, along with susceptibility to radiation-induced issues, will be addressed at the molecular and cellular levels compared to the current treatment mode. Behavioral changes during the long-term mission will be monitored continuously and an appropriate treatment plan will be in place. The human-centered design of the vehicle, coupled with sophisticated just-in-time training and appropriate environmental conditions, will enhance the performance of the human during these missions. LEO missions have a viable evacuation strategy that can provide definitive medical care within hours. Exploration DRMs, however, do not have near-real-time communications or an evacuation capability. In exploration missions, we need to fly more medical hardware and increase crew training so that they may operate independently for longer periods of time.

An astronaut onboard the ISS checks her vision using an innovative medical diagnostic device

Benefits of Technology

A number of proposed technologies align with today's Medical Prognosis Team items and can be transitioned to medical practice once they have been fully validated. Screening technologies that are designed to recruit, train, and rehabilitate crew members could be used for many challenging mission assignments. Enriched oxygen generators, generation of medical-grade water, miniaturized imaging technologies, and biosample analytical methodologies could be used in home healthcare and remote conditions, such as rural, battlefield, and wilderness medicine. Inherent features of NASA technology—miniaturization, ease of use, reusability, and autonomy—are well-suited for the abovementioned terrestrial conditions.

In addition to analysis of biological samples, in-flight imaging is another method to monitor crew health and provide real-time diagnostic data for researchers and flight surgeons. Technologies that need a minimum amount of biological samples should also be developed. Non-invasive enabling technology is required to guide studies aimed at accurately assessing bone structure, muscle mass, cardiovascular function, and vision changes, as well as diagnosing musculoskeletal and soft tissue injuries or other medical conditions. Currently on the ISS, Office of the Chief Technologist, Tonometer, and ultrasound are available, along with Fundoscope to assess and treat vision impairment. These devices are onboard the ISS to measure ocular structure and function (e.g., intraocular pressure, fundus imaging, optic nerve sheath and ocular morphology imaging), along with AcuityPro software to measure visual acuity. A two-dimensional (2D) ultrasound unit is also onboard the ISS to assess crew health. Non-ionizing, full-body, dynamic, three-dimensional (3D) imaging for in-situ physiological monitoring, diagnosis, and treatment should be in place for future missions. Potential technologies include Magnetic Resonance Imaging (MRI), ultrasound, Raman, and near infrared (NIR) to enhance the current capabilities. Miniaturization and integration with other diagnostic or in-flight analysis tools is highly desired.

Minimally invasive diagnostic sensor suites that can be donned or doffed are being developed. While addressing the potential medical conditions that might require spaceflight surgery, development in the area of sterile, closed-loop fluid and ventilations systems for trauma and other surgeries are being explored.

Table 12. TA 6.3.1 Technology Candidates – not in priority order

TA	Technology Name	Description
6.3.1.1	Emerging Screening Technologies; Preventative Countermeasures	Identify pre-flight predisposition screening methods for crew selection process and countermeasures to prevent potential medical conditions that may occur during long-duration missions.
6.3.1.2	Flexible Ultrasound Platform, Novel Ultrasound Probes and Protocols, Near-Infrared Imaging Modalities	An integrated suite of imaging technologies (with diagnostic and therapeutic modalities) that will allow crew members to address medical conditions of concern for exploration missions.
6.3.1.3	Suite of Laboratory Analysis Platforms and Assays	An in-flight lab analysis platform for exploration missions must include the ability to measure hematologic and basic metabolic panels, blood gases, cardiac and liver markers, and urine analytes. The platform must also exhibit expanded assay capability; extended shelf-life of consumables (e.g. reagents, cartridges); minimize mass, volume, power, and consumables; and provide sample containment.
6.3.1.4	Stethoscope	The next-generation stethoscope will enable medical and non-medical personnel to listen to internal auscultation sounds that are generated by the body in a noisy environment.
6.3.1.5	Sterile Fluid Generation Device	The intravenous (IV) fluid delivery system will enable the generation of sterile fluid from an exploration vehicle's existing potable water supply.
6.3.1.6	Radiofrequency Identification (RFID)-Based Medical Inventory Tracking Hardware and Software	A medical inventory capability, such as the Medical Consumable Tracking (MCT) system, will use RFID technology to electronically track consumable contents within a medical kit.
6.3.1.7	Suite of Medication Packaging Options	The medication packaging materials and design will preserve stability and shelf life during long-duration exploration missions with limited re-supply capability.
6.3.1.8	Medical Equipment Sterilization	The system will enable sterilization of medical equipment that is to be used more than once on an exploration mission.
6.3.1.9	Integrated Medical Equipment and Software Suite	Development of a data architecture to efficiently manage crew health and human performance data generated in support of an exploration mission will fill this gap. The ideal architecture will enable plug-and-play connectivity, automate routine data management tasks, and allow for future expansion of the system.

TA 6.3.2 Long-Duration Health

Technical Capability Objectives and Challenges

Ongoing progress made in the fields of genomics, physiomics, transcriptomics, proteomics, metabolomics, imaging, advanced computing and interfaces, microfluidics, intracellular Nanobots for diagnosis and treatment, materials, and other relevant technologies will significantly enhance our ability to address the medical needs of the human system. Measuring in-flight changes in bone mass and structure over the course of ISS missions is important. Increased understanding of the effects of spaceflight on bone (particularly of hip and spine) will improve the probabilistic assessment of fracture risk during long-term missions. Challenges associated with providing for long-duration health include providing a system that combines both resistive and cardiovascular exercise, providing vibration isolation and stabilization systems, developing monitoring capabilities that can be used for long-term missions, ensuring the stability of pharmaceuticals, and improving the shelf life of consumables used for biosample analysis. Additionally, providing crew members with a multi-spectral, controllable suite that enables quality sleep is also a challenge, but is critical to the long-term health of crew.

The countermeasures that are used consistently to date in the U.S. human space program are fluid loading, compression garment or antigravity suit for orthostatic intolerance, physical exercise to counteract the skeletal muscle atrophy and loss of muscle strength and endurance that is associated with microgravity exposure. Other crosscutting technologies provide significant value to other discipline teams – one example is artificial gravity (AG), which is seen as a potential game-changing technology. Aside from being a promising countermeasure for many body systems, AG development would require a new approach to vehicle design and potentially revolutionize the way we explore space. AG may reduce requirements for other countermeasures and reconditioning after spaceflight. AG alone or in combination with another countermeasure can be used to combat multiple-system deconditioning of bone, muscle, cardiovascular, sensorimotor, and other physiological systems. The biggest challenge for developing and assessing the efficacy of AG is the lack of a baseline or reference mission design and architecture to compare and contrast solutions for implementation (e.g., hyper- vs. hypo-gravity, exposure prescription), along with quantifying the health impacts.

An astronaut onboard the ISS exercises to prevent the physiological effects of long-duration spaceflight

Other needed capabilities include understanding the effects of microgravity and radiation on human systems, as will be ascertained using model systems (Biosentinels) such as cells, 3D tissue, micro-organisms, and small animals. Induced pluripotent stem cells could be used to generate individualized treatments for astronauts on long-duration missions. These model systems should be evaluated using robotic precursor missions with platforms (including altered-gravity capabilities) at the ISS, free-flyer-hosted payloads including micro- and nano-satellites (Edison), and commercial or international collaborative missions like Bions.

Advanced exercise equipment and methods, which also meet mass, volume, and other constraints, are needed to support extended missions beyond LEO to maintain crew fitness levels. Several exercise countermeasures are currently deployed on the ISS: the Combined Operational Load Bearing External Resistive Treadmill (COLBERT), Advanced Resistive Exercise Device (ARED), and cyclic ergometer. Current exercise prescriptions using rack-mounted hardware consume large amounts of space and stowage in the vehicle. In addition, both the treadmill and cycle ergometer require power levels that may not be available in new vehicles. A pharmaceutical countermeasure against spaceflight-induced bone loss is also in place. For future exploration missions, low-power and more reliable, robust equipment; a monitoring capability; and a vibration isolation system (VIS) that can be easily deployed and adjusted to various gravitational environments. Additionally, robust, efficacious, and validated nutritional, radio-protective, and pharmacological countermeasures should be geared towards various physiological systems affected by spaceflight environment.

With the inability for rapid return to Earth, other required technologies including lab-on-a-chip are needed to prevent and address crew injury and physiological changes such as for predicted visual changes, immune compromise and the possibility of decompression sickness. Quality sleep and circadian management will also be essential to crew health. Overall nutrition or consumables and monitoring technologies, such as pharmaceuticals and technology for detection of microbes in water and on surfaces are also essential for ensuring crew health and preventing illness. A primary challenge is that most of the aforementioned technologies do not yet exist, and should be developed and tested in a space environment (e.g., on the ISS) prior to being employed on a long-duration mission. Monitoring technologies are needed to assess the degree of bone and muscle loss during the mission and customize countermeasures needed for the crew.

In-flight research is essential to understand in “real time” the effects of long-duration spaceflight and develop countermeasures. As exploration missions increase in duration and distance beyond our present experience, it will be necessary to monitor crew health and provide real-time diagnostic data for researchers and flight surgeons. Preservation and return of biological samples for analysis on Earth will become increasingly difficult due to vehicle stowage constraints and refrigeration requirements. Currently, portable clinical blood analyzers with limited analysis capabilities are used, and samples are preserved and returned to Earth for later analysis. Consequently, most results are only available well after flight crews return. In the future, instruments will analyze biological fluids (e.g., blood, urine, saliva, sweat) in-flight and provide real-time feedback on crew health. Assays for complete blood count with white blood cell differential, blood gases, metabolic panel, cardiac panel, liver panel, urinalysis, and biomarkers of stress, fatigue, deoxyribonucleic acid (DNA) damage, bone loss, and numerous other analytes will be assessed. Assays to detect pathogenic bacteria and viruses are also needed.

Benefits of Technology

Developing a benchmark for the requisite level of crew strength and endurance is required to accomplish future long-duration mission objectives. Once this benchmark is developed, specialized exercise hardware and a safe exercise regimen with equivalent or improved benefits that reduce the time dedicated to daily physical exercise could be created.

Early development of countermeasure technologies will be essential to maintain the crew’s health. Critical biomedical technologies include on-orbit bioanalysis, lab-on-a-chip and other diagnostic capabilities, cell and animal models (biosentinels), advanced imaging, and countermeasures like artificial gravity (AG). Integrating individual devices into hand-held, in-flight, reportable units with increased capability and reduced mass, volume, and power is necessary for feasible implementation of these technologies in the smaller vehicles, expected to be used for more advanced missions. These technologies are being developed and validated on the ISS. The lab-on-a-chip technologies developed for assessing real time crew health can be used for bed-side monitoring under terrestrial conditions.

Table 13. TA 6.3.2 Technology Candidates – not in priority order

TA	Technology Name	Description
6.3.2.1	Artificial Gravity	Provide partial or complete artificial gravity living conditions.
6.3.2.2	Cell/Tissue Culture, Animal Models	An automated cell culture and animal model systems. A comprehensive sample analysis system onboard. Nanosatellite platforms to carry out space environment effects on cells, microbes, plants, and microcellular organisms.
6.3.2.3	Induced Pluripotent Stem Cells	Organ regeneration using induced pluripotent stem (IPS) cells for crew.

Table 13. TA 6.3.2 Technology Candidates – not in priority order - Continued

TA	Technology Name	Description
6.3.2.4	Exercise Equipment	Novel exercise countermeasure hardware and protocols (integrated exercise devices, integrated biomechanics and advanced resistive exercise device (ARED), small and compact exercises devices, controlled resistance exercise device, rapid deploy or stow exercise devices).
6.3.2.5	Integrated Prevention and Treatment for Visual Changes and Non-Invasive Intracranial Pressure Measurement	In-flight tool to measure intracranial pressure (ICP) and optimal diagnostic tools to measure ocular structure and function.
6.3.2.6	Water Control Standards for Microbes, Probiotic Delivery, Antimicrobial Medications	Flight microbial detection and effective countermeasures to prevent crew illness due to microbial exposure
6.3.2.7	Integrated Technologies to Monitor Crew Performance During Exercise	Measurement of crew performance during exercise and evaluation of crew fitness levels during a mission. The suite could include heart rate and blood pressure monitoring and electrocardiogram. Heart rate data quality is poor largely due to the strict dependence on physical contact of the sensors and electrodes with the torso and proximity of the transmitter to the receiver, which is also very directional.
6.3.2.8	Vibration Isolation Technologies for Exercise Equipment	New generation VIS technologies to minimize exercise-induced loads and disturbance to microgravity environment and increase the effective life of vehicle's structure while counteracting pitch, yaw, and roll of the exercise system.

TA 6.3.3 Behavioral Health

Technical Capability Objectives and Challenges

NASA currently employs a number of countermeasures to support crew behavioral health and performance during short- to mid-length missions in LEO. As we expand our mission durations and distance from Earth, it will be necessary to expand the capabilities of this support, which currently relies on close proximity to Earth. In particular, countermeasures to ensure astronauts maintain adequate team cohesion, cooperation, and communication are needed, as are means to keep the crew connected to family and friends on Earth. Likewise, measures to ensure crew obtain adequate sleep, rest, and recreation; maintain cognitive function; and balance stress and workload levels are also needed.

Current approaches to prevent behavioral conditions and psychiatric disorders begin during crew selection and continue post-flight. The objective of the behavioral health component of the astronaut selection process is to identify individuals who, at the time of application, have diagnoses that are incompatible with the demands of spaceflight, and then further identify those who are believed to be best suited, psychologically, to be astronauts. Countermeasures are a second line of defense to prevent behavioral conditions and psychiatric disorders from occurring pre-flight, during flight, and post-flight. For example, psychological support services are provided to crew members and their families before, during, and after missions.

Selection, training, and countermeasures will still apply to future missions. However, desired technologies to support the more highly autonomous, highly confined exploration ventures should be feasible in spaceflight, have high user acceptability, be individualized (where applicable), and provide real-time feedback to crew members. The challenge is to be minimally invasive while remaining sensitive to changes over time. An example of needed technology is one that brings together unobtrusive measures of the sleep and wake cycle, associated crew performance, and possible environmental stressors, to provide further context to the behavioral health and performance of the crew.

Missions beyond LEO will pose significant challenges to astronauts' psychological health, due to confined living quarters, delayed communications, no view of Earth, and separation from loved ones, among other factors. Potential deleterious outcomes associated with these risk factors increase as mission duration extends beyond six months; nonetheless, some missions may last up to three years. Additional technologies are needed to identify, characterize, and prevent or reduce risks associated with space travel, exploration, and return to terrestrial life on astronauts' behavioral health and performance. Unobtrusive measures and technologies will provide the ability to detect when countermeasures may be needed. Technologies will yield preventative countermeasures as well, such as virtual worlds for sensory stimulation and connection to family and friends back home; just-in-time training to facilitate team coordination and skills throughout the mission; and dynamic lighting systems to support a day-night cycle for optimal physiological and psychological health.

Benefits of Technology

Currently in spaceflight, multiple methods are employed to prevent an adverse behavioral condition. While systematic data collection is lacking, anecdotal reports indicate that overall, crew member behavioral health and performance is maintained throughout six-month missions to LEO. However, future exploration missions will pose unique stressors and challenges. Identifying individual, team, and environmental factors that increase the likelihood and consequence of adverse outcomes will improve the efficacy of prevention and treatment in missions to come. Known contributors to performance decrements, adverse behavioral conditions, or psychiatric disorders include sleep and circadian disruption, conflict, lack of autonomy, daily personal irritants, workload, fatigue, monotony, cultural and organizational factors, family and interpersonal issues, and environmental factors, such as confined spaces, poor lighting, noise control, and CO_2 levels.

Table 14. TA 6.3.3 Technology Candidates – not in priority order

TA	Technology Name	Description
6.3.3.1	Psychomotor Vigilance Task (PVT)	A tool for objectively measuring fatigue, as well as providing objective evidence of the effects of fatigue and workload of spaceflight crews over the course of long-duration spaceflight.
6.3.3.2	Objective Sleep Measures for Spaceflight Operations	An objective measure of sleep-wake activity (and lighting) while fitting into the spaceflight mission environment.
6.3.3.3	Optimal Use of Light as a Countermeasure	Lighting countermeasure regimes that integrate lighting properties and provide hardware specifications for future vehicles.
6.3.3.4	Medications to Promote Sleep, Alertness, and Circadian Entrainment	Identifies sleep medications and dosages that produce the fewest cognitive effects and adverse reaction in individual astronauts.
6.3.3.5	Scheduling Software	Individualized scheduling tools that predict the effects of sleep-wake cycles, light, and other countermeasures on performance.
6.3.3.6	Countermeasure to Enhance Behavioral Health	Tools to enhance behavioral health, such as software-generated exercise partners, self-help conflict management, and virtual reality technologies.
6.3.3.7	Tool to Predict, Detect, and Assess Decrements in Behavioral Health	Optimal tools to predict, detect, and assess decrements in behavioral state and cognition that could negatively impact performance before, during, and after long-duration spaceflight missions.
6.3.3.8	Cognitive Assessment Tool	Validated measure of cognitive capability.
6.3.3.9	Tools for Treating Behavioral Health Problems During Long-Duration Spaceflight Missions	Tools for treating the individual to remedy behavioral health problems during spaceflight, including the use of behavioral health medications.
6.3.3.10	Tool to Effectively Monitor and Measure Team Health and Performance Fluctuations	Tool to monitor and capture crew member behavior as it occurs and identify potential behavioral, interpersonal, and psychosocial issues.
6.3.3.11	Social Support Countermeasures	Set of social support countermeasures targeting key indications that maintain team function and psychosocial heath.

Table 14. TA 6.3.3 Technology Candidates – not in priority order - Continued

TA	Technology Name	Description
6.3.3.12	Advanced Exercise Software to Enhance Psychological and Physiological Benefits	Improved software that incorporates customized, enjoyable interfaces (including virtual reality augmentation) for the crew while seamlessly integrating prescriptions and hardware performance data and providing physiological feedback for improved health results.

TA 6.3.4 Human Factors

Technical Capability Objectives and Challenges

NASA currently employs interface designs and training methodologies that reflect decades-old technology. Whereas these “tried and true” operations have functioned reliably for LEO missions (e.g., Shuttle and the ISS), this design paradigm will not extend gracefully to next-generation exploration missions. Instead, NASA will require human-systems technologies that afford the crew a higher level of autonomous function, including far better integration with onboard automation. Less ground-based support will also necessitate improved onboard training and decision-support tools, including systems that support recurrent or refresher and just-in-time training for both nominal and off-nominal operational events.

The primary objective of Human Factors is for human space exploration to preserve the safety of the crew, promote human performance, and increase efficiency during all phases of the mission. This objective is achieved by integrating human factors principles into the environmental and architectural design of hardware, software, vehicles, and habitats. In particular, effective on-orbit environmental conditions and architectural design are critical for the health and well-being of crew members, as well as the habitability of vehicles and habitats. Optimized usability in the design of workspaces, equipment, and tools for the remote spaceflight environment is also important.

Many human performance errors that have been experienced in long-duration spaceflight have been directly related to poor system and task design. Poor task design results from a lack of integration and consideration of the human throughout the operational process. The human-system interface and tasks that require human involvement must be designed to elicit appropriate inputs from the operator.

If the roles and responsibilities for accomplishing tasks are not clearly defined, there will be a risk of serious errors of omission or commission. This risk may relate to interactions among multiple crew members, interactions between crew and robotics, and between crew and ground control personnel. Evidence for the risk that is associated with poor task design is related to both human and automated tasks.

Although operator errors are common in all work environments, task errors that occur during human spaceflight missions could have drastic consequences. Errors can be due to inadequate information, which, in turn, may be caused by: a) a lack of situational awareness that can result from poorly-designed interfaces, poorly-designed tasks, or cognitive decrements caused by, for example, fatigue or exposure to toxic environments; b) forgetting, which can result from inadequate training, poorly-designed procedures, or cognitive decrements; c) an inability to access appropriate data and procedures, which can result from poorly-designed interfaces, poorly-designed tasks, or cognitive decrements; and d) a failure of judgment, which can result from incorrectly perceiving or interpreting cues, inappropriately estimating results of decisions, or inadequate data.

Effective performance by the crew is dependent upon advanced user interface concepts, including task-tuned displays and controls, smart habitats and human-robotic interaction, and interactive visualization technologies to increase the capacity, usability, and reliability of information transfer. Human-systems integration (HSI) standards, methods, and tools should be implemented. These include the HSI scorecard (for human factors requirements and processes assessment for human-rating the spacecraft), the Maneuverability Assessment Scale (for real-time data collection), and the System Consistency Scale (for hardware and software design assessment).

Robust training technologies, enabling both pre-flight and in-flight training methods and tools are critical, especially for long-duration missions with communication delays. A long-duration mission habitat and workstation design that encompasses enhanced tools for assessing habitability impact to ensure crew's health and performance and anthropometric consideration for human capabilities is required. It is important to develop improved human-computer and robotic interfaces to ensure safety and productivity.

Benefits of Technology

A successful human spaceflight program depends heavily on the crew's ability to interact effectively, reliably, and safely with their environments. The Human Factors area represents a commitment to developing effective, efficient, usable, adaptable, and evolvable systems to achieve mission success, based on increased understanding of human performance (perception, cognition, action) and human capabilities and constraints in the operational context.

Table 15. TA 6.3.4 Technology Candidates – not in priority order

TA	Technology Name	Description
6.3.4.1	Advanced User Interface Concepts	Universal human-systems interface providing minimal human operator training and intuitive common operation between different systems, and increased capability, usability, and reliability.
6.3.4.2	Physical, Cognitive, and Behavior Augmentation; Tele-Operations, Remote Operations	Crosscutting technologies for physical and cognitive aids; wireless communication in the vehicle. Physical and cognitive aids that extend human capabilities by leveraging vehicle and habitat systems through portable, wearable, and automated interfaces.
6.3.4.3	Human Systems Integration Tools	Human System Integration Scorecard and human factors engineering analysis tools for human factors requirements and process assessment for human rating the spacecraft; Maneuverability Assessment Scale for real-time data collection; System Consistency Scale for use in hardware and software design assessment.
6.3.4.4	Crew Member Training Aids	Onboard training display formats and hardware for decision aiding concepts.
6.3.4.5	Long-Duration Microgravity Workstation and Habitat Tools	Net Habitability Volume (NHV) and Habitability Modeling Tool; Computational Human Modeling as a Habitability Assessment Tool; Automatic Video-based Motion Analysis; Habitability-Human Factors; and Habitability Assessment Tool.
6.3.4.6	Human-Systems Interfaces for Increased Autonomy and New Environments	Physiological computing to affect changes to the human-systems interfaces based on physiological data from the user.
6.3.4.7	Human-Robotic Interfaces for Increased Autonomy	Work allocation tools; model-based simulation design tool and a metrics toolkit that characterizes the safety and efficiency of a human automation interaction.
6.3.4.8	Ergonomics of Crew Hardware Interface	Modeling tool of crew hardware interface with an ergonomics perspective. Ergonomic modeling should consider addressing adequacy of the crew-hardware interface for the entire crew population based on limited human-in-the-loop testing data. Modeling must show accommodation, fit, performance limitations, and risk to injury. It also must be able to provide results on whether the design excludes certain ranges of the crew population. The modeling should be based on sound ergonomic principles.
6.3.4.9	Physical Accommodation	Techniques to ensure crew in EVA suits can safely perform diverse tasks. Proper and adequate accommodation of suited crew in a safe manner is a necessary requirement to ensure new and existing space hardware is designed effectively.

TA 6.4: Environmental Monitoring, Safety, and Emergency Response

A primary requirement for manned spaceflight is the generation and maintenance of a safe environment in the habitable volume of the spacecraft. To meet such a requirement, technology is needed to assess and manage the risks to environmental health during the mission. In manned spaceflight, risks can arise from degradation or loss of active controls, combustion events, leaks from system or payload equipment, and crew activities or actions, such as EVAs, personal hygiene, housekeeping, payload operations, and normal metabolism (for example, the generation of CO_2). As such, these risks not only affect crew health, but they can also affect the ECLSS within the vehicle, which were designed to generate an environment suitable for sustaining human life.

Monitoring data confirms the performance of ECLSS technologies and manages potential crew health risks. Environmental monitoring data is used to manage acute crew health problems associated with contamination events that may result in exposures; to make more informed assessments of crew-reported symptoms and potential links to contaminant exposure and/or cabin environmental observations; and to guide crew actions and successful recovery during off-nominal environmental problems. In addition, monitoring can provide early warning of off-nominal situations where controls degrade or fail, necessary data to assist in correcting failures and determining their root cause, and data on a variety of toxicological compounds and environmental factors that may have specific crew health impacts.

Technologies in the Environmental Monitoring, Safety, and Emergency Response area (6.4) crosscut with other sub-areas in TA 6, as well as with other TAs. Within TA 6, the technologies that require maturation to support EVA Systems (6.2) may contribute to Protective Clothing and Breathing (6.4.3). There may be opportunities for synergistic technology development between Air Revitalization (6.1.1) and the more acute demands of environmental Remediation (6.4.4). Similar synergies may exist between Air Revitalization (6.1.1), Water Recovery and Management (6.1.3), and Sensors: Air, Water, Microbial, and Acoustic (6.4.1). The 6.4.1 area will likely benefit from advances made in TA 10 Nanotechnology, as well.

Sub-Goals

The sub-goals of environmental monitoring, safety, and emergency response are to develop technologies that ensure crew health and safety by protecting against spacecraft hazards, and for effective response should an accident occur. The two major technology sub-goals for environmental monitoring are the monitoring of microorganisms and microbial identification and enumeration and advance water analysis with speciation (inorganic and organic species). Microbial characterization and comprehensive water analysis for the ISS have relied on sample returns and subsequent ground analysis. Despite logistics issues and costs, manned missions within LEO have the option for sample return, whereas long-duration missions well beyond LEO do not. This limit on sample return for missions beyond LEO drives the need for technology that can provide more information in-flight than what current water and microbial monitoring provides.

Increasing the degree of autonomy is also needed. By automating the routine operations and procedures, requirements for crew time can be reduced significantly. Ground commanding of systems is already possible. Systems can also be configured to automatically operate at predefined intervals and perform data analysis. However, further developments in automation to decrease over-reliance on ground support to verify in-flight results using sample returns and ground analysis is required. In-flight validation protocols to ensure proper instrument functionality and data integrity are quite limited with current monitoring hardware. A limited degree of data validation is usually accomplished through redundancy and comparison to ground analyses. (Ground support may be present, albeit in a limited manner, but a great degree of autonomy is required as missions travel farther from LEO.)

The typically physical characteristics imposed by any mission vehicle used beyond LEO apply to all environmental monitoring hardware as well. All hardware must be small in size and volume, have low power requirements, have little to no consumables, and properly sample the environment. Multi-functional hardware can be desirable, but further assessment may be required since the loss of hardware can potentially translate into the loss capabilities.

Table 16. Summary of Level 6.4 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
6.0 Human Health, Life Support, and Habitation Systems	Goals:	Enable long-duration, deep-space human exploration within permissible space radiation exposure limits, minimal resupply consumables, and increased Earth independence.
Level 2		
6.4 Environmental Monitoring, Safety, and Emergency Response	Sub-Goals:	Ensure crew health and safety by protecting against spacecraft hazards and to ensure effective response should an accident occur.
Level 3		
6.4.1 Sensors: Air, Water, Microbial, and Acoustic	Objectives:	Develop sensors capable of monitoring environmental health and accurately determining and controlling the physical, chemical, biological, and acoustic environments of crew living areas and their environmental control systems. Reduce crew time spent monitoring and controlling the spacecraft environment.
	Challenges:	Acoustic risks, such as increases in noise levels due to aging vehicle systems and off-nominal situations.
	Benefits:	Reduces crew time spent monitoring spacecraft environment. Provides physical, chemical, biological, and acoustic monitoring that can reliably provide information germane to the management of the habitable environment needed for human space exploration.
6.4.2 Fire: Detection, Suppression, and Recovery	Objectives:	Ensure crew health and safety by reducing the likelihood of a fire, or, if one occurs, minimizing risk to the crew, mission, and/or system.
	Challenges:	Verifying the flammability limit at length and time scales relevant for spacecraft. Predicting flammability, evaluating material toxicity, and potential toxic or corrosive gas generation in various environments and gravity fields. Advanced fire suppression agents, architectures, and hardware for various types of fires with various spatial configurations in spacecraft under low- and partial-gravity.
	Benefits:	Minimizes false alarms of both particulate and gaseous species detection, as well as distributed sensors. Reduces size and power consumption of both particulate and gaseous species sensors, as well as increased information content and sensor lifetime.
6.4.3 Protective Clothing and Breathing	Objectives:	Provide multi-use and multi-function respirator systems and mask.
	Challenges:	Verify the efficacy of protective articles and respirators for use in another off-nominal event. Human factors issues, such as fit, comfort, and mobility.
	Benefits:	Reduces weight and cost, yet still provides effective protective clothing and breathing capabilities that may be deployed when needed. Provides coveralls and gloves that are resistant to fire, chemicals, and microbes.
6.4.4 Remediation	Objectives:	Provide effective remediation capabilities that can be deployed by the crew as needed, and that have reduced mass and cost over current methods.
	Challenges:	None identified.
	Benefits:	Provides crew the ability to rectify off-nominal events by returning a volume of spacecraft back into habitable space.

TA 6.4.1 Sensors: Air, Water, Microbial, and Acoustic

Technical Capability Objectives and Challenges

Monitoring the habitable environment of manned spacecraft relies primarily on sample return and subsequent ground analysis. Most of the SOA provides simple indications of the state of the environment onboard the vehicle. Many ground-based laboratory technologies are assisted by gravity and as such, is not readily translated into in-flight monitoring. Relatively simple and robust monitoring technology is required to provide crew with information to properly manage the vehicle environment during the mission.

An astronaut works on the Major Constituent Analyzer (MCA) in Node 3 of the ISS

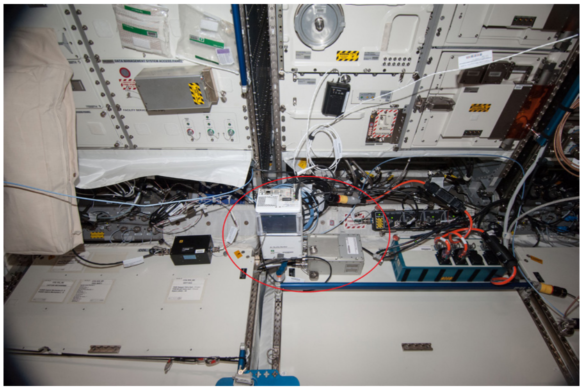
The primary limitation with the SOA is reliance on sample return, ground analysis, and ground support. Hardware onboard the manned vehicle should provide sufficient information for real-time, operational decisions. Other limitations include reliance on resupply of consumables. Contributing to this is limited calibration and battery life of the SOA. The need to reduce crew-time is also a limitation. Tasks as simple as checking calibration, changing batteries, and sampling surfaces with a cotton swab would take a few minutes when performed on the ground, but may take up to an hour in flight. Increasing the reliability of monitoring hardware will address these challenges.

The focus of this area is to provide future spacecraft with advanced sensors capable of monitoring environmental health and accurately determining and controlling the physical, chemical, biological, and acoustic environments of crew living areas and their environmental control systems. Existing technologies will not meet the needs of future exploration for LEO and beyond, for which logistical resupply will be impractical and mission lengths will be far greater, necessitating greater independence from Earth. Crew time spent monitoring and controlling the spacecraft environment must be reduced. Related technologies in physical, chemical, biological, and acoustic monitoring and advanced control must be assembled and be tied synergistically to provide necessary technologies for future human space exploration.

The focus will also be on adapting readily-available technology for reliable, long-term operation in the space environment and on meeting the constraints imposed by the vehicle without sacrificing capability. In some cases, NASA-unique needs will require unique solutions. Challenges in the sensor area may be met by a combination of technologies. Analytical techniques that have been demonstrated aboard the ISS, such as Fourier transform infrared spectrometry (FTIR), differential mobility spectrometry (DMS), and gas chromatography-mass spectrometry (GC-MS) can serve as the basis for environmental monitoring instrumentation. Combinations of these analytical techniques can create a single 'suite' of sensors applicable to atmospheric and water quality monitoring. Properly designed sample preparation and inlet devices can enable monitoring of multiple gas- and liquid-phase targets with the 'suite' of sensors. Additional sample processing stages may enable microbial monitoring as well. Microbial monitors and sensors should be able to distinguish the presence of undesirable microbes against a background of benign, or even essential, organisms. In all cases, needs for manned spaceflight are more constraining than terrestrial needs. This is true not only in terms of

An astronaut installs a total organic carbon analyzer in the U.S. lab of the ISS

mass, volume, and long-term reliability, but also in terms of the operational aspect of the technology, such as ensuring calibration and translating the information provided by these technologies into a suitable form such that crew can manage nominal and off-nominal situations. Extended-duration missions will require mitigation of acoustic risks, such as increases in noise levels due to aging vehicle systems and off-nominal situations, and lack of crew time to adequately monitor and analyze frequency or spatial coverage in order to recognize increased noise levels. Also, crew desensitization to gradual increases in noise may result in exposure to higher-than-acceptable noise levels.



Air quality monitor in the Columbus Module of the ISS

Benefits of Technology

An alerting capability for acoustic monitoring must be provided to combat crew desensitization to gradual increases in cabin noise. The approach to developing environmental monitoring sensors is to leverage the rapidly-advancing communities in microelectronics, biotechnology, and chemical and biological terrorism defense, and the intrinsic drive in the commercial market for the development of smaller, more reliable, and more capable technology.

Table 17. TA 6.4.1 Technology Candidates – not in priority order

TA	Technology Name	Description
6.4.1.1	Cabin Air Sensor	Sensor for continuous monitoring of target trace volatile organic species (VOCs) in the habitable cabin without reliance on ground sample testing.
6.4.1.2	Major Constituents Sensor	Sensor for continuous monitoring of the major constituents (oxygen, nitrogen, water vapor, carbon dioxide, hydrogen, and methane) in the habitable cabin air.
6.4.1.3	Target Gas Sensors	Sensor or system to identify and quantify target gases (carbon dioxide, oxygen, formaldehyde, combustion products, and system chemicals) in the habitable cabin during contingencies and without any reliance on ground return.
6.4.1.4	Airborne Particle Sensor	Sensor to quantify, by size and concentration, the respirable particles in the habitable cabin.
6.4.1.5	Water Quality Sensor	Sensor to identify and quantify target organic and inorganic chemical species in the water of manned spacecraft without any reliance on ground analysis.
6.4.1.6	Biocide Sensor	Sensor to identify and quantify biocide in potable water.
6.4.1.7	Water Total Organic Carbon Sensor	Sensor to measure total organic and total inorganic carbon in the potable water of manned spacecraft.
6.4.1.8	Air Microbial Sensor	Sensor to sample and process the air of the habitable spacecraft cabin to enumerate and identify microbial presence without any reliance on ground analysis.
6.4.1.9	Water Microbial Sensor	Sensor to sample and process the potable water of manned spacecraft to enumerate and identify microbial presence, including coliform bacteria, without reliance on ground analysis.
6.4.1.10	Surface Microbial Sensor	Sensor to sample and process the surfaces of the habitable spacecraft cabin to enumerate and identify microbial presence without any reliance on ground analysis.

TA 6.4.2 Fire: Detection, Suppression, and Recovery

Technical Capability Objectives and Challenges

The SOA in fire detection relies primarily on the obscuration of light by smoke particles. Because of the presence of particulates, this type of fire detection is susceptible to false alarms in a zero-gravity environment. This detection scheme is coupled to a single-use, pressurized fire-suppression bottle to manage fires onboard spacecraft. To help mitigate a fire emergency scenario, information from ground assessments of material flammability in normal gravity at the highest operational oxygen concentration is used in the material selection process during vehicle design.

The SOA for fire suppression is a single-use, pressurized vessel of CO_2 that removes the oxygen leg of the fire triangle. However, when discharged, CO_2 concentrations in the immediate area increase well beyond safe levels for crew, requiring isolation of the area and supplemental CO_2 scrubbing. Moreover, CO_2 is not effective for combustion events involving a fuel source that generates self-sustaining heat due to the lack of natural convection in microgravity necessitating the use of single-use, pressurized water mist extinguishers.

The objective of spacecraft fire safety is to develop technologies that ensure crew health and safety by reducing the likelihood of a fire, or, if one occurs, minimizing risk to the crew, mission, and system. This is accomplished by addressing the flammability of materials in low and partial gravity, fire detection, fire suppression, and post-fire cleanup. Verifying the flammability limit at length and time scales relevant for spacecraft and evaluating material toxicity and potential toxic or corrosive gas generation in various environments and gravity fields will be a challenge. Advanced fire suppression agents and architectures and hardware for various types of fires with various spatial configurations in spacecraft under low- and partial-gravity will be a challenge.

Knowledge of combustion events has greatly benefited from experiments performed onboard the ISS in microgravity, as well as ground-based experiments. These experiments, coupled with material flammability testing, have provided a solid basis not only for managing combustion events on spacecraft, but also in the design of the spacecraft environment. A major objective for fire detection and suppression is gaining a greater understanding of the combustion event in low- or partial-gravity at the different pressures and oxygen concentrations defined by the various missions; for example, a low-pressure environment with high oxygen concentrations. Knowing the behavior of combustion events under these intermediate conditions will help determine the strategies needed to manage potential cabin fires during surface missions.

The major challenge for fire research is predicting flammability in low-pressure and partial-gravity environments, as materials can burn at lower oxygen concentrations than they do in normal gravity. This means that materials that are non-flammable in normal gravity in certain configurations may actually allow a flame to propagate in low or partial gravity in those same configurations. A deeper understanding of flame propagation within this context is needed to properly design and build appropriate fire detection and suppression systems. Development of hybrid fire detection technology that combines gaseous and particulate detection systems will eliminate the potential for false positives that plague current systems. Fire suppressants used in spacecraft should be efficient and nontoxic, and should cause little or no damage to the equipment. They also should be easy to clean up with onboard resources and have the ability to reach any corner of the spacecraft. Technologies should also be multi-use; specifically, fire suppression system must be rechargeable during the mission.

These topics will be even more critical for long-duration exploration missions, since rapid return to Earth is not an option and the ability to safely continue the mission will substantially increase the probability of mission success. This must be accomplished without adding complexity to the fire-response process or increasing required consumables.

Benefits of Technology

Early fire detection improvements to minimize false alarms require both particulate and gaseous species detection, as well as distributed sensors. Reducing the size and power consumption of both particulate and gaseous species sensors, as well as increasing information content and sensor lifetime, is also required for this capability to be realized. These fire detection systems could potentially be combined with sensors to monitor post-fire cleanup, thereby reducing mass and simplifying crew emergency operations.

Table 18. TA 6.4.2 Technology Candidates – not in priority order

TA	Technology Name	Description
6.4.2.1	Combustion Model in Low and Partial Gravity	Tools to model combustion process in low and partial gravity.
6.4.2.2	Cabin Fire: Detection System	System to detect and monitor fire in the habitable cabin of crewed spacecraft with hybrid gaseous and particulate fire detection systems to eliminate false positives.
6.4.2.3	Cabin Fire Extinguisher	System to extinguish a fire in the habitable cabin of manned spacecraft at nominal and elevated oxygen levels in low- and partial-gravity.

TA 6.4.3 Protective Clothing and Breathing

Technical Capability Objectives and Challenges

The SOA in protective clothing and breathing technologies for in-flight, off-nominal events relies heavily on the ability to resupply. Typical protective clothing and breathing technology are single-use only and designed for one type of off-nominal event. Silver-shield gloves protect hands from various liquid and solid chemicals but are designed for single use. Respirators with user-changeable cartridges and oxygen masks protect crew from gaseous chemicals. Protective clothing must be able to provide protection in multiple off-nominal situations that may be encountered during a mission. In addition to this degree of protection, a multi-use capability is required to alleviate the need for resupply.

The objective of this area is to provide crews with sufficient capability to address off-nominal situations within the habitable compartments of spacecraft. Off-nominal events include fire, chemical release, microbial contamination, and unexpected depressurization. Existing technologies will not meet the needs of future exploration, which requires greater independence from Earth because logistical resupply from Earth is not practical. Advancements are needed to reduce weight and cost, yet still provide effective protective clothing and breathing capabilities that can be deployed when needed.

Personal protection technology provides crew with the protection necessary to manage off-nominal situations, such as a fire or a chemical release. Current personal protection technologies are highly specialized for a particular event and are typically single-use only. Given the limited space in spacecraft and the lack of resupply, these characteristics are not compatible with long-duration missions beyond LEO. Multi-use and multi-function personal protection technologies are a major objective. This technology development, as well as the development of remediation technologies, depends upon the development of new materials. Integrating various types of personal protection technologies for multi-use and multi-functions must result in protective clothing and respirators without gaps or loss of protection. Development should be cognizant of human factors so as not to hinder mobility and communication.

Personal protection technology depends on the ability of materials to provide a barrier to hazardous agents and physical stresses. As such, the development of personal protection technology is tied directly to materials development. Materials that are resistant to chemicals, not permeable to liquids, and resistant to tears are required in order to develop the personal protection technology needed for exploration missions. Additionally, human factors issues such as fit, comfort, and mobility should be addressed at the design stage. Multi-use capability, which is dictated by the limitations of resupply during long-duration missions, will necessitate the need to verify the cleanliness and integrity of the personal protection technology. Breathing technology will also depend on materials development. Multi-use capability may drive the development of respirator filters containing multiple type of filtering media. Crew comfort, flow rates, and other human factor issues must be addressed early in the development of breathing technology.

Benefits of Technology

Protective clothing and breathing technologies for in-flight, off-nominal events rely heavily on the ability to resupply. Advancements are needed to reduce weight and cost, yet still provide effective protective clothing and breathing capabilities that can be deployed when needed. Protective gloves need to provide protection in a multitude of situations and still allow crew to perform precision movements. Proper ocular protection will also be required. Protective clothing should provide a great degree of comfort while simultaneously providing the required protection.

Protective clothing and breathing technologies must be effective, regenerable (if applicable), and deployable by crew in various off-nominal situations. Improvements are needed to evolve coveralls and gloves that are resistant to fire, chemicals, and microbes. The difficulty in this effort lies in the ability to verify the efficacy of protective articles and respirators for use in another off-nominal event. Functionality, as well as cleanliness, needs to be assessed immediately after use, and means to ensure the protective clothing can be used in a subsequent off-nominal event must be developed.

Table 19. TA 6.4.3 Technology Candidates – not in priority order

TA	Technology Name	Description
6.4.3.1	Advanced Respirator	Face mask that protects crew of manned spacecraft from chemical and particle exposure and provides breathing capability during contingencies.
6.4.3.2	Advanced Clothing	Clothing that protects crew from chemical exposure and bodily harm during nominal and off-nominal contingencies.

TA 6.4.4 Remediation

Technical Capability Objectives and Challenges

The focus of remediation is to provide crew with the ability to clean the habitable environment of the spacecraft in the event of an off-nominal situation. Off-nominal events include fire, an inadvertent chemical release (toxic leak event), or microbial contamination. The SOA in remediation technologies for in-flight off-nominal events relies heavily on the ability to resupply. Methods to regenerate current materials employ heat to desorb contaminants from the surface, thereby increasing power requirements. Metallocenes and hybrid organic or inorganic catalysts have been shown to immobilize contaminants. Combining this capturing ability with the ability to undergo light-induced conformational changes in the geometry of the catalyst, regenerable remediation technology may be possible with very low power requirements. Although these technologies are at the research level, they represent the type of development required for future missions.

Advancements are needed to reduce weight and cost over current methods, yet still provide effective remediation capabilities that can be deployed when needed. Remediation technologies must be effective, regenerable (if applicable), and deployable by crew in various off-nominal situations. Personal protective equipment suitable for spaceflight and provide multi-use protection from chemical, combustion, and microbial contamination hazards are needed.

Benefits of Technology

Remediation technology will provide crew with the ability to rectify off-nominal events by returning a volume of spacecraft back into habitable space. Remediation technology also provides a level of protection to the nominal functions of a vehicle's ECLS systems by helping remove the burden an off-nominal situation can create. Designed operating margins of safety can be maintained throughout the mission, and design lifetime can be achieved. Remediation techniques may be incorporated into the ECLSS architecture and/or operate independently of the ECLSS to offer operational flexibility and functional factors of safety.

Table 20. TA 6.4.4 Technology Candidates – not in priority order

TA	Technology Name	Description
6.4.4.1	Contingency Air Scrubber	System that reduces the concentration of chemical and particle contaminants in the air of the habitable cabin to acceptable levels following a release.
6.4.4.2	Contingency Microbial Remediation	System to reduce microbial growth on the surfaces of the habitable cabin to acceptable levels.
6.4.4.3	Post-Fire Air Scrubber	System to reduce the concentration of combustion products, particles, and extinguishing material released into the air of the habitable cabin due to a fire, to acceptable levels.

TA 6.5: Radiation

This area focuses on developing knowledge and technologies to understand and quantify radiation health and performance risks, develop mitigation countermeasures, and minimize exposure by forcasting radiation environmental changes and using material shielding systems. Possible other improvements include combining shielding with biological countermeasures to enhance effectiveness and developing higher-fidelity space radiation monitoring capabilities in the form of miniaturized active personal dosimetry. These improvements will help minimize crew radiation risk and support operations for long-duration, human exploration missions beyond LEO.

Exposure to space radiation poses both acute and chronic risks to crew health and safety that have clinically-relevant, lifelong implications. The major risks include radiation carcinogenesis, acute syndromes, acute and late central nervous system (CNS) effects, and degenerative tissue (e.g., cardiac, gastro-intestinal, circulatory) effects. The major technical challenge for future human space exploration is determining the best way to protect humans from the high-charge and high-energy galactic cosmic radiation (GCR) permeating interplanetary space. With our current knowledge base, there is a need to provide mitigation technologies (such as biological countermeasures and shielding) against GCR for missions occurring beyond LEO for more than than about 100 days to remain below PELs for space radiation. Exposure estimates for longer missions, including Mars, are estimated at about three to five times above PELs. This technical challenge is extremely difficult because 1) GCR heavy ions cause damage at the cellular and tissue levels that is substantially different from the damage caused by terrestrial radiation (such as x-rays or gamma rays), as GCR heavy ions have significantly higher ionization density and large associated uncertainties exist in quantifying the associated biological response; and 2) shielding against GCR is much more difficult than shielding against terrestrial radiation, due to severe mass constraints and the ability of GCR to penetrate shielding material (high-charge and high-energy).

Shielding from solar particle events (SPEs) is much easier than shielding from GCR. Protecting humans from SPEs may be a solvable problem in the near-term by maturing identified shielding solutions through design and configuration. However, mission operational planning has a major knowledge gap of forecasting the occurrence and magnitude, as well as all-clear periods, of SPEs.

Primary radiation technologies requiring advancement include radiation risk projection models that use validated ground and flight data, radiation mitigation measures, space weather forecasting, radiation protection, and radiation monitoring. Without accurate risk projection models, the effectiveness of shielding materials for GCR, mitigation measures, and crew selection criteria are poorly defined. The accuracy of risk models must improve as the level of risk increases from the ISS to near-Earth asteroids (NEAs) and Mars in order to develop the technologies necessary to ensure crew safety.

The Radiation area (6.5) has technologies that crosscut with other sub-areas in TA 6, as well as with other TAs. Within TA 6, the predictive models and lifelong monitoring tools that require maturation to support Long-Duration Health (6.3.2) will also benefit radiation Risk Assessment Modeling (6.5.1). Similarly, there will be synergistic technologies between EVA Systems (6.2) and radiation Protection Systems (6.5.3). Radiation Protection Systems (6.5.3) will benefit from technology advances in TA 12 Materials, Structures, Mechanical Systems and Manufacturing; similarly, radiation Risk Assessement Modeling (6.5.1) and radiation Monitoring Technology (6.5.5) may benefit from advances in TA 11 Modeling, Simulation, Information Technology, and Processing. Radiation Monitoring Technology (6.5.5) may also benefit from advances in TA 10 Nanotechnology.

Sub-Goals

Unlike some other aspects of space travel, space radiation exposure has clinically-relevant implications for the lifetime of the crew. It is currently estimated that long-term missions could increase the chance of fatal cancer anywhere from five to 21 percent above the baseline risk. Radiation health and performance risks include carcinogenesis, acute syndromes, acute and late CNS effects, and tissue degeneration. The challenge of ensuring crew safety means that 'risk limits' are sufficiently understood, defined, and not exceeded.

The purpose of the radiation sub-goals is to ensure that the radiation risk to astronauts is reduced to as low as reasonably achieved (ALARA). The focus is on developing technologies to increase crew mission duration in the free-space radiation environment while remaining below the space radiation PELs. Specifically, the five technology development objectives center on reducing uncertainty in assessing the risk of death due to radiation exposure, extending the number of safe days in space using biological countermeasures (BCMs) or shielding, improving the ability to predict the future space weather events and their duration to prepare and protect the crew, and developing small, low-mass, low-power, crew-friendly sensors for monitoring the radiation environment.

It is generally accepted that extending crew mission duration in free space will be accomplished using a combination of shielding, BCMs, improved understanding of risks, and the improved means to predict and monitor the radiation environment.

Table 21. Summary of Level 6.5 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
6.0 Human Health, Life Support, and Habitation Systems	Goals:	Enable long-duration, deep-space human exploration within permissible space radiation exposure limits, minimal resupply consumables, and increased Earth independence.
Level 2		
6.5 Radiation	Sub-Goals:	Increase crew mission duration in the free-space radiation environment while remaining below the space radiation permissible exposure limits.
Level 3		
6.5.1 Risk Assessment Modeling	Objectives:	Reduce uncertainty in assessing the risk of death due to radiation exposure. Improve risk assessments for cancer and include circulatory and central nervous system (CNS) effects.
	Challenges:	Acquiring sufficient ground and flight data on living systems exposed to the relevant space environment. Developing models that accurately predict radiation risks, identifying genetic selection factors, and developing mitigation measures for remaining risk.
	Benefits:	Provides well-understood radiation risk assessment and modeling tools with minimal uncertainty to assess astronaut risk due to space radiation exposure for improved mission operations, mission planning, and system design for LEO, deep-space, lunar, and Mars missions.
6.5.2 Radiation Mitigation and Biological Countermeasures	Objectives:	Develop biological countermeasures that reduce the risk of adverse effects from radiation by 50% of the mission duration.
	Challenges:	One type of BCM will not be sufficient; a suite of BCMs will be needed to address the various health problems expected.
	Benefits:	Provides countermeasures for in-flight acute radiation syndrome, in-flight CNS effects, degenerative effects, and cancer. Provides a pharmaceutical interaction tool to evaluate drug response and interactions individually and in combination with other drugs, and an individual sensitivity toolkit to determine effectiveness and toxicity of biological countermeasures for individual astronauts.

Table 21. Summary of Level 6.5 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
6.5.3 Protection Systems	Objectives:	Provide reasonable (mass and power) shielding for 365 safe days for near-Earth asteroid (NEA) and 1,000 safe days for Mars, in combination with countermeasures.
	Challenges:	Protective shielding cannot completely protect against galactic cosmic radiation (GCR), and shielding options combined with BCMs will be needed for long-duration missions.
	Benefits:	Provides lightweight, cost-effective multifunctional materials and structures that can minimize exposure while providing other functionalities, like thermal insulation and micrometeoroid and orbital debris (MMOD) protection. Provides a cross-discipline, integrated systems approach to vehicle design for radiation protective functions. Provides active shielding components, such as lightweight structures and magnets, improved active cooling systems, and high-temperature superconductor technology.
6.5.4 Space Weather Prediction	Objectives:	Develop real-time monitoring and forecasting space weather models.
	Challenges:	Forecasting the occurrence and magnitude of solar particle events, as well as all-clear periods.
	Benefits:	Provides forecasting models that include an all clear forecasting tool, tool for forecasting intensity and evolution, ensemble coronal mass ejection (CME) forecasting, and a high-performance computing architecture.
6.5.5 Monitoring Technology	Objectives:	Reduce mass and power, extend battery life, and improve data communications of devices.
	Challenges:	Low enough power requirements and be small enough to be distributed throughout and integrated into the spacecraft.
	Benefits:	Improves monitoring technologies for exploration missions.

TA 6.5.1 Risk Assessment Modeling

Technical Capability Objectives and Challenges

Current radiation risk assessment models are used to estimate cancer risk from radiation to crew during operations in LEO. These models do not include synergistic, circulatory, or CNS effects. In addition, they are based on scaling data derived from terrestrial radiation exposures to the spaceflight environment and are not truly representative of the free-space radiation environment. Additionally, current cancer models have 350 percent uncertainty. For missions beyond LEO, modeling tools need to be improved to more accurately and precisely predict lifetime risk of morbidity and mortality, and to appropriately sum risk from different endpoints, such as cancer, CNS, and other degenerative diseases, and degradation of performance.

Major advances are required to reduce uncertainties associated with radiation risk projection models for both NEA and Mars missions so that the impacts of optimized use of shielding designs, mission length, crew selection, and mitigation measures can be quantified. The objective is to improve the models such that uncertainty is reduced to 50 percent for all radiation exposure risk for Mars missions (1,000-day mission), and to 200 percent for near-term NEA missions (365-day mission). A major challenge for radiation will be to acquire sufficient ground analog and flight data on living systems exposed to the relevant space environment, develop models that accurately predict radiation risks, identify genetic factors, and develop mitigation measures for remaining risk.

Benefits of Technology

Radiation risk assessment and modeling tools that are well understood and provide minimal uncertainty are needed to assess astronaut risk due to space radiation exposure. These will improve mission operations, mission planning, and system design for LEO, deep-space, lunar, and Mars missions. Tools currently used to estimate cancer risk from radiation to crew during operations in LEO do not include synergistic effects.

Table 22. TA 6.5.1 Technology Candidates – not in priority order

TA	Technology Name	Description
6.5.1.1	Integrated Mortality Risk Projection Model Tool	Computational tool enabling the accurate prediction of lifetime risk of morbidity and mortality from radiation exposures in combination with other spaceflight stressors (e.g. microgravity). This tool integrates risk from different endpoints: cancer, central nervous system (CNS) effects, and other degenerative conditions, such as circulatory disease.
6.5.1.2	Cancer Risk Projection Model	Improved statistical model for risk of cancer due to radiation exposure.
6.5.1.3	Degenerative Risk Projection Model (Includes Heart and Circulatory)	Statistical model for risk of organ degeneration due to radiation exposure, incorporating circulatory risks.
6.5.1.4	Central Nervous System (CNS) Risk Projection Model	Statistical model for risk to the CNS due to radiation exposure.
6.5.1.5	Performance Degradation Model Set (Acute and Central Nervous System)	Tool that models degradation of performance, ability to complete tasks, and the steps needed to mitigate the degradation.
6.5.1.6	Digital Twin	Tool that combines the Performance Degradation Model and the Mortality Risk Projection model into a predictive tool for determining crew risk of degradation of health, death, and degradation of task performance due to radiation exposure.
6.5.1.7	Transport and Nuclear Physics Modeling Tool(s) for Radiation Exposure (Transport Codes)	Computational tools enabling the accurate prediction of radiation exposures within the human body given a known free-space radiation environment (i.e. tools that account for modifications to the particle environment as radiation transits planetary atmosphere, vehicle materials, and human tissue). Models need to interface with NASA design processes within reasonable timeframes.

TA 6.5.2 Radiation Mitigation and Biological Countermeasures

Technical Capability Objectives and Challenges

New molecular or genetic-based systems biology approaches are needed to achieve the uncertainty levels required for long-duration missions (missions lasting more than about 100 days). Biological countermeasures need to reduce the risk of adverse biological effects due to space radiation without having adverse side effects or causing a loss of life. Significant advances are required to integrate fundamental research on the cellular, molecular, and tissue damage caused by space radiation into modeling major signaling pathways that cause cancer, CNS effects, and degenerative diseases. Once these are understood, BCMs can be developed that minimize or prevent physical, cognitive, and behavior disorders due to space radiation. BCMs also need to protect against radiation-induced oxidative stress; mitigate cancer initiation and promotion; protect against cardiovascular disease and cardiac events; and protect against immune dysfunction and radiation-induced burns and delayed wound healing.

Currently, mitigation strategies for radiation exposure are based on acute exposure to gamma radiation. Several BCMs have been studied to prevent or mitigate the effect of radiation and are approved for use under these conditions. Few treatments have been investigated in a simulated space environment. There are currently no BCMs approved to mitigate or prevent the deleterious effects of space radiation. Some agents have been developed for low linear energy transfer (LET) radiation at high doses. However, the terrestrial agents are based on historical data from terrestrial radiation sources and do not translate well to the space radiation environment.

Computational tools to model pharmaceutical interactions are also needed. This would enable the evaluation of drug response and interactions individually and in combination with other drugs, and provide an individual sensitivity toolkit to determine effectiveness and toxicity of BCMs for individual astronauts.

Benefits of Technology

There have been minimal studies performed to assess BCMs in a simulated space radiation environment, representing an acute exposure or high LET radiation, and no studies have been performed under a simulated low-dose, chronic space radiation environment.

Radiation countermeasures must demonstrate a reduction in the risk of adverse effects due to radiation and a corresponding increased number of safe days for the crew. An objective would be to reduce the risk of adverse effects to less than the three percent Risk of Exposure Induced Death (REID), or increase the days the BCMs can protect the crew for a total mission (transit and stays). The BCMs effects would be combined with other protective measures to minimize the risk of radiation-induced effects to the crew. A challenge is that one type of BCM will not be enough. A suite of BCMs will need to be developed to address the various health problems expected due to the radiation exposure.

Table 23. TA 6.5.2 Technology Candidates – not in priority order

TA	Technology Name	Description
6.5.2.1	Countermeasures for In-Flight Acute Radiation Syndrome	Biological treatments to counter the effects of in-flight acute radiation syndrome. Protect against or mitigate radiation effects on health from hematopoietic and immune failure. Treatments to address prodromal syndrome (nausea, vomiting, fatigue).
6.5.2.2	Countermeasures for In-Flight Central Nervous System (CNS) Effects	Biological treatments to counter the effects of in-flight CNS effects from radiation exposure. Protects against or mitigates radiation effects on behavior and performance (example includes radioprotectants).
6.5.2.3	Countermeasures Against Degenerative Effects	Biological treatments to counter the degenerative effects of in-flight radiation exposure. Protects against or mitigates radiation effects on biological degeneration, such as cardiovascular disease, cardiac events, gastrointestinal, skin, and cataracts.
6.5.2.4	Countermeasures Against Cancer	Biological treatments to counter the effects of cancer resulting from radiation exposure. Protects against or mitigates radiation effects on development of cancer
6.5.2.5	Combined Pharmaceutical Interaction Tool	Experimental models of BCMs for specific space radiation risk will not be generally applicable to other space radiation risks. Need an integrated computational model to evaluate efficacy and benefits across all radiation-induced risks, as well as other identified spaceflight health risks.
6.5.2.6	Individual Sensitivity Toolkit	Reduce uncertainties, and develop optimal individualized BCMs. Enable missions by reducing costs and extending durations. Address individual sensitivity. Toolkit has promise to lower mission costs and enable longer duration missions.

TA 6.5.3 Protection Systems

Technical Capability Objectives and Challenges

The design of integrated radiation protection shielding that extend beyond LEO exploration missions duration by more than 60 days, within the scope of reasonable vehicle design and mass. Limited passive shielding options that consist of rearranging moveable components to create a shield or using additive slabs of polyethylene exist for mitigating radiation exposure during SPEs, but there is no shielding option for long-duration protection from GCR. The types of materials that can provide passive shielding of humans against radiation are well known, but mission designers will need to take a cross-disciplinary, integrated systems approach to develop lightweight, cost-effective, multi-functional solutions. Active radiation shielding is at low TRL. High-fidelity simulations of active radiation shielding systems are needed to determine which of the system components will give the largest improvements in shielding capability. Areas that hold the most promise are advances in lightweight structures and magnets, superconductors, and active cooling systems. It is generally accepted that protective shielding cannot completely protect against GCR. Therefore, shielding options combined with BCMs will be needed to protect humans for long-duration missions.

Shielding from SPEs is much easier than shielding from GCR. Protecting humans from SPEs may be a solvable problem in the near-term by maturing identified shielding solutions through design and configuration. Shielding systems must be developed while considering vehicle design and mass versus the amount of protection achieved.

The objective is to optimize systems to achieve reductions in crew exposure to GCR and SPE for beyond-LEO missions. There are two approaches to determine performance: 1) percent reduction in astronaut exposure for percent increase in mass over SOA vehicle design, and/or 2) number of days for mission for accepted PELs with reasonable increase in mass of SOA vehicle design.

Benefits of Technology

Development of advanced radiation protection systems will allow crew members to stay within the NASA PELs for longer-duration exploration missions beyond LEO while impacting the overall vehicle mass as little as possible.

Table 24. TA 6.5.3 Technology Candidates – not in priority order

TA	Technology Name	Description
6.5.3.1	Radiation Protective Materials and Material Systems for Primary and Secondary Structures	Develop and advance structural performance of high-hydrogen-content materials and material systems to replace traditional materials for primary and secondary spacecraft structure (reference TA 12 material technologies).The goal is to replace mass with better mass for radiation protection that also meets structural requirements. High-hydrogen materials can include polymer matrix composites, where the polymer and/or fibers are high in hydrogen content.
6.5.3.2	In-Situ Passive Shielding from and in the Spacecraft	Develop vehicle equipment and components from radiation-protective materials. Develop shielding technology that utilizes the stowage of hydrogen-rich logistics (potentially food, water sources, supplies, and waste) as multipurpose shielding. Develop multi-purpose containers for bio-material that can utilize human waste without affecting crew (smell, leakage, handling transfer). Other technology development includes developing water walls for crew quarters or vehicle walls for waste, potable water, and drinking water.
6.5.3.3	In-Situ Passive Shielding from Planetary Surface Materials	Develop regolith manipulation; processing of building materials; transforming regolith into shields, structures, and tunnels; additive manufacturing using regolith; characterizing regolith for use in shielding. Regolith can be consolidated by sintering using conventional, solar, microwave, or laser heat sources. Regolith can be combined with polymer-matrix materials to increase hydrogen content. (Reference regolith TA 12 and TA 7 in-situ technologies and material developments)
6.5.3.4	High-Temperature Superconductor Technology and Performance for Active Shielding Systems	Develop technologies for structural components to keep magnet cold and to keep it from flexing. Higher-temperature superconductors and splicing technologies.
6.5.3.5	Lightweight Structural Materials for Magnet Fixtures for Active Shielding Systems	Magnets for active shielding are predicted to be large and massive. In addition structural fixtures are required to react the magnetic forces generated. Develop technology to enable lightweight magnets and magnet structural fixtures.
6.5.3.6	Cooling Systems for Active Shielding	Develop improved active and passive cooling systems (see TA 14).
6.5.3.7	Integrated Design Tool	Integrate multidisciplinary modeling. Includes physics, systems analysis, vehicle design, and biological models. Validated analysis tools for vehicle design. Vehicle design optimization and mission planning. Performance: efficiency and fidelity of model.
6.5.3.8	Uncertainty Models for Thick Shielding	Analysis codes to assess the effect of thick shielding on radiation exposure. Performance: uncertainty reduction.
6.5.3.9	Active Shielding Modeling Tool Set	Combined analysis toolset to analyze and assess active shielding protection. Performance: efficiency and fidelity of model.

TA 6.5.4 Space Weather Prediction

Technical Capability Objectives and Challenges

Mission operators currently function by reacting in real-time to adverse space weather conditions. This limits mission efficiency and could increase the likelihood of damaging vehicle systems and increasing astronaut radiation exposure. Of primary concern for future long-duration missions outside of LEO are Solar Energetic Proton (SEP) events (i.e., the transient increase in energetic protons levels), and large Coronal Mass Ejections (CMEs). There is no current ability to predict the onset, intensity, and evolution of SEPs and CME arrival time.

Although SEP exposure can, in theory, be mitigated by passive shielding, vehicle mass constraints can limit the degree of mitigation for any future long-duration mission. It is thus vital that tools for forecasting occurrence and magnitude be developed for future exploration to alert flight control teams and crews of impending adverse conditions. The objective of these tools would be to provide forecasts on time windows from days to weeks with high confidence and low false alarm rates.

Benefits of Technology

Forecasting solutions will allow flight control teams to conduct missions with higher efficiency and greater safety. Advanced warning will allow critical systems to be safed prior to adverse space weather conditions. Probabilistic models will allow for higher fidelity mass trades of future vehicles, resulting in better mission risk assessment. Ensemble forecasting techniques will provide better integration of multiple space weather data streams for gleaning the most relevant information needed for mission-critical operational decision points.

Table 25. TA 6.5.4 Technology Candidates – not in priority order

TA	Technology Name	Description
6.5.4.1	Tool for All-Clear Forecasting of Solar Particle Event Onset	Technology to indicate "all clear" (i.e. no event expected) solar conditions. All clear should be given in multiple time windows: e.g., hours or days.
6.5.4.2	Tool for Forecasting of Solar Particle Event ntensity and Evolution	Technology to forecast the dynamic evolution of solar particle events (SPEs). This includes forecasting the time profile of appropriate SPE fluxes.
6.5.4.3	Probabilistic Models (Tools) of Solar Particle Event Spectral Characteristics and Astronaut Risks	Models that calculate risk from SPE exposure for a given mission duration, including variation in possible SPE events.
6.5.4.4	Ensemble Coronal Mass Ejection Forecasting for Mission Impact Assessment	Technology to carry out ensemble coronal mass ejection (CME) predictions (locations impacted, the time of impact) throughout the solar system.
6.5.4.5	High-Performance Computing Architecture that Supports Real-Time Implementation of Operation Forecasts	Technology that enables use of large-scale, state of the art, physics-based models for space weather forecasting.

TA 6.5.5 Monitoring Technology

Technical Capability Objectives and Challenges

Radiation Monitoring technologies need to be developed to support current and future mission scenarios. Current monitoring technologies for in-mission radiation environmental measurements are either passive (crew badges, area monitors), requiring return to ground for analysis post-facto, or are larger, multi-kilogram, approximately 10 Watt (W) systems for ambient monitoring, perhaps away from crews and sensitive vehicle systems. Further advancements are needed in the design and development of miniaturized personal dosimeters for crew, low mass and low-power active radiation instrumentation, and advanced warning systems for spacecraft to minimize and monitor exposures during operations.

Currently, astronaut exposure to radiation is monitored through passive personal dosimeters. A variety of other measurement devices have also been used on the ISS with output dose, dose equivalent, or particle fluence. These devices are not integrated into ISS systems and therefore require astronaut time for deployment. Advanced, miniaturized radiation measurement devices will need to be adapted to spaceflight hardware prototypes and demonstrated and matured on available platforms as integrated vehicle systems. Additionally, advancements need to be made in the mass, power required, measured quantity, battery life, and wireless capability of personal dosimetry monitoring technologies. Active personal dosimeters should have batteries sufficient for long missions and be small enough to be worn by astronauts. Additionally, they should be able to communicate with vehicle systems wirelessly. Active area dosimeters should have low enough power requirements and be small enough (smart phone size or smaller) that they can be distributed throughout the spacecraft and integrated into the vehicle monitoring systems. Charged particle and neutron spectrometers should be no bigger than the Radiation Assessment Dosimeter (RAD) used on the robotic Mars mission Mars Science Laboratory (MSL) and be able to measure the particles and energy ranges at least as broad as those measured by current compact systems.

Benefits of Technology

Improvements to monitoring devices will enable better mapping of the radiation environment of exploration vehicles and habitats; improved data streams communicated to the crew and ground; and reduced volume, mass, and power consumption by these monitoring devices.

Table 26. TA 6.5.5 Technology Candidates – not in priority order

TA	Technology Name	Description
6.5.5.1	Active Personal Dosimetry for Intravecular Activities and Extravehicular Activities	Real-time individual dosimetry monitors that can be worn by each astronaut for intravehicular activities (IVAs) and extravehicular activities (EVAs).
6.5.5.2	Compact Biological Dosimetry (Biodosimetry)	Dosimetry for non-invasive (spit or blood drop) radiation diagnostics. Compact biological dosimetry technologies that can be used in flight on long-duration missions. Diagnostic tool for damage done by radiation. Biomarkers to track risks; dosimetry tracks damage.
6.5.5.3	In-Situ Active Warning and Monitoring Dosimetry	Proton event warning system. Compact, dose-equivalent area monitors for missions beyond LEO.
6.5.5.4	Miniaturized Low-Power Charged-Particle Spectrometers with Active Warning	Compact, low-power, charged-particle spectrometers that can be used during missions beyond LEO. Measures radiation environment.
6.5.5.5	Miniaturized Low-Power Neutron Spectrometers with Active Warning	Measures neutron spectrum on long-duration crewed missions outside LEO to meet operational requirements and determine exposure contribution to crew during the mission.

Appendix

Acronyms

2D	Two-Dimensional
3D	Three-Dimensional
ACES	Advanced Crew Escape Suit
AEMU	Advanced Extravehicular Mobility Unit
AG	Artificial Gravity
AI	Articulation Index
ALARA	As Low As Reasonably Achieved
ARED	Advanced Resistive Exercise Device
AQM	Air Quality Monitor
BCM	Biological CounterMeasures
BHP	Behavioral Health and Performance
BP	Blood Pressure
CCC	Contaminant Control Cartridge
CDMK	Carbon Dioxide Monitoring Kit
CE	Capillary Electrophoresis
CEVIS	Cycle Ergometer with Vibration Isolation and Stabilization System
CFD	Computational Fluid Dynamics
CME	Coronal Mass Ejection
CMS	CounterMeasure System
CNS	Central Nervous System
COLBERT	Combined Operational Load Bearing External Resistive Treadmill
COTS	Commercial Off The Shelf
CPC	Condensate Particle Counters
CQ	Crew Quarters
CTB	Crew Transfer Bag
DDT&E	Design, Development, Test, and Evaluation
DMA	Differential Mobility Analyzers
DMS	Differential Mobility Spectrometry
DNA	DeoxyriboNucleic Acid
DRM	Design Reference Mission
DTO	Development Test Objective
ECG	ElectroCardioGram
ECLSS	Environmental Control and Life Support Systems
EDO	Extended Duration Orbit
EHS	Environmental Health System
EMSER	Environmental Monitoring, Safety, and Emergency Response
EMI	ElectroMagnetic Interference

EMU	Extravehicular Mobility Unit
ESI-MS	ElectroSpray Ionization Mass Spectrometry
EUE	Experiment-Unique Equipment
EVA	ExtraVehicular Activity
FMK	Formaldehyde Monitoring Kit
FTIR	Fourier Transform Infrared Spectrometry
FSO	Full-Scale Output
GC-DMS	Gas Chromatography-Differential Mobility Spectrometry
GC-MS	Gas Chromatography-Mass Spectrometry
GCR	Galactic Cosmic Ray/Radiation
GLA	General Luminaire Assemblies
GPS	Global Positioning System
GSC	Grab-Sample Containers
HD	High-Definition
HEPA	High-Efficiency Particulate Adsorption
HERA	Hybrid Electronic Radiation Assessor
HHP	Human Health and Performance
HMC	Heat Melt Compactor
HRI	Human-Robotic Interaction
HSF	Human SpaceFlight
HSI	Human-Systems Integration
HSIS	Human-Systems Integration Standard
HUD	Heads Up Display
IC	Ion Chromatography
ICP	Intracranial Pressure
IntelliCLAD	Intelligent Coatings for Location and Detection of Leaks
IPS	Induced Pluripotent Stem
ISRU	In-Situ Resource Utilization
ISS	International Space Station
IV	IntraVenous
IVA	IntraVehicular Activity
IV TEPC	IntraVehicular Tissue Equivalent Proportional Counter
LC-MS	Liquid Chromatography-Mass Spectrometry
Le	Listening effort
LEA	Launch, Entry, and Abort
LED	Light Emitting Diode
LEO	Low-Earth Orbit
LET	Linear Energy Transfer
Lq	Listening quality
MACES	Modified Advanced Crew Escape Suit
MAG4	MAGnetorgram Forecast
MAPTIS	Materials And Processing Technical Information System

MAS	Microbial Air Sampler
MCA	Major Constituent Analyzer
MCC	Mission Control Center
MCT	Medical Consumable Tracking
MCTB	Multi-purpose Cargo Transfer Bag
MEMS	MicroElectroMechanical Systems
MEOSAR	Medium-Earth Orbit Search and Rescue
MGM	Multi-Gas Monitor
MMOD	Micrometeroroid and Orbital Debris
MOS	Mean Opinion Score
MRI	Magnetic Resonance Imaging
MSL	Mars Science Laboratory
NBL	Neutral Buoyancy Lab
NC	Noise Cancellation
NDIR	NonDispersive InfraRed
NEA	Near-Earth Asteroid
NEO	Near-Earth Object
NHV	Net Habitability Volume
NIR	Near InfraRed
OCT	Office of the Chief Technologist
OCT	Optical Coherence Tomography
OLTARIS	On-Line Tool for the Assessment of Radiation in Space
ONSD	Optic Nerve Sheath Diameter
OPC	Optical Counters
ORU	Orbital Replacement Unit
PAS	Power, Avionics, and Software
PBA	Portable Breathing Apparatus
PEL	Permissible Exposure Limits
PFE	Portable Fire Extinguisher
PGS	Pressure Garment System
PLB	Personal Locating Beacon
PLOC	Probability Loss Of Crew
PLOM	Probability Loss Of Mission
PLSS	Portable Life Support System
POM	Portable Oxygen Monitor
PVT	Psychomotor Vigilance Task
QCM	Quartz Crystal Microbalance
qPCR	Qualitative Polymerase Chain Reaction
RAD	Radiation Assessment Detector
RCA	Rapid Cycle Amine
REID	Risk of Exposure Induced Death
RF	RadioFrequency

RFID	RadioFrequency IDentification
SAR	Search And Rescue
SBIR	Small Business Innovation Research
SOA	State Of the Art
SCR	Solar Cosmic Rays
SEE	Safe Exposure Estimate
SEP	Solar Energetic Proton
SEM	Subject Matter Expert
SPE	Solar Particle Event
SSK	Surface Sampling Kit
SSLA	Solid State Light Assemblies
SWME	Spacesuit Water Membrane Evaporator
TA	Technology Area
TCD	TransCranial Doppler
TEOM	Tapered Element
TLD	ThermoLuminescence Dosimeters
TOC	Total Organic Carbon
TOCA	Total Organic Carbon Analyzer
TRL	Technology Readiness Level
TtG	Trash-to-Gas
TVIS	Treadmill with Vibration Isolation and Stabilization
UHF	Ultra High Frequency
URA	Urine Receptical Assembly
UWMS	Universal Waste Management System
U.S.	United States
UV	UltraViolet
UV-Vis	UltraViolet-Visible
VIS	Vibration Isolation System
VOC	Volatile Organic Compound
WCS	Waste Collection System
WinScat	Spaceflight Cognitive Assessment Tool for Windows

Abbreviations and Units

Abbreviation	Definition
ACFM	Actual Cubic Feet per Minute
AgO	Silver Oxide
BTU	British Thermal Unit
C	Celsius
cc	Cubic Centimeter
CFU	Colony-Forming Units
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CM	CrewMember
CM-day	Crew Member-day
dB	Decibel
F	Fahrenheit
g	Grams
G	Unit of Earth surface gravity
H_2	Hydrogen
H_2O	Water
Hr	Hour
in.	Inch
kg	Kilogram
kRad	KiloRad
Krpm	1000 Revolutions per Minute
kW	Kilowatt
L	Liter
lb	Pounds
lbm	Pound-Mass
LiOH	Lithium Hydroxide
m^3	Cubic Meters
MetOx	silver oxide
MeV	Megaelectron Volts
μg	Micrograms
mg	Milligrams
MHz	MegaHertz
ml	Miilliters
mmHg	Millimeter of mercury
NH_3	Ammonia
nm	Nanometers
O_2	Oxygen

Abbreviation	Definition
pH	Measure of acidity or basicity of an aqueous solution
$ppCO_2$	Partial Pressure Carbon Dioxide
Ppm	Parts per million
psia	Pounds per square inch absolute
psid	Pounds per square inch differential
Rpm	Revolutions per minute
SCCM	Standard Cubic Centimeters per Minute
SCFM	Standard Cubic Feet per Minute
Torr	Unit of pressure
UV	Ultraviolet
Vdc	Volts Direct Current
VOC	Volatile Organic Compound
W	Watts
Wh	Watt-hour
Yr	Year
Yrs	Years
µg/L	Micrograms per liter

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Technology Candidate Snapshots

6.1 Environmental Control and Life Support Systems and Habitation Systems
6.1.1 Air Revitalization

6.1.1.1 Carbon Dioxide (CO_2) Removal (Closed Loop)

TECHNOLOGY

Technology Description: Systems that remove metabolically-generated carbon dioxide from the spacecraft atmosphere to safe levels for the crew, and deliver the carbon dioxide to onboard processes dedicated to the recovery of oxygen.

Technology Challenge: Long-term, maintenance-free reliability. Performance required to maintain $ppCO_2$ below 2 mmHg without significant impacts to resource requirements, such as power, and adsorber size and integration with CO_2 reduction equipment (see 6.1.1.2).

Technology State of the Art: Alternate sorbent materials and formats. Alternate water save materials and formats.

Parameter, Value:

Various sorbent materials and formats are available on the commercial market and in non-government research and development laboratories. Performance under conditions applicable to spacecraft life support are yet to be validated.

TRL: 2

Technology Performance Goal: Improve performance and robustness of closed loop CO_2 removal systems as validated for a spacecraft.

Parameter, Value:

Power (w/crewperson): 100.

CO_2 removal rate (crew-equivalent/torr $ppCO_2$): 2.0.

TRL: 6

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

CAPABILITY

Needed Capability: CO_2 removal (closed loop).

Capability Description: Remove carbon dioxide from the cabin atmosphere and deliver to onboard processes dedicated to the recovery of oxygen.

Capability State of the Art: Carbon dioxide adsorbed from cabin atmosphere by packed beds of zeolites operated in alternating adsorption/ desorption thermal cycle modes, with upstream desiccant beds providing water save functionality.

Parameter, Value:

Time interval between crew maintenance tasks (yrs): 0.5.

Time averaged power (W/crewperson @3.8 torr $ppCO_2$): 124*.

Volume envelope (ft^3): 13.7.

CO_2 removal (crew-equivalent/torr $ppCO_2$): 1.77, *based on 155 minute half-cycle and 20.4 scfm.

Capability Performance Goal: Increase time between crew maintenance tasks, reduce power, and control CO_2 concentrations in cabin to lower levels.

Parameter, Value:

Time interval between crew maintenance tasks (yrs): 3.

Time averaged power (w/crewperson @ 3.8 torr $ppCO_2$): 100.

Volume envelope (ft^3): <13.7.

CO_2 removal rate (crew-equivalent/torr $ppCO_2$): 2.0.

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	4 years
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

6.1 Environmental Control and Life Support Systems and Habitation Systems
6.1.1 Air Revitalization

6.1.1.2 Carbon Dioxide (CO_2) Reduction

TECHNOLOGY

Technology Description: Systems that recover oxygen from carbon dioxide removed from the spacecraft atmosphere through chemical reactions that reduce the carbon dioxide to other products.

Technology Challenge: Integrated system size and complexity, catalyst life, carbon formation control and handling, increased tolerance to moisture entrained in reactant gases, and integration with CO_2 removal equipment (see 6.1.1.1).

Technology State of the Art: Increase the recovery of O_2 from CO_2 by increasing the utilization of available hydrogen, recovering re-useable hydrogen from by-products, or applying biological processes.

Parameter, Value:

75-90% O_2 recovery from CO_2.
Breakeven point for 4 crew: various > 180 days.

TRL 2

Technology Performance Goal: Increase the percentage of O_2 recovered from metabolic CO_2.

Parameter, Value:

75-90% O_2 recovery from CO_2.

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: CO_2 reduction.

Capability Description: Recover a higher percentage of oxygen from carbon dioxide in the cabin atmosphere.

Capability State of the Art: Metabolic CO_2 reacted with H_2 (by-product generated from electrolysis of water for metabolic O_2 supply) in a Sabatier process to yield H_2O and CH_4.

Parameter, Value:

42% O_2 recovery from CO_2.
Breakeven point for 4 crew: 126 days.

Capability Performance Goal: Increase the percentage of O_2 recovered from metabolic CO_2, while keeping the life cycle mass break-even point within 6 months.

Parameter, Value:

75-90% O_2 recovery from CO_2.
Breakeven point for 4 crew: < 180 days.

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

6.1 Environmental Control and Life Support Systems and Habitation Systems
6.1.1 Air Revitalization

6.1.1.3 Trace Contaminant Control

TECHNOLOGY

Technology Description: Systems that remove toxins from the spacecraft cabin atmosphere to below the Spacecraft Maximum Allowable Concentrations. Contaminants may be either metabolically generated or off-gassed from equipment and materials over time.

Technology Challenge: High sorbent capacities, effectiveness against problematic siloxanes.

Technology State of the Art: Commercially-available sorbents and catalysts, specialty catalytic processes including visible and ultraviolet (UV) photocatalysis, specialty substrates including microliths.

Parameter, Value:

Various sorbent and catalyst materials, processes, and substrates are available on the commercial market and in non-government research and development laboratories. Performance under conditions applicable to spacecraft life support are yet to be validated.

TRL
3

Technology Performance Goal: Replace obsolete sorbent with spacecraft validated commercially-available materials with higher capacities, and reduce system size and power.

Parameter, Value:

Adsorbent capacity (NH_3), mg/g @ 1 ppm: 32.2.

Adsorbent capacity (volatile organic compounds, or VOCs), mg/g: > 5.4. Average power: 20.8 W/crewperson.

TRL
9

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

CAPABILITY

Needed Capability: Trace contaminant control.

Capability Description: Remove contaminants from the cabin atmosphere with minimal consumables.

Capability State of the Art: Combination of activated charcoal (no longer commercially available) and high-temperature catalytic oxidation with post-scrubbing. Limited effectiveness against siloxanes can potentially lead to degradation of some other environmental control and life support system (ECLSS) functions such as CO_2 removal and water recovery.

Parameter, Value:

Adsorbent capacity (NH_3), mg/g @ 1 ppm: 11.9.

Adsorbent capacity (VOCs), mg/g: 5.4.

Average power, w/crewperson: 29.1.

Initial mass, lb/crewperson: 33.3.

Resupply mass, lb/crew-year: 8.2.

Capability Performance Goal: Reduce mass and power requirements for controlling trace contaminants in spacecraft cabin atmospheres, including contaminants that represent hazards to both crew and vehicle systems health.

Parameter, Value:

Adsorbent capacity (NH_3), mg/g @ 1 ppm: 32.2.

Adsorbent capacity (VOCs), mg/g: > 5.4.

Average power: 20.8 W/crewperson.

Initial mass, lb/crewperson: 28.6.

Resupply mass, lb/crew-year: 7.7.

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

6.1 Environmental Control and Life Support Systems and Habitation Systems
6.1.1 Air Revitalization

6.1.1.4 Particulate and Microbial Control

TECHNOLOGY

Technology Description: System that remove particulates (generated from crew, clothing, etc.) and microbial contamination from the spacecraft cabin atmosphere.

Technology Challenge: Size, removal efficiency, and service life are challenges.

Technology State of the Art: Surface and depth filtration, electrostatic precipitators, cyclonic separators, indexing media, etc.

Parameter, Value:
Various filtration media, precipitators, and separators are available on the commercial market and in non-government research and development laboratories. Performance under conditions applicable to spacecraft life support are yet to be validated.

TRL 3

Technology Performance Goal: Extend services life of cabin filters and limit exposure of crew to planetary surfaces dust particles 0.1 micron in size or larger.

Parameter, Value:
Safe Exposure Estimate (SEE), lunar dust down to 0.1 micron, mg/m^3: 0.5.

TRL 4

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

CAPABILITY

Needed Capability: Particulate and microbial control.

Capability Description: Provide particulate and microbial control in cabin atmosphere.

Capability State of the Art: Airborne particulates and micro-organisms are removed from cabin atmosphere via circulation through High Efficiency Particulate Adsorption (HEPA) filters.

Parameter, Value:
99.97% removal efficiency for particulates 0.3 microns or larger.
Cabin air filter service life (with periodic cleaning): 2.5 years.

Capability Performance Goal: Lunar and Mars surface missions introduce the potential for surface dust to be brought into the habitat through extravehicular acvitity (EVA) exposure. Physical characteristics introduce health risks to crew members for particulates as small as 0.1 microns in size.

Parameter, Value:
SEE, lunar dust down to 0.1 micron, mg/m^3: 0.5.
Cabin air filter service life (with periodic cleaning): >3 years.

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	Enabling	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)	Enabling	2033	--	2027	4 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	4 years

6.1 Environmental Control and Life Support Systems and Habitation Systems
6.1.1 Air Revitalization

6.1.1.5 Temperature and Humidity Control

TECHNOLOGY

Technology Description: Systems that control the temperature and humidity levels within a spacecraft cabin and can collect humidity water for recovery.

Technology Challenge: Hydrophilic surface property life, durability, chemical stability, and antimicrobial endurance are challenges.

Technology State of the Art: Hydrophillically-coated condensing heat exchangers (for longer missions needing condensate recovery).

Parameter, Value:

Coatings slough: periodic.

Coatings catalyze problematic siloxane formation in condensate.

TRL: 9

Technology Performance Goal: Condensing heat exchangers that have long-lived coatings that are stable physically and chemically.

Parameter, Value:

Coating (if any) does not degrade physically or chemically.

Coating (if any) is chemically inert.

TRL: 9

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

CAPABILITY

Needed Capability: Temperature and humidity control.

Capability Description: Provide temperature and humidity control of the cabin atmosphere.

Capability State of the Art: Non-condensing heat exchanger (for short duration missions) and hydrophillically-coated condensing heat exchangers (for longer missions needing condensate recovery), periodically dried to retard microbial growth.

Parameter, Value:

Time interval between dryouts for microbial control: 28 days.

Coatings slough: periodic.

Coatings catalyze problematic siloxane formation in condensate.

Capability Performance Goal: Condensing heat exchangers that require no periodic dryout, do not promote microbial growth nor chemical conversion of organics, and have long-lived coatings that are stable physically and chemically.

Parameter, Value:

No periodic dryout required for microbial control. Coating (if any) does not degrade physically or chemically.

Coating (if any) is chemically inert.

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

6.1 Environmental Control and Life Support Systems and Habitation Systems
6.1.1 Air Revitalization

6.1.1.6 Oxygen (O_2) Supply

TECHNOLOGY

Technology Description: Systems that provide oxygen from stored supplies or onboard generation systems to meet crew metabolic needs and makeup for cabin atmosphere leakage or re-pressurization makeup.

Technology Challenge: Maintaining effective hazard controls while minimizing system complexity, cell stack operation life, and reliable and long-life hydrogen leak detection are challenges.

Technology State of the Art: Ground tests and engineering assessments are underway aimed at identifying and then demonstrating opportunities to simplify the SOA such that necessary hazard control capabilities are maintained but with less balance-of-plant hardware and with a H_2 sensor having a longer calibration life.

Parameter, Value:

Oxygen generator assembly launch mass: 700 lb.

Specific O_2 generation mass, non-recurring + recurring: 0.19 lb equipment/lb O_2 produced.

Specific O_2 generation mass, recurring: 0.07 lb equipment/lb O_2 produced.

TRL: 4

Technology Performance Goal: Smaller, simpler system with higher reliability.

Parameter, Value:

Oxygen generator assembly launch mass: < 640 lb.

Specific O_2 generation mass: < 0.05 lb equipment/lb O_2 produced.

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: Oxygen supply.

Capability Description: Provide oxygen to the crew in the spacecraft.

Capability State of the Art: Oxygen generated from recovered water in a liquid cathode feed water electrolysis system. Oxygen delivered directly to crew cabin at ambient pressure with crew maintenance time per year.

Parameter, Value:

Oxygen generator assembly launch mass: 740 lb. Specific O_2 generation mass, non-recurring + recurring: 0.23 lb equipment/lb O_2 produced.

Specific O_2 generation mass, recurring: 0.09 lb equipment/lb O_2 produced.

Crew maintenance time: 12 crew-hours/year.

Capability Performance Goal: Smaller, simpler system with higher reliability, requiring less crew maintenance time and equipment resupply.

Parameter, Value:

Oxygen generator assembly launch mass: 640 lb.

Specific O_2 generation mass, non-recurring + recurring: 0.05 lb equipment/lb O_2 produced.

Specific O_2 generation mass, recurring: 0.01 lb equipment/lb O_2 produced.

Crew maintenance time: 0 crew-hours over 3 years.

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

6.1 Environmental Control and Life Support Systems and Habitation Systems
6.1.1 Air Revitalization

6.1.1.7 High-Pressure Oxygen (O_2) Supply

TECHNOLOGY

Technology Description: Systems that supply oxygen at high pressure to recharge storage tanks for use during extravehicular activities or short duration crewed vehicles or spacecraft.

Technology Challenge: High pressure O_2 safety, O_2 purity, operation life, and system complexity are challenges.

Technology State of the Art: Production of oxygen between 2000-3600 psia from oxygen generated onboard from electrolysis either through high pressure electrolysis, ambient/moderate pressure electrolysis with supplemental compression, or concentration from ambient cabin atmosphere with supplemental compression.

Parameter, Value:

Delivery pressure: 2000-3600 psia. Purity: 99.5-99.9% O_2 by volume. Insufficient development data to fully assess system masses based on alternative technologies.

TRL: 4

Technology Performance Goal: Production of oxygen at 3600 psia from oxygen generated onboard either through high pressure electrolysis, ambient/moderate pressure electrolysis with supplemental compression, or concentration from ambient cabin atmosphere with supplemental compression.

Parameter, Value:

Delivery pressure: 3600 psia.

Specific high pressure O_2 system mass: < 0.5 lb equipment/lb O_2 produced.

TRL: 6

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

CAPABILITY

Needed Capability: High-pressure oxygen supply.

Capability Description: Provide high-pressure oxygen for extravehicular activity.

Capability State of the Art: Resupply of gaseous oxygen (6000 psia) in cylinders periodically launched from Earth.

Parameter, Value:

Specific O_2 resupply mass: 1.8 lb equipment and packaging per lb O_2 supplied.

Capability Performance Goal: Production of oxygen at up to 3600 psia from oxygen generated onboard with a high degree of purity.

Parameter, Value:

Delivery pressure: 3600 psia.

Purity: 99.989% O_2 by volume, with acceptable trace constituents.

Specific high pressure O_2 system mass: < 0.5 lb equipment/lb 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 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

6.1 Environmental Control and Life Support Systems and Habitation Systems
6.1.2 Water Recovery and Management

6.1.2.1 Wastewater Collection

TECHNOLOGY

Technology Description: Systems that collect wastewater, including condensate and urine, stabilize it (if necessary), and store it prior to disposal or processing.

Technology Challenge: Achieving effective stabilization and precipitation prevention with a non-toxic pretreatment solution.

Technology State of the Art: Phosphoric acid replaces sulfuric acid to acidify chromium trioxide.

Parameter, Value:

Toxicity hazard rating: 1.

Does not contribute to solids precipitation up to 85% recovery from urine.

Non-corrosiveness to system wetted materials is being tested through long-duration exposure tests.

TRL: 5

Technology Performance Goal: A low-toxicity, less corrosive solution that either eliminates microbes or prevents their growth and stabilizes urine for handling, storage, and processing.

Parameter, Value:

Does not contribute to solids precipitation.

Non-corrosive to system wetted materials.

Does not contribute to precipitation up to 85% recovery from urine.

*per Johnson Space Center (JSC) 26895, "Guidelines for Assessing the Toxic Hazard of Spacecraft Chemicals and Test Materials"

TRL: 6

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

CAPABILITY

Needed Capability: Wastewater collection.

Capability Description: Collect, stabilize, and store wastewater.

Capability State of the Art: Urine is "pretreated" upon collection with a solution containing chromium trioxide and sulfuric acid to preclude microbial growth that may degrade equipment operation and reduce the quality of recovered water.

Parameter, Value:

Pretreatment solution is highly acidic (pH of 1), corrosive, and rated as a toxicity hazard of 1. Sulfuric acid component contributes to solids precipitation that hinders water recovery efficiency.

Capability Performance Goal: A low-toxicity, less corrosive solution that stabilizes urine for handling, storage, and processing and that does not contribute to precipitation up to 85% recovery from urine.

Parameter, Value:

Toxicity hazard rating: ≤ 2*, Does not contribute to solids precipitation, Non-corrosive to system wetted materials.

Does not contribute to precipitation up to 85% recovery from urine.

*per JSC 26895, "Guidelines for Assessing the Toxic Hazard of Spacecraft Chemicals and Test Materials"

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

6.1 Environmental Control and Life Support Systems and Habitation Systems
6.1.2 Water Recovery and Management

6.1.2.2 Wastewater Processing

TECHNOLOGY

Technology Description: Systems that process urine, humidity condensate, hygiene, CO_2 reduction product, and other sources of water generated on orbit that cannot be considered potable without some processing for purification.

Technology Challenge: Long-duration, reliable production of safe water with minimal expendable usage and crew maintenance. Tolerance to dormancy between operational periods.

Technology State of the Art: Various combinations of technologies (distillation, adsorption, ion exchange, oxidation, membrane separations, filtration, biological processes, etc.).

Parameter, Value:

Various technologies are available on the commercial market and in non-government research and development laboratories. Performance under conditions applicable to spacecraft life support are yet to be validated.

TRL: 2

Technology Performance Goal: Higher water recovery efficiency (depending on mission trades).

Parameter, Value:

Water recovery efficiency from urine: 90%

Urine process assembly and water process assembly launch mass: 900 lb. Specific H_2O production mass, recurring: 0.05 lb equipment/lb H_2O produced.

Specific H_2O production from brine: < 0.25 lb hardware/ lb brine water recovered over 500 days.

TRL: 6

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

CAPABILITY

Needed Capability: Wastewater processing.

Capability Description: Produce potable water from multiple wastewater sources.

Capability State of the Art: Pretreated urine is processed via vapor compression distillation. The distillate product is combined with humidity condensate and purified through a sequence of particulate filters, adsorbents and resins, catalytic oxidation, and biocide dosing.

Parameter, Value:

Water recovery efficiency from urine: 74%.

Urine process assembly and water process assembly launch mass: 1000 lb.

Specific H_2O production mass, recurring: 0.11 lb equipment/lb H_2O produced.

Crew unplanned maintenance interval, months: 6.

Dormancy tolerance, months: < 1.

Capability Performance Goal: High reliability requiring less crew maintenance and equipment resupply. Higher water recovery efficiency (depending on mission trades).

Parameter, Value:

Water recovery efficiency from urine: 90%.

Urine process assembly and water process assembly launch mass: 900 lb.

Specific H_2O production mass, recurring: 0.05 lb equipment/lb H_2O produced.

Specific H_2O production from brine: < 0.25 lb hardware/ lb brine water recovered over 500 days.

Crew unplanned maintenance interval, months: 36.

Dormancy tolerance, months: 18.

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	4 years
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

6.1 Environmental Control and Life Support Systems and Habitation Systems
6.1.2 Water Recovery and Management

6.1.2.3 Brine Processing

TECHNOLOGY

Technology Description: Systems that recover water from concentrated by-product solutions ("brines") that remain after primary wastewater processing. Such systems must be tolerant of the formation of, and facilitate the efficient disposal of, precipitated solids.

Technology Challenge: Recovery of water from solutions that are nearly saturated with a complex mixture of inorganic and organic chemical species. As water is separated from such solutions, precipitation reactions yield solid and liquid mixtures with physical properties that are a challenge to overcome with system mass, power, volume, and crewtime resources that do not negate the potential mission benefits of the additional water recovered.

Technology State of the Art: Various combinations of technologies (conduction and spray drying, freeze drying, filtration and membranes, electrical separation and decomposition, and distillation).

Parameter, Value:

Various technologies are available on the commercial market and in non-government research and development laboratories. Performance under conditions applicable to spacecraft life support are yet to be validated.

TRL: 2

Technology Performance Goal: High-reliability recovery of water from concentrated brines. Mass, power, volume, and crewtime resources must not negate the mission benefits of the additional water recovered.

Parameter, Value:

Specific H_2O production from brine: < 0.25 lb hardware/ lb brine water recovered over 500 days.

Operating interval without failure, months: 36.

Dormancy tolerance, months: 18.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Two phase (gas-liquid) fluid behavior, freeze/thaw, and particulate dispersion/ sedimentation in partial or microgravity.

CAPABILITY

Needed Capability: Wastewater processing.

Capability Description: Produce potable water from multiple wastewater sources.

Capability State of the Art: Pretreated urine is processed via vapor compression distillation. The distillate product is combined with humidity condensate and purified through a sequence of particulate filters, adsorbents and resins, catalytic oxidation, and biocide dosing.

Parameter, Value:

Water recovery efficiency from urine: 74%.

Urine processor assembly and water process. Assembly launch mass: 1000 lb.

Specific H_2O production mass, recurring: 0.11 lb equipment/lb H_2O produce.

Crew unplanned maintenance interval, months: 6.

Dormancy tolerance, months: < 1.

Capability Performance Goal: High reliability requiring less crew maintenance and equipment resupply. Higher water recovery efficiency (depending on mission trades).

Parameter, Value:

Water recovery efficiency from urine: 90%.

Urine processor assembly and water processor assembly launch mass: 900 lb.

Specific H_2O production mass, recurring: 0.05 lb equipment/lb H_2O produced.

Specific H_2O production from brine: < 0.25 lb hardware/ lb brine water recovered over 500 days.

Operating interval without failures: 36.

Dormancy tolerance, months: 18.

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

6.1 Environmental Control and Life Support Systems and Habitation Systems
6.1.2 Water Recovery and Management

6.1.2.4 Potable Water Microbial Control

TECHNOLOGY

Technology Description: Systems that ensure potable water meets microbial limits for consumption by the crew. This can include biocides, point-of-use filters, or other means.

Technology Challenge: Dosing and maintaining silver at safe, biocidal levels is a challenge.

Technology State of the Art: Silver used by international partners on the International Space Station (ISS) as residual biocide in resupplied and reclaimed water systems.

Parameter, Value:

Stabilization time: < 2 years.

TRL 4

Technology Performance Goal: Single biocide that is stable long-term.

Parameter, Value:

Stabilizaton time: 3-5 years.

TRL 6

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

CAPABILITY

Needed Capability: Potable water microbial control.

Capability Description: Maintain potable water standard with respect to microbial contamination.

Capability State of the Art: On the ISS, U.S. water supplies are dosed with iodine at a concentration of 2 mg/l. Due to potential health effects from long-term consumption, residual iodine is removed prior to crew consumption. In the ISS, international partner water supplies are dosed with silver (0.2 mg/l), which is safe for long-term human consumption, but must be routinely replenished due to depletion. Waters dosed with iodine and silver can not be mixed due to the formation of precipitants.

Parameter, Value:

Biocidal iodine concentration (2 mg/l) is unsafe for long-term human consumption; silver biocide requires replenishment. Precipitants form if waters containing iodine and silver are mixed.

Stabilization time: < 2 years.

Capability Performance Goal: Single biocide that is stable long term and safe for human consumption at biocidal concentrations.

Parameter, Value:

Stabilization time: 3-5 years.

Safe for human consumption at biocidal concentrations.

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

6.1 Environmental Control and Life Support Systems and Habitation Systems
6.1.3 Waste Management

6.1.3.1 Metabolic Waste Management

TECHNOLOGY

Technology Description: System that collects, contains, and stores or processes metabolically-generated solid waste.

Technology Challenge: Operation after extended dormancy. Hygienic collection for female simultaneous urination and defecation, microgravity operation of separator during transient flow conditions.

Technology State of the Art: Universal waste management system (UWMS) based on extended duration orbiter (EDO) waste collection systems (WCS) fecal collection that used separate fans and separators. Did not adequately address simultaneous urination and defecation challenges.

Parameter, Value:

Fecal compaction: ~50% (EDO), ~60-70% (UWMS).

System mass: 250 lb (EDO), 105 lb (UWMS).

Simultaneous urination and defecation accommodation: moderately effective.

Volume efficiency: poor, due to separate fans, odor/bacteria filter, and redundant systems. Consumables: 0.7 lb/crew-day.

TRL: 4

Technology Performance Goal: Universal waste management system suitable for collection and containment in any future exploration vehicle, and compatible with water recovery and long-term waste stabilization systems.

Parameter, Value:

Fecal compaction: 80%.

System mass: 90 lb.

Simultaneous urination and defecation accommodation: effective.

Volume efficiency (suitable for small vehicles).

Consumables: 0.5 lb/crew-day.

TRL: 6

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

CAPABILITY

Needed Capability: Universal metabolic waste management.

Capability Description: Hygienically collect and manage metabolic waste in systems that are common across all types of exploration vehicles.

Capability State of the Art: Fecal waste and associated consumables (wipes) are collected in fixed canister fitted within individual porous bags. Airflow entrains waste and draws full bag into canister. No additional compaction is exerted. Full canisters are removed, capped, and disposed of. Frequent escapes of urine and fecal materials.

Parameter, Value:

Fecal compaction: none.

Simultaneous urination and defecation accommodation: limited effectiveness.

Volume efficiency: poor (rack size).

Capability Performance Goal: Universal toilet useable in all short- and long-duration exploration vehicles.

Parameter, Value:

Fecal compaction: 80%.

System mass: 90 lb.

Simultaneous urination and defecation accommodation: effective

Volume efficiency: suitable for small vehicles. Consumables: 0.5 lb/crew-day.

Mission: Short- and long-duration.

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

6.1 Environmental Control and Life Support Systems and Habitation Systems
6.1.3 Waste Management

6.1.3.2 Contingency Urine Collection

TECHNOLOGY

Technology Description: Device, with no moving parts, that collects and temporarily contains urine for overboard disposal.

Technology Challenge: Challenges include developing advanced capillary geometry, hydrophilic, hydrophobic, and antimicrobial coatings.

Technology State of the Art: Urine Receptacle Assembly (URA) developed for Apollo program, with internal honeycomb structure to control fluid in microgravity environment. High Technology Readiness Level (TRL) during the Apollo era.

Parameter, Value: (TRL 9)

Passive device (URA) only suitable for male crew. Urine escapes regularly occurred. Limited to short Apollo-style missions up of 12 days.

Technology Performance Goal: Passive device suitable for male and female crew. Minimal urine escape. Long operational life without fouling. Compatible with overboard venting or transfer to internal storage.

Parameter, Value: (TRL 6)

Passive urine collection and containment device. Compatible with overboard urine vent. Compatible with male and female use.

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

CAPABILITY

Needed Capability: Contingency urine collection.

Capability Description: Provide reliable means to collect urine without requiring spare urine rotary phase separator(s). Long-term hygienic collection for male and female crews.

Capability State of the Art: Rotary phase separator device separates urine from entrained air and delivers the urine to overboard vent (Orion) or downstream urine processing equipment (International Space Station). Spare rotary separator(s) required to continue capability to collect urine in event of primary separator failure.

Parameter, Value:

Contingency capability: spare rotary phase separator device.

Duration: up to 12 days.

Capability Performance Goal: Passive device with no moving parts to collect and temporarily contain urine in the event a primary rotary urine separator fails. Device should be able to interface to overboard urine vent to enable disposal.

Parameter, Value:

Passive device suitable for male and female crew.

< 1% urine escape.

Operational life of 180 crew-days.

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

6.1 Environmental Control and Life Support Systems and Habitation Systems
6.1.3 Waste Management

6.1.3.3 Trash Management System

TECHNOLOGY

Technology Description: A device that reduces the volume of trash (paper and plastic products, residual foods, beverages and containers, used housekeeping and hygiene wipes) and stabilizes it for safe storage and disposal.

Technology Challenge: Off-gassing control, energy efficiency, and cooling time. Trapped water in trash allows for microbial reactivation.

Technology State of the Art: First generation heat melt compactor proof-of-concept prototype, tabletop-size unit, mechanical compaction with heating and reduced pressure. Trash tile diameter of 8 inches.

Parameter, Value:

Compaction ratio: ~75-90% (depending on temperature and pressure).

Energy: 1.3 kW-hr/kg.

Water activity (in compacted trash): 0.6-0.8.

Installed mass: ~300 lb.

TRL: 4

Technology Performance Goal: Compact and sterilize crew trash with mechanical compaction to maximize compaction ratio. Heating system used to sterilize and recover water.

Parameter, Value:

Compaction ratio: ~85-95% (depending on temperature and pressure).

Energy: 0.8 kW-hr/kg.

Water activity (in compacted trash): < 0.6.

TRL: 6

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

CAPABILITY

Needed Capability: Long-term trash management.

Capability Description: Alternative methods for storing and repurposing trash to increase habitable volume in smaller vehicles.

Capability State of the Art: Wet and dry trash is collected in bags, temporarily stowed without any compaction or stabilization, and discarded in departing logistics vehicles.

Parameter, Value:

Stabilization: none.

Compaction: none.

Water recovery: none.

Capability Performance Goal: Wet and dry trash is collected, compacted, and stabilized to enable long-duration storage. Low mass.

Parameter, Value:

Stabilization time: 3 years.

Compaction ratio: 10:1.

Water recovery: accommodated.

Water activity (in compacted trash): < 0.6

Installed mass: < 180 lb.

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

6.1 Environmental Control and Life Support Systems and Habitation Systems
6.1.3 Waste Management

6.1.3.4 Trash-to-Gas (TtG)

TECHNOLOGY

Technology Description: System that uses trash as feedstock to produce gases (methane) for propulsion. Venting of gas is also a possible disposal means.

Technology Challenge: Long-term management of oxidation front, trash loading, management of by-products other than CH_4 and H_2, and residual ash removal are challenges. Preventing catalysts and membrane poisoning by complex waste stream is also a challenge.

Technology State of the Art: Near full scale 1-g compatible batch processing hardware capable of 5.4 kg/day trash. Methane separation and purification not demonstrated. Tar and ash residual tolerance not demonstrated.

Parameter, Value:	TRL
> 85% of H_2 in trash converted to CH_4 > 85% carbon converted to CH_4 (with additional H or H_2O) ~25% CH_4 purity	4

Technology Performance Goal: Convert all trash to methane. Two cases: H-limited and C-limited. Produce propulsion-grade methane. Support mission to Mars transit. Energy efficient, continuous processing.

Parameter, Value:	TRL
> 98% of hydrogen in trash converted to CH_4 > 95% of carbon in trash converted to CH_4 (with additional H or H_2O)	6

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

CAPABILITY

Needed Capability: Long-term trash stabilization, volume reduction.

Capability Description: Reduce trash burden on habitable volume through alternative processing methods.

Capability State of the Art: Wet and dry trash collected in bags and temporarily stowed. No compaction or stabilization. Discarded in departing vehicles.

Parameter, Value:

> 85% of H_2 in trash converted to CH_4

> 85% carbon converted to CH_4 (with additional H or H_2O)

~25% CH_4 purity Stabilization: none.

Capability Performance Goal: Convert all trash to methane. Two cases: H-limited and C-limited. Produce propulsion-grade methane. Support mission to Mars transit. Energy efficient, continuous processing. Commonality with Mars in-situ resource utilization (ISRU) methane production.

Parameter, Value:

> 98% of hydrogen in trash converted to CH_4

> 95% of carbon in trash converted to CH_4 (with additional H or H_2O)

> 98% CH_4 purity.

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

6.1 Environmental Control and Life Support Systems and Habitation Systems
6.1.4 Habitation

6.1.4.1 Free-Water Shower for Full Body Cleansing

TECHNOLOGY

Technology Description: Private enclosure with water system for full-body cleansing. Limits or prevents water escapes and collects wastewater for environmental control and life support system (ECLSS) reclamation. Provides ventilation and lighting.

Technology Challenge: Efficient water reclamation, full water containment, and ventilation-airflow balance.

Technology State of the Art: Crew quarters hygiene liner. Rack-sized Teflon liner for containing water during *partial-body* cleansing. Provides ventilation and lighting.

Parameter, Value:

Body cleansing: *partial only*.

System volume: ~75 ft^3.

Water containment: moderate (filtration system to capture water droplets).

TRL 6

Technology Performance Goal: Shower for *full-body* cleansing that is minimal volume with water recovery system that is compatible with ECLS (water volume, surfactants).

Parameter, Value:

Water recovery: > 90%

System volume: 60 ft^3

Water containment: high (no liquid escape).

TRL 6

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

CAPABILITY

Needed Capability: Water containment and collection during partial and full-body cleansing.

Capability Description: Increase privacy, limit water escapes during hygiene activities, and water recovery.

Capability State of the Art: Waste and hygiene compartment used for hygiene activities. No hygiene water containment (open-ended rack volume). Some privacy in hygiene stall (open-end stall).

Parameter, Value:

Body cleansing: partial via wetted washcloth.

Water containment: moderate (washcloth air dries in cabin).

Capability Performance Goal: Private enclosure with full-body cleansing and maximum water recovery.

Parameter, Value:

Water recovery: > 90%.

Body cleansing: full body (with 100% privacy – enclosed volume).

System volume: 60 ft^3

Water containment: high (no liquid escape).

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

6.1 Environmental Control and Life Support Systems and Habitation Systems
6.1.4 Habitation

6.1.4.2 Multi-Purpose Cargo Transfer Bag (MCTB)

TECHNOLOGY

Technology Description: Reconfigurable logistics stowage bag that unfolds into a flat sheet used for outfitting crew structures. Reduces stowage volume for empty bags.

Technology Challenge: Structural design (meet launch loads and cargo load) and integration with other vehicle systems are challenges.

Technology State of the Art: Prototype MCTBs designed and manufactured. Prototypes built for evaluation of acoustic attenuation, lightweight crew quarter (CQ) concepts, and automated inventory management systems.

Parameter, Value:
Estimated mass savings through re-purposing bags: ~41 kg/CM/year.

TRL 3

Technology Performance Goal: Cargo bags that store logistics during launch. Once emptied, bags are used for outfitting crew structures.

Parameter, Value:
Repurpose ~50% MCTBs for outfitting.

TRL 7

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

CAPABILITY

Needed Capability: Repurposing logistics carriers for outfitting crew structures.

Capability Description: Lightweight, reconfigurable crew quarters, acoustic reduction for habitable volumes, radiation shielding, and water storage and processing.

Capability State of the Art: Cargo bags (different sizes) used to carry logistical items to the International Space Station. Bags are not reconfigurable. Once emptied, the bags are stowed and then trashed in departing vehicle.

Parameter, Value:
Crew Transfer Bag (CTB) mass: 81 kg/crew member (CM)/year.

Capability Performance Goal: Standard size logistics carriers for protecting equipment and supplies during launch. Repurposed for other functions once logistics are removed.

Parameter, Value:
Mass savings: ~41 kg/CM/year.
Repurpose ~50% MCTBs for outfitting.

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

6.1 Environmental Control and Life Support Systems and Habitation Systems
6.1.4 Habitation

6.1.4.3 Adaptive Intelligent Noise Control System

TECHNOLOGY

Technology Description: Active system to reduce acoustic levels. Detects noise levels and emits anti-noise.

Technology Challenge: Small speaker size capable of low-frequency cancellation. Adaptive system to account for multi-path noise interferences.

Technology State of the Art: Dedicated and stationary active noise control system. Prototype demonstrated in crew quarters ventilation system mockup.

Parameter, Value:

Noise attenuation: > 15 dB.

TRL: 3

Technology Performance Goal: Multipurpose and deployable. Active noise control in open cabin environment.

Parameter, Value:

> 25 dB

Variable cancellation geometry

TRL: 7

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

CAPABILITY

Needed Capability: Source acoustical mitigation for quiet crew interiors.

Capability Description: Active acoustic control for habitable volumes.

Capability State of the Art: Passive acoustic control with acoustic blankets and abatements in the International Space Station (ISS) crew quarters. Reduced noise levels from the ISS and crew quarters fans.

Parameter, Value:

Mass: 40 lbs/crew quarters of acoustic abatements and blankets (~5% of total mass).

Volume: 11 ft^3/crew quarters of acoustic abatements and blankets (~15% of total volume). Acoustic attenuation: 12 dBA/crew quarters.

Capability Performance Goal: Reduce volume and mass associated with attenuating acoustic emissions. Ability to separate acoustic privacy from visual and physical privacy to enable low mass crew quarters.

Parameter, Value:

Launch mass dedicated to acoustic attenuation: < 1%.

Launch volume dedicated to acoustic attenuation: < 5%.

Noise attenuation: > 25 dB.

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

6.1 Environmental Control and Life Support Systems and Habitation Systems
6.1.4 Habitation

6.1.4.4 Quiet Fans

TECHNOLOGY

Technology Description: Lightweight, efficient fans for ventilation systems in human vehicles or modules. Fans and ducting with reduced and lower acoustic noise levels.

Technology Challenge: Accurate computational fluid dynamics (CFD) code for small cabin and equipment fans.

Technology State of the Art: Quiet fan database developed. Some small fan advanced diagnostics.

Parameter, Value:

Acoustic treatment mass (as % of fan mass): ~57%.

TRL 2

Technology Performance Goal: Develop computational fluid dynamics (CFD) analysis and perform fan evaluations to predict fan noise contributions to cabin environment noise levels.

Parameter, Value:

Acoustic treatment mass (as % of fan mass): < 30%.

TRL 8

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

CAPABILITY

Needed Capability: Source acoustical mitigation for quiet crew interiors.

Capability Description: Improved CFD analysis to determine complex interaction of aerodynamic fan features. This will reduce mass and volume penalty for passive acoustic adsorption.

Capability State of the Art: International Space Station (ISS) fans (various sizes, mass) with additional mufflers and/or acoustic treatments to mitigate noise levels.

Parameter, Value:

Acoustic treatment mass (as % of fan mass): < 30%

Capability Performance Goal: Reduce need for acoustic mitigation techniques by improving fan efficiency and acoustic output.

Parameter, Value:

Acoustic treatment mass (as % of fan mass): < 30%

Minimal noise levels.

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

6.1 Environmental Control and Life Support Systems and Habitation Systems
6.1.4 Habitation

6.1.4.5 Long-Wear Clothing (Advanced Clothing)

TECHNOLOGY

Technology Description: Lightweight, antimicrobial clothing for extended wear. Reduces mass, volume, and disposal rate of clothing. Non-cotton-based clothing reduces lint.

Technology Challenge: Flammability requirements for higher-oxygen environments, crew acceptability, and microbial mitigation are challenges.

Technology State of the Art: Ground study results (2013) tested antimicrobial treatment effectiveness. Untreated wool provided longest usage, based on participant acceptance during exercise.

Parameter, Value: Clothing mass: 0.4 lb/crew member (CM)-day (0.2 kg/CM-day).

TRL: 5

Technology Performance Goal: Increase the usage rate of clothing. Requires fabrics that mitigate microbial growth to increase the crew acceptance to reuse the clothing.

Parameter, Value: Clothing mass: < 0.2 lb/CM-day.

TRL: 8

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

CAPABILITY

Needed Capability: Reduce clothing mass and volume.

Capability Description: Reduce clothing mass and volume for all mission durations.

Capability State of the Art: Clothing articles used for short periods (2-3 days) and then trashed (crew decides too dirty to wear). No cleaning or freshening capability available.

Parameter, Value:
Clothing mass: 0.4 lb/CM-day (0.2 kg/CM-day).
Not low-lint.

Capability Performance Goal: Extended wear clothing, linens, and towels or washcloths that remain hygienically safe and acceptable for use and that do not release fibers and lint into the cabin environment during use.

Parameter, Value:
Clothing mass: < 0.2 lb/CM-day.
Low-lint clothing and towels.

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

6.1 Environmental Control and Life Support Systems and Habitation Systems
6.1.4 Habitation

6.1.4.6 Laundry Freshening System (Simple Laundry)

TECHNOLOGY

Technology Description: Freshening system to extend clothing life. Removes odors from clothing and restores hygienic cleanliness.

Technology Challenge: Minimizing water usage, identifying effective freshening method or agent, and achieving crew acceptability for clothing freshness with no cleaning capability are challenges.

Technology State of the Art: International Space Station clothing is used for short periods and then discarded. Proposal for a microgravity laundry system that provides laundry-freshening and some cleaning (water-based). Laundry trade study for water-based systems, disposable clothing, and freshening systems.

Parameter, Value:

Clothing mass: 0.4 lb/crewmember (CM)-day (0.2 kg/CM-day).

TRL 3

Technology Performance Goal: Laundry cleaning system that extends the usage rate of clothing for longer missions.

Parameter, Value:

Clothing mass: 0.13 lb/CM-day (0.06 kg/CM-day).

TRL 7

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

CAPABILITY

Needed Capability: Reduce clothing mass and volume.

Capability Description: Reduce clothing mass and volume for long-duration missions.

Capability State of the Art: Clothing articles used for short periods (5-7 days) and then become trash (crew decides too dirty to wear). No cleaning/freshening capability available.

Parameter, Value:

Clothing mass: 0.4 lb/CM-day (0.2 kg/CM-day).

Clothing life: ~5-7 days.

Capability Performance Goal: Extend clothing life (crew acceptability) by providing the capability to remove odors from clothing.

Parameter, Value:

Laundering system mass: < 20 lbs

Laundering system volume: < 1 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	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

6.1 Environmental Control and Life Support Systems and Habitation Systems
6.1.4 Habitation

6.1.4.7 Lightweight Crew Quarters

TECHNOLOGY

Technology Description: Minimal mass crew quarters for sleeping and privacy. Constructed from multi-purpose cargo transfer bags (MCTBs) to provide acoustic mitigation and radiation shielding (compacted trash). Integrated active noise cancellation system.

Technology Challenge: Radiation shielding integration, acoustic mitigation, adequate ventilation in enclosed volume, and adequate structure for crew vehicle attachment are challenges.

Technology State of the Art: Low-fidelity concepts using the Multi-Purpose Cargo Transfer Bags. No integrated acoustic mitigation or radiation shielding.

Parameter, Value:

System mass: 100 lbs/crew quarters (CQ) (40 kg/CQ) (only includes structure for radiation shielding integration).

System volume: ~54 ft^3 (1.5 m^3)/CQ.

TRL: 2

Technology Performance Goal: Repurpose logistical stowage bags for a minimum mass sleep station that provides adequate ventilation, light, and acoustic privacy and radiation protection.

Parameter, Value:

System mass: 50 lbs/crew quarters.

Acoustics: < Noise cancellation (NC)-40 dB awake, > NC-25 dB sleep.

TRL: 8

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

CAPABILITY

Needed Capability: Minimal impact (mass/volume) crew structures.

Capability Description: Habitable volumes for crew use that are easily deployed in any location (no dedicated volume required). Also includes storm shelter capability for radiation events.

Capability State of the Art: Rack size dedicated, volume for sleeping. Provides crew privacy, personal stowage, ventilation, radiation protection, and acoustic and light isolation.

Parameter, Value:

System mass: ~840 lbs/CQ (~380 kg/CQ) (includes radiation protection mass).

Acoustics: 3 - 5 dB exceedance of NC-40 dB @ 250 - 750 Hz.

System volume: ~75 ft^3 (2.1 m^3)/CQ.

Radiation protection mass: 250 lbs/CQ.

Capability Performance Goal: Reduce launch mass through re-purposing of logistical materials for crew structures (sleep station) and outfitting cabin environment. Requires the ability to separate acoustic privacy from visual and physical privacy to enable low mass crew quarters.

Parameter, Value:

System mass: 50 lbs/crew quarters.

Acoustics: < NC-40 dB awake, > NC-25 dB sleep.

Radiation protection mass: < 100 lbs/CQ.

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

6.1 Environmental Control and Life Support Systems and Habitation Systems
6.1.4 Habitation

6.1.4.8 Reusable Wet Wipes (Housekeeping Only)

TECHNOLOGY

Technology Description: Wet wipes that can be laundered for multiple uses. Includes generating wetting solution for wet wipes.

Technology Challenge: Cleaning and surface disinfection effectiveness, cleaning agent compatibility with environmental control systems, laundering techniques, and methods for wetting wipes for reuse are challenges.

Technology State of the Art: Hydrogen peroxide generator for potential solvent application.

Parameter, Value:

Percent reusable wet wipes: 0%.

Wet wipes mass: ~17 lbs/year (7.5 kgs/yr) (for a crew of 4).

TRL 2

Technology Performance Goal: Increase the usage rate of wet wipes.

Parameter, Value:

Percent reusable wet wipes: >50% (housekeeping only).

TRL 8

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

CAPABILITY

Needed Capability: Reduce consumables mass and volume.

Capability Description: Reduce consumables mass and volume. Extend usage rate of consumables for housekeeping.

Capability State of the Art: Variety of disposable wipes (disinfectant, dry, tempo, baby) and cleaners (commercial-off-the-shelf (COTS) surfactants) screened for toxicity and compatibility with air and water purification systems. Dry and wet vacuums and adhesive tape used for particulates and liquids.

Parameter, Value:

Wipes usage: one-time use.

Capability Performance Goal: Reusable or launderable wipes, in-situ generated cleansers that are compatible with life support systems, and vacuum and cleaning systems suitable for safely removing and containing ultrafine, potentially hazardous planetary dust from surfaces and extravehicular garments.

Parameter, Value:

Percent reusable wet wipes: > 50% (housekeeping only).

Effective cleaning and disinfection solution that is compatible with environmental control systems.

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	1 year
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	1 year
Exploring Other Worlds: DRM 8 Crewed to Mars Moons	Enhancing	2027	2027	2021	1 year
Planetary Exploration: DRM 8a Crewed Mars Orbital	Enhancing	2033	--	2027	1 year
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	1 year
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	1 year

6.1 Environmental Control and Life Support Systems and Habitation Systems
6.1.4 Habitation

6.1.4.9 Packaged Food Mass Reduction

TECHNOLOGY

Technology Description: Packaged food mass reduction technology development.

Technology Challenge: Developing a meal replacement that is calorically dense, macro/micro nutritionally balanced, and highly acceptable to crew.

Technology State of the Art: Various packaging technologies currently exist.

Parameter, Value:

Food packaging mass penalty (individual servings, not including delivery containers, and lockers): 15%.

TRL: 3

Technology Performance Goal: Reduced upmass of the food system.

Parameter, Value:

Food packaging mass penalty: < 5%.

TRL: 6

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

CAPABILITY

Needed Capability: Food packaging mass reduction.

Capability Description: Packaged food mass reduction technology development.

Capability State of the Art: Various packaging technologies currently exist.

Parameter, Value:

Food packaging mass penalty (individual servings, not including delivery containers, lockers): 15%.

Capability Performance Goal: Reduce upmass of the food system and trash volume.

Parameter, Value:

Food packaging mass penalty: < 5%.

Incorporate meal replacement beverages and bars into food system to reduce trash volume.

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

6.1 Environmental Control and Life Support Systems and Habitation Systems
6.1.4 Habitation

6.1.4.10 Vegetable Cleaning and Safety Verification

TECHNOLOGY

Technology Description: Cleaning vegetables in-flight such that they are safe for consumption.

Technology Challenge: Protocols to make grown food safe to eat on a surface mission are currently unknown.

Technology State of the Art: The methodology and requirements to safely process and prepare nutritious and acceptable food from a bioregenerative system on a surface mission are currently unknown.

Parameter, Value: Development of the capabilities, methodologies, and requirements for feasibility of microbiological testing.

TRL: 1

Technology Performance Goal: Cleaning and safety verification of vegetables.

Parameter, Value: Safe for consumption.

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: Vegetable cleaning.

Capability Description: Develop methods for cleaning vegetables in-flight such that they are safe for consumption.

Capability State of the Art: The methodology and requirements to safely process and prepare nutritious and acceptable food from a bioregenerative system on a surface mission are currently unknown.

Parameter, Value: Integrated bioregenerative food system.

Capability Performance Goal: In-flight vegetable cleaning to include verification.

Parameter, Value: 100% safe for consumption.

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

6.1 Environmental Control and Life Support Systems and Habitation Systems
6.1.4 Habitation

6.1.4.11 Stabilized Foods

TECHNOLOGY

Technology Description: Development of innovative packaging, innovative processing, and stable nutrient content and acceptability.

Technology Challenge: Integrating food with a stable nutrient content that is acceptable to crew with innovative packaging technologies, with a focus on the interaction of packaging material with different sterilization processes.

Technology State of the Art: The strategies to increase stability while developing new packaging and processing techniques has not been fully analyzed.

Parameter, Value:
Packaged food shelf life: 1 year

TRL: 9

Technology Performance Goal: Packaging and processing, and stable nutrient content and acceptability.

Parameter, Value:
Packaged food shelf life: 5 years

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: Stabilized foods.

Capability Description: Development of innovative packaging and processing, and stable nutrient content and acceptability.

Capability State of the Art: Contribute to database with types of possible food systems and operational limits. Prepackaged food system (h/w).

Parameter, Value:
Packaged food shelf life: 1 year

Capability Performance Goal: Optimize the quality and nutrient content of fortified shelf-stable foods while investigating different packaging and processing technologies.

Parameter, Value:
Packaged food shelf life: 5 years
Packaging material with different sterilization 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 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

6.2 Extravehicular Activity Systems
6.2.1 Pressure Garment

6.2.1.1 Launch, Entry, and Abort (LEA) Arm Mobility via Soft Disconnect

TECHNOLOGY

Technology Description: A soft disconnect, which would allow change-out of components on a launch entry, and abort (LEA) suit. Tasks include modification of an existing LEA suit with soft disconnect at the arm joint and development of a more mobile LEA arm utilizing a soft disconnect.

Technology Challenge: Current suit mobility joints are limited by the launch and landing requirements. Having arms that can be installed on-orbit allows use of features, such as bearings that are not compatible with the launch and landing environment.

Technology State of the Art: Modified Advanced Crew Escape Suit (MACES) (MACES) is being developed with improved mobility when compared to the Advanced Crew Escape Suit (ACES). Investigations to determine if it is adequate for limited extravehicular activity (EVA) uses. Current MACES does not allow for component change out on-orbit or provide high mobility because those features interfere with LEA protection functions.

Parameter, Value:

No component change out.

TRL 3

Technology Performance Goal: Change out components on a LEA suit while on orbit.

Parameter, Value:

10 min arm change out using no tools (per arm).

System scalable for all sizes (5th to 95th percentile American).

Arm mobility: demonstrated ability to perform EVA tasks in a neutral buoyance lab (NBL) environment.

TRL 6

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

CAPABILITY

Needed Capability: Spacesuit arm soft disconnect.

Capability Description: Ability to change out components on a LEA suit.

Capability State of the Art: The ACES was the LEA suit utilized for Shuttle. The ACES did not include the capability to change out components on-orbit or have adequate mobility to allow it to perform EVA tasks.

Parameter, Value:

No softgoods disconnect.

Capability Performance Goal: Change out components on a LEA suit while on orbit and utilize that capability to improve EVA capability by installing alternate arms once on orbit which cannot be installed during launch and landing phases of a mission.

Parameter, Value:

Low leakage at disconnect (100 sccm). Tensile strength across soft disconnect (250 lb/in).

10 min arm change out using no tools (per arm).

System scalable for all sizes (5th to 95th percentile American).

Arm mobility: demonstrated ability to perform EVA tasks in a NBL 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	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

6.2 Extravehicular Activity Systems
6.2.1 Pressure Garment

6.2.1.2 Launch, Entry, and Abort (LEA), In-Suit Waste Containment

TECHNOLOGY

Technology Description: In-suit waste management system, which will allow the crew to spend long durations in a pressurized suit (days) without access to a pressurized cabin volume (such as during a contingency Orion depressurization).

Technology Challenge: Need to contain human waste without causing septic shock or skin infections, and without contaminating the vehicle environmental control and life support system (ECLSS). From efforts during Constellation, it appears that the most difficult part is preventing human injury or death due to long-term contact with human feces.

Technology State of the Art: The Maximum Absorbency Garment (MAG) is currently used for extravehicular activities (EVAs).

Parameter, Value:

Wear time: 12 hours

TRL 2

Technology Performance Goal: Preclude human waste leakage, allow for extended days in suit (vehicle contingency) without causing occupant injury or death.

Parameter, Value:

Wear time: 5 days minimum

TRL 7

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

CAPABILITY

Needed Capability: In-suit waste management.

Capability Description: Provide in-suit metabolic waste management system.

Capability State of the Art: The MAG is currently used for EVAs. Limited capacity.

Parameter, Value:

Wear time: 12 hours

Urine capacity: 950 ml

Feces capacity: up to 2L total capacity for urine, blood and/or fecal matter.

Capability Performance Goal: Design must preclude human waste leakage, allow for extended days in suit (vehicle contingency) without causing occupant injury or death. Increase capacity.

Parameter, Value:

Wear time: 5 days minimum

Urine capacity: 5 L minimum

Feces capacity: 375 g and 375 ml minimum.

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

6.2 Extravehicular Activity Systems
6.2.1 Pressure Garment

6.2.1.3 Pressurized Suit Ingress Systems

TECHNOLOGY

Technology Description: Technologies or systems for donning and doffing pressurized suits, such as with suitport.

Technology Challenge: NASA suitport project testing demonstrated that current suitport-compatible suits (NASA's Z1 Suit) could not be donned or doffed in a pressurized environment with sufficient efficiency and acceptability.

Technology State of the Art: The Extravehicular Mobility Unit (EMU) is the space suit used for extravehicular activity (EVA) on the International Space Station (ISS) and is donned at cabin pressure (0 psid).

Parameter, Value:	**TRL**
None – does not exist.	3

Technology Performance Goal: Allow unassisted donning and doffing suits that are pressurized while maintaining all other features of existing pressure suits (mass, sizability, life, mobility, and environmental protection).

Parameter, Value:	**TRL**
Unassisted pressurized donning and doffing at approximately 9 psid with maximum rating of 3 on Modified Cooper Harper Scale or Likert Acceptability Scale.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Development and advancement of suitport.

CAPABILITY

Needed Capability: Pressuized suit donn/doff.

Capability Description: Provide pressurized suit donning and doffing.

Capability State of the Art: The EMU has been donned in a cabin environment (unpressurized donning).

Parameter, Value:

Excessive time period to don suit.

Capability Performance Goal: Allow donning and doffing suits while maintaining all other features of existing pressure suits (mass, sizability, life, mobility, and environmental protection) but within an acceptable period of time.

Parameter, Value:

Unassisted pressurized donning and doffing at approximately 9 psid completed in less than 5 minutes each (from start point of all pre-donning steps completed to end point of ready to close the hatch) with maximum rating of 3 on Modified Cooper Harper Scale or Likert Acceptability Scale.

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

6.2 Extravehicular Activity Systems
6.2.1 Pressure Garment

6.2.1.4 Dust Protectant Mobility Bearings

TECHNOLOGY

Technology Description: Develop dust proof seals and bearings. Prove long-duration performance after extended exposure to dusty environment.

Technology Challenge: Bearings provide the mobility necessary to efficiently perform extravehicular activities (EVAs). The presence of a human in the middle of the system introduces a number of complexities, such as the oxygen environment necessary to support life, and the necessity of low torque. These factors are complicated by the necessity to tolerate a dust environment.

Technology State of the Art: Components being identified for sensitivity in dust environment and evaluated in special dust chamber for contamination and operations.

Parameter, Value:

None – does not exist.

TRL 2

Technology Performance Goal: A bearing that is durable and low mass.

Parameter, Value:

Durability: no more than a 20% increase in torque after performing 100 EVAs of 8 hours.

Mass: 40% reduction in bearing mass.

TRL 5

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Mars mission simulation, development test objective (DTO) on the International Space Station (ISS) in 2021

CAPABILITY

Needed Capability: Dust protectant mobility bearings.

Capability Description: Enable frequent suit use in the dusty environment of planetary surfaces.

Capability State of the Art: Apollo suits were the last suits used in a dusty operational environment. They had limited mobility, performed a small number of EVAs, and typically returned with dust induced problems even after just a few EVAs. The ISS Extravehicular Mobility Unit (EMU) is designed with more mobility and durability, but is much heavier and not designed to operate in a dusty environment.

Parameter, Value:

229 hrs operation in no dust environment without servicing.

Capability Performance Goal: Bearing that is durable, low mass, and dust resistant.

Parameter, Value:

Durability: no more than a 20% increase in torque after performing 100 EVAs of 8 hours each in a dusty (Mars or lunar) environment.

Mass: 40% reduction in bearing mass.

Resistant to dust: 100%

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

6.2 Extravehicular Activity Systems
6.2.1 Pressure Garment

6.2.1.5 Pressure Garment System (PGS) Materials Layup – Vacuum

TECHNOLOGY

Technology Description: PGS material layup that accounts for material exposure to dust, abrasion, punctures, cuts, hypervelocity impacts (micrometeoroids and secondary ejecta), plasma and shock, and general vehicle materials compatibility (such as ammonia) without compromising existing suit mobility. Layup may include developing self-healing materials.

Technology Challenge: Current suits are not designed for operations in future mission environments.

Technology State of the Art: Candidate advanced and/or multifunctional materials and layup techniques being identified and evaluated at the coupon level.

Parameter, Value:

PGS weight: 0.35 lbs per square foot of layup.

TRL: 2

Technology Performance Goal: Increased capability (e.g., abrasion resistance, self-healing); ability for many extravehicular activities (EVAs) to support mission needs without extensive servicing, maintenance, or need for ground support.

Parameter, Value:

Durability/life during exposure to the environment such as dust (100 EVAs (800 hours of use) minimum life).
Thermal e* = 0.085 or better.

Self-healing within 5 seconds after a 1 inch long cut.

TRL: 6

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

CAPABILITY

Needed Capability: PGS materials layup – vacuum.

Capability Description: Provide PGS material layup that protects occupant in the space vacuum environment.

Capability State of the Art: The Extravehicular Mobility Unit (EMU) has been used for orbital space missions in a vacuum environment, with maintenance, servicing and changeout with ground support.

Parameter, Value:

PGS weight: 0.35 lbs per square foot of layup,

25 EVAs without servicing, maintenance, or change out.

Thermal: e* = 0.085

No self-healing capability.

Capability Performance Goal: Reduced mass over current EMU with increased capability (e.g., abrasion resistance, self-healing); ability for many EVAs to support mission needs without extensive servicing, maintenance, or need for ground support.

Parameter, Value:

Mass 25% reduction

Durability/life during exposure to the environment such as dust (100 EVAs (800 hours of use) minimum life).

Thermal e* = 0.085 or better.

Self-healing within 5 seconds after a 1 inch long cut.

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

6.2 Extravehicular Activity Systems
6.2.1 Pressure Garment

6.2.1.6 Mars Pressure Garment System (PGS) Layup

TECHNOLOGY

Technology Description: Presure Garment System (PGS) material layup accounting for material exposure to dust, abrasion, punctures, cuts, hypervelocity impacts (micrometeoroids and secondary ejecta), plasma and shock, general vehicle materials compatibility (such as ammonia), and Mars thermal environment (including seasonal variation) without compromising existing suit mobility. Develop and evaluate flexible aerogel materials to increase durability of the material when used as a thermal insulator within the suit.

Technology Challenge: On the surface of Mars, convection is the dominant mode of heat transfer for an extravehicular activity (EVA) system. Materials that insulate from convective heat transfer are typically either stiff or brittle (such as aerogels) or are very bulky. When a bulky thermal layer is added to the other necessary layers of a pressure garment, the garment loses significant mobility and becomes difficult to utilize. Therefore, the challenge is either to make aerogel type materials more flexible and durable or make the bulkier materials less bulky and then pair that thermal layer with technologies that have worked well in the remainder of the pressure garment systems.

Technology State of the Art: Candidate advanced and multifunctional materials and layup techniques being identified and evaluated at the coupon level. In particular, semi-flexible aerogels are being developed and evaluated, but are not yet robust enough to meet mission needs.

Parameter, Value:	TRL
None – does not exist.	2

Technology Performance Goal: Maintain mobility with increased capability over current Extravehicular Mobility Unit (EMU) (e.g., abrasion resistance, self-healing); ability for many EVAs to support mission needs without extensive servicing, maintenance, or need for ground support.

Parameter, Value:	TRL
Durability/life during exposure to the environment such as dust (100 EVAs minimum). Convective thermal e*=0.085 with Martian atmosphere.	6

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

CAPABILITY

Needed Capability: Mars PGS layup.

Capability Description: Provide PGS material layup that protects occupant in the Mars environment.

Capability State of the Art: The EMU has been used for orbital space missions in a vacuum environment, with maintenance, servicing and changeout with ground support.

Parameter, Value:

PGS weight: 0.35 lbs per square foot of layup

25 EVAs without servicing, maintenance, or change out.

Thermal: e*=0.085

No self-healing capability.

Capability Performance Goal: Maintain mobility while significantly reducing mass over current EMU with increased capability (e.g., abrasion resistance, self-healing); ability for many EVAs to support mission needs without extensive servicing, maintenance, or need for ground support.

Parameter, Value:

Mass 0.25 lbs per square foot.

Durability/life during exposure to the environment such as dust (100 EVAs minimum).

Convective thermal e*=0.085 with Martian atmosphere.

Self-healing within 5 seconds after a 1 inch long cut.

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	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

6.2 Extravehicular Activity Systems
6.2.1 Pressure Garment

6.2.1.7 Pressure Garment System (PGS) for 5th to 95th Percentile American

TECHNOLOGY

Technology Description: A suit capable of fitting an occupant who is the 5th to 95th percentile American in any or all of the critical dimensions. Understand the system implications and break-over points for designing a pressure garment system, which can be utilized by occupants with 5th to 95th percentile American dimensions in any or all of the identified critical dimensions.

Technology Challenge: Anthropometric variability between different people is extensive. An individual who is small in one dimension may be quite large in another dimension. The greatest challenge in accommodating the sizing range is accommodating required suit interface hardware (life support, displays, and controls), which does not change in size based on the size of the suit occupant while also providing acceptable mobility to individuals of all relevant anthropometric variations. Numerous attempts to develop small suits have occurred over the years.

Technology State of the Art: Candidate techniques and designs to include and for scaling being identified and evaluated.

Parameter, Value:
40th – 95th percentile American.

TRL: 2

Technology Performance Goal: Crew comfort, fit level, ease of use, amount of components needed (mass and volume).

Parameter, Value:
Anthropometry: fits 5th – 95th percentile American.

TRL: 5

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

CAPABILITY

Needed Capability: Suit outfitting for 5th – 95th percentile American.

Capability Description: Provide a suit that fits 5th percentile crew members in all critical dimensions.

Capability State of the Art: The Extravehicular Mobility Units (EMUs) utilized on the International Space Station (ISS) are meant to support a wide range of crew size and allow for on-orbit resizing and nominally accommodate 40th to 95th percentile individuals.

Parameter, Value:
40th – 95th percentile.

Capability Performance Goal: Crew comfort, fit level, ease of use, amount of components needed (mass and volume) with minimal duration of crew time to resize.

Parameter, Value:
Anthropometry: fits 5th – 95th percentile American.
Time to resize: minimal.

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

6.2 Extravehicular Activity Systems
6.2.1 Pressure Garment

6.2.1.8 Advanced Helmet Systems

TECHNOLOGY

Technology Description: Advanced helmet technologies to be developed include permanent anti-fogging, more durable (anti-scratch) helmet approaches, and Orbital Replacement Unit (ORU) visor assemblies (to allow changeout when damage does occur).

Technology Challenge: The challenge is in developing technologies that can be integrated to meet the desired end product. Often, solutions to one problem make solutions to other problems non-viable. Also, hardcoat antifog solutions developed in the past have proven to be non-viable due to two primary challenges. First, the slight expansion and contraction that happens during pressurization of the helmet must be addressed by the coating without causing cracking and crazing of the coating. Second, the coating must be durable enough to withstand 100 extravehicular activities (EVAs) of use (including helmet cleaning that is often necessary between EVAs).

Technology State of the Art: The Z2 suit (currently in development) includes a new helmet geometry that will address a subset of these issues (particularly helmet shape and vent inlet for CO_2 washout). Durable permanent antifog solutions have been attempted under the Extravehicular Mobility Unit (EMU) program without success. Coatings have proven less durable than required or crack/ craze upon pressurization.

Parameter, Value:	TRL
Life (50 EVAs) CO_2 washout: maintains CO_2 washout with <6 actual cubic feet per minute (ACFM) of O_2 flow.	2

Technology Performance Goal: Durable helmet with on-orbit replaceable helmet system to address exploration needs. A helmet that achieves required CO_2 washout with a lower flow rate that reduces power consumption from the fan. A hardcoat antifog solution would resolve known eye irritation issues experienced during EVA.

Parameter, Value:	TRL
Antifog: coating applied no more frequently than once every 50 EVAs. CO_2 washout: maintain CO_2 washout with < 4 ACFM of O_2 flow.	5

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

CAPABILITY

Needed Capability: Advanced helmet.

Capability Description: Improve long-term visibility in the helmet.

Capability State of the Art: EMU uses liquid surfactant antifog, which is an eye irritant. EMU also has visors, which are susceptible to damage and must be changed out on the ground only.

Parameter, Value:

Life (50 EVAs)

Visor changeout: ground only Antifog: coating applied after every EVA.

CO_2 washout: maintains CO_2 washout with < 6 ACFM of O_2 flow.

Capability Performance Goal: Durable helmet with on-orbit replaceable helmet system to address exploration needs. A helmet that achieves required CO_2 washout with a lower flow rate that reduces power consumption from the fan. A hardcoat antifog solution would resolve known eye irritation issues experienced during EVA. Longer life and quick changeout.

Parameter, Value:

Life (100 EVA minimum).

Visor changeout without tools in less than 5 minutes in relevant gravity environment.

Antifog: coating applied no more frequently than once every 50 EVAs.
CO_2 washout: maintain CO_2 washout with < 4 ACFM of O_2 flow.

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

6.2 Extravehicular Activity Systems
6.2.1 Pressure Garment

6.2.1.9 High-Performance Extravehicular Activity (EVA) Gloves

TECHNOLOGY

Technology Description: Advancements necessary for an exploration-class glove for use on the pressure garment. Areas requiring improvement include: mobility of the complete assembly, reducing injury potential during use, reducing system mass, increasing thermal operational range, and increasing durability for longer life in the lunar or Martian dust environment.

Technology Challenge: Historically, astronauts have commented that pressurized glove tactility and mobility is a high priority for improvement with pressure garments. Human hand physiology puts numerous joints in close proximity, making design challenging. Additionally, human hand variation is considerable. The human hand has some of the smallest muscles in the body, but they are also the most used muscles in an EVA scenario. All of these factors make glove design a difficult task. Also, a priority for future missions is mitigation of injuries during use.

Technology State of the Art: The Phase VI Glove is utilized as a part of the Extravehicular Mobility Unit (EMU).

Parameter, Value:

Mobility at 20% of barehanded capability.

Durability: 8 EVAs without maintenance.

Thermal: International Space Station (ISS) environments only. Mass: 1.8 Lbs/glove (no bearing).

Pressure: 4.3 psid

TRL 2

Technology Performance Goal: Improved mobility of the hands during EVA while also increasing suit pressure and glove durability and thermal protection, as required by exploration missions.

Parameter, Value:

Improve mobility to 40% of barehanded capability.

Durability: 25 EVAs without maintenance.

Thermal protection in lunar and Mars environments.

Mass reduction: 20%.

Pressure: 8.3 psid

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Modified Advanced Crew Escape Suit (MACES) demonstration on the ISS.

CAPABILITY

Needed Capability: High-performance EVA gloves.

Capability Description: Significant advancement of gloves for future missions to reduce mass and to maintain temperature, minimize or eliminate injury, reduce astronaut fatigue, improve dexterity, and improve durability.

Capability State of the Art: The Phase VI glove is utilized as a part of the EMU.

Parameter, Value:

Mobility at 20% of barehanded capability.

Durability: 8 EVAs without maintenance.

Thermal: ISS environments only.

Mass: 1.8 lbs/glove (no bearing).

Pressure: 4.3 psid

Capability Performance Goal: Improved mobility of the hands during EVA while also increasing suit pressure and glove durability and thermal protection as required by exploration missions. In addition, reduce injury potential.

Parameter, Value:

Improve mobility to 40% of barehanded capability.

Durability: 25 EVAs without maintenance.

Thermal protection in lunar and Mars environments.

Mass reduction: 20%.

Pressure: 8.3 psid

Eliminate injuries.

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

6.2 Extravehicular Activity Systems
6.2.1 Pressure Garment

6.2.1.10 Reusable Drink/Nutrition Bag

TECHNOLOGY

Technology Description: Long life, high use, and reusable in-suit drink or nutrition bag.

Technology Challenge: The challenge will be developing a bag that can either be dried on orbit between extravehicular activities (EVAs) without significant systematic impact, can include advanced materials to avoid microorganisms growing in liquid content over time, or some other solution to allow for long-duration drink/nutrition bag usage without the need to carry a prohibitive amount of logistics.

Technology State of the Art: On space shuttle, a reusable drink bag was utilized. On the International Space Station (ISS), disposable drink bags are utilized.

Parameter, Value:

Durability: 144 uses (reusable)

TRL 2

Technology Performance Goal: A reusable drink/nutrition bag that is not susceptible to biological build-up and that requires limited maintenance between EVA uses.

Parameter, Value:

Keep liquid content contained with the drink/nutrition bag within 100 colony forming units (CFU) with more than 18 days between fill and drain cycles. Durability: 100 fills.

TRL 5

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

CAPABILITY

Needed Capability: Reusable drink bag.

Capability Description: Provide a reusuable hydration and nutrient system for the crew during EVA.

Capability State of the Art: On space shuttle, a reusable drink bag was utilized. Duration of use was limited to that experienced during a shuttle mission. On the ISS, disposable drink bags are utilized.

Parameter, Value:

CFU: N/A (less than 18 day missions)

Durability: 144 Uses (reusable)

Life: 8 years

Capability Performance Goal: Need a reusable drink/nutrition bag that is not susceptible to biological build-up and requires limited maintenance between EVA uses. Decrease the amount of logistics during long-duration missions due to length of life.

Parameter, Value:

Keep liquid content contained with the drink/nutrition bag within 100 CFU with more than 18 days between fill and drain cycles.

Durability: 100 fills.

Life: 5 years minimum.

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	2 years
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

6.2 Extravehicular Activity Systems
6.2.1 Pressure Garment

6.2.1.11 Launch, Entry, and Abort (LEA) Occupant Protection Materials, Analytical Tools, and Technologies

TECHNOLOGY

Technology Description: Products, materials, and analytical tools leading to enhanced occupant protection in the capsule landing loads environment.

Technology Challenge: Dynamic flight phases present a real and current danger to spaceflight crew members, necessitating advancement in occupant protection methodologies. With current efforts to reduce mass on manned flight vehicles, advancements must be made to reduce occupant protection material mass impacts while enhancing crew survivability measures. Long-duration spaceflight and deconditioning effects on occupant dynamic flight responses need to be understood and modelled to influence future flight vehicle designs.

Technology State of the Art: Occupant protection measures include seat restraints, conventionally-machined/ manufactured shoulder bolsters, and methods for lower body extremity restraints for prevention of flail injuries. Foreign vehicles also utilize custom molded seats in conjunction with seat stroke attenuators for landing event occupant protection. Current methods, while adequate, represent mass threats to vehicle design and opportunities for capability gap closure to address long-duration spaceflight effects on occupant protection issues.

Parameter, Value:	TRL
Prevent crew injury and mitigate dynamic flight acceleration, vibration, and flail events for short duration spaceflights.	4

Technology Performance Goal: Limitation of vibration, acceleration, and flail injuries during dynamic flight phases including landing in a capsule environment. Emphasis on enhancement of crew member protection in conjunction with material mass reduction.

Parameter, Value:	TRL
Uninjured crew member egress of spacecraft after long-duration spaceflight with no occupant protection-related adverse effects.	6

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

CAPABILITY

Needed Capability: Prevent crew member acceleration, vibration, or extremity flail injury from dynamic flight phase events. Computation methodologies for prediction and prevention of injury to crew members returning from long-duration space missions.

Capability Description: New material development and enhancement of computational methodolgies for prediction and prevention of injuries due to acceleration, vibration, or extremity flail.

Capability State of the Art: Current capabilities address known acceleration loads.

Parameter, Value:

Acceptable Probability Loss of Mission (PLOM) and Acceptable Probability Loss of Crew (PLOC) for short-duration spaceflights.

Capability Performance Goal: Minimize crew injury and maximize crew survival in acceleration environments.

Parameter, Value:

Prevent crew member acceleration, vibration, and/or extremity flail injury during dynamic mission events. Minimum PLOM and PLOC.

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 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	5 years

6.2 Extravehicular Activity Systems
6.2.2 Portable Life Support System

6.2.2.1 Closed-Loop Heat Rejection System with Zero Consumables; Spacesuit Water Membrane Evaperator (SWME)-Radiator Hybrid

TECHNOLOGY

Technology Description: Heat rejection components are used to reject metabolic heat from the suit occupant and internal components.

Technology Challenge: Hardware must be developed to reject heat in a Martian atmosphere while fitting within a small enough mass and volume box to be effectively packaged into a life support system that can be carried by an astronaut. Radiator approaches seem to hold the most promise. Current simple radiator designs reject heat at a relatively steady rate, but the rate of heat generation by the astronaut can vary from 70 to 730 W; a radiator must allow adjustment of the heat removal rate, without penalty against other parameters compared to SOA.

Technology State of the Art: Advanced portable life support system (PLSS) that uses a spacesuit water membrane evaperator (SWME) to reject heat. SWME evaporates water and the vapor is released to space.

Parameter, Value:

8 hours @ 850 British Thermal Units (BTU)/hr (250 Watts). Heat rejection via sublimator.

TRL: 4

Technology Performance Goal: Significant increase in heat rejection performance and provision for closed loop operations (no venting to environment).

Parameter, Value:

810 Watts (2770 BTU/hr).

Venting: 0

Power: 0 (passive).

TRL: 5

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Fluid boiling/evaporation and condensation phase change behavior in partial or microgravity. Mars mission simulation, development test objective (DTO) on the International Space Station (ISS) in 2021.

CAPABILITY

Needed Capability: Closed-loop heat rejection system with zero consumables.

Capability Description: Maintain thermal environment for suit occupant while adhering to planetary protection requirements.

Capability State of the Art: Sublimator is utilized as a part of the Extravehicular Mobility Unit (EMU) to reject heat (metabolic heat plus system generated heat). Sublimator evaporates water and the vapor is released to space. System is not closed loop and will not function in a Martian atmosphere.

Parameter, Value:

8 hours @ 850 BTU/hr (250 Watts). Heat rejection via sublimator. Not Mars functionable.

Capability Performance Goal: Significant increase in heat rejection performance and provision for closed loop operations (no venting to environment) found in a Martian atmosphere. Possess variable heat rejection capability.

Parameter, Value:

810 Watts (2770 BTU/hr).

Venting: 0

Power: 0 (passive); variable heat rejection capability between 70 – 810 W.

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

6.2 Extravehicular Activity Systems
6.2.2 Portable Life Support System

6.2.2.2 Closed-Loop Heat Rejection System with Zero Consumables; Heat Pump Radiator Hybrid

TECHNOLOGY

Technology Description: Heat-rejection components are used to reject metabolic heat from the suit occupant and internal components. Goal is to develop hardware that can be utilized to reject heat in a Martian atmosphere, does not vent, works with potable water, and is appropriate volume and mass to package into a portable life support system (PLSS).

Technology Challenge: Hardware must be developed to reject heat in a Martian atmosphere while fitting within a small enough mass and volume box to be effectively packaged into a life support system that can be carried by an astronaut. Radiator approaches seem to hold the most promise. Current simple radiator designs reject heat at a relatively steady rate, but the rate of heat generation by the astronaut can vary from 70 to 730 W; a radiator must allow adjustment of the heat removal rate, without penalty against other parameters compared to SOA.

Technology State of the Art: Advanced PLSS that uses a spacesuit water membrane evaporator (SWME) to reject heat. SWME evaporates water and the vapor is released to space. System is not closed loop and will not function in a Martian atmosphere.

Parameter, Value:

8 hours @ 850 British Thermal Units (BTU)/hr (250 Watts).

TRL: 4

Technology Performance Goal: Significant increase in heat rejection performance and provision for closed loop operations (no venting to environment).

Parameter, Value:

810 Watts (2770 BTU/hr)

Venting: 0

Power: 0 (passive)

TRL: 5

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Fluid boiling/evaporation and condensation phase change behavior in partial or microgravity.

CAPABILITY

Needed Capability: Closed-loop heat rejection system with zero consumables.

Capability Description: Maintain thermal environment for suit occupant while adhering to planetary protection requirements.

Capability State of the Art: Sublimator is utilized as a part of the Extravehicular Mobility Unit (EMU) to reject heat (metabolic heat plus system generated heat). Sublimator evaporates water and the vapor is released to space. System is not closed loop and will not function in a Martian atmosphere.

Parameter, Value:

8 hours @ 850 BTU/hr (250 Watts).

Heat rejection via sublimator.

Capability Performance Goal: Significant increase in heat rejection performance and provision for closed loop operations (no venting to environment) with variable heat rejection capability.

Parameter, Value:

810 Watts (2770 BTU/hr)

Venting: 0

Power: 0 (passive); variable heat rejection capability between 70 – 810 W.

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

6.2 Extravehicular Activity Systems
6.2.2 Portable Life Support System

6.2.2.3 Closed-Loop Heat Rejection System with Zero Consumables; Portable Life Support System (PLSS) Radiator

TECHNOLOGY

Technology Description: Heat-rejection components are used to reject metabolic heat from the suit occupant and internal components. Goal is to develop hardware that can be utilized to reject heat in a Martian atmosphere, does not vent, works with potable water, and is appropriate volume and mass to package into a PLSS.

Technology Challenge: Hardware must be developed to reject heat in a Martian atmosphere while fitting within a small enough mass and volume box to be effectively packaged into a life support system that can be carried by an astronaut. Radiator approaches seem to hold the most promise. Current simple radiator designs reject heat at a relatively steady rate, but the rate of heat generation by the astronaut can vary from 70 to 730 W; a radiator must allow adjustment of the heat removal rate, without penalty against other parameters compared to SOA.

Technology State of the Art: Advanced PLSS that uses a spacesuit water membrane evaporator (SWME) to reject heat. SWME evaporates water and the vapor is released to space. System is not closed loop and will not function in a Martian atmosphere.

Parameter, Value:

8 hours @ 850 British Thermal Units (BTU)/hr (250 Watts).

TRL: 4

Technology Performance Goal: Significant increase in heat rejection performance and provision for closed loop operations (no venting to environment).

Parameter, Value:

810 Watts (2770 BTU/hr).

Venting: 0

Power: 0 (passive)

TRL: 5

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

CAPABILITY

Needed Capability: Closed-loop heat rejection system with zero consumables.

Capability Description: Maintain thermal environment for suit occupant while adhering to planetary protection requirements.

Capability State of the Art: Sublimator is utilized as a part of the Extravehicular Mobility Unit (EMU) to reject heat (metabolic heat plus system generated heat). Sublimator evaporates water and the vapor is released to space. System is not closed loop and will not function in a Martian atmosphere.

Parameter, Value:

8 hours @ 850 BTU/hr (250 Watts).

Heat rejection via sublimator.

Capability Performance Goal: Significantly reduce the amount of expendable water consumed in the sublimator by using a radiator to reject heat during an extravehicular activity (EVA). Closed loop. Variable heat rejection capabilitly.

Parameter, Value:

810 Watts (2770 BTU/hr).

Venting: 0

Power: 0 (passive); variable heat rejection capability between 70 – 810 W.

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

6.2 Extravehicular Activity Systems
6.2.2 Portable Life Support System

6.2.2.4 Portable Life Support System (PLSS) Fan

TECHNOLOGY

Technology Description: PLSS fan is responsible for circulating the gas in the ventilation loop. Needs to provide adequate head rise to circulate 6 actual cubic feet per minute (ACFM) through the Advanced Extravehicular Mobility Unit (AEMU) ventilation loop.

Technology Challenge: Current centrifugal blower designs achieve high aero efficiency but with very tight tolerances (<0.003 in) and high shaft speeds (20 krpm+). This technology would seek to open the tolerances and increase the head-rise, while lowering shaft speed and keeping the volume approximately the same as the current technology.

Technology State of the Art: Technology can be scaled with impeller size and shaft speed to increase the head-rise but with tight tolerances that result in sensitivity to contamination.

Parameter, Value:

Current Extravehicular Mobility Unit (EMU) fan design runs at 20 krpm to generate 2.7 in-H_2O head-rise at 6 ACFM and 4.3 psia.

TRL 3

Technology Performance Goal: Advanced fan design with significant performance improvements.

Parameter, Value:

Flow rate (min): 6 ACFM.

Head rise @ 4.3 psia (min): 5.8 inches of water.

Revolutions per minute (RPM) (max): 5000.

TRL 4

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

CAPABILITY

Needed Capability: Advanced PLSS fan.

Capability Description: Improve circulation in the suit ventilation loop.

Capability State of the Art: The centrifugal fan approach is used in the current International Space Station (ISS) EMU with < 150 micron filtration at the inlet that will have to be made finer to address the potential particulate loading from lunar and Martian environments.

Parameter, Value:

2.7 in-H_2O head-rise at 6 ACFM and 4.3 psia.

Capability Performance Goal: Advanced fan design with significant performance improvements to include aero efficiency.

Parameter, Value:

Flow rate (min): 6 ACFM.

Head rise @ 4.3 psia (min): 5.8 inches of water.

RPM (max): 5000.

Aero efficiency > 40%

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

6.2 Extravehicular Activity Systems
6.2.2 Portable Life Support System

6.2.2.5 Portable Life Support System (PLSS) Pressure Sensor

TECHNOLOGY

Technology Description: Pressure sensor that is a small form factor, high reliability, radiation hardened, and consumes little power.

Technology Challenge: While the microelectromechanical systems (MEMS) and sputtered approaches enable very small, accurately-fabricated strain-gauges, the increased accuracy is also obtained from precision-matched resistors and active compensation circuits that draw more power and make the sensor more susceptible to radiation effects.

Technology State of the Art: Sensors on the International Space Station (ISS) Extravehicular Mobility Unit (EMU) utilize a potentiometer/wiper that is attached to a bellows.

Parameter, Value:

Accuracy: 2-3% full scale output (FSO)

Radiation-hard as passive potentiometer.

TRL 2

Technology Performance Goal: Small form factor sensor(s) with significant increase in accuracy and radiation resistance.

Parameter, Value:

Accuracy: < 0.1% FSO

Volume: < 20 cc

Total dose: > 10 kRad (Si)

TRL 4

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

CAPABILITY

Needed Capability: Advanced PLSS pressure sensor.

Capability Description: Provide accurate suit pressure data.

Capability State of the Art: Existing pressure transducers utilized in the ISS EMU are potentiometer based resulting in lower accuracies to achieve the low power consumption.

Parameter, Value:

Accuracy: 2-3% FSO

Volume: ~30 cc

Power: ~5 mW

Radiation-hard as passive potentiometer.

Capability Performance Goal: Advanced sensor(s) with significant increase in accuracy and radiation resistance as well as minimal power consumption.

Parameter, Value:

Accuracy: < 0.1% FSO

Volume: < 20 cc

Power: < 30 mW

Single event latchup (SEL) > 75 MeV-cm^2/mg

Total dose: > 10 kRad(Si)

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

6.2 Extravehicular Activity Systems
6.2.2 Portable Life Support System

6.2.2.6 Closed-Loop On-Back Regenerable Carbon Dioxide (CO_2) and Humidity Control

TECHNOLOGY

Technology Description: Concepts for CO_2 and H_2O removal system that is compatible with the development of portable life support system (PLSS) architectures. Need an on-back, regenerable solution, which requires significant vehicle power.

Technology Challenge: Developing closed-loop CO_2 removal is necessary if stringent planetary protection requirements are implemented. Current technology requires a separate large oven that would have a large impact on pressurized mobile assets, such as rovers. Developing regenerable non-venting CO_2 removal hardware which does not have a separate regenerator will require significant out of the box thinking.

Technology State of the Art: Technology uses a single sorbent bed of AgO, which binds the CO_2 into Ag_2CO_3. This then must be heated in an oven to 400°F post-extravehicular activity (EVA) to reverse the reaction and liberate the CO_2 into the cabin. The bed size is limited and is tracked as a consumable that limits EVA duration; it is especially sensitive to pre-EVA water loading from the ventilation loop as it requires the H_2O to catalyze the reaction.

Parameter, Value:

EVA CO_2 load: 1.48 lbs
EVA CO_2 loading rate: < 152 g/hr EVA H_2O loading rate: N/A
On-back (PLSS) mass: 32 lbs
Life cycles: 55 EVA

TRL
2

Technology Performance Goal: Closed-loop system for stringent planetary protection requirements with significant improvement in performance (e.g., mass and power reduction).

Parameter, Value:

EVA CO_2 loading rate: > 200 g/hr
EVA H_2O loading rate: > 140 g/hr
On-back (PLSS) mass: < 18 lbm

TRL
6

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

CAPABILITY

Needed Capability: Closed-loop on-back regenerable CO_2 and humidity control.

Capability Description: PLSS-compatible regenerable CO_2 and H_2O removal.

Capability State of the Art: International Space Station (ISS) Extravehicular Mobility Unit (EMU) utilizes either a LiOH or AgO single sorbent bed to absorb CO_2 during the EVA. The system is not regenerable during the EVA. In the case of LiOH, it is a consumable. For AgO, it is regenerated in a heated oven for 14 hours post-EVA. The single sorbent bed is a consumable that is tracked by the EMU during the EVA and in the case of MetOx (AgO) often limits the EVA duration. Neither system enables the control of relative humidity in the ventilation loop as that is done by a separate system: sublimator slurper and pitot separator.

Parameter, Value:

EVA CO_2 load: 1.48 lbs
EVA CO_2 loading rate: < 152 g/hr
EVA H_2O loading rate: N/A
Power consumed in regeneration: ~8550 Wh.
On-back (PLSS) mass: 32 lbs
Life cycles: 55 EVA

Capability Performance Goal: Closed-loop system for stringent planetary protection requirements with significant improvement in performance (e.g., mass and power reduction). Possesses regenerable capability with extended life cycles

Parameter, Value:

Consumables: 0
EVA CO_2 loading rate: > 200 g/hr
EVA H_2O loading rate: > 140 g/hr
On-back (PLSS) mass: < 18 lbm
Life cycles: > 100 EVA

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

6.2 Extravehicular Activity Systems
6.2.2 Portable Life Support System

6.2.2.7 Closed-Loop Consumable Carbon Dioxide (CO_2) Removal, Low Mass

TECHNOLOGY

Technology Description: Concepts for CO_2 and H_2O removal system that is compatible with the development of portable life support system (PLSS) architectures. Need a lightweight, non-regenerable CO_2 and H_2O removal system that is compatible with in-development PLSS architectures.

Technology Challenge: Developing closed-loop, CO_2 removal is necessary if stringent planetary protection requirements are implemented. Current technology requires a separate large oven which would be a large impact on pressurized mobile assets such as rovers. Developing small non-regenerable non-venting CO_2 removal hardware is anticipated to require significant out of the box thinking. LiOH is the closest current technology available in this area, but it is too large and heavy to be practical from a logistics standpoint.

Technology State of the Art: Technology uses a single sorbent bed of AgO, which binds the CO_2 into Ag_2CO_3 that then must be heated to 400° F post- extravehicular activity (EVA) to reverse the reaction and liberate the CO_2 into the cabin. The bed size is limited and is tracked as a consumable that limits EVA duration; it is especially sensitive to pre-EVA water loading from the ventilation loop as it requires the H_2O to catalyze the reaction.

Parameter, Value:

EVA CO_2 loading rate: < 152 g/hr EVA H_2O loading rate: N/A

On-back (PLSS) mass: 32 lbs

TRL: 2

Technology Performance Goal: Closed loop system for stringent planetary protection requirements.

Parameter, Value:

EVA CO_2 loading rate: > 2.6 lbs

EVA H_2O loading rate: > 200 g/hr

TRL: 2

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

CAPABILITY

Needed Capability: Closed loop consumable CO_2 removal.

Capability Description: Provide lightweight PLSS-compatible non-regenerable CO_2 and H_2O removal.

Capability State of the Art: The current International Space Station (ISS) Extravehicular Mobility Unit (EMU) utilizes either a LiOH or AgO single sorbent bed to absorb CO_2 during the EVA. The system is not regenerable during the EVA. In the case of LiOH, it is a consumable. For AgO, it is regenerated in a heated oven for 14 hours post-EVA. The single sorbent bed is a consumable that is tracked by the EMU during the EVA and in the case of MetOx (AgO) often limits the EVA duration. Neither system enables the control of relative humidity in the ventilation loop as that is done by a separate system: sublimator slurper and pitot separator.

Parameter, Value:

EVA CO_2 loading rate: < 152 g/hr

EVA H_2O loading rate: N/A

On-back (PLSS) mass: 32 lbs

Capability Performance Goal: Closed-loop system for stringent planetary protection requirements while including significant improvement in increased loading rate and mass reduction.

Parameter, Value:

EVA CO_2 loading rate: > 2.6 lbs,

EVA H_2O loading rate: > 200 g/hr

On-back (PLSS) mass: < 18 lbs

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

6.2 Extravehicular Activity Systems
6.2.2 Portable Life Support System

6.2.2.8 Alternate Carbon Dioxide (CO_2) Sorbent

TECHNOLOGY

Technology Description: Alternate CO_2 sorbent systems used within the rapid cycle amine (RCA). Alternate chemistries may provide a greater capacity and efficiency in removing CO_2 and provide a lower preference for removing water and therefore result in less loop drying.

Technology Challenge: The challenge is to improve on the performance of the SA9T sorbent while at the same time mitigating non-desirable aspects, such as NH_3 liberation into the ventilation loop. Additionally, if trace contaminant control functionality can be integrated, carbon or other swingbed or passive membrane approaches could be developed that meet the functional requirements while mitigating NH_3 production. Implementation of the swingbed approach over a single sorbent bed also offers the complexity of the valving and motor actuators to facilitate the bed swing which must be addressed. A passive membrane approach must have a high selectivity > 1400 for CO_2 over O_2 in order to be acceptable at the system level; this has yet to be achieved at ambient temperature.

Technology State of the Art: One of the technologies for accomplishing this task, amine swingbed, can meet many of the functional requirements but also releases NH3 into the ventilation loop and concentrates it during storage periods. The current technology uses a single sorbent bed of AgO, which binds the CO_2 into Ag_2CO_3 that then must be heated to 400° F post- extravehicular activity (EVA) to reverse the reaction and liberate the CO_2 into the cabin. The bed size is limited and is tracked as a consumable that limits EVA duration; it is especially sensitive to pre-EVA water loading from the ventilation loop as it requires the H_2O to catalyze the reaction. The metox cartridge also includes 0.25lb of activated charcoal for trace contaminant control.

Parameter, Value:

EVA CO_2 load: 1.48 lbs

EVA CO_2 loading rate: <152 g/hr EVA H_2O loading rate: N/A

On-back (portable life support system (PLSS)) mass: 32 lbs

Life cycles: 55 EVA

TRL: 2

Technology Performance Goal: CO_2 sorbent with a greater capacity/efficiency in removing CO_2 and improved water removal.

Parameter, Value:

EVA CO_2 load: maximize

EVA CO_2 loading rate: > 200 g/hr

EVA H_2O loading rate: > 140 g/hr

On-back (PLSS) mass: < 18 lbs

Life cycles: > 100 EVA

TRL: 2

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

CAPABILITY

Needed Capability: High capacity CO_2 sorbent.

Capability Description: Provide sorbents with a higher CO_2 removal capacity.

Capability State of the Art: The current International Space Station (ISS) Extravehicular Mobility Unit (EMU) utilizes either a LiOH or AgO single sorbent bed to absorb CO_2 during the EVA. The system is not regenerable during the EVA. In the case of LiOH, it is a consumable. For AgO, it is regenerated in a heated oven for 14 hours post-EVA. The single sorbent bed is a consumable that is tracked by the EMU during the EVA and in the case of Metox (AgO) often limits the EVA duration. Neither system enables the control of relative humidity in the ventilation loop as that is done by a separate system: sublimator slurper and pitot separator.

Parameter, Value:

Consumable: Yes

EVA CO_2 load: 1.48 lbs

EVA CO_2 loading rate: < 152 g/hr EVA H_2O loading rate: N/A

Power consumed in regeneration: ~8550 Wh.

On-back (PLSS) mass: 32 lbs

Life cycles: 55 EVA

Capability Performance Goal: CO_2 sorbent with a significantly greater capacity/efficiency in removing CO_2 and improved water removal. No conumable with imiprovement in power consumption during regeneration.

Parameter, Value:

Consumable: No

EVA CO_2 load: maximize

EVA CO_2 loading rate: > 200 g/hr

EVA H_2O loading rate: > 140 g/hr

Power consumed during regeneration: < 10W

On-back (PLSS) mass: < 18 lbs

Life cycles: > 100 EVA

Trace contaminant: NH_3, CH_2O

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

6.2 Extravehicular Activity Systems
6.2.2 Portable Life Support System

6.2.2.9 Atmospheric Constituent Sensor

TECHNOLOGY

Technology Description: Modular sensor that is sized appropriately for inclusion in a portable life support system (PLSS), not susceptible to humidity, has accurate readings in 3 psia to 23 psia range, and has low time between each sample collection and its associated reporting. Sensor should be a common sensor and avionics package to be used by extravehicular activity (EVA), environmental control an life support system (ECLSS) and others; that is, capable of sensing a variety of gas constituents (e.g. ammonia, CO_2, water vapor, and O_2).

Technology Challenge: The challenges are sensitivity to liquid water and stability and materials compatibility.

Technology State of the Art: The NDIR approach using an incandescent source and filter is limited in its means of improving upon the performance values stated and hence, not necessarily suitable for the planned missions without further development.

Parameter, Value:

Range: 0.1 – 30 mmHg.

Pressure range: 3.3 – 23.5 psia.

Moisture range: 0-100% non-condensing.

TRL: 2

Technology Performance Goal: Small sensor with significant enhanced capability and accuracy over SOA.

Parameter, Value:

Range: 0.1 – 30 mmHg

Pressure range: 3.3 – 23.5 psi

Moisture range: 0-100%

Uncertainty: < 5% at 5 mmHg

TRL: 5

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Modified Advanced Crew Escape Suit (MACES) demonstration on the International Space Station (ISS).

CAPABILITY

Needed Capability: Advanced atmospheric constituent sensor.

Capability Description: Improve CO_2 and other gas constituent sensing in the PLSS.

Capability State of the Art: The current ISS Extravehicular Mobility Unit (EMU) utilizes a non-dispersive infra-red sensor that computes the partial pressure of CO_2 in the cell based on Beer's Law. The sense uses interleaved reference sensors to address source, filter, window loss changes through life. An additional algorithm is used by the external monitoring system, Caution and Warning System, to correct for pressure.

Parameter, Value:

Range: 0.1 – 30 mmHg.

Pressure range: 3.3 – 23.5 psia.

Moisture range: 0-100% non-condensing.

Free-water sensitivity: fails in presence of water.

Pressure compensation: external. Power: 2.4 W.

Response time: < 15 sec.

Uncertainty: > 20% at 5 mmHg.

Capability Performance Goal: Modular sensor that is sized appropriately for inclusion in a PLSS, not susceptible to humidity, has accurate readings in designated range, and has low time between each sample collection and its associated reporting.

Parameter, Value:

Range: 0.1 – 30 mmHg.

Pressure range: 3.3 – 23.5 psi.

Moisture range: 0-100%.

Free-water sensitivity: insensitive.

Pressure compensation: internal.

Power: < 1.5 W.

Response time: < 3 sec.

Uncertainty: < 5% at 5 mmHg.

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

6.2 Extravehicular Activity Systems
6.2.2 Portable Life Support System

6.2.2.10 Alternate Contaminant Control Cartridge (CCC) Sorbent

TECHNOLOGY

Technology Description: Alternate sorbent for CCC function.

Technology Challenge: Obtaining a sorbent that has the affinity to adsorb compounds at trace levels and then at the same time without addition of considerable energy release those same compounds with a relatively minor pressure swing to vacuum is a challenging task. In addition, evaluation should be completed for hydrogen build-up from metabolic sources, to address flammability concerns in a 100% O_2 environment.

Technology State of the Art: The activated charcoal used as part of the Extravehicular Mobility Unit (EMU) trace contaminant control cartridge is a broad adsorber that covers the two most prevalent contaminants, NH_3 and CH_2O, as well as a host of others.

Parameter, Value:

Trace contaminant: NH_3, CH_2O, others.

TRL: 2

Technology Performance Goal: Sorbent for absorbing compounds at trace levels.

Parameter, Value:

Trace contaminant: NH_3, CH_2O, others. NH_3 uptake: > 20 mg/g.

TRL: 6

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

CAPABILITY

Needed Capability: Advanced CCC sorbent.

Capability Description: A sorbent that can absorb trace contaminants, especially NH_3 and CH_2O, from a space suit ventilation loop that can be regenerated with a vacuum swing during an extravehicular activity (EVA).

Capability State of the Art: The current International Space Station (ISS) EMU utilizes 0.25 lbs of activated charcoal that is regenerated or replaced after each EVA as it is installed in the Metox (AgO) canister or the LiOH canister.

Parameter, Value:

Consumable: yes.

Trace contaminant: NH_3, CH_2O, others.

Capability Performance Goal: Sorbent for absorbing compounds at trace levels without addition of considerable energy, i.e., regenrable.

Parameter, Value:

Consumable: none; regenerable.

Trace contaminant: NH_3, CH_2O, others.

NH_3 uptake: > 20mg/g

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

6.2 Extravehicular Activity Systems
6.2.2 Portable Life Support System

6.2.2.11 Carbon Dioxide (CO_2) and Water (H_2O) Membrane

TECHNOLOGY

Technology Description: Membrane-based systems to remove CO_2 and water vapor from the vent loop without requiring moving parts.

Technology Challenge: Early versions of the membrane required heating to high temperatures which in an extravehicular activity (EVA) perspective would be prohibitive from a power perspective. As the Small Business Innovation Research (SBIR) has progressed, these requirements have been significantly reduced, but are anticipated to require continued attention. The technology will need to be challenged under more flight-like environments and eventually incorporated into a system to demonstrate its viability.

Technology State of the Art: Technology preferentially allows CO_2 and H_2O to pass through to vacuum while maintaining the O_2 in the loop.

Parameter, Value:

EVA CO_2 loading rate: < 152 g/hr.

TRL 5

Technology Performance Goal: Membrane-based removal system at a modest power draw.

Parameter, Value:

EVA CO_2 loading rate: > 200 g/hr.

EVA H_2O loading rate: > 140 g/hr.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Two-phase (gas-liquid) fluid dynamics in partial or microgravity. Mars mission simulation on the International Space Station (ISS).

CAPABILITY

Needed Capability: CO_2 and H_2O membrane.

Capability Description: Provide passive CO_2 and water vapor removal from the suit vent loop.

Capability State of the Art: ISS Extravehicular Mobility Unit (EMU) utilizes either a LiOH or AgO single sorbent bed to absorb CO_2 during the EVA. The system is not regenerable during the EVA. In the case of LiOH, it is a consumable. Neither system enables the control of relative humidity in the ventilation loop as that is done by a separate system: sublimator slurper and pitot separator.

Parameter, Value:

EVA CO_2 loading rate: < 152 g/hr.

Consumable: Yes (AgO)

Regeneration time: 14 hours post-EVA (AgO)

Capability Performance Goal: CO_2 and H_2O membrane-based removal system at a modest power draw without moving parts.

Parameter, Value:

No moving parts.

EVA CO_2 loading rate: > 200 g/hr.

EVA H_2O loading rate: > 140 g/hr.

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

6.2 Extravehicular Activity Systems
6.2.3 Power, Avionics, and Software

6.2.3.1 Battery Package

TECHNOLOGY

Technology Description: A new battery chemistry with a form factor that is usable in an Advanced Extravehicular Mobility Unit (AEMU) portable life support system (PLSS) battery volume and other AEMU systems. Includes vehicle support hardware, such as battery rechargers, as required. NOTE: Current frequency and level of crew time for in-flight calibration of power tools is not acceptable for long-duration missions beyond low-Earth orbit (LEO).

Technology Challenge: The primary challenge is improved power density. Li-ion cells do not have adequate power density to meet the needs of PLSSs of the future.

Technology State of the Art: International Space Station (ISS) Extravehicular Mobility Unit (EMU) uses Li-ion battery chemistries to power the PLSS critical loads, such as the fan, pump, and separator.

Parameter, Value:	TRL
Nominal voltage: 28 Vdc Operating temperature: 10-30° C	2

Technology Performance Goal: Increased capacity battery with improved power density.

Parameter, Value:	TRL
Packaged power density: 150 Wh/Kg minimum.	5

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

CAPABILITY

Needed Capability: Long-duration, advanced suit battery package.

Capability Description: Improve battery chemistry for long-duration use.

Capability State of the Art: Li-Ion battery chemistries to power the PLSS critical loads such as the fan/pump/separator, etc. within a select operating temperature range and nominal voltage.

Parameter, Value:

Capacity: 540 Wh

Mass: 15.5 lbm

Nominal voltage: 28 Vdc

Operating temperature: 10-30° C

Capability Performance Goal: Increased capacity battery with improved power density as compared to the SOA.

Parameter, Value:

Packaged power density: 150 Wh/Kg minimum.

Mass: 15.5 lbm max.

Nominal voltage: 28 Vdc.

Operating temperature: 10-30° 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
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

6.2 Extravehicular Activity Systems
6.2.3 Power, Avionics, and Software

6.2.3.2 Extravehicular Activity (EVA) Informatics

TECHNOLOGY

Technology Description: EVA informatics system (to include field geology) that accurately records the position of the Advanced Extravehicular Mobility Unit (AEMU) relative to a known point such as a rover; records audio from the AEMU (such as spoken field notes); records high-definition (HD) video from a camera; and provides real time access to the astronaut to review findings while still EVA and for situational awareness.

Technology Challenge: New technologies (audio technology miniaturization and radiation hardening, camera HD imager radiation hardening, efficient HD motion imagery compression, panoramic motion imagery acquisition, etc.) must be developed and proven for Earth-based applications and then modified to support space missions, including integration with a spacesuit (either wirelessly or hard-wired).

Technology State of the Art: Earth field geology are now exploring advanced technologies, like augmented reality and digital electronics.

Parameter, Value:

None – does not exist.

TRL: 2

Technology Performance Goal: Key technologies to replace the 20th-century Earth-based tools, e.g., electronics to record audio notes, automatic tracking and recording of location and devices to display information (traditional or heads-up display (HUD)) to the crew member.

Parameter, Value:

Record location with 1 m accuracy at a distance of 200 m from a known point.

Data transmission latency < than 3 seconds.

TRL: 5

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Field testing.

CAPABILITY

Needed Capability: EVA informatics.

Capability Description: EVA informatics.

Capability State of the Art: Space field geology has not been conducted since Apollo; only analogs are currently active and are limited to standard Earth-based techniques, such as manual logging and photography. The International Space Station (ISS) system uses a paper cuff checklist for procedures and an alpha numeric display to interact with crew member.

Parameter, Value:

None – does not exist.

Capability Performance Goal: Key technologies to replace the 20th-century Earth-based tools, e.g., electronics to record audio notes, automatic tracking and recording of location and devices to display information (traditional or HUD) to the crew member. Extended data storage and high resolution.

Parameter, Value:

O_2 compatible or external crew display readability in all lighting conditions.

Record location with 1 m accuracy at a distance of 200 m from a known point.

Data transmission latency < than 3 seconds.

Resolution: 1080p.

Data storage for 8 hours of video and audio.

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

6.2 Extravehicular Activity Systems
6.2.3 Power, Avionics, and Software

6.2.3.3 Integrated Radio/Audio System

TECHNOLOGY

Technology Description: Radiation-hardened, integrated radio and audio system that is small enough to package into a portable life support system (PLSS) and can operate simultaneously on ultra high frequency (UHF) and second frequency with high data throughput, and that does not use a communications cap or other head-worn equipment. The system should be tolerant of noise internal to the suit and a wide pressure regime. Communications data transfer and networking, such as via the Deep Space Network and associated accessibility, are addressed in the roadmap for TA 5 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems.

Technology Challenge: Technologies in speech intelligibility, speech quality, listening quality, and listening effort for in-helmet vocal communications. A primary focus is improving the interface between crew member and the acoustic pickup (microphones) and generation (speaker) systems.

Technology State of the Art: Space suits are equipped with radio transmitters and receivers so that spacewalking astronauts can talk with ground controllers and/or other astronauts. The astronauts wear headsets with microphones and earphones. The transmitters and receivers are located in the backpacks worn by the astronauts and only operate in the ultra-high frequency (UHF) band.

Parameter, Value:	TRL
Operates on UHF band.	2

Technology Performance Goal: Extravehicular activities (EVAs) with ntegrated radio/audio technologies compatible with the unique suit environment, including a reduced/low pressure and 100% oxygen.

Parameter, Value:	TRL
UHF Communication, Mean Opinion Score (MOS) for Listening Quality (Lq) and Listening Effort (Le) of 3.9 or greater, or Articulation Index (AI) of 0.7 or better or 90% intelligibility in the crew member’s native language for both inbound and outbound speech communication.	5

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

CAPABILITY

Needed Capability: Integrated suit radio/audio system.

Capability Description: Provide noise-tolerant, radiation-hardened audio system for the suit. Provide radiation-hardened high data throughput radio for the suit.

Capability State of the Art: Space suits are equipped with radio transmitters and receivers so that spacewalking astronauts can talk with ground controllers and other astronauts. The astronauts wear headsets with microphones and earphones. The transmitters and receivers are located in the backpacks worn by the astronauts and only operate in the UHF band. No high rate date.

Parameter, Value:

Only operates on UHF band.

No high rate data.

Capability Performance Goal: EVAs with integrated radio and audio technologies to include low-power cameras; user-friendly, minimally invasive crew member information displays; and technologies that provide improvements in speech quality, listening quality and listening effort for in-helmet vocal communications. Future technologies must be compatible with the unique suit environment, including a reduced pressure and 100% oxygen.

Parameter, Value:

High data rate protocol: 802.11n or 802.11ac.

UHF Communication, MOS for Lq and Le of 3.9 or greater, or AI of .7 or better or 90% intelligibility in the crew member’s native language for both inbound and outbound speech communication.

Size: 115 cubic inches maximum.

Mass: 5.5 pounds maximum.

Power: 15 watts total power consumption maximum.

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

6.2 Extravehicular Activity Systems
6.2.3 Power, Avionics, and Software

6.2.3.4 Autonomous Checkout

TECHNOLOGY

Technology Description: An autonomous suit checkout system to confirm readiness of the extravehicular activity (EVA) suit system to perform an EVA. Checkout system will operate with minimal crew time investment and screen the EVA system for relevant failure modes. Development needs to be integrated with EVA suit and portable life support system (PLSS) development efforts.

Technology Challenge: Autonomous system to perform EVA suit system checkout, with minimal crew time, to assess readiness of the EVA suit system prior to performing an EVA.

Technology State of the Art: International Space Station (ISS) Extravehicular Mobility Unit (EMU) checkout pre-EVA is manual and crew time intensive.

Parameter, Value:	TRL
Extensive crew time.	2

Technology Performance Goal: Autonomous system checkout of the full EVA suit system.

Parameter, Value:	TRL
Autonomous checkout and reporting to crew and Mission Control Center (MCC).	9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Development or maturation of this technology is dependent on the development/advancement of the EVA Pressure Garment (TA 6.2.1) and the Portable Life Support System (PLSS) TA 6.2.2.

CAPABILITY

Needed Capability: Autonomous EVA system checkout system.

Capability Description: Design, development, test, and evaluation (DDT&E) of an autonomous suit checkout system to confirm readiness of the EVA suit system to perform an EVA. Checkout system will operate with minimal crew time investment and screen the EVA system for relevant failure modes. Development needs to be integrated with EVA suit and PLSS development efforts (reference TAs 6.2.1 and 6.2.2).

Capability State of the Art: EMU checkout. Manual commanding. Multiple pieces of ancillary equipment. Time-intensive operations.

Parameter, Value:

Extensive crew time, manual commanding and monitoring.

Capability Performance Goal: Autonomous checkout operations with minimal crew time; findings reported to crew and MCC.

Parameter, Value:

Minimal crew time, autonomous checkout and reporting to crew and MCC.

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

6.2 Extravehicular Activity Systems
6.2.3 Power, Avionics, and Software

6.2.3.5 Suit-Integrated Personal Locating Technologies

TECHNOLOGY

Technology Description: System that automatically (without crew intervention) provides search and rescue (SAR) assets in the event of contingency cabin egress.

Technology Challenge: Current suits do not have this technology, and challenges include integration into the suit within other design constraints (e.g., mass) and the reliability and efficacy of this type of system.

Technology State of the Art: PRC-112G, global positioning system (GPS)-enabled geo-locating line-of-sight SAR radio and T-SUB A 121.5 MHz homing beacon.

Parameter, Value:

Operating frequencies: 121.5/243/406 MHz.

TRL 3

Technology Performance Goal: Full integration of Personal Locating Beacon (PLB) and antenna systems into launch, entry, and abort (LEA) suit cover layer. Incorporate quicker location determination and transmission technologies by combining GPS-based electronics with next-generation Medium Earth Orbit Search and Rescue (MEOSAR) Doppler-based satellite constellation systems.

Parameter, Value:

Operating frequencies: 406 MHz with MEOSAR/next generation satellite constellation compatibility.

TRL 6

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

CAPABILITY

Needed Capability: Low-mass suit-integrated personal locating system.

Capability Description: Provide timely, higher accuracy, autonomous geo-location of crew members during adverse post-landing scenarios while reducing overall technology mass.

Capability State of the Art: PRC-112 system was used during Shuttle program in conjunction with T-SUB A 121.5 MHz beacon. Does not provide autonomous crew member location. Presents high mass impact. GPS and COSPAS/SARSAT location detection can be obscured by terrain and satellite viewability constraints, lengthening time needed to determine crew member location.

Parameter, Value:

Mass: 2.65 lbs

Operating frequencies: 121.5/243/406 MHz

Suit integration: none / minimal

Autonomous triggering: none

Beacon transmission life: varied

Capability Performance Goal: Significantly reduced mass over shuttle-heritage locating technologies; capability for faster location of crew members, coupled with reduction in geographic regions where satellite viewablity may be delayed due to satellite constellation orbital mechanics. Enhancements in beacon triggering systems. Combination of Doppler-based geolocation with GPS-enabled locating technologies for high accuracy and quick location determination.

Parameter, Value:

Mass: 0.33-0.5 lbs

Operating frequencies: 406 MHz with MEOSAR/next generation satellite constellation compatibility

Suit integration: beacon form factor and antenna fully integrated

Autonomous triggering: fully autonomous

Beacon transmission life: 24 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	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

6.3 Human Health and Performance
6.3.1 Medical Diagnosis and Prognosis

6.3.1.1 Emerging Screening Technologies; Preventative Countermeasures

TECHNOLOGY

Technology Description: Identify pre-flight predisposition screening for crew selection process and countermeasures to prevent potential medical conditions that may occur during long-duration missions.

Technology Challenge: Prevent possible fatal or debilitating medical conditions that would require rapid mission abort capability. Shall be used to reduce risk to an acceptable level and shall include increased levels of advanced care in the form of medications, equipment, training, or consumables. The training and caliber of the caregiver shall be at the physician level. Return to Earth is not a viable option for more serious illness or injuries.

Technology State of the Art: Standard medical evaluation protocols.

Parameter, Value: Pre-flight screening of candidates and countermeasures to prevent certain medical conditions exist.

TRL: 3

Technology Performance Goal: Pre-flight assessments that take into account crew member predisposition to potential medical conditions that may occur during long-duration missions.

Parameter, Value: Pre-flight assessments that take into account crew member predisposition to potential medical conditions that may occur during long-duration missions.

TRL: 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Long-term prediction of diseased-conditions.

CAPABILITY

Needed Capability: Prevent medical conditions.

Capability Description: Pre-flight screening of candidates for predisposition to potential medical conditions that may occur during long-duration missions and countermeasures to prevent conditions.

Capability State of the Art: Pre-flight assessments performed, but for conditions which may occur during short-duration missions.

Parameter, Value: Pre-flight screening of candidates and countermeasures to prevent certain medical conditions exist for short-duration missions.

Capability Performance Goal: Screen candidates for predisposition to potential medical conditions and countermeasures to prevent potential medical conditions that may occur during long-duration missions.

Parameter, Value: Pre-flight predisposition screening and preventative countermeasures for long-duration missions, e.g., > 100 days.

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

6.3 Human Health and Performance
6.3.1 Medical Diagnosis and Prognosis

6.3.1.2 Flexible Ultrasound Platform, Novel Ultrasound Probes and Protocols, Near-Infrared Imaging Modalities

TECHNOLOGY

Technology Description: The integrated suite of imaging technologies (with diagnostic and therapeutic modalities) will allow crew members to address medical conditions of concern for exploration missions.

Technology Challenge: A moderate to high level of potential risk exists that personnel may experience medical problems on orbit. Risk to mission is greater for medical issues beyond routine ambulatory medicine. The ability to support chronic illness is limited. Intervention strategies shall be used to reduce risk to an acceptable level and shall include increased levels of advanced care in the form of medications, equipment, training, or consumables. Return to Earth is not readily available and takes days for more serious illness or injuries.

Technology State of the Art: Miniaturized ultrasound imaging system for diagnosis.

Parameter, Value:

High-quality images for diagnosis.

TRL 9

Technology Performance Goal: *Non-invasive* imaging system that can diagnose and treat a diseased condition.

Parameter, Value:

High-quality images for diagnosis and treatment.

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Reliable treatment protocol using the integrated ultrasound system.

CAPABILITY

Needed Capability: Ultrasound and infrared (IR) imaging.

Capability Description: Provide imaging capabilities with diagnostic and therapeutic modalities.

Capability State of the Art: Currently, ultrasound is the primary modality for non-invasive imaging of the internal body on the International Space Station (ISS).

Parameter, Value:

High-quality ultrasound images for diagnosis.

Capability Performance Goal: Non-invasive imaging with diagnostic and therapeutic modalities.

Parameter, Value:

Detect medical symptoms that may occur during long-duration 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
Into the Solar System: DRM 5 Asteroid Redirect - Crewed in DRO	Enabling	2022	2022	2015-2021	4 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

6.3 Human Health and Performance
6.3.1 Medical Diagnosis and Prognosis

6.3.1.3 Suite of Laboratory Analysis Platforms and Assays

TECHNOLOGY

Technology Description: An in-flight lab analysis platform for exploration missions must include the ability to measure hematologic and basic metabolic panels, blood gases, cardiac and liver markers, and urine analytes. The platform must also exhibit expanded assay capability; extended shelf-life of consumables (e.g. reagents, cartridges); minimize mass, volume, power, and consumables; and provide sample containment.

Technology Challenge: Miniaturized hardware with minimum consumables stored at room temperature.

Technology State of the Art: Handheld in-flight analyzer.

Parameter, Value: Blood gases and biochemical profile.

TRL 6

Technology Performance Goal: Integrated system for laboratory analytes measurement.

Parameter, Value: Blood gases and biochemical profile.

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Storage and lifetime of the consumables used in the analysis platform.

CAPABILITY

Needed Capability: Suite of lab analysis platforms and assays.

Capability Description: Measure clinical analytes of interest with minimal consumables that have extended shelf life. A capability needs to exist to detect medical symptoms that may occur during long-duration missions.

Capability State of the Art: i-Stat handheld analyzer in flight using cartridges.

Parameter, Value:
Hematologic and basic metabolic panels, blood gases, cardiac and liver markers, and urine analytes—but uses cartriddges.

Capability Performance Goal: Integrated system for laboratory analytes measurement with minimal reagents.

Parameter, Value:
Hematologic and basic metabolic panels, blood gases, cardiac and liver markers, and urine analytes.

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

6.3 Human Health and Performance
6.3.1 Medical Diagnosis and Prognosis

6.3.1.4 Stethoscope

TECHNOLOGY

Technology Description: The next-generation stethoscope will enable medical and non-medical personnel to listen to internal auscultation sounds that are generated by the body in a noisy environment.

Technology Challenge: A high level of potential risk exists that personnel may experience medical problems on orbit. Risk to mission is greater for medical issues beyond routine ambulatory medicine. The ability to support chronic illness is limited. Intervention strategies shall be used to reduce risk to an acceptable level and shall include increased levels of advanced care in the form of medications, equipment, training, or consumables. The training and caliber of the caregiver shall be at the physician level. Return to Earth is not a viable option for more serious illness or injuries.

Technology State of the Art: Terrestrial stethoscope.

Parameter, Value:	**TRL**
Transmit the body sounds.	6

Technology Performance Goal: Stethoscope for auscultation, transmission, and recording of body sounds.

Parameter, Value:	**TRL**
Transmit and record body sounds.	9

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

CAPABILITY

Needed Capability: A capability needs to exist to detect medical symptoms that may occur during long-duration missions.

Capability Description: Stethoscope.

Capability State of the Art: A stethoscope, which has the option of using a tunable diaphragm (based on applied pressure against the body), or a traditional bell on the reverse of the double-sided chest piece.

Parameter, Value:
Transmit the body sounds but limited to a relatively quiet environment Stethoscope for auscultation, transmission, and recording of body sounds. Stethoscope can be used by medical and non-medical personnel.

Capability Performance Goal: Stethoscope for auscultation, transmission, and recording of body sounds. Stethoscope can be used by medical and non-medical personnel.

Parameter, Value:
Transmit and record body sounds within a noisy environment. Ease of 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 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

6.3 Human Health and Performance
6.3.1 Medical Diagnosis and Prognosis

6.3.1.5 Sterile Fluid Generation Device

TECHNOLOGY

Technology Description: The intravenous (IV) fluid delivery system will enable generation of sterile fluid from an exploration vehicle's existing potable water supply.

Technology Challenge: Generating and validating medical grade water for IV fluid.

Technology State of the Art	Technology Performance Goal
Technology State of the Art: NASA has created a functional prototype.	**Technology Performance Goal:** System for intravenous fluid generation.
Parameter, Value: IV delivery system on an exploration vehicle. **TRL** 6	**Parameter, Value:** IV delivery system on an exploration vehicle. **TRL** 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Validation of the sterile water product.

CAPABILITY

Needed Capability: Sterile fluid generation.

Capability Description: Generate sterile fluid for IVs in-flight from the potable water supply.

Capability State of the Art	Capability Performance Goal
Capability State of the Art: Currently on the ISS, IV fluids are available in the form of a limited quantity of manufacturer-packaged bags, which have a limited shelf life.	**Capability Performance Goal:** System for intravenous fluid generation using potable water suplly of an exploration vehicle.
Parameter, Value: Single use sterile fluid product.	**Parameter, Value:** Sterile water for IV fluid production.

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	4 years
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

6.3 Human Health and Performance
6.3.1 Medical Diagnosis and Prognosis

6.3.1.6 Radiofrequency Identification (RFID)-Based Medical Inventory Tracking Hardware and Software

TECHNOLOGY

Technology Description: A medical inventory capability, such as the Medical Consumable Tracking (x) system, will use RFID technology to electronically track consumable contents within a medical kit.

Technology Challenge: A moderate to high level of potential risk exists that personnel may experience medical problems on orbit. Risk to mission is greater for medical issues beyond routine ambulatory medicine. The ability to support chronic illness is limited. Intervention strategies shall be used to reduce risk to an acceptable level and shall include increased levels of advanced care in the form of medications, equipment, training, or consumables. Return to Earth is not readily available and takes days for more serious illness or injuries.

Technology State of the Art: Not available at the International Space Station (ISS).

Parameter, Value:
Technology not available at the ISS.

TRL: None

Technology Performance Goal: System for medical inventory tracking.

Parameter, Value:
Tracking the medication consumption and the stock.

TRL: 7

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

CAPABILITY

Needed Capability: RFID system for medical hardware and software inventory.

Capability Description: Manage medical inventory in-flight that provides status and usage data and can securely integrate with the vehicle inventory management system.

Capability State of the Art: Currently on the ISS, the crew periodically inventories contents of the medical kit via visual inspection or digital photography.

Parameter, Value:
Manual inventory operations.

Capability Performance Goal: System for medical inventory tracking using RFID technology.

Parameter, Value:
Medication availability by electronically tracking consumable contents within a medical kit and report the information to the ground to determine usage over time with 100% accuracy.

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)	Enabling	2033	--	2027	4 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	4 years

6.3 Human Health and Performance
6.3.1 Medical Diagnosis and Prognosis

6.3.1.7 Suite of Medication Packaging Options

TECHNOLOGY

Technology Description: The medication packaging materials and design will preserve stability and shelf life during long-duration exploration missions with limited re-supply capability.

Technology Challenge: Long-duration storage in the spaceflight environment may have direct effects on stored drugs, leading to premature inactivation or degradation of stored drugs or accumulation of toxic degradation products.

Technology State of the Art: Over-wrapped medication.

Parameter, Value: Optimal drug stability.

TRL: 4

Technology Performance Goal: Stable pharmaceuticals under repackaged storage conditions.

Parameter, Value: Safe, effective medications that have known pharmacokinetic properties and known pharmacodynamic actions.

TRL: 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: New generation materials that prevent diffusion of oxygen and water vapor.

CAPABILITY

Needed Capability: Medication suite.

Capability Description: Preserve stability and shelf life of medication during long-duration missions.

Capability State of the Art: Current packaging techniques (manufacturer's packaging, plastic bags, pre-filled syringes) are suitable for the International Space Station due to frequent re-supply.

Parameter, Value: Optimal drug stability.

Capability Performance Goal: A suite of stable medication, as a result of drug formulation, packaging, and stability testing.

Parameter, Value: Packaging that preserves stability and shelf life during long-duration exploration missions with limited re-supply capability thus providing safe and effective medications that have known pharmacokinetic properties and known pharmacodynamic actions.

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 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

6.3 Human Health and Performance
6.3.1 Medical Diagnosis and Prognosis

6.3.1.8 Medical Equipment Sterilization

TECHNOLOGY

Technology Description: The system will enable sterilization of medical equipment that is to be used more than once on an exploration mission.

Technology Challenge: Compact sterilization system with minimum consumables.

Technology State of the Art: Technology not available for the space environment

Parameter, Value: None — **TRL:** None

Technology Performance Goal: Sterilization system for multiple use.

Parameter, Value: Sterilized hardware. — **TRL:** 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Miniaturized sterilization methodology.

CAPABILITY

Needed Capability: Sterilization of medical equipment.

Capability Description: Sterilize medical equipment in-flight during mission.

Capability State of the Art: Currently on the International Space Station (ISS), any medical equipment that requires sterility is flown as a single-use item and is resupplied if needed.

Parameter, Value:
Sterillized single-use medical hardware.

Capability Performance Goal: Medical equipment sterilization.

Parameter, Value:
Sterilized multi-use medical 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
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

6.3 Human Health and Performance
6.3.1 Medical Diagnosis and Prognosis

6.3.1.9 Integrated Medical Equipment and Software Suite

TECHNOLOGY

Technology Description: Development of a data architecture to efficiently manage crew health and human performance data generated in support of an exploration mission will fill this gap. The ideal architecture will enable plug-and-play connectivity, automate routine data management tasks, and allow for future expansion of the system.

Technology Challenge: A moderate to high level of potential risk exists that personnel may experience medical problems on orbit. Risk to mission is greater for medical issues beyond routine ambulatory medicine. The ability to support chronic illness is limited. Intervention strategies shall be used to reduce risk to an acceptable level and shall include increased levels of advanced care in the form of medications, equipment, training, or consumables. Return to Earth is not readily available and takes days for more serious illness or injuries.

Technology State of the Art: Data collected in subsets and no integrated system.

Parameter, Value:
Unified system.

TRL 1

Technology Performance Goal: Comprehensive medical data management.

Parameter, Value: Integrated system.

TRL 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Integrated data transfer.

CAPABILITY

Needed Capability: Integration of medical equipment and software.

Capability Description: Detect medical conditions and manage medical data in-flight generated during a mission.

Capability State of the Art: Currently on the International Space Station (ISS), medical data management includes a combination of data collection and distribution methods that are minimally integrated with the onboard medical devices and systems.

Parameter, Value:
Unified system.

Capability Performance Goal: Comprehensive medical data management.

Parameter, Value:
Integrated system that allows plug-and-play connectivity, automated routine data management tasks, and expansibility.

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	4 years
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

6.3 Human Health and Performance
6.3.2 Long-Duration Health

6.3.2.1 Artificial Gravity

TECHNOLOGY

Technology Description: Provide partial or complete artificial gravity living conditions.

Technology Challenge: Establishing ground analog study and determining the cost impact to develop spaceflight systems are challenges.

Technology State of the Art: Short-term centrifuge under terrestrial conditions.

Parameter, Value:
Physiological decondition minimized/ reduced.

TRL 3

Technology Performance Goal: Countermeasures to offset deconditioned physiological system due to microgravity.

Parameter, Value:
No physiological deconditioning under microgravity conditions.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Results from the ground pilot study.

CAPABILITY

Needed Capability: Artificial gravity during exploration missions.

Capability Description: Provide partial or complete artificial gravity living conditions.

Capability State of the Art: Short radius centrifuge with bed-rest study infrastructure. Does not exist for spaceflight.

Parameter, Value:
Does not exist for spaceflight.

Capability Performance Goal: No need for the countermeasures to offset deconditioned physiological system due to microgravity.

Parameter, Value:
No physiological deconditioning under microgravity conditions. Partial or complete artificial gravity living conditions

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	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

6.3 Human Health and Performance
6.3.2 Long-Duration Health

6.3.2.2 Cell/Tissue Culture, Animal Models

TECHNOLOGY

Technology Description: An automated cell culture and animal model systems. A comprehensive sample analysis system onboard. Nanosatellite platforms to carry out space environment effects on cells, microbes, plants and microcellular organisms.

Technology Challenge: Small, autonomous, pioneering exploration satellites using cells or small animal models to assess impacts of long-duration exposure of microgravity and radiation to living organisms.

Technology State of the Art: Cell culture system to grow microbes and mammalian cells.

Parameter, Value: Grow tissue; take samples for genomic analysis on the ground.

TRL: 6

Technology Performance Goal: Tissue growth and factors influencing the tissue growth in microgravity.

Parameter, Value: To process and analyze sample on-orbit; provide a 1-G reference on-orbit.

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Reliable hardware with minimum supplies (upmass).

CAPABILITY

Needed Capability: Tissue culture and animal models.

Capability Description: Provide automated system to study cell cultures and animal models in a relevant environment.

Capability State of the Art: Cell culture system.

Parameter, Value: Limited, primarily Experiment- Unique Equipment (EUE).

Capability Performance Goal: Comprehensive, onbaord sample system to analyze tssue growth and factors influencing the tissue growth in microgravity.

Parameter, Value: Anomaly in the tissue grown under microgravity conditions.

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	3 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	3 years

6.3 Human Health and Performance
6.3.2 Long-Duration Health

6.3.2.3 Induced Pluripotent Stem Cells

TECHNOLOGY

Technology Description: Organ regeneration using induced pluripotent stem (IPS) cells for crew.

Technology Challenge: Individualized IPS-based stem cell replacement to enable longer mission duration. Cost effective breakthroughs in anti-radiation therapies.

Technology State of the Art: Technology available in ground.

Parameter, Value:
Transplant-quality tissue.

TRL 2

Technology Performance Goal: Organ regeneration; acceptable quality of the product for implant/ transplant.

Parameter, Value:
Transplant-quality tissue.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Economically viable technology to produce the organ.

CAPABILITY

Needed Capability: Organ regeneration.

Capability Description: Provide organ regeneration.

Capability State of the Art: None; does not exist for spaceflight.

Parameter, Value: Does not exist for spaceflight.

Capability Performance Goal: Organ regeneration from pluripotent stem cells with acceptable quality of tissue for implant.

Parameter, Value:
Transplant quality tissue with acceptable differentiated tissue.

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 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	7 years

6.3 Human Health and Performance
6.3.2 Long-Duration Health

6.3.2.4 Exercise Equipment

TECHNOLOGY

Technology Description: Novel exercise countermeasure hardware and protocols (integrated exercise devices, integrated biomechanics and Advanced Resistive Exercise Device (ARED), small and compact exercises devices, controlled resistance exercise device, rapid deploy or stow exercise devices).

Technology Challenge: The mass, power, volume, and crew time requirements for equipment used on the International Space Station (ISS) cannot be met on the non-ISS, exploration platforms.

Technology State of the Art: ARED, Cycle Ergometer with Vibration Isolation and Stabilization System (CEVIS), T2 treadmill.

Parameter, Value: | **TRL**

Smaller footprint with minimum use of vehicle resources. | 3

Technology Performance Goal: Small mass, volume, and power exercise equipment. Rapid deploy and storage exercise equipment.

Monitor spaceflight induced degenerative tissue and physiological effects.

Parameter, Value: | **TRL**

Small mass, volume, and power exercise equipment. Rapidly deploy and storage exercise equipment.

Monitor spaceflight induced degenerative tissue/ physiological effects. | 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Integrated device with minimum resource requirements.

CAPABILITY

Needed Capability: Maintain bone, muscle, and cardiovascular health.

Capability Description: Provide aerobic and resistive exercise equipment and protocols.

Capability State of the Art: ARED, CEVIS, T2 treadmill.

Parameter, Value:

Uses large vehicle resources.

High crew time.

Capability Performance Goal: Prevent unacceptable decrements in crew member bone and muscle mass and cardiovascular performance. A suite of novel exercise hardware equipment/devices and exercise prescriptions (protocol countermeasures).

Parameter, Value:

Measure of unacceptable physiological decrements.

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 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

6.3 Human Health and Performance
6.3.2 Long-Duration Health

6.3.2.5 Integrated Prevention and Treatment for Visual Changes and Non-Invasive Intracranial Pressure Measurement

TECHNOLOGY

Technology Description: In-flight tool to measure intracranial pressure (ICP) and optimal diagnostic tools to measure ocular structure and function.

Technology Challenge: Challenges include developing a non-invasive technology that can survive long-duration exposure to microgravity.

Technology State of the Art: Ultrasound device, capable of measuring both optic nerve sheath diameter (ONSD) and transcranial Doppler (TCD), both of which have been shown terrestrially to correlate with ICP.

Parameter, Value: Ultrasound device, capable of measuring both ONSD and TCD, both of which have been shown terrestrially to correlate with ICP.

TRL: 3

Technology Performance Goal: *Non-invasive* in-flight tool to measure ICP and optimal diagnostic tools to measure ocular structure and function.

Parameter, Value: *Non-invasive* measurement of ICP.

TRL: 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Availability of a reliable technology to measure ICP in space.

CAPABILITY

Needed Capability: Predict, prevent, and treat spaceflight-induced intracranial hypertension and vision alterations.

Capability Description: Astronauts on long-duration International Space Station (ISS) missions have experienced increased ICP (as measured post-flight), ophthalmic anatomical changes and visual performance decrements of varying degrees.

Capability State of the Art: Evaluation of ICP.

Parameter, Value: Disc edema, corroidal fold, ICP, intraocular pressure, sheath diameter.

Capability Performance Goal: Compile a set of flight-validated, in-flight techniques and tools to characterize and quantify ICP, ocular structure, and ocular function.

Parameter, Value: Prevent crew member visual acuity and cognitive impairment.

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 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

6.3 Human Health and Performance
6.3.2 Long-Duration Health

6.3.2.6 Water Control Standards for Microbes, Probiotic Delivery, Antimicrobial Medications

TECHNOLOGY

Technology Description: Flight microbial detection and effective countermeasures to prevent crew illness due to microbial exposure.

Technology Challenge: Challenges include determining the stimuli and impact of spaceflight conditions, including reduced gravity, on microbial ecology and medically significant characteristics.

Technology State of the Art: Heterotropic bacteria monitor; coliform detection kit. Current preventative measures, such as the Health Stabilization Program and microbial monitoring limit crew health risk.

Parameter, Value:	TRL
Heterotropic bacteria and coliform.	9

Technology Performance Goal: In-flight microbial identification and determination of changes in microbial characteristics (i.e., antibiotic resistance, virulence characteristics). Prevent or remediate microbial contamination and enable the use of beneficial microorganisms (i.e. probiotics).

Parameter, Value:	TRL
To assess the environment, water, and food for microbiological threats.	9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Integrated miniaturized system.

CAPABILITY

Needed Capability: Spacecraft microbial monitoring and mitigation.

Capability Description: Focused on understanding and mitigating the risk of microbial contamination of the spacecraft, leading to crew health issues.

Capability State of the Art: Heterotropic bacteria monitor; coliform detection kit.

Parameter, Value:

Heterotripic bacteria and coliform.

In-flight microbial monitoring is performed through culture-based technology with limited shelf life and detection capabilities.

Capability Performance Goal: Detect microbial levels in flight, remediate contamination, and prevent adverse crew health conditions through the removal or addition of selected microorganisms.

Parameter, Value:

To assess the environment, water, and food for microbiological threats thus preventing crew illnesses due to microbial 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 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

6.3 Human Health and Performance
6.3.2 Long-Duration Health

6.3.2.7 Integrated Technologies to Monitor Crew Performance During Exercise

TECHNOLOGY

Technology Description: Measurement of crew performance during exercise and evaluation of crew fitness levels during a mission. The suite could include heart rate and blood pressure monitoring and electrocardiogram. Heart rate data quality is poor largely due to the strict dependence on physical contact of the sensors and electrodes with the torso and proximity of the transmitter to the receiver, which is also very directional.

Technology Challenge: Reliability of heart rate quality and synchronization with countermeasure system (CMS) exercise hardware. Acquiring consistent electrocardiogram (ECG) and blood pressure (BP) signals during exercise.

Technology State of the Art: BP-ECG suite and Modified Polar transmitter and Polar Smart Fabric Sensor chest strap. Heart rate monitoring receiver boards are custom and only receive magnetic pulse signals from the transmitter.

Parameter, Value:

Heart rate, cardio, and other physiological parameters.

TRL 3

Technology Performance Goal: Monitoring of heart rate, blood pressure and electrocardiogram with minimum mass, volume, and power that is highly reliable during exercise, extravehicular activity (EVA), and quiet periods.

Parameter, Value:

Heart rate, cardio, and other physiological parameters

TRL 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Advancements in the consumer market and characterization of the EMI environment on the International Space Station (ISS). Alternative to the electromagnetic interference (EMI) characterization, identification of a wireless transmission protocol that is not so extremely limited in range and more robust to outside EMI.

CAPABILITY

Needed Capability: Ideally, a single heart rate monitoring device could be used during exercise, EVA, and for quiet medical assessment. Data should be collected continuously without dropouts, recorded in a beat-by-beat fashion, be synchronized with exercise hardware during exercise activity, and be able to synchronize with other medical diagnostic devices during medical examination.

Capability Description: A wireless system with strong detection and transmission of heart rate data during exercise that can be synchronized with exercise hardware, easy to use, and does not interfere with the user's activity.

Capability State of the Art: Bluetooth protocol has been identified as not being prone to multipath fadeout. Optical sensors, ear bud based sensors, and updated chest strap technologies are under evaluation in the Exercise Physiology and Countermeasures Project laboratory.

Parameter, Value:

Heart rate, cardio, and other physiological parameters.

Capability Performance Goal: High-quality heart rate, blood pressure and electrocardiogram data collection during continuous and interval exercise training on the spacecraft.

Parameter, Value:

Integrated heart rate, cardio, and other physiological parameters without any data loss (< 5% dropout).

Within local proximity.

Low power and 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 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

6.3 Human Health and Performance
6.3.2 Long-Duration Health

6.3.2.8 Vibration Isolation Technologies for Exercise Equipment

TECHNOLOGY

Technology Description: New generation vibration isolation system (VIS) technologies to minimize exercise-induced loads and disturbance to microgravity environment and increase the effective life of vehicle's structure while counteracting pitch, yaw, and roll of the exercise system.

Technology Challenge: Efficient vibration isolation technologies without disturbing the microgravity environment that require less volume and mass and are easy to maintain.

Technology State of the Art: Exercise-specific passive VIS capability and Treadmill with Vibration Isolation and Stabilization (TVIS) for active VIS capability in the International Space Station (ISS).

Parameter, Value:	TRL
Minimum change in the microgravity environment in the vehicle during the use of the exercise device	7

Technology Performance Goal: VIS systems that can handle larger ranges of exercise activities and meet ISS isolation spectra requirements.

Parameter, Value:	TRL
Minimum change in the microgravity environment in the vehicle during the use of the exercise device	9

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

CAPABILITY

Needed Capability: Exercise movements when not isolated both add rapidly to the fatigue and structural life of space vehicles, but also have been found to align with harmonic frequencies of space vehicles.

Capability Description: Develop VIS systems that can handle larger ranges of exercise activities and meet ISS isolation spectra requirements, yet are smaller in mass and/or volume.

Capability State of the Art: Exercise specific passive VIS capability and TVIS for active VIS capability in the ISS.

Parameter, Value: Minimum change in the microgravity environment in the vehicle during the use of the exercise device.

Capability Performance Goal: Develop VIS systems that can handle larger ranges of exercise activities and meet ISS isolation spectra requirements, yet are smaller in mass and volume.

Parameter, Value:
Minimum change in the microgravity environment in the vehicle during the use of the exercise device.

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

6.3 Human Health and Performance
6.3.3 Behavioral Health

6.3.3.1 Psychomotor Vigilance Task (PVT)

TECHNOLOGY

Technology Description: A tool for objectively measuring fatigue, as well as providing objective evidence of the effects of fatigue and workload of spaceflight crews over the course of long-duration spaceflight.

Technology Challenge: Challenges include developing an integrated suite of minimally obtrusive tools.

Technology State of the Art: The pschomotor vigilance task (PVT) is used in the sleep research.

Parameter, Value:

Current technology requires too much crew time and can be cumbersome for the crew.

TRL: 5

Technology Performance Goal: Monitor and measure fatigue and associate changes to performance and cognitive functionally.

Parameter, Value:

Monitor and measure fatigue and associated changes to performance and cognitive functionally, unobtrusively, while providing operationally relevant feedback related to sleep and performance.

TRL: 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Reliable and universal validated technique.

CAPABILITY

Needed Capability: Fatigue management.

Capability Description: Behavioral Health and Performance includes the functions necessary to monitor psychological health, diagnose incipient impairments, and provide treatment. Impairments include stress, anxiety, fatigue, depression, cognitive impairment, altered affect, and reduced team cohesion.

Capability State of the Art: There is no objective measure of fatigue currently used operationally on the International Space Station (ISS).

Parameter, Value:

Maintain individual crew member behavioral health during long-duration spaceflight.

Capability Performance Goal: Autonomous detection and treatment of adverse psychological states (excessive stress, anxiety, fatigue, depression, cognitive impairment, and altered affect) in an individual crew member without the assistance of ground support.

Parameter, Value:

Maintain individual crew member behavioral health during long-duration spaceflight.

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

6.3 Human Health and Performance
6.3.3 Behavioral Health

6.3.3.2 Objective Sleep Measures for Spaceflight Operations

TECHNOLOGY

Technology Description: An objective measure of sleep-wake activity (and lighting) while fitting into the spaceflight mission environment.

Technology Challenge: Challenges include developing an integrated suite of minimally intrusive tools.

Technology State of the Art: An actigraph with integrated light recording capability is in use in the sleep study.

Parameter, Value:
Current technology requires too much crew time and can be cumbersome for the crew. Light integrated actigraph not approved for flight.

TRL 5

Technology Performance Goal: Monitor and measure sleep and associate changes to performance and cognitive functionality.

Parameter, Value:
An unobtrusive objective measure of sleep-wake activity (and lighting) providing real-time data related to sleep and activity levels so that risk can be mitigated.

TRL 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Reliable cognitive functional assessment tool.

CAPABILITY

Needed Capability: Autonomous detection and treatment of adverse psychological states (excessive stress, anxiety, fatigue, depression, cognitive impairment, and altered affect) in an individual crew member without ground support.

Capability Description: Behavioral Health and Performance includes the functions necessary to monitor psychological health, diagnose incipient impairments, and provide treatment. Impairments include stress, anxiety, fatigue, depression, cognitive impairment, altered affect, and reduced team cohesion.

Capability State of the Art: There is no objective measure of sleep-wake activity currently used operationally on the International Space Station (ISS).

Parameter, Value:
Maintain individual crew member behavioral health during long-duration spaceflight.

Capability Performance Goal: Objective measure of sleep-wake activity (and lighting) while fitting into the spaceflight mission environment.

Parameter, Value:
Maintain individual crew member behavioral health during long-duration spaceflight.

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

6.3 Human Health and Performance
6.3.3 Behavioral Health

6.3.3.3 Optimal Use of Light as a Countermeasure

TECHNOLOGY

Technology Description: Lighting countermeasure regimes that integrate lighting properties and provide hardware specifications for future vehicles.

Technology Challenge: To develop environmental specifications and operational regimes for using light to prevent and mitigate health and performance decrements.

Technology State of the Art: Light emitting diode (LED)-based lighting system (Solid State Light Assemblies (SSLA); International Space Station (ISS) lighting system will offer three setting via manual toggle; vehicles for future exploration systems should provide increased capability in an automated fashion. Automated light simulating a modified diurnal cycle.

Parameter, Value:
Dim and static nature.

TRL: 5

Technology Performance Goal: Environmental specifications and operational regimes for using light.

Parameter, Value:
Prevent and mitigate health and performance decrements.

TRL: 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Optimal optical parameters for the crew population.

CAPABILITY

Needed Capability: Autonomous detection and treatment of adverse psychological states (excessive stress, anxiety, fatigue, depression, cognitive impairment, and altered affect) in an individual crew member without ground support.

Capability Description: Behavioral Health and Performance includes the functions necessary to monitor psychological health, diagnose incipient impairments, and provide treatment. Impairments include stress, anxiety, fatigue, depression, cognitive impairment, altered affect, and reduced team cohesion.

Capability State of the Art: General Luminaire Assemblies (GLA).

Parameter, Value:
Dim and static nature.

Capability Performance Goal: Automated systems that provide high-intensity light enriched in the “blue” portion of the spectrum for the morning, nighttime operations, and schedule shifting; a crisp daytime intensity to support visual acuity; and a low-intensity, non-blue enriched light in evening (pre-sleep). ISS SSLAs will offer three settings manual toggle. Lighting in future vehicles to provide increased flexibility.

Parameter, Value:
Maintain individual crew member behavioral health during long-duration spaceflight.

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

6.3 Human Health and Performance
6.3.3 Behavioral Health

6.3.3.4 Medications to Promote Sleep, Alertness, and Circadian Entrainment

TECHNOLOGY

Technology Description: Identifies sleep medications and dosages that produce the fewest cognitive effects and adverse reaction in individual astronauts.

Technology Challenge: Challenges include identifying the sleep medications and dosages that produce the fewest cognitive effects and adverse reaction in individual astronauts.

Technology State of the Art: Sleep medications.

Parameter, Value: Effects on waking cognitive functions during an alarm.

TRL: 5

Technology Performance Goal: Sleep medications and dosages that produce the fewest cognitive effects and adverse reaction in individual astronauts.

Parameter, Value: Fewest cognitive effects and fewest adverse reaction in individual astronauts.

TRL: 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Bioavailability of the drug during spaceflight.

CAPABILITY

Needed Capability: Autonomous detection and treatment of adverse psychological states (excessive stress, anxiety, fatigue, depression, cognitive impairment, and altered affect) in an individual crew member without ground support.

Capability Description: Behavioral Health and Performance includes the functions necessary to monitor psychological health, diagnose incipient impairments, and provide treatment. Impairments include stress, anxiety, fatigue, depression, cognitive impairment, altered affect, and reduced team cohesion.

Capability State of the Art: Sleep medications used in spaceflight are approved for sleep periods of 8 hours or more.

Parameter, Value: Limited effectiveness shown in the International Space Station (ISS) environment.

Capability Performance Goal: Sleep medications used in spaceflight are approved for sleep period of 8 hours or more, but have not been studied for their effects on waking cognitive functions during an alarm-based awakening from sleep less than 8 hours.

Parameter, Value: Maintain individual crew member behavioral health during long-duration spaceflight.

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

6.3 Human Health and Performance
6.3.3 Behavioral Health

6.3.3.5 Scheduling Software

TECHNOLOGY

Technology Description: Individualized scheduling tools that predict the effects of sleep-wake cycles, light, and other countermeasures on performance.

Technology Challenge: Challenges include developing a tool to make informed decisions, particularly for critical operations.

Technology State of the Art: Blue light therapy during different times of the day to alleviate sleep irregularities.

Parameter, Value:

Current guidelines provide a subjective value to treat different forms of sleep disruption.

TRL: 1

Technology Performance Goal: Performance predictions based on sleep-wake activity to contribute to risk mitigation.

Parameter, Value:

Accurate predictions of performance based on sleep-wake activity to contribute to risk mitigation;

Inform spaceflight scheduling decisions in realtime as a countermeasure.

TRL: 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Personalized prescription of the optical parameters.

CAPABILITY

Needed Capability: Autonomous detection and treatment of adverse psychological states (excessive stress, anxiety, fatigue, depression, cognitive impairment, and altered affect) in an individual crew member without the assistance of ground support.

Capability Description: Behavioral Health and Performance includes the functions necessary to monitor psychological health, diagnose incipient impairments, and provide treatment. Impairments include stress, anxiety, fatigue, depression, cognitive impairment, altered affect, and reduced team cohesion.

Capability State of the Art: Scheduling based on Subject Matter Experts (SMEs).

Parameter, Value:

Maintain individual crew member behavioral health during long-duration spaceflight.

Capability Performance Goal: Integration of crew member data over time to follow behavioral state trends throughout the mission, predicting vulnerabilities before decrements occur, and target interventions as necessary.

Parameter, Value:

Maintain individual crew member behavioral health during long-duration spaceflight.

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

6.3 Human Health and Performance
6.3.3 Behavioral Health

6.3.3.6 Countermeasure to Enhance Behavioral Health

TECHNOLOGY

Technology Description: Tools to enhance behavioral health, such as software-generated exercise partners, self-help conflict management, and virtual reality technologies.

Technology Challenge: Longer-duration mission with prolonged isolation and confinement, increasing crew autonomy, absence of synchronous communications, longer pre-mission training period, and longer post-mission recovery are challenges.

Technology State of the Art: Technology not available for space environment.

Parameter, Value:
None

TRL: None

Technology Performance Goal: Suite of countermeasures that prevent and treat adverse consequences from the occurrence of behavioral health risks during long-duration spaceflight.

Parameter, Value:
Preserve the behavioral ecology of living and working in the spaceflight environment.

TRL: 7

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

CAPABILITY

Needed Capability: Autonomous detection and treatment of adverse psychological states (excessive stress, anxiety, fatigue, depression, cognitive impairment, and altered affect) in an individual crew member without ground support.

Capability Description: Behavioral Health and Performance includes the functions necessary to monitor psychological health, diagnose incipient impairments, and provide treatment. Impairments include stress, anxiety, fatigue, depression, cognitive impairment, altered affect, and reduced team cohesion.

Capability State of the Art: Crew-care packages, private family conferences, email, crew member websites, voice over Internet protocol (VoIP) telephony, and private medical conference.

Parameter, Value:
Maintain individual crew member behavioral health during long-duration spaceflight.

Capability Performance Goal: A suite of countermeasures that enhance behavioral health, such as software-generated exercise partners, self-help conflict management, and virtual reality technologies.

Parameter, Value:
Maintain individual crew member behavioral health during long-duration spaceflight.

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

6.3 Human Health and Performance
6.3.3 Behavioral Health

6.3.3.7 Tool to Predict, Detect, and Assess Decrements in Behavioral Health

TECHNOLOGY

Technology Description: Optimal tools to predict, detect, and assess decrements in behavioral state and cognition that could negatively affect performance, before, during, and after long-duration spaceflight missions.

Technology Challenge: Longer-duration mission with prolonged isolation and confinement, increasing crew autonomy, absence of synchronous communications, longer pre-mission training period, and longer post mission recovery are challenges.

Technology State of the Art: Technology not available for space environment.

Parameter, Value:	TRL
None	None

Technology Performance Goal: Suite of countermeasures that prevent and treat adverse consequences from the occurrence of behavioral health risks during long-duration spaceflight.

Parameter, Value:	TRL
Preserve the behavioral ecology of living and working in the spaceflight environment.	7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Reliable technology for cognitive assessment.

CAPABILITY

Needed Capability: Autonomous detection and treatment of adverse psychological states (excessive stress, anxiety, fatigue, depression, cognitive impairment, and altered affect) in an individual crew member without ground support.

Capability Description: Behavioral Health and Performance includes the functions necessary to monitor psychological health, diagnose incipient impairments, and provide treatment. Impairments include stress, anxiety, fatigue, depression, cognitive impairment, altered affect, and reduced team cohesion.

Capability State of the Art: Largely based on self-report during crew member private medical conferences, or by another crew member, and based upon the assessment of the crew psychiatrist who has five contact hours for their complete flight period.

Parameter, Value:

Maintain individual crew member behavioral health during long-duration spaceflight.

Capability Performance Goal: Predict, detect, and assess decrements in behavioral state and cognition that could negatively affect performance, before, during, and after long-duration spaceflight missions.

Parameter, Value:

Maintain individual crew member behavioral health during long-duration spaceflight.

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

6.3 Human Health and Performance
6.3.3 Behavioral Health

6.3.3.8 Cognitive Assessment Tool

TECHNOLOGY

Technology Description: Validated measure of cognitive capability.

Technology Challenge: Challenges include obtaining crew buy-in and sensitivity to decrements.

Technology State of the Art: Technology not available for space environment.

Parameter, Value:
None

TRL: None

Technology Performance Goal: Suite of countermeasures for detecting and assessing cognitive performance during long-duration spaceflight.

Parameter, Value:
Longer-duration mission and mission of one-year and longer to an isolated and confined environment may result in cognitive performance decrements in concentration and attention and may persist for up to one year post mission.

TRL: 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Quantitative evaluation tool.

CAPABILITY

Needed Capability: Autonomous detection and treatment of adverse psychological states (excessive stress, anxiety, fatigue, depression, cognitive impairment, and altered affect) in an individual crew member without ground support.

Capability Description: Behavioral Health and Performance includes the functions necessary to monitor psychological health, diagnose incipient impairments, and provide treatment. Impairments include stress, anxiety, fatigue, depression, cognitive impairment, altered affect, and reduced team cohesion.

Capability State of the Art: Spaceflight cognitive assessment tool for Windows (WinScat) is a cognitive measure currently on the International Space Station (ISS). It is made to be insensitive to fatigue, and detect a gross decrement such as one resulting from exposure to a toxin or a hit on the head.

Parameter, Value:
Requirement to take WinScat monthly. However, this requirement is often waived. Maintain individual crew member behavioral health during long-duration spaceflight.

Capability Performance Goal: Assessing cognitive performance before, during and after spaceflight.

Parameter, Value:
Maintain individual crew member behavioral health during long-duration spaceflight.

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

6.3 Human Health and Performance
6.3.3 Behavioral Health

6.3.3.9 Tools for Treating Behavioral Health Problems During Long-Duration Spaceflight Missions

TECHNOLOGY

Technology Description: Tools for treating the individual to remedy behavioral health problems during spaceflight, including the use of behavioral health medications.

Technology Challenge: Challenges include the prevalence of communication delays.

Technology State of the Art: Technology not available for space environment.

Parameter, Value:

None

TRL

None

Technology Performance Goal: Tools to detect and treat adverse psychological states.

Parameter, Value:

Maximum efficacy in returning the crew member back to a state of health so as not to jeopardize mission objectives.

TRL

7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Personalized treatment protocol.

CAPABILITY

Needed Capability: Autonomous detection and treatment of adverse psychological states (excessive stress, anxiety, fatigue, depression, cognitive impairment, and altered affect) in an individual crew member without ground support.

Capability Description: Behavioral Health and Performance (BHP) includes the functions necessary to monitor psychological health, diagnose incipient impairments, and provide treatment. Impairments include stress, anxiety, fatigue, depression, cognitive impairment, altered affect, and reduced team cohesion.

Capability State of the Art: Psychological support is facilitated by ground operations. BHP psychologists and psychiatrists ensure crew member receive real-time clinical care if needed.

Parameter, Value:

Maintain individual crew member behavioral health during long-duration spaceflight.

Capability Performance Goal: Asynchronous telemedicine techniques for the effective treatment of long-duration crew members suffering from behavioral health issues.

Parameter, Value:

Maintain individual crew member behavioral health during long-duration spaceflight.

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

6.3 Human Health and Performance
6.3.3 Behavioral Health

6.3.3.10 Tool to Effectively Monitor and Measure Team Health and Performance Fluctuations

TECHNOLOGY

Technology Description: A tool to monitor and capture crew member behavior as it occurs and identify any potential behavioral, interpersonal, and psychosocial issues.

Technology Challenge: Very little quantitative evidence exists on how to best train teamwork team skills required for autonomous long-duration spaceflight.

Technology State of the Art: Technology not available for space environment.

Parameter, Value: None

TRL: None

Technology Performance Goal: Monitor and assess team health and performance unobtrusively.

Parameter, Value: Valuable team-related information (i.e., teamwork performance metric).

TRL: 7

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

CAPABILITY

Needed Capability: Autonomous detection and treatment of inadequate team cohesion (cooperation, coordination, communication, and psychosocial adaptation within a team) without the assistance of behavioral health ground support.

Capability Description: Behavioral Health and Performance includes the functions necessary to monitor psychological health, diagnose incipient impairments, and provide treatment. Impairments include stress, anxiety, fatigue, depression, cognitive impairment, altered affect, and reduced team cohesion.

Capability State of the Art: No methods or tools to monitor and measure team health and performance fluctuations.

Parameter, Value: Not methods currently available.

Capability Performance Goal: Monitor and capture crew member behavior as it occurs and identify any potential behavioral, interpersonal, and psychosocial issues.

Parameter, Value: Maintain team cohesion during long-duration spaceflight.

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

6.3 Human Health and Performance
6.3.3 Behavioral Health

6.3.3.11 Social Support Countermeasures

TECHNOLOGY

Technology Description: Set of social support countermeasures targeting key indicators that maintain team function and psychosocial heath.

Technology Challenge: Challenges include the prevalence of communication delays.

Technology State of the Art: Technology not available for space environment.

Parameter, Value:
None

TRL
None

Technology Performance Goal: Social support countermeasures targeting key indicators that maintain team function and psychosocial heath for pre-mission preparation, in-flight self sustainment and team readiness, post-mission transition and rehabilitation.

Parameter, Value:
Within 90% of current International Space Station (ISS) psychological operations support levels.

TRL
7

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

CAPABILITY

Needed Capability: Autonomous detection and treatment of inadequate team cohesion (cooperation, coordination, communication, and psychosocial adaptation within a team) without the assistance of behavioral health ground support.

Capability Description: Behavioral Health and Performance includes the functions necessary to monitor psychological health, diagnose incipient impairments, and provide treatment. Impairments include stress, anxiety, fatigue, depression, cognitive impairment, altered affect, and reduced team cohesion.

Capability State of the Art: Significant infrastructure of both social and operational support.

Parameter, Value:
Social support can include health, psychological, and technical systems such as communication aids and tools.

Capability Performance Goal: Assess and maintain team function and psychosocial heath.

Parameter, Value:
Maintain team cohesion during long-duration spaceflight.

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 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

6.3 Human Health and Performance
6.3.3 Behavioral Health and Performance

6.3.3.12 Advanced Exercise Software to Enhance Psychological and Physiological Benefits

TECHNOLOGY

Technology Description: Improved software that incorporates customized, enjoyable interfaces (including virtual reality augmentation) for the crew while seamlessly integrating prescriptions and hardware performance data and providing physiological feedback for improved health results.

Technology Challenge: Challenges include developing "smart" software that adjusts uniquely to provide customized interfaces most enjoyable to each crew member while meeting conditioning performance requirements and integrating with the latest exercise hardware systems, including the monitoring necessary for exercise systems in space; developing virtual reality software to work with the latest equipment that can be used during exercise; and developing software that integrates latest biometric and biomechanical sensor data.

Technology State of the Art: International Space Station (ISS) exercise systems software, especially in the area of prescription integration. Commercial-off-the-shelf (COTS) software for usable interfaces, games, social networking. Commercially-available virtual reality systems.

Parameter, Value:	TRL
Integrating the supporting software with exercise prescription.	2

Technology Performance Goal: Software that is integrated seamlessly with exercise systems that are proven to reduce the deleterious physiological and psychological effects of space travel.

Parameter, Value:	TRL
100%+ completion of prescribed exercise.	9

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

CAPABILITY

Needed Capability: Mitigation of a crew's sense of being confined in a very small volume with limited views of the rest of the galaxy (and no view of Earth) for extended periods of time.

Capability Description: Dynamic software interfaces that may include social integration, gaming, and a virtual reality simulation that places crew members in familiar situations while performing exercise will greatly improve the psychological benefits provided by exercise. Form and performance feedback will allow the crew to get more benefit from exercises. Integrated family and friends virtually exercising with the user could become beneficial for long-term motivation.

Capability State of the Art: ISS exercise suite of software.

Parameter, Value:

Integrating the supporting software with exercise prescription.

Capability Performance Goal: Dynamic software interfaces that may include social integration, gaming, and a virtual reality simulation with form and performance feedback.

Parameter, Value:

100%+ completion of prescribed exercise.

Provide accurate performance and psychological feedback for improved health results.

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	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

6.3 Human Health and Performance
6.3.4 Human Factors

6.3.4.1 Advanced User Interface Concepts

TECHNOLOGY

Technology Description: Universal human-systems interface providing minimal human operator training and intuitive common operation between different systems, and increased capability, usability, and reliability.

Technology Challenge: Challenges include selection and development of interfaces for unique spacecraft environment; developing effective, low cost, mass, volume, and power integrated systems for human spaceflight; and scalability to real-time scientific and engineering data.

Technology State of the Art: Standard displays and controls.

Parameter, Value: Visibility, less fatigue.

TRL: 3

Technology Performance Goal: Multimodal interfaces, including visual displays, tactile feedback, computer vision, speech recognition, synthesized voice, motion technology, and alternative information presentation technologies.

Parameter, Value: User interface response.

TRL: 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Power consumption and size.

CAPABILITY

Needed Capability: Advanced user interface concepts, displays and control smart habitats, and human-robotic interaction. Advanced human-systems interfaces across all vehicles and habitats should be common to decrease re-training and increase crew efficiency.

Capability Description: Provide efficient, easy to use interfaces for crew interaction with onboard systems. Optimized easy to use interfaces between a human and vehicle or habitat. Multi modal interfaces include, but are not limited to, visual displays, tactile feedback, computer vision, speech recognition, synthesized voice, and motion technology.

Capability State of the Art: Standard digital displays and controls.

Parameter, Value:
Interactive visualization, multimodal technologies (haptic, auditory, visual), intuitive wireless controls, human robotic interaction (HRI), smart habitats. Commonality, interchangeability, and maintainability for human/systems interfaces and interactions.

Capability Performance Goal: Level of usability, effectiveness, and user acceptability. Control of more than one vehicle or habitat using the same Human Systems Interface optimized for usability, effectiveness, and user acceptability.

Parameter, Value:
The applicable parameters are selected from the Human-Systems Integration Standards (HSIS) STD-3001.

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

6.3 Human Health and Performance
6.3.4 Human Factors

6.3.4.2 Physical, Cognitive, and Behavior Augmentation; Tele-Operations, Remote Operations

TECHNOLOGY

Technology Description: Cross-cutting technologies for physical and cognitive aids; wireless communication in the vehicle. Physical and cognitive aids that extend human capabilities by leveraging vehicle and habitat systems through portable, wearable, and automated interfaces.

Technology Challenge: Challenges include developing effective, low cost, mass, volume and power integrated systems for human spaceflight.

Technology State of the Art: Visible light communication or Li-Fi can replace wireless communication.

Parameter, Value: Visible light communication provides weight and power savings and can be used in the radio frequency (RF) sensitive region.

TRL: 5

Technology Performance Goal: Crosscutting technologies for physical and cognitive aids

Parameter, Value: Reliable interaction with crew systems.

TRL: 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Neural cognitive development mapping.

CAPABILITY

Needed Capability: Physical cognitive aids.

Capability Description: Provide cross-cutting technologies for physical and cognitive aids and wireless communication in the vehicle.

Capability State of the Art: Several batteries of tests at an elementary level.

Parameter, Value:
Radio frequency identification (RFID), motion tracking, wireless communication, wearable computing, adaptive training anddecision support systems, tele-operations. Integration of multiple devices into portable and body-worn units with increased capability and usability.

Capability Performance Goal: Wireless communication in the vehicle. Physical and cognitive aids that extend human capabilities by leveraging vehicle and habitat systems through portable, wearable, and automated interfaces; voice based personal recognition.

Parameter, Value:
Level of usability, effectiveness, and user acceptability.

The applicable parameters are selected from the Human-Systems Integration Standards (HSIS) STD-3001.

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	--	2021	6 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	6 years

6.3 Human Health and Performance
6.3.4 Human Factors

6.3.4.3 Human Systems Integration Tools

TECHNOLOGY

Technology Description: Human System Integration Scorecard and human factors engineering analysis tools for human factors requirements and process assessment for human rating the spacecraft; Maneuverability Assessment Scale for real-time data collection; System Consistency Scale for use in hardware and software design assessment.

Technology Challenge: Challenges include effectively transferring or evolving other governmental agencies' approaches to a model effective to space environment and culture and directly applying commercial tools and methods in the space environment.

Technology State of the Art: A pilot version is available for evaluation.

Parameter, Value:
The life cycle cost should be reduced.

TRL: 4

Technology Performance Goal: Integrated human systems tools.

Parameter, Value:
Successful validation of automated tools.

TRL: 8

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Integrated performance of the various tools and the metrics.

CAPABILITY

Needed Capability: Human systems integration tools, methods, and standards.

Capability Description: Standardizes human system integration with spacecraft.

Capability State of the Art: A set of scorecards are in use.

Parameter, Value:
Other governmental agencies' activities; NASA Human System Integration Score Card; Human Systems Integration (HSI) standards. Emphasize human consideration in system design to optimize fully integrated system performance and to reduce life-cycle cost.

Capability Performance Goal: Human factors engineering analysis tools for human factors requirements and process assessment for human rating the spacecraft; real-time data collection; System Consistency Scale for use in hardware and software design assessment.

Parameter, Value:
Output will need to be at minimum comparable to currently utlized tools and metrics.

Successful validation of the automated tools and metrics.

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	--	2021	5 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years

6.3 Human Health and Performance
6.3.4 Human Factors

6.3.4.4 Crew Member Training Aids

TECHNOLOGY

Technology Description: Onboard training display formats and hardware for decision aiding concepts.

Technology Challenge: Long-duration operations in deep space do not allow for assignment of new crew or rotation of crew to ground for training.

Technology State of the Art: Miniaturized digital devices with video capabilities.

Parameter, Value: Specifically trained crew members for complex mission critical tasks. Closely monitored and supported by flight controller.

TRL: 5

Technology Performance Goal: Improved training aids (ground-based pre-flight training, in-space recurrent, and just-in-time training) and associated technologies, including autostereoscopic, transparent and deformable displays, near-to-eye displays, computer vision, computer-mediated reality, computer haptics, and immersive environments.

Parameter, Value: Incidents of crew errors and inefficiencies are minimal. Risk to crew injury is low.

TRL: 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Power consumption and size.

CAPABILITY

Needed Capability: Crew member training.

Capability Description: Focuses on ensuring that pre-flight and in-space training methods and tools are sufficient, particularly in missions with long-durations and communication delays.

Capability State of the Art: Miniaturized digital devices with video capabilities.

Parameter, Value: Trained crew members for complex, mission-critical tasks.

Capability Performance Goal: More advanced systems for creation of intelligent simulations and decision aids to prepare future crews for nominal and off-nominal scenarios.

Parameter, Value: Prevent and reduce crew performance 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	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

6.3 Human Health and Performance
6.3.4 Human Factors

6.3.4.5 Long-Duration Microgravity Workstation and Habitat Tools

TECHNOLOGY

Technology Description: Net Habitability Volume (NHV) and Habitability Modeling Tool; Computational Human Modeling as a Habitability Assessment Tool; Automatic Video-based Motion Analysis; Habitability-Human Factors and Habitability Assessment Tool.

Technology Challenge: Longer-duration mission require greater habitat space.

Technology State of the Art: 70% of the required net habitable volume habitats.

Parameter, Value: Current knowledge does not take into account the deconditioning effects to the crew related to long-duration missions. Need to consider human capabilities and limitations.

TRL 5

Technology Performance Goal: Tools for designing habitat and workspace that accommodates variations in human physical characteristics and capabilities.

Parameter, Value: Incidents of crew errors and inefficiencies are minimal. Risk to crew injury is low.

TRL 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Integrated user space with modular designs.

CAPABILITY

Needed Capability: Prevent, monitor, and detect crew habitability issues.

Capability Description: Enhanced tools for assessing habitability impact to ensure crew member health and optimal performance (accommodating the crew along all anthropometric ranges and considering human capabilities and limitations and how these may change during long-duration spaceflight preventing injuries, crew frustration, and mission failure).

Capability State of the Art: 70% of the required net habitable volume habitats.

Parameter, Value: Enhanced physical and psychological performance.

Capability Performance Goal: Suite of tools for countermeasures and guidelines to promote crew productivity and ensure crew safety.

Parameter, Value: Prevent and reduce crew decrements.

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

6.3 Human Health and Performance
6.3.4 Human Factors

6.3.4.6 Human-Systems Interfaces (HSI) for Increased Autonomy and New Environments

TECHNOLOGY

Technology Description: Physiological computing to affect changes to the human-systems interfaces based on physiological data from the user.

Technology Challenge: Achieving greater dependency on human-computer interaction is a challenge.

Technology State of the Art: Current training and performance assessment are made with limited digital devices.

Parameter, Value:

Critical tasks are closely monitored and supported by flight controller, who has access to more information.

TRL 5

Technology Performance Goal: Human-system interfaces that support crew tasks effectively with critical information.

Parameter, Value:

Incidents of crew errors and inefficiencies are minimal. Risk to crew injury is low.

TRL 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Integrated suite and volume requirements.

CAPABILITY

Needed Capability: More efficient, usable, and common human interface design.

Capability Description: Focuses on developing improved human-system and human robotics interfaces to promote crew productivity and ensure crew safety.

Capability State of the Art: Current training and performance assessment are made with limited digital devices.

Parameter, Value:

Autonomous use by the crew.

Capability Performance Goal: Develop appropriate human-system interfaces suite countermeasures, standards, hardware and software, and guidelines to promote crew productivity and ensure crew safety.

Parameter, Value:

Prevent and reduce crew decrements.

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

6.3 Human Health and Performance
6.3.4 Human Factors

6.3.4.7 Human-Robotic Interfaces for Increased Autonomy

TECHNOLOGY

Technology Description: Work allocation tools; model-based simulation design tool and a metrics toolkit that characterizes the safety and efficiency of a human automation interaction.

Technology Challenge: Achieving greater dependency on automation and robotics is a challenge.

Technology State of the Art: Robonaut in the International Space Station (ISS).

Parameter, Value: Most work in space performed by crew, supported by onboard automated systems (i.e. environmental control) and by ground-based mission control.

TRL: 4

Technology Performance Goal: Automation and robotics that support crew tasks effectively with critical information systems.

Parameter, Value: Incidents of crew errors and inefficiencies are minimal. Risk to crew injury is low.

TRL: 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Reliable distribution of the tasks.

CAPABILITY

Needed Capability: Human interface design.

Capability Description: Focuses on developing improved human-computer and human robotics interfaces to promote crew productivity and ensure crew safety.

Capability State of the Art: Robonaut with limited capabilities and functions.

Parameter, Value: Delegation of challenging tasks and the success rate of performance.

Capability Performance Goal: Human-system interface suite countermeasures and guidelines to promote crew productivity and ensure crew safety.

Parameter, Value: Prevent and reduce crew decrements.

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

6.3 Human Health and Performance
6.3.4 Human Factors and Performance

6.3.4.8 Ergonomics of Crew Hardware Interface

TECHNOLOGY

Technology Description: Modeling tool of crew hardware interface with an ergonomics perspective. Ergonomic modeling should consider addressing adequacy of the crew-hardware interface for the entire crew population based on limited human-in-the-loop testing data. Modeling must show accommodation, fit, performance limitations, and risk to injury. It also must be able to provide results on whether the design excludes certain ranges of the crew population. The modeling should be based on sound ergonomic principles.

Technology Challenge: Identifying the issues with and developing mitigation strategies for a crew hardware interface is a challenge.

Technology State of the Art: Current modeling technology has a limited data set.

Parameter, Value:	TRL
Laser-scanned humanoid images and suit parameters are processed in a Solid Works platform.	2

Technology Performance Goal: An ergonomics modeling tool that shows accommodation, fit, performance limitations, and risk to injury; could be expanded as the knowledge grows.

Parameter, Value:	TRL
Biomechanical analysis (body segment/joint force analysis for performanc and injury considerations). Kinematic analysis (body movement analysis). Strength factors (captured using various dynamometers and load cells). Mobility factors (primarily arm, but also includes leg and back ranges of motion). Suit fit (predicted suit fit used by suit techs for sizing as well as initial actual suit fit in development). Vehicle-seat fit analysis (includes ingress and egress for unsuited and suited conditions). Suit-body volume analysis. Task completion times. Suit-body contact forces. Epidemiology assessment for injury analysis. Surface temperatures (for materials and bodies).	2

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Ability to obtain necessary basic information for building the modeling framework.

CAPABILITY

Needed Capability: A comprehensive ergonomic model.

Capability Description: A comprehensive ergonomic model that considers anthropometry, mobility, dynamic postural movement, risk to injury, and functional strength to predict the assessment of a specific task activity and be able to identify both the worst-case incident and perform the assessment for the entire population.

Capability State of the Art: Ability to put the data together for a specific situation.

Parameter, Value:

Minimize injury while performing tasks.

Capability Performance Goal: A comprehensive ergonomic model that becomes versatile with future data collection.

Parameter, Value:

Optimal suit fit with minimal injury while performing tasks.

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 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

6.3 Human Health and Performance
6.3.4 Human Factor and Performance

6.3.4.9 Physical Accomodation

TECHNOLOGY

Technology Description: Techniques to ensure crew in EVA suits can safely perform diverse tasks. Proper and adequate accommodation of suited crew in a safe manner is a necessary requirement to ensure new and existing space hardware is designed effectively.

Technology Challenge: The limited number of available suit components make it difficult to assess the full range accommodation; hence, alternative techniques are needed to accomplish the assessment.

Technology State of the Art: Currently, there are no techniques to accomplish this goal.

Parameter, Value:
No techniques currently available.

TRL: None

Technology Performance Goal: Assessment design tool that enables the gathering of relevant data during testing and be able to assess the overall physical accommodation.

Parameter, Value:
Comfortable fit for static and dynamic functional activities.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Ability to have access to observe and gather necessary data for accommodation analysis.

CAPABILITY

Needed Capability: Assessment design tool that predicts during early stages of prototyping, as well as during the final verification stage, whether physical accommodation is accomplished during static and dynamic functional activities that are critical for a successful mission.

Capability Description: This new methodology and procedure should be easily deployable during a design and development cycle in such a way that the designers and testers are able to determine whether there would be any issues in accommodating the crew.

Capability State of the Art: Limited capability exists but requires extensive data collection.

Parameter, Value:
Critical anthropometric parameters for comfortable fit.

Capability Performance Goal: An EVA assessment design tool that provides easily implementable feedback that can be readily accepted by the designers and engineers.

Parameter, Value:
Optimized suit fit to perform static and dynamic functional activities.

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 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

6.4 Environmental Monitoring, Safety, and Emergency Response
6.4.1 Sensors: Air, Water, Microbial, and Acoustic

6.4.1.1 Cabin Air Sensor

TECHNOLOGY

Technology Description: Sensor for continuous monitoring of target trace volatile organic compounds (VOCs) in the habitable cabin without reliance on ground sample testing.

Technology Challenge: Technology needs to analyze target chemical species in a complex mixture in a continuous manner using minimal consumables and have a reliable method to handle unknown chemical species.

Technology State of the Art: Gas Chromatography-Differential Mobility Spectrometry (GC-DMS); current Air Quality Monitor (AQM); Fourier Transform-Infrared Spectroscopy (FT-IR); Gas-Chromatography-Mass Spectrometer (GC-MS).

Parameter, Value:	TRL
Continuous operations ≥ 2 years.	8

Technology Performance Goal: Cabin air sensor in continuous operations without non-routine maintenance or need for sample return for ground analysis.

Parameter, Value:	TRL
Operation: continuous Routine maintenance interval: ≥ 1 year	8

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

CAPABILITY

Needed Capability: Air quality monitoring.

Capability Description: Provide in-flight characterization of air quality in the cabin atmosphere.

Capability State of the Art: AQM - based on gas chromatography-differential mobility spectrometry; portable unit; 2 units deployed; battery ops capable for remote sampling.

Grab-Sample Containers (GSCs) - evacuated canisters used for sampling International Space Station (ISS) air; returned for ground analysis.

Parameter, Value:

Continuous operation for 6 months with routine maintenance interval every 6 months.

Capability Performance Goal: Continuously monitor air quality with minimal maintenance.

Parameter, Value:

Continuous operations ≥ 2 years in a relevant environment with maintenance interval ≥ 1 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
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

6.4 Environmental Monitoring, Safety, and Emergency Response
6.4.1 Sensors: Air, Water, Microbial, and Acoustic

6.4.1.2 Major Constituents Sensor

TECHNOLOGY

Technology Description: Sensor for continuous monitoring of the major constituents (oxygen, nitrogen, water vapor, carbon dioxide, hydrogen, and methane) in the habitable cabin air.

Technology Challenge: Technology needs to quantify the required major constituents using minimal consumables.

Technology State of the Art: Magnetic-sector mass spectrometry; current major constituent analyzer (MCA); quadrupole mass spectrometry; Raman spectroscopy.

Parameter, Value:

Operations: normal sampling at 2-minute intervals and rapid sampling at 2-second intervals.

Routine maintenance interval: 180-days.

Constituents monitored: oxygen, nitrogen, water vapor, carbon dioxide, hydrogen, methane.

TRL 4

Technology Performance Goal:

Parameter, Value:

Operations: normal sampling at 2-minute intervals and rapid sampling at 2-second intervals.

Constituents monitored: oxygen, nitrogen, water vapor, carbon dioxide, hydrogen, methane.

TRL 6

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

CAPABILITY

Needed Capability: Major constituents monitoring.

Capability Description: Provide in-flight major constituent gas monitoring in the cabin atmosphere.

Capability State of the Art: Major constituent analyzer (MCA) - based on magnetic-sector mass spectrometry; rack-based analyzer with an approximate mass and volume of 55-kg and 22-L.

Parameter, Value:

Operation: sample at 2-minute and 2-second intervals.

Routine maintenance interval: 180-days.

Major constituents to monitor: oxygen, nitrogen, water vapor, carbon dioxide, hydrogen, methane.

Capability Performance Goal: In-flight major constituent gas monitoring in the cabin atmosphere without non-routine maintenance.

Parameter, Value:

Operation: sample at 2-minute and 2-second intervals.

Routine maintenance interval: ≥ 2 years.

Major constituents to monitor: oxygen, nitrogen, water vapor, carbon dioxide, hydrogen, methane.

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 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

6.4 Environmental Monitoring, Safety, and Emergency Response
6.4.1 Sensors: Air, Water, Microbial, and Acoustic

6.4.1.3 Target Gas Sensors

TECHNOLOGY

Technology Description: Sensor or system to identify and quantify target gases (carbon dioxide, oxygen, formaldehyde, combustion products, and system chemicals) in the habitable cabin during contingencies and without any reliance on ground return.

Technology Challenge: Laser spectroscopy can provide the needed calibration but it is dependent on the availability of low-power, solid-state lasers at the proper wavelength.

Technology State of the Art: Tunable diode laser spectroscopy.

Parameter, Value:
Calibration life ≥ 1 year (starting at the time of calibration).

TRL: 5

Technology Performance Goal: Sensor or system to identify and quantify target gases with increase calibration life.

Parameter, Value:
Calibration life ≥ 2 years (starting at the time of calibration).

TRL: 4

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

CAPABILITY

Needed Capability: Target gas monitoring.

Capability Description: Provide in-flight characterization of target gases in the cabin atmosphere.

Capability State of the Art: Calibration life of various ways to monitor target gases range from nine months to two years from time of calibration in laboratory. Includes current SOA Formaldehyde Monitoring Kits (FMK); Portable Oxygen Monitor (POM); Carbon Dioxide Monitoring Kit (CDMK); Multi-Gas Monitor (MGM).

Parameter, Value:
Nine months ≤ calibration life ≤ 2 years (starting at the time of calibration).

Capability Performance Goal: In-flight characterization of target gases (carbon dioxide, oxygen, formaldehyde, combustion products, and system chemicals) in the cabin atmosphere.

Parameter, Value:
Calibration life ≥ 2 years (starting at the time of calibration).
Operable during contingencies and without any reliance on ground return.

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

6.4 Environmental Monitoring, Safety, and Emergency Response
6.4.1 Sensors: Air, Water, Microbial, and Acoustic

6.4.1.4 Airborne Particle Sensor

TECHNOLOGY

Technology Description: Sensor to quantify, by size and concentration, the respirable particles in the habitable cabin.

Technology Challenge: Developing real-time monitors with binning capability for fine (300 nm-10 microns) and ultrafine (30 nm-1 micron) particulates.

Technology State of the Art: Optical counters (OPC): concentration and size for ≥ 0.3µm.

Differential Mobility Analyzers (DMA): concentration and size for ≤ 0.5µm.

Condensate Particle Counters (CPC): concentration only for ≤ 3µm.

Tapered element (TEOM) and Quartz Crystal Microbalance (QCM): direct mass reading, not size specific.

Parameter, Value:

Measure airborne particle concentration for particles 10 micrometers and smaller.

TRL: 4

Technology Performance Goal: Airborne particle sensor that continuously monitors ambient particle concentrations in the habitable cabin.

Parameter, Value:

Requirement is 0.3 mg/m^3 for particles of 10 micrometers and smaller.

TRL: 6

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

CAPABILITY

Needed Capability: Airborne particle monitoring.

Capability Description: Characterize respirable particles in the cabin atmosphere.

Capability State of the Art: No in-flight technology currently in use.

Parameter, Value:

Particle concentration, presently expressed in terms of mass loading for particle sizes of 10 micrometers and smaller. Desirable to separately report ultrafine content (20-100 nm).

Capability Performance Goal: Continuously monitor and characterize ambient particle concentrations in the habitable cabin.

Parameter, Value:

Requirement 0.3 mg/m^3 for particles of 10 micrometers and smaller.

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

6.4 Environmental Monitoring, Safety, and Emergency Response
6.4.1 Sensors: Air, Water, Microbial, and Acoustic

6.4.1.5 Water Quality Sensor

TECHNOLOGY

Technology Description: Sensor to identify and quantify target organic and inorganic chemical species in the water of manned spacecraft without any reliance on ground analysis.

Technology Challenge: Microgravity-compatible technology needs to meet the constraints imposed by the mission and the vehicle (mass, volume, and power) and be capable of analyzing target chemical species in a complex mixture using minimal consumables.

Technology State of the Art: Gas chromatography-mass spectrometry (GC-MS); Ion Chromatography (IC); Liquid chromatography-mass spectrometry (LC-MS); Electrospray Ionization-mass spectrometry (ESI-MS); Ultraviolet-Visible (UV-Vis) Spectrophotometry; potentiometric methods (e.g., pH, conductivity); Capillary Electrophoresis (CE).

Parameter, Value:
Laboratory instrument to identify and quantify target species in potable water. Minimum detection limit: 5µg/L.

TRL: 3

Technology Performance Goal: Water quality sensor that identifies and quantifies target organic and inorganic chemical species in water samples.

Parameter, Value:
In water samples: targets, minimum detection limit (500µg/L): 500µg/L.

TRL: 6

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

CAPABILITY

Needed Capability: Water quality monitoring.

Capability Description: Provide in-flight characterization of water quality consumed by the crew.

Capability State of the Art: Sample return for ground analyses; no in-flight technology currently in use

Parameter, Value:
For ground analysis: laboratory instrument to identify and concentrate volatile, semi-volatile, non-volatile species; water-soluble inorganics/minerals; organic and inorganic carbon; metals; and silicon-containing compounds.

Capability Performance Goal: Portable water quality instrument to identify and quantify target organic and inorganic chemicals in water samples.

Parameter, Value:
Portable identify and quantify target organic and inorganic chemicals in water samples: targets, minimum detection limit (500µg/L).
No reliance on ground analysis.

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

6.4 Environmental Monitoring, Safety, and Emergency Response
6.4.1 Sensors: Air, Water, Microbial, and Acoustic

6.4.1.6 Biocide Sensor

TECHNOLOGY

Technology Description: Sensor to identify and quantify the biocide in the potable water.

Technology Challenge: Technology needs to meet the constraints imposed by the mission and the vehicle (mass, volume, and power) and be capable of analyzing target chemical species in a complex mixture using minimal consumables.

Technology State of the Art: Spectrophotometric with ultraviolet-visible (UV-Vis) spectrophotometer; handheld.

Parameter, Value:

Nominal crew time required: 1 hour per session; one session every 3 months, 4 hours per year.

TRL 5

Technology Performance Goal: Automated sensor to identify and quantify the biocide in potable water.

Parameter, Value:

Nominal crew time required: none.

TRL 6

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

CAPABILITY

Needed Capability: Water biocide monitoring.

Capability Description: Characterize the composition and concentration of biocide in the potable water supply.

Capability State of the Art: Colorimetric Water Quality Monitoring Kit (CWQMK): light emitting diode (LED)-based, spectroscopic biocide monitor for silver biocide; employ indicator-embedded solid-phase microextraction to determine silver concentration.

Parameter, Value:

Nominal crew time required: 1 hour per session; 1 session every 3 months; 4 hours per year.

Capability Performance Goal: Water sensor that characterizes the composition and concentration of biocide in the potable water supply with no impact on crew time.

Parameter, Value:

Accuracy: 100%

Nominal crew time required: none.

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

6.4 Environmental Monitoring, Safety, and Emergency Response
6.4.1 Sensors: Air, Water, Microbial, and Acoustic

6.4.1.7 Water Total Organic Carbon Sensor

TECHNOLOGY

Technology Description: Sensor to measure total organic and total inorganic carbon in the potable water of manned spacecraft.

Technology Challenge: Technology needs to provide total organic carbon (TOC) in potable water without the need for reagents.

Technology State of the Art: Oxidation-based Total Organic Carbon Analyzer (TOCA).

Parameter, Value: Reagents required.

TRL 4

Technology Performance Goal: Reagentless total organic carbon analyzer to monitor TOC in potable water.

Parameter, Value: No reagents required.

TRL 6

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

CAPABILITY

Needed Capability: Total organic carbon monitoring.

Capability Description: Measure TOC in the potable water supply.

Capability State of the Art: TOCA: monitors total organic carbon in International Space Station (ISS) water; rack-based unit with a mass of approximately 34-kg and a volume of 67-L, requiring buffer and calibration reagents; measurements once per week.

Parameter, Value: Reagents required: buffer and calibration.

Capability Performance Goal: Reagentless total organic carbon analyzer to monitor and measure total organic and total inorganic carbon in the potable water of manned spacecraft.

Parameter, Value: No reagents required.

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

6.4 Environmental Monitoring, Safety, and Emergency Response
6.4.1 Sensors: Air, Water, Microbial, and Acoustic

6.4.1.8 Air Microbial Sensor

TECHNOLOGY

Technology Description: Sensor to sample and process the air of the habitable spacecraft cabin to enumerate and identify microbial presence without any reliance on ground analysis.

Technology Challenge: Air sampler that can sample and process to identify and enumerate microbes in the air.

Technology State of the Art: Qualitative polymerase chain reaction (qPCR) with appropriate air sample processing kit.

Parameter, Value: Identify and quantify microbes in air sample.

TRL: 5

Technology Performance Goal: Air microbial sensor to enumerate and identify microbes present in air sample

Parameter, Value: Enumerate and identify microbe in air sample.

TRL: 6

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

CAPABILITY

Needed Capability: Microbial monitoring in air.

Capability Description: Provide in-flight characterization of airborne microbes in the cabin atmosphere.

Capability State of the Art: Microbial Air Sampler (MAS): culture-based enumeration only (2-7 days). Ground analysis of returned samples to determine species.

Parameter, Value: Enumeration of microbe in colony forming units.

Capability Performance Goal: In-flight microbial monitoring in air samples to enumerate and characterization of airborne microbes in the cabin atmosphere.

Parameter, Value: High accuracy (100%) in enumerating and identifying microbes in air.

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

6.4 Environmental Monitoring, Safety, and Emergency Response
6.4.1 Sensors: Air, Water, Microbial, and Acoustic

6.4.1.9 Water Microbial Sensor

TECHNOLOGY

Technology Description: Sensor to sample and process the potable water of manned spacecraft to enumerate and identify microbial presence, including the presence of coliform bacteria, without reliance on ground analysis.

Technology Challenge: Challenges include developing a water sampler that can sample and process, without crew time, as well as identify and enumerate microbes in air.

Technology State of the Art: Qualitative polymerase chain reaction (qPCR) with appropriate water sample processing kit.

Parameter, Value: Identify and quantify microbes in water sample.

TRL: 5

Technology Performance Goal: Water microbial sensor that processwa water samples to enumerate and identify microbes present.

Parameter, Value: Enumerate and identify microbe in water sample.

TRL: 6

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

CAPABILITY

Needed Capability: Microbial monitoring in water.

Capability Description: Provide in-flight characterization of the microbial population in the potable water supply.

Capability State of the Art: Environment health system (EHS) Water Kit: culture-based enumeration only (2-7 days), coliform test (2 days). Ground analysis of returned samples to determine species.

Parameter, Value: Enumeration of microbe in colony forming units.

Capability Performance Goal: In-flight microbial monitoring that characterizes the microbial population in the potable water supply.

Parameter, Value: Enumerate and identify microbe in water sample with high accuracy (100%).

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

6.4 Environmental Monitoring, Safety, and Emergency Response
6.4.1 Sensors: Air, Water, Microbial, and Acoustic

6.4.1.10 Surface Microbial Sensor

TECHNOLOGY

Technology Description: Sensor to sample and process the surfaces of the habitable spacecraft cabin to enumerate and identify microbial presence without any reliance on ground analysis.

Technology Challenge: Challenges include developing a surface sampler that can sample and process, without crew time, as well as identify and enumerate microbes in air. Human space flight (HSF)-rated coatings used for detection of harmful toxicity levels to humans on surfaces, filters, pipes, and mechanisms. Other challenges include longevity degradation of the coating; non-harmful off-gassing; and reliability of the coating.

Technology State of the Art: Qualitative polymerase chain reaction (qPCR) with appropriate surface sample processing kit. Biotechnology coating for toxicity detection, government labs have developed Intelligent Coatings for Location And Detection of leaks (IntelliCLAD), a new class of smart coatings that are non-odorous, but that release an odor in the presence of selected gases of concern.

Parameter, Value: Identity and quantify microbes in surface sample.

TRL: 5

Technology Performance Goal: Surface microbial sensor that processes surface samples to enumerate and identify microbes present.

Parameter, Value: Enumerate and identify microbe in water sample.

TRL: 6

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

CAPABILITY

Needed Capability: Microbial monitoring on surfaces.

Capability Description: Provide in-flight characterization of the microbial population on cabin surfaces.

Capability State of the Art: Surface Sampling Kit (SSK): culture-based enumeration only (2-7 days). Ground analysis of returned samples to determine species.

Parameter, Value: Enumeration of microbe in colony forming units.

Capability Performance Goal: In-flight microbial characterization of the microbial population on cabin surfaces.

Parameter, Value: Process surface samples to enumerate and identify microbes present in surface sample with a high degree of accuracy (100%).

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

6.4 Environmental Monitoring, Safety, and Emergency Response
6.4.2 Fire: Detection, Suppression, and Recovery

6.4.2.1 Combustion Model in Low and Partial Gravity

TECHNOLOGY

Technology Description: Tools to model combustion process in low and partial gravity.

Technology Challenge: Challenges include developing combustion studies at low- and partial-gravity in nominal and elevated oxygen levels.

Technology State of the Art: Assessment of material flammability in normal-gravity at highest operational oxygen concentration.

Parameter, Value:	TRL
Combustion models at 1-g and microgravity.	2

Technology Performance Goal: Combustion models at low- and partial-gravity in nominal and elevated oxygen levels.

Parameter, Value:	TRL
Combustion models at low- and partial-gravity in nominal and elevated oxygen levels that accurately predicts flammability properties of materials.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Material flammability and flame propagation characteristics.

CAPABILITY

Needed Capability: Fire prevention.

Capability Description: Predictive models for low- and partial-gravity material flammability to lower the risk of fire in the habitable cabin.

Capability State of the Art: Combustion models at 1-g and at microgravity; materials and processing techical information system (MAPTIS).

Parameter, Value:

Combustion models at 1-g and microgravity; database of flammability properties of different materials.

Capability Performance Goal: Generate models of combustion process of various materials in low and partial gravity.

Parameter, Value:

Combustion models at low and partial gravity at nominal oxygen levels. Combustion studies in low and partial gravity at elevated oxygen levels. Possesses high correlation to modeled events.

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	4 years
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

6.4 Environmental Monitoring, Safety, and Emergency Response
6.4.2 Fire: Detection, Suppression, and Recovery

6.4.2.2 Cabin Fire: Detection System

TECHNOLOGY

Technology Description: System to detect and monitor fire in the habitable cabin of crewed spacecraft with hybrid gaseous and particulate fire detection systems to eliminate false positives.

Technology Challenge: Technology needs to meet the constraints imposed by the mission and the vehicle (mass, volume, and power) and capable of analyzing target chemical species in a complex mixture using minimal consumables.

Technology State of the Art: Non-discriminate particulate detection; smoke filtering and dedicated instrument to monitor CO, CO_2, and other combustion products during clean-up.

Parameter, Value:	**TRL**
Multi-sensor input for zero false positives.	3

Technology Performance Goal: System to detect and monitor fire in the habitable cabin of crewed spacecraft.

Parameter, Value:	**TRL**
Probability of false positives: 0	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Material flammability and flame propagation characteristics.

CAPABILITY

Needed Capability: Fire detection.

Capability Description: Provide improved fire detection systems.

Capability State of the Art: Smoke detection by obscuration - fire detected by presence of smoke in path of laser light, obscuring light detection.

Parameter, Value:
Fire alarm with no probability of false positives.

Capability Performance Goal: Fire detection in the habitable cabin of crewed spacecraft with hybrid gaseous and particulates.

Parameter, Value:
Probability of false positives: 0

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	4 years
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

6.4 Environmental Monitoring, Safety, and Emergency Response
6.4.2 Fire: Detection, Suppression, and Recovery

6.4.2.3 Cabin Fire Extinguisher

TECHNOLOGY

Technology Description: System to extinguish a fire in the habitable cabin of manned spacecraft at nominal and elevated oxygen levels in low- and partial-gravity.

Technology Challenge: Developing recharging capability while minimizing total logistics, mass, and volume of vehicle is a challenge.

Technology State of the Art: Properly-sized fire extinguisher that is rechargeable. Common types include air-pressurized water, dry chemical, and CO_2.

Parameter, Value: | **TRL**
Multi-use capable. | 2

Technology Performance Goal: Fire extinguisher in the habitable cabin of manned spacecraft at nominal and elevated oxygen levels in low and partial gravity.

Parameter, Value: | **TRL**
Number of uses per unit: > 1. | 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Material flammability and flame propagation characteristics.

CAPABILITY

Needed Capability: Fire suppression.

Capability Description: Provide fire suppression systems for a variety of partial pressure oxygen levels and gravity environments.

Capability State of the Art: Portable Fire Extinguishers (PFE): CO_2-based extinguishers; not rechargeable in-flight.

Parameter, Value:
Number of uses per unit: 1.

Capability Performance Goal: Multi-use fire extinguisher while minimizing total logistics, mass, and volume.

Parameter, Value:
Number of uses per unit: > 1.
Reduction in logistics, mass and volume of current state of the art.

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

6.4 Environmental Monitoring, Safety, and Emergency Response
6.4.3 Protective Clothing and Breathing

6.4.3.1 Advanced Respirator

TECHNOLOGY

Technology Description: Face mask that protects crew of manned spacecraft from chemical and particle exposure and provides breathing capability during contingencies.

Technology Challenge: Developing chemical rebreather for ≥ 8 hour life.

Technology State of the Art: Rebreather.

Parameter, Value:

Application: fire and chemical release.

TRL: 6

Technology Performance Goal: Provide breathing capability to crew from multiple off-nominal contingencies.

Parameter, Value:

Protection: ≥ 8 hours.

Applications: fire and chemical release.

TRL: 7

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

CAPABILITY

Needed Capability: Portable emergency respirator.

Capability Description: Provide portable breathing capability to crew during chemical, particle, and/or fire exposure.

Capability State of the Art: Portable Breathing Apparatus (PBA): full-face mask delivering 100% O_2 for 15 minutes.

Ammonia and fire respirator: one-size-fits-all with integrated hood; cartridge-based filtration user changeable.

Parameter, Value:

Provide time to evacuate module in ≤15 minutes (PBA). Provide time for ammonia scrubbers to reduce ammonia levels from 10K ppm to mask doffing levels of 100 pm in ≤8 hours (ammonia and fire respirator).

Capability Performance Goal: Portable emergency respirator that protects crew from multiple off-nominal contingencies.

Parameter, Value:

Protection: ≥ 8 hours.

Applications: fire and chemical release.

Portable.

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	4 years
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

6.4 Environmental Monitoring, Safety, and Emergency Response
6.4.3 Protective Clothing and Breathing

6.4.3.2 Advanced Clothing

TECHNOLOGY

Technology Description: Clothing that protects crew from chemical exposure and bodily harm during nominal and off-nominal contingencies.

Technology Challenge: Different materials may be needed to protect from various chemicals in the solid, liquid, and/or gas state(s).

Technology State of the Art: Chemical- and tear-resistant protective clothing.

Parameter, Value:
Tear-resistant, non-reactive, full-body protection.
Permeation of liquids and gases: 0

TRL 4

Technology Performance Goal: Chemical-resistant and tear-resistant clothing.

Parameter, Value:
Permeation of liquids and gases: 0

TRL 6

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

CAPABILITY

Needed Capability: Protective clothing.

Capability Description: Provide protection against chemical exposure and/or off-nominal contingencies.

Capability State of the Art: No in-flight technology currently in use; hand and face protection only.

Parameter, Value:
Tear-resistant
Non-reactive
Permeation of liquids and gases: 0
Hand and face protection

Capability Performance Goal: Chemical-resistant and tear-resistant clothing that offers full-body protection.

Parameter, Value:
Tear-resistant
Non-reactive
Permeation of liquids and gases: 0
Full-body 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
Into the Solar System: DRM 5 Asteroid Redirect - Crewed in DRO	Enabling	2022	2022	2015-2021	4 years
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

6.4 Environmental Monitoring, Safety, and Emergency Response
6.4.4 Remediation

6.4.4.1 Contingency Air Scrubber

TECHNOLOGY

Technology Description: System that reduces the concentration of chemical and particle contaminants in the air of the habitable cabin to acceptable levels following a release.

Technology Challenge: Developing regenerable capability while minimizing total logistics, mass, and volume of vehicle is a challenge.

Technology State of the Art: Regenerable chemical removing media.

Parameter, Value: Multi-use filter to reduce air contaminant acceptable levels in ≥ 8 hours.

TRL 2

Technology Performance Goal: Filter to reduce air contaminant to acceptable levels.

Parameter, Value: Multi-use filter to reduce air contaminant acceptable levels in ≤ 8 hours.

TRL 5

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

CAPABILITY

Needed Capability: Air contamination control.

Capability Description: Provide multi-use cabin atmosphere remediation following chemical or particle release.

Capability State of the Art: Activated Charcoal filters, High-Efficiency Particulate Adsorption (HEPA) filters, and fan units.

Parameter, Value: Single use filters reduce air contaminant to acceptable levels in ≤ 8 hours.

Capability Performance Goal: Multi-use filter to reduce air contaminant acceptable levels following chemical or particle release.

Parameter, Value: Number of contingency uses > 1; time to reduce contaminants ≤ 8 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	Enabling	2022	2022	2015-2021	4 years
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

6.4 Environmental Monitoring, Safety, and Emergency Response
6.4.4 Remediation

6.4.4.2 Contingency Microbial Remediation

TECHNOLOGY

Technology Description: System to reduce microbial growth on the surfaces of the habitable cabin to acceptable levels.

Technology Challenge: Developing a water purification system that can treat water containing higher levels of alcohol without decreasing bed life is a challenge.

Technology State of the Art: Sodium hypochlorite solution (bleach), isopropyl alcohol, biocidal ultraviolet (UV) light.

Parameter, Value: Microbial growth reduced to acceptable levels of colony forming units (CFUs).

TRL: 5

Technology Performance Goal: Reduce microbial growth to acceptable levels.

Parameter, Value: Microbial growth reduced to acceptable levels of CFUs.

TRL: 5

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

CAPABILITY

Needed Capability: Microbial contaminant remediation.

Capability Description: Reduce microbial growth on cabin surfaces by means compatible with vehicle environmental control and life support system (ECLSS).

Capability State of the Art: Single-use benzalkonium chloride wipes for surfaces; silver biocide for water.

Parameter, Value: Microbial growth reduced to zero CFUs.

Capability Performance Goal: Multi-use means to reduce microbial growth to acceptable levels.

Parameter, Value: Microbial growth reduced to zero CFUs.

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

6.4 Environmental Monitoring, Safety, and Emergency Response
6.4.4 Remediation

6.4.4.3 Post-Fire Air Scrubber

TECHNOLOGY

Technology Description: System to reduce the concentration of combustion products, particles, and extinguishing material released into the air of the habitable cabin due to a fire, to acceptable levels.

Technology Challenge: Developing regenerable capability while minimizing total logistics, mass, and volume of vehicle is a challenge.

Technology State of the Art: Regenerable filtration medium.

Parameter, Value:
Use for > 1 post-fire scrubbing.

TRL 5

Technology Performance Goal: Reduce concentrations of combustion products and particles generated in the habitable volume by a fire.

Parameter, Value:
Use for > 1 post-fire scrubbing.

TRL 6

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

CAPABILITY

Needed Capability: Post-fire remediation.

Capability Description: Reduce fire-related airborne contaminants with multi-use filtration.

Capability State of the Art: LiOH cartridges; activated carbons and targeted gas sorbents (formaldehyde, ammonia/amines, acid gases); oxidation catalysts (ambient temperature CO, thermal oxidation catalysts for volatile organic compounds, or VOCs); fan assembly; monitors for CO, CO_2, and acid gases (combustion products); and AFOT unit.

Parameter, Value:
Single-use device able to treat a 500 ft^3 volume to allow for mask doffing ≤ 6 hours from the start of scrubbing.

Capability Performance Goal: Multi-use filtration to reduce combustion products and particles generated by a fire.

Parameter, Value:
Multi-use device able to treat a 500 ft^3 volume to allow for mask doffing ≤ 6 hours from the start of scrubbing.

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	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	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

6.5 Radiation
6.5.1 Risk Assessment Modeling

6.5.1.1 Integrated Mortality Risk Projection Model Tool

TECHNOLOGY

Technology Description: Computational tool enabling the accurate prediction of lifetime risk of morbidity and mortality from radiation exposures in combination with other spaceflight stressors (e.g., microgravity). This tool integrates risk from different endpoints: cancer, central nervous system (CNS) effects, and other degenerative conditions, such as circulatory disease.

Technology Challenge: Challenges include validating data, scaling from terrestrial space, and using a systems biology approach. Additional challenges in addressing CNS risks.

Technology State of the Art: Integrated tool does not exist. Cancer model exists with uncertainty of 350, and initial circulatory disease with unknown uncertainties. No data for CNS.

Parameter, Value:	TRL
350% uncertainty.	1

Technology Performance Goal: Computational tool enabling the accurate prediction of lifetime risk of morbidity and mortality from radiation exposures in combination with other spaceflight stressors.

Parameter, Value:	TRL
Reduce uncertainty in radiation risk modeling and analysis for astronaut exposure to space radiation.	9

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

CAPABILITY

Needed Capability: Radiation risk assessment modeling and analysis.

Capability Description: Ability to assess astronaut risk due to space radiation exposure, with minimal uncertainty, for improved mission operations, mission planning, and system design for low-Earth orbig (LEO), deep-space, lunar, and Mars missions.

Capability State of the Art: Tools currently used to estimate cancer risk from radiation to crew during operations in LEO do not include synergistic effects. In addition, these models are based on scaling of terrestrial radiation exposures to spaceflight environment and are not truly representative of the free space radiation environment. Risk models currently used for LEO operations do not include circulatory or CNS effects.

Parameter, Value:

Percent uncertainty in the model results. Cancer models exist with a 350% uncertainty. Little or no risk models that include circulatory or CNS effects.

Capability Performance Goal: Assessment tool that integrates risk from different endpoints: cancer, CNS effects, and other degenerative conditions, such as circulatory disease; assess astronaut risk due to space radiation exposure, with minimal uncertainty, for improved mission operations, mission planning, and system design for LEO, deep-space, lunar, and Mars missions.

Parameter, Value:

Near term: 200% uncertainty for all radiation exposure risks for near-Earth object (NEO) missions (365 days).

Long term: 50% uncertainty for all radiation exposure risks for Mars missions (1000 days).

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	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	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

6.5 Radiation
6.5.1 Risk Assessment Modeling

6.5.1.2 Cancer Risk Projection Model

TECHNOLOGY

Technology Description: Improved statistical model for risk of cancer due to radiation exposure.

Technology Challenge: Challenges include validating data, scaling from terrestrial space, and using a systems biology approach.

Technology State of the Art: Baseline cancer risk projection model exists for low-Earth orbit (LEO) environment with 350% uncertainty.

Parameter, Value: 350% uncertainty.

TRL: 4

Technology Performance Goal: Statistical model for risk of cancer due to radiation exposure.

Parameter, Value: Reduce uncertainty in radiation risk modeling and analysis for astronaut exposure to space radiation.

TRL: 9

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

CAPABILITY

Needed Capability: Radiation risk assessment modeling and analysis.

Capability Description: Ability to assess astronaut risk due to space radiation exposure, with minimal uncertainty, for improved mission operations, mission planning, and system design for LEO, deep space, lunar, and Mars missions.

Capability State of the Art: Tools currently used to estimate cancer risk from radiation to crew during operations in LEO do not include synergistic effects. In addition, these models are based on scaling of terrestrial radiation exposures to spaceflight environment and are not truly representative of the free space radiation environment. Risk models currently used for LEO operations do not include circulatory or central nervous system (CNS) effects.

Parameter, Value:
Percent uncertainty in the model results. Cancer models exist with a 350% uncertainty. Little or no risk models that include circulatory or CNS effects.

Capability Performance Goal: Radiation risk assessment modeling and analysis that reduces astronaut risk due to space radiation exposure, with minimal uncertainty.

Parameter, Value:
Near term: 200% uncertainty for all radiation exposure risks for near-Earth object (NEO) missions (365 days).

Long term: 50% uncertainty for all radiation exposure risks for Mars missions (1000 days).

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	Enabling	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	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

6.5 Radiation
6.5.1 Risk Assessment Modeling

6.5.1.3 Degenerative Risk Projection Model (Includes Heart and Circulatory)

TECHNOLOGY

Technology Description: Statistical model for risk of organ degeneration due to radiation exposure, incorporating circulatory risks.

Technology Challenge: Challenges include validating data, scaling from terrestrial space, and using a systems biology approach.

Technology State of the Art: Initial modeling only of circulatory disease with unknown uncertainties.

Parameter, Value:

Parameter - % uncertainty.

Value - unknown.

TRL: 2

Technology Performance Goal: Statistical model for risk of organ degeneration due to radiation exposure.

Parameter, Value:

Reduce uncertainty in radiation risk modeling and analysis for astronaut exposure to space radiation.

TRL: 9

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

CAPABILITY

Needed Capability: Radiation risk assessment modeling and analysis.

Capability Description: Ability to assess astronaut risk due to space radiation exposure, with minimal uncertainty, for improved mission operations, mission planning, and system design for low-Earth orbit (LEO), deep space, lunar, and Mars missions.

Capability State of the Art: Tools currently used to estimate cancer risk from radiation to crew during operations in LEO do not include synergistic effects. In addition, these models are based on scaling terrestrial radiation exposures to spaceflight environment and are not truly representative of the free space radiation environment. Risk models currently used for LEO operations do not include circulatory or central nervous system (CNS) effects.

Parameter, Value:

Percent uncertainty in the model results. Cancer models exist with a 350% uncertainty. Little or no risk models that include circulatory or CNS effects.

Capability Performance Goal: Radiation risk assessment modeling and analysis that incorporates circulatory and organ degeneration risk for astronauts due to space radiation exposure, with minimal uncertainty

Parameter, Value:

Near term: 200% uncertainty for all radiation exposure risks for near-Earth object (NEO) missions (365 days).

Long term: 50% uncertainty for all radiation exposure risks for Mars missions (1000 days).

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	Enabling	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	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

6.5 Radiation
6.5.1 Risk Assessment Modeling

6.5.1.4 Central Nervous System (CNS) Risk Projection Model

TECHNOLOGY

Technology Description: Statistical model for risk to the CNS due to radiation exposure.

Technology Challenge: Challenges include validating data and determining a course of action for CNS.

Technology State of the Art: Technology does not exist.

Parameter, Value:
Parameter - % uncertainty.
Value - unknown

TRL 1

Technology Performance Goal: Statistical model for risk to the CNS due to radiation exposure.

Parameter, Value:
Reduce uncertainty in radiation risk modeling and analysis for astronaut exposure to space radiation.

TRL 9

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

CAPABILITY

Needed Capability: Radiation risk assessment modeling and analysis.

Capability Description: Ability to assess astronaut risk due to space radiation exposure, with minimal uncertainty, for improved mission operations, mission planning, and system design for low-Earth orbit (LEO), deep space, lunar, and Mars missions.

Capability State of the Art: Tools currently used to estimate cancer risk from radiation to crew during operations in LEO do not include synergistic effects. In addition, these models are based on scaling terrestrial radiation exposures to spaceflight environment and are not truly representative of the free space radiation environment. Risk models currently used for LEO operations do not include circulatory or CNS effects.

Parameter, Value:
Percent uncertainty in the model results. Cancer models exist with a 350% uncertainty. Little or no risk models that include circulatory or CNS effects.

Capability Performance Goal: CNS radiation risk assessment modeling and analysis that assess astronaut risk due to space radiation exposure, with minimal uncertainty, for improved mission operations, mission planning, and system design for LEO, deep space, lunar, and Mars missions

Parameter, Value:
Near term: 200% uncertainty for all radiation exposure risks for near-Earth object (NEO) missions (365 days).

Long term: 50% uncertainty for all radiation exposure risks for Mars missions (1000 days).

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	Enhancing	2027	2027	2021	5 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

6.5 Radiation
6.5.1 Risk Assessment Modeling

6.5.1.5 Performance Degradation Model Set (Acute and Central Nervous System)

TECHNOLOGY

Technology Description: Tool that models degradation of performance, ability to complete tasks, and the steps needed to mitigate the degradation.

Technology Challenge: Challenges include validating data and determining a course of action for central nervous system (CNS), scaling from terrestrial space to a systems biology approach, and validating from animal systems to humans. Additional challenges exist in addressing CNS risks.

Technology State of the Art: Baseline models exist to quantify acute radiation-induced health and performance risks. No computation models exist to quantify CNS or degenerative tissue health and performance risks.

Parameter, Value: | **TRL**
Parameter - % uncertainty .
Value - unknown.
TRL: 1

Technology Performance Goal: Tool that models degradation of performance, ability to complete tasks, and the steps needed to mitigate the degradation.

Parameter, Value: | **TRL**
Reduce uncertainty in radiation risk modeling and analysis for astronaut exposure to space radiation.
TRL: 9

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

CAPABILITY

Needed Capability: Radiation risk assessment modeling and analysis.

Capability Description: Ability to assess astronaut risk due to space radiation exposure, with minimal uncertainty, for improved mission operations, mission planning, and system design for low-Earth orbit (LEO), deep space, lunar, and Mars missions.

Capability State of the Art: Tools currently used to estimate cancer risk from radiation to crew during operations in LEO do not include synergistic effects. In addition, these models are based on scaling terrestrial radiation exposures to spaceflight environment and are not truly representative of the free space radiation environment. Risk models currently used for LEO operations do not include circulatory or CNS effects.

Parameter, Value:
Percent uncertainty in the model results. Cancer models exist with a 350% uncertainty. Little or no risk models that include circulatory or CNS effects.

Capability Performance Goal: Performance degradation (acute and CNS) radiation risk assessment modeling and analysis that assess astronaut risk due to space radiation exposure, with minimal uncertainty, for improved mission operations, mission planning, and system design for LEO, deep space, lunar, and Mars missions

Parameter, Value:
Near term: 200% uncertainty for all radiation exposure risks for near-Earth object (NEO) missions (365 days).
Long term: 50% uncertainty for all radiation exposure risks for Mars missions (1000 days).

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	4 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	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

6.5 Radiation
6.5.1 Risk Assessment Modeling

6.5.1.6 Digital Twin

TECHNOLOGY

Technology Description: Tool that combines the Performance Degradation Model and the Mortality Risk Projection Model into a predictive tool for determining crew risk of degradation of health, death, and degradation of task performance due to radiation exposure.

Technology Challenge: Same gaps as Integrated Mortality Risk Projection tool and Performance Degradation Model set.

Technology State of the Art: Integrated tool does not exist. Cancer model exists with uncertanty of 350, and initial circulatory disease with unknown uncertainties. No central nervous system (CNS). Baseline models exist to quantify acute radiation induced health and performance risks. No computation models exist to quantify performance risks.

Parameter, Value:

Parameter - % uncertainty

Value - 350% for cancer, unknown for CNS, performance.

TRL

1

Technology Performance Goal: Predictive tool that combines the Performance Degradation Model and the Mortality Risk Projection Model.

Parameter, Value:

Reduce uncertainty in radiation risk modeling and analysis for astronaut exposure to space radiation.

TRL

9

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

CAPABILITY

Needed Capability: Radiation risk assessment modeling and analysis.

Capability Description: Ability to assess astronaut risk due to space radiation exposure, with minimal uncertainty, for improved mission operations, mission planning, and system design for low-Earth orbit (LEO), deep space, lunar, and Mars missions.

Capability State of the Art: Tools currently used to estimate cancer risk from radiation to crew during operations in LEO do not include synergistic effects. In addition, these models are based on scaling terrestrial radiation exposures to spaceflight environment and are not truly representative of the free space radiation environment. Risk models currently used for LEO operations do not include circulatory or CNS effects.

Parameter, Value:

Percent uncertainty in the model results. Cancer models exist with a 350% uncertainty. Little or no risk models that include circulatory or CNS effects.

Capability Performance Goal: Predictive tool that combines the Performance Degradation Model and the Mortality Risk Projection Model to reduce uncertainty in radiation risk modeling and analysis for astronaut exposure to space radiation.

Parameter, Value:

Near term: 200% uncertainty for all radiation exposure risks for near-Earth object (NEO) missions (365 days).

Long term: 50% uncertainty for all radiation exposure risks for Mars missions (1000 days).

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 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

6.5 Radiation
6.5.1 Risk Assessment Modeling

6.5.1.7 Transport and Nuclear Physics Modeling Tool(s) for Radiation Exposure (Transport Codes)

TECHNOLOGY

Technology Description: Computational tools enabling the accurate prediction of radiation exposures within the human body given a known free-space radiation environment (i.e. tools that account for modifications to the particle environment as radiation transits planetary atmosphere, vehicle materials, and human tissue). Models need to interface with NASA design processes within reasonable timeframes.

Technology Challenge: Validation and uncertainty quantification for thick shields, improved modeling of three-dimensional (3D) scattering of neutrons in complex geometry, improved modeling of some light ions, improved modeling of the effects of magnetic fields, improved ability to analyze complex geometry environments, and integration of high-fidelity human phantoms.

Technology State of the Art: Models currently exist but need to be modified or replaced to achieve reduction in uncertainties. Also, more extensive verification, validation, and uncertainty quantification is needed for both currently used models and those under development.

Parameter, Value:

Parameters - % uncertainty, mission/vehicle analysis turnaround time.

Value - unknown.

TRL 9

Technology Performance Goal: Models with well-quantified and minimal uncertainties capable of rapidly turning around analysis of vehicle and mission configurations.

Parameter, Value:

Reduce uncertainty in radiation risk modeling and analysis for astronaut exposure to space radiation.

TRL 9

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

CAPABILITY

Needed Capability: Radiation risk assessment modeling and analysis.

Capability Description: Ability to assess astronaut risk due to space radiation exposure, with minimal uncertainty, for improved mission operations, mission planning, and system design for low-Earth orbit (LEO), deep space, lunar, and Mars missions.

Capability State of the Art: Capability currently exists for space environments but uncertainties need to be reduced to meet long-term goals.

Parameter, Value:

Uncertainty: estimates range between 15% and 100%, depending on source of the estimate and mission/vehicle details.

Capability Performance Goal: Computational tools enabling the accurate prediction of radiation exposures within the human body given a known free-space radiation environment.

Parameter, Value:

Near term: 200% uncertainty for all radiation exposure risks for near-Earth object (NEO) missions (365 days).

Long term: 50% uncertainty for all radiation exposure risks for Mars missions (1000 days).

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 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

6.5 Radiation
6.5.2 Radiation Mitigation and Biological Countermeasures

6.5.2.1 Countermeasures for In-Flight Acute Radiation Syndrome

TECHNOLOGY

Technology Description: Biological treatments to counter the effects of in-flight acute radiation syndrome. Protects against or mitigates radiation effects on health from hematopoietic and immune failure. Treatments due to prodromal syndrome (nausea, vomiting, fatigue).

Technology Challenge: Challenges include developing biological countermeasures to address various health problems expected during chronic space radiation exposure.

Technology State of the Art: A minimal number of biological countermeasures have been tested in space radiation simulated environments on animals. Acute radiation syndrome is the most understood of all radiation exposure spectrums.

Parameter, Value:	TRL
Limited, based on terrestrial applications and a few animal experiments performed in space radiation simulated environments.	2

Technology Performance Goal: A combination of biological countermeasures to mitigate and protect from acute radiation sickness and to treat symptoms arising from acute radiation exposure, such as nausea, vomiting, fatigue, and burns.

Parameter, Value:	TRL
Protects against or mitigates radiation effects on health from hematopoietic and immune failure.	9

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

CAPABILITY

Needed Capability: Acute radiation syndrome biological countermeasures.

Capability Description: Ability to rescue the hematopoietic and immune system due to acute radiation sickness. Treatment for nausea, vomiting, and fatigue due to prodromal symptoms. Burn or wound healing countermeasures as a result of radiation exposure to skin. Cardiovascular treatment to mitigate against cardiovascular disease and cardiac related events.

Capability State of the Art: Antiemetics currently used to treat prodromal syndrome. Antioxidants from nutritional means. Antibiotics. Most acute radiation syndrome treatments are from terrestrial applications related potential nuclear fallout. This area is quite advanced and NASA can take advantage of the information from these programs.

Parameter, Value:

Reduction of risk to < 3% risk of exposure induced death (REID).

Capability Performance Goal: Acute radiation syndrome biological countermeasures with ability to rescue the hematopoietic and immune system due to acute radiation sickness; includes addressing symptoms arising from acute radiation exposure, such as nausea, vomiting, fatigue, and burns.

Parameter, Value:

< 3% REID (Mars 1,000 days), < 3% REID (near-Earth object (NEO) 365 days).

Number of days for biological countermeasures (BCMs) alone: 500 days Mars, 250 days NEO.

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 8 Crewed to Mars Moons	Enabling	2027	2027	2021	6 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

6.5 Radiation
6.5.2 Radiation Mitigation and Biological Countermeasures

6.5.2.2 Countermeasures for In-Flight Central Nervous System (CNS) Effects

TECHNOLOGY

Technology Description: Biological treatments to counter the effects of in-flight CNS effects from radiation exposure. Protects against or mitigates radiation effects on behavior and performance (example includes radioprotectants).

Technology Challenge: Challenges include developing biological countermeasures to address various health problems expected during chronic space radiation exposure.

Technology State of the Art: Some data on antioxidants has been collected by a limited number of models and radiation qualities considered. No technology to extrapolate efficacy to humans has been developed.

Parameter, Value: Limited, based on terrestrial applications.

TRL: 1

Technology Performance Goal: Biological treatments to counter the effects of in-flight CNS effects from radiation exposure.

Parameter, Value: High level of protection against or mitigates radiation effects on behavior and performance.

TRL: 9

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

CAPABILITY

Needed Capability: Biological countermeasure for cognitive and behavioral disorders due to long-duration, deep-space missions.

Capability Description: A biological countermeasure that can minimize or prevent cognitive and behavioral disorders. This would be used to augment exercise and sleep, which can both support maintaining healthy CNS.

Capability State of the Art: Exercise and sleep are primary therapeutics used to mitigate agains CNS-related issues. Exercise and sleep are relevant for extended missions but will need to be augmented with biological countermeasures to minimize cognitive and behavioral disorders during longer-duration missions.

Parameter, Value: Critical to crew health and mission success.

Capability Performance Goal: A combination of biological countermeasures, exercise, and sleep to mitigate and protect from acute and late effects on the CNS.

Parameter, Value:

< 3% risk of exposure induced death (REID) (Mars 1000 days), < 3% REID (near-Earth object (NEO) 365 days).

Number of days for biological countermeasures (BCMs) alone: 500 days Mars, 250 days NEO.

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	Enhancing	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	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

6.5 Radiation
6.5.2 Radiation Mitigation and Biological Countermeasures

6.5.2.3 Countermeasures Against Degenerative Effects

TECHNOLOGY

Technology Description: Biological treatments to counter the degenerative effects of in-flight radiation exposure. Protects against or mitigates radiation effects on biological degeneration, such as cardiovascular disease, cardiac events, gastrointestinal, skin, and cataracts.

Technology Challenge: Develop a suite of biological countermeasures to address various health problems expected during chronic space radiation exposure.

Technology State of the Art: Countermeasures have been developed for low-linear energy transfer (LET) radiation at high doses. None have been tested for chronic galactic cosmic ray (GCR) and few have been studied under dose-rates representative of solar particle events (SPEs). Does not exist for degenerative risks.

Parameter, Value:	TRL
Limited, based on terrestrial applications.	1

Technology Performance Goal: A suite of biological countermeasures (BCMs) to address various health problems expected during chronic space radiation exposure.

Parameter, Value:	TRL
High degree of protection against or mitigates radiation effects on biological degeneration.	9

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

CAPABILITY

Needed Capability: Degenerative effects are anticipated based on current research in space radiation using animal models. The cardiovascular system and other organs are at risk due to longer duration chronic exposure. Biological countermeasures to minimize or protect against these effects are needed.

Capability Description: Biological countermeasure to mitigate adverse events and effects to the cardiovascular system, gastrointestinal system, and other organs susceptible to degeneration due to space radiation.

Capability State of the Art: Current technology includes statins to treat cardiovascular disease, and antioxidants as protectors from oxidative stress. This is an understudied area terrestrially and recently gaining ground related to the side effects of radiation treatment for cancer. Areas of focus terrestrially are lung, heart, and non-targeted organs. The doses and dose-rates are higher than anticipated on a space mission.

Parameter, Value:

Critical to crew health and mission success.

Capability Performance Goal: Biological countermeasures to protect and mitigate against anticipated degenerative effects based on current research in space radiation using animal models related to areas identified to be susceptible to radiation degradation.

Parameter, Value:

< 3% risk of exposure induced death (REID) (Mars 1000 days), < 3% REID (near-Earth object (NEO) 365 days).

Number of days for BCM alone: 500 days Mars, 250 days NEO.

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	Enhancing	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	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

6.5 Radiation
6.5.2 Radiation Mitigation and Biological Countermeasures

6.5.2.4 Countermeasures Against Cancer

TECHNOLOGY

Technology Description: Biological treatments to counter the effects of cancer resulting from radiation exposure. Protects against or mitigates radiation effects on development of cancer.

Technology Challenge: Determine biological countermeasures that will support astronaut health and reduce the risk of cancer associated with space by either preventing initiation or mitigating the biological response.

Technology State of the Art: Treatments for cancer disease have been developed but biological countermeasures to protect, prevent, and treat cancer due to space radiation have not been tested.

Parameter, Value:	TRL
Limited, based on terrestrial applications and a few animal experiments performed in space radiation simulated environments.	1

Technology Performance Goal: Biological treatments to counter the effects of cancer resulting from radiation exposure.

Parameter, Value:	TRL
High degree of protection against or mitigates radiation effects on development of cancer.	9

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

CAPABILITY

Needed Capability: A combination of biological countermeasures and radiation shielding to minimize radiation exposure levels. Biological radiation protectors and mitigators to facilitate cell death to minimize mutations, antioxidants to scavenge free radicals, and pathway blockers to prevent and/or arrest cancer development.

Capability Description: Cancer due to ionizing radiation is an intensely studied area. There has been a significant amount of research for terrestrial applications related to epidemiological data from radiation exposure, cancer therapy, and radiation exposure from medical testing. Biological countermeasures that can arrest cancer-developing cells, treat cells and organs that have acquired cancer, and protect against the cells and organs mutating to cause cancer.

Capability State of the Art: Current technology includes chemotherapy and radiation therapy to treat cancer after it has developed. New pharmaceuticals are being explored and many are in clinical trials that block various pathways linked to cancer. Treatment of cancer disease is a heavily studied area terrestrially. Biologicals that protect against radiation-induced cancer have not been a significant focus area terrestrially. Research related to risk for space-radiation-induced cancer has been primarily derived from epidemiological models. There has been some research using various cell culture and animal models but countermeasures to protect against cancer in space radiation has not been explored adequately for the space radiation environment. While we can learn much from epidemiology and terrestrial data, the doses, dose-rates, and qualities of radiation are significantly different in the space environment.

Parameter, Value:

Critical to crew health and mission success, particularly upon return to Earth. Leukemia highest cancer risk during mission.

Capability Performance Goal: Biological radiation protectors and mitigators to minimize mutations, antioxidants to scavenge free radicals, and pathway blockers to prevent and/or arrest cancer development.

Parameter, Value:

< 3% risk of exposure induced death (REID) (Mars 1000 days), < 3% REIC (near-Earth object (NEO) 365 days).

Number of days for biological countermeasures (BCMs) alone: 500 days Mars, 250 days NEO.

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	Enhancing	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	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

6.5 Radiation
6.5.2 Radiation Mitigation and Biological Countermeasures

6.5.2.5 Combined Pharmaceutical Interaction Tool

TECHNOLOGY

Technology Description: Experimental models of biological countermeasures (BCMs) for specific space radiation risk will not be generally applicable to other space radiation risks. Need an integrated computational model to evaluate efficacy and benefits across all radiation-induced risks, as well as other identified spaceflight health risks.

Technology Challenge: Modeling of BCMs is a challenge.

Technology State of the Art: Drug interactions are currently monitored by pharmacists with patients being able to perform web searches to determine interactions on their own.

Parameter, Value:

Ability to determine adverse spaceflight risks due to combinations of biological countermeasures being administered.

TRL

1

Technology Performance Goal: Integrated computational model to evaluate efficacy and benefits across all radiation-induced risks, as well as other identified spaceflight health risks.

Parameter, Value:

High degree of correlation to radiation risk.

TRL

9

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

CAPABILITY

Needed Capability: Computational tool to evaluate drug response and interactions individually and in combination with other drugs.

Capability Description: Pharmaceuticals will be critical for human missions beyond low-Earth orbit (LEO). The performance of the drugs and interactions with other drugs need to be determined to prevent undesirable side effects and non-targeted effects that may exacerbate other spaceflight health risks.

Capability State of the Art: This technology has not reached maturity to be used in ground-based medical scenarios. Research in pharmaceutical development has been enhanced with computational models. However, drug interaction is still determined by local pharmacists. There are low-fidelity models that will compare drug interactions using web-based searches. The U.S. government has a working group on drug development and drug interactions.

Parameter, Value:

Valuable to crew health and mission success. Interactions between biological countermeasures used to treat spaceflight risks may resut in adverse reactions, causing effects worse than the original treatment was intended.

Capability Performance Goal: A computational tool to determine if biological countermeasures used to treat space radiation and other spaceflight risks will be effective and remain nontoxic when combined with other biological countermeasures.

Parameter, Value:

< 3% risk of exposure induced death (REID) (Mars 1000 days), < 3% REID (near-Earth object (NEO) 365 days).

Number of days for BCMs alone: 500 days Mars, 250 days NEO.

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	Enhancing	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	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

6.5 Radiation
6.5.2 Radiation Mitigation and Biological Countermeasures

6.5.2.6 Individual Sensitivity Toolkit

TECHNOLOGY

Technology Description: Reduce uncertainties and develop optimal individualized biological countermeasures (BCMs). Enable missions by reducing costs and extending durations. Address individual sensitivity. Toolkit has promise to lower mission costs and enable longer-duration missions.

Technology Challenge: Determining individual sensitivities and personalizing the BCMs.

Technology State of the Art: Personalized medicine is currently being developed and is not available terrestrially.

Parameter, Value:	TRL
Ability to determine adverse spaceflight risks due to individual sensitivity.	1

Technology Performance Goal: Individual sensitivity toolkit for individualized BCMs.

Parameter, Value:	TRL
Reduce uncertainties and develop optimal individualized BCMs.	9

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

CAPABILITY

Needed Capability: Computational tool to determine effectiveness and toxicity of biological countermeasures for individual astronauts.

Capability Description: Individual sensitivity to pharmaceuticals, radiation, and other stressors has been demonstrated. Personalized medicine will improve astronaut health due to multiple spaceflight risks, including drug-drug interactions.

Capability State of the Art: Personalized medicine is currently being developed and is not available terrestrially.

Parameter, Value:

Valuable to crew health and mission success. Individual sensitivities may influence effectiveness and interactions between biological countermeasures used to treat spaceflight risks potentially resulting serious adverse events.

Capability Performance Goal: A computational model that takes individual response to spaceflight risks and sensitivity to biological countermeasures into account for personalized treatment.

Parameter, Value:

< 3% risk of exposure induced death (REID) (Mars 1000 days), < 3% REID (near-Earth object (NEO) 365 days).

Number of days for BCMs alone: 500 days Mars, 250 days NEO.

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	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

6.5 Radiation
6.5.3 Protection Systems

6.5.3.1 Radiation Protective Materials and Material Systems for Primary and Secondary Structures

TECHNOLOGY

Technology Description: Develop and advance structural performance of high-hydrogen-content materials and material systems to replace traditional materials for primary and secondary spacecraft structure (reference TA 12). The goal is to replace mass with better mass for radiation protection that also meets structural requirements. High-hydrogen materials can include polymer matrix composites, where the polymer and/or fibers are high in hydrogen content.

Technology Challenge: Developing hydrogen-rich materials that meet current structural and material efficiencies is a challenge.

Technology State of the Art: On the International Space Station (ISS), some polyethylene shielding has been added to the modules for shielding as needed. ISS crew quarters have polyethylene designed into them for crew protection.

Parameter, Value:	TRL
For solar particle event (SPE): 50% reduction in astronaut exposure with < 100 lbm. Parasitic mass gain over SOA vehicle design. 100 mission days for free space mission assuming one SPE event without exceeding accepted permissible exposure limits (PELs) with current vehicle design. For galactic cosmic ray (GCR): 100 mission days for free space mission without exceeding accepted PELs with current vehicle design.	9

Technology Performance Goal: Advance structural performance of high-hydrogen-content materials and material systems to replace traditional materials for primary and secondary spacecraft structure.

Parameter, Value:	TRL
Replace mass with better mass for radiation protection that also meets structural requirements.	6

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

CAPABILITY

Needed Capability: Radiation protective systems.

Capability Description: Advancements in the design of integrated radiation protection shielding technologies are needed that extend beyond low-Earth orbit (LEO) exploration missions duration by greater than six days, within the scope of reasonable vehicle design and mass. It is generally accepted that shielding cannot completely protect against GCR and that biological countermeasures and a drastic reduction in the uncertainty associated with radiation risk assessment will need to be developed for missions.

Capability State of the Art: Limited shielding options currently used, since missions are in LEO. Radiation shielding plan for Orion consists of rearranging movable components to create a shield. On the ISS, some polyethylene shielding has been added for SPE crew shielding if needed. No long-term shielding of GCR available.

Parameter, Value:

Parameter: days in space without exceeding PELs. Value: ~100 days in free space (GCR + SPE) without exceeding PELs in vehicle without parasitic shielding mass.

Capability Performance Goal: Integrated radiation protection shielding technologies that extend beyond LEO exploration missions duration by greater than six days, within the scope of reasonable vehicle design and mass.

Parameter, Value:

SPE: 50% reduction in astronaut exposure for < 100 lbm increase in mass.

GCR: 10-20% reduction in astronaut exposure for < 1000 lbm increase in mass.

Days in space without exceeding PELs.

Value: ~100 days in free space (GCR + SPE) without exceeding PELs in vehicle without parasitic shielding mass.

365 safe days for near-Earth object (NEO) missions from combining shielding protection with other mitigations.

1,000 safe days for Mars missions from combining shielding protection with other mitigations.

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	Enabling	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	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

6.5 Radiation
6.5.3 Protection Systems

6.5.3.2 In-Situ Passive Shielding From and In the Spacecraft

TECHNOLOGY

Technology Description: Develop vehicle equipment and components from radiation-protective materials. Develop shielding technology that utilizes the stowage of hydrogen-rich logistics (potentially food, water sources, supplies, and waste) as multipurpose shielding. Develop multi-purpose containers for bio-material that can utilize human waste without affecting crew (smell, leakage, handling transfer). Other technology development includes developing water walls for crew quarters or vehicle walls for waste, potable water, and drinking water.

Technology Challenge: Utilizing the stowage of hydrogen-rich logistics (potentially food, water sources, supplies, and waste) as multi-purpose shielding and utilizing human waste without affecting crew (smell, leakage, handling transfer) are challenges.

Technology State of the Art: Radiation shielding plan for Orion consists of rearranging movable components to create a shield. Early development of converting trash into “plastic” bricks for shielding (Heat Melt Compactor, or HMC)/ galactic cosmic ray (GCR) and solar particle event (SPE) protection.

Parameter, Value:	TRL
For SPE: 50% reduction in astronaut exposure with < 100 lbm parasitic mass gain over SOA vehicle design. 100 mission days for free space mission, assuming one SPE event without exceeding accepted permissible exposure limits (PELs) with current vehicle design. For GCR: 100 mission days for free space mission without exceeding accepted PELs with current vehicle design.	1

Technology Performance Goal: Vehicle equipment and components made from radiation-protective materials.

Parameter, Value:	TRL
High degree of protection from radiation effects.	6

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

CAPABILITY

Needed Capability: Radiation protective systems.

Capability Description: Advancements in the design of integrated radiation protection shielding technologies are needed that extend mission duration for missions beyond low-Earth orbit (LEO) to greater than 60-90 days, within the scope of reasonable vehicle design and mass. It is generally accepted that shielding cannot completely protect against GCR and that biological countermeasures and a drastic reduction in the uncertainty associated with radiation risk assessment will need to be developed for missions.

Capability State of the Art: Limited shielding options currently used since missions are in LEO. Radiation shielding plan for Orion consists of rearranging movable components to create a shield. On the International Space Station (ISS), some polyethylene shielding has been added for SPE crew shielding, if needed. No long-term shielding of GCR available.

Parameter, Value:

Parameter: days in space without exceeding PELs.

Value: ~100 days in free space (GCR + SPE) without exceeding PELs in vehicle without parasitic shielding mass.

Capability Performance Goal: Integrated radiation protection shielding technologies that extend mission duration for missions beyond LEO to greater than 60-90 days, within the scope of reasonable vehicle design and mass.

Parameter, Value:

SPE: 50% reduction in astronaut exposure for < 100 lbm increase in mass.

GCR: 10-20% reduction in astronaut exposure for < 1000 lbm increase in mass.

Days in space without exceeding PELs.

Value: ~100 days in free space (GCR + SPE) without exceeding PELs in vehicle without parasitic shielding mass.

365 safe days for near-Earth object (NEO) missions from combining shielding protection with other mitigations.

1,000 safe days for Mars missions from combining shielding protection with other mitigations.

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	Enabling	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	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

6.5 Radiation
6.5.3 Protection Systems

6.5.3.3 In-Situ Passive Shielding from Planetary Surface Materials

TECHNOLOGY

Technology Description: Develop regolith manipulation; processing of building materials; transforming regolith into shields, structures, and tunnels; additive manufacturing using regolith; characterizing regolith for use in shielding. Regolith can be consolidated by sintering using conventional, solar, microwave, or laser heat sources. Regolith can be combined with polymer-matrix materials to increase hydrogen content (Reference regolith TA 12 and TA 7 in-situ technologies and material developments).

Technology Challenge: In-space mining and manufacturing of regolith for radiation protection.

Technology State of the Art: Some work going on in transforming regolith to building materials (point to advance habitation, in-situ resource utilization (ISRU), and materials development).

Parameter, Value: Galactic cosmic ray (GCR) reduction main focus. Will be protected duration of surface mission days.

TRL 2

Technology Performance Goal: Manipulation regolith or transform regolith into shielding as applied to building materials, structures, and tunnels.

Parameter, Value:
High degree of protection from radiation effects.

TRL 6

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

CAPABILITY

Needed Capability: In-situ radiation protective systems.

Capability Description: Advancements in the design of integrated in-situ radiation protection shielding technologies are needed that extend mission duration for missions beyond low-Earth orbit (LEO) to greater than 60-90 days, within the scope of reasonable vehicle design and mass. It is generally accepted that shielding cannot completely protect against GCR and that biological countermeasures and a drastic reduction in the uncertainty associated with radiation risk assessment will need to be developed for missions.

Capability State of the Art: Limited shielding options currently used since missions are in LEO. Radiation shielding plan for Orion consists of rearranging movable components to create a shield. On the International Space Station (ISS), some polyethylene shielding has been added for solar particle event (SPE) crew shielding if needed. No long-term shielding of GCR available.

Parameter, Value:

Parameter: days in space without exceeding permissible exposure limits (PELs).

Value: ~100 days in free space (GCR + SPE) without exceeding PELs in vehicle without parasitic shielding mass.

Capability Performance Goal: Use regolith either that has been transformed and/or manipulated as radiation protective shielding.

Parameter, Value:

SPE: 50% reduction in astronaut exposure for < 100 lbm increase in mass.

GCR: 10-20% reduction in astronaut exposure for < 1000 lbm increase in mass.

Days in space without exceeding PELs.

Value: ~100 days in free space (GCR + SPE) without exceeding PELs in vehicle without parasitic shielding mass.

365 safe days for near-Earth object (NEO) missions from combining shielding protection with other mitigations.

1,000 safe days for Mars missions from combining shielding protection with other mitigations.

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	Enabling	2027	2027	2021	5 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	10 years

6.5 Radiation
6.5.3 Protection Systems

6.5.3.4 High-Temperature Superconductor Technology and Performance for Active Shielding Systems

TECHNOLOGY

Technology Description: Develop technologies for structural components to keep magnet cold and keep it from flexing. Higher-temperature superconductors and splicing technologies.

Technology Challenge: Developing higher-temperature conductors is a challenge.

Technology State of the Art: Limited work on superconductor stability.

Parameter, Value:

Safety; scalability; field geometric adaptability; supporting systems mass; and power requirements.

TRL 1

Technology Performance Goal: High-termperature superconductor for active shielding systems.

Parameter, Value:

Deflection effectiveness; risk; mass; power; temperature.

Protection from solar cosmic rays (SCRs) at all energies and the reduction by a factor > 2 of the GCRs flux.

TRL 6

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

CAPABILITY

Needed Capability: Strong magnetic fields with total system mass less than that required for the corresponding passive system.

Capability Description: Magnetic fields and supporting technologies capable of supporting protection systems for the ‘living’ modules (International Space Station (ISS)-like modules: Ø≈4m, L≈5m) from the solar cosmic rays (SCRs) at all energies and the reduction by a factor > 2 of the galactic cosmic ray (GCRs) flux.

Capability State of the Art: Demonstrated for small magnetic fields and volumes, scaling up remains problematic and protection from higher-energy particles has not been demonstrated.

Parameter, Value:

Safety; scalability; field geometric adaptability; supporting systems mass; and power requirements.

Capability Performance Goal: Strong magnetic fields safe to crew and systems capable of supporting protection systems for the ‘living’ modules (ISS-like modules: Ø≈4m, L≈5m). from the SCRs at all energies and the reduction by a factor > 2 of the GCRs flux.

Parameter, Value:

Deflection effectiveness; risk; mass; power.

Protection from SCRs at all energies and the reduction by a factor > 2 of the GCRs flux.

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 8a Crewed Mars Orbital	Enabling	2033	--	2027	12 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	12 years

6.5 Radiation
6.5.3 Protection Systems

6.5.3.5 Lightweight Structural Materials for Magnet Fixtures for Active Shielding Systems

TECHNOLOGY

Technology Description: Magnets for active shielding are predicted to be large and massive. In addition, structural fixtures are required to react the magnetic forces generated. Develop technology to enable lightweight magnets and magnet structural fixtures.

Technology Challenge: Extremely lightweight, extremely strong, and stiff structure for magnetic field loads.

Technology State of the Art: Limited to none.

Parameter, Value: Mass value unknown.

TRL: 1

Technology Performance Goal: Lightweight magnets and magnet structural fixtures for active shielding.

Parameter, Value: Extremely lightweight, strong and stiff for magnetic field loads.

TRL: 6

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

CAPABILITY

Needed Capability: Materials with the right physical properties to support strong magnetic fields; total mass less than that required for the corresponding passive system.

Capability Description: Materials in support of active protection systems for the 'living'modules (International Space Station (ISS)-like modules: Ø≈4m, L≈5m) from the solar cosmic rays (SCRs) at all energies and the reduction by a factor > 2 of the galactic cosmic ray (GCR) flux.

Capability State of the Art: Demonstrated for small magnetic fields and volumes, scaling up remains problematic and protection from higher-energy particles has not been demonstrated.

Parameter, Value:
Physical properties and performance under various conditions; supporting systems mass and power requirements.

Capability Performance Goal: Materials with the right physical properties to support strong magnetic fields required for active shielding systems.

Parameter, Value:
Total mass less than that required for the corresponding passive system.

Protect the 'living'modules (ISS-like modules: Ø≈4m, L≈5m) from the SCRs at all energies and the reduction by a factor > 2 of the galactic cosmic ray (GCR) flux.

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 8a Crewed Mars Orbital	Enabling	2033	--	2027	12 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	12 years

6.5 Radiation
6.5.3 Protection Systems

6.5.3.6 Cooling Systems for Active Shielding

TECHNOLOGY

Technology Description: Develop improved active and passive cooling systems (see TA 14).

Technology Challenge: Long-duration cooling systems.

Technology State of the Art: Limited to none.

Parameter, Value:
Mass and power values unknown.

TRL 1

Technology Performance Goal: Cooling systems for active shielding.

Parameter, Value:
Long duration.

TRL 6

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

CAPABILITY

Needed Capability: Cryogenic coolers and support system masses less than the corresponding passive system.

Capability Description: Cooling solutions to support active protection for the ‘living’ modules (International Space Station (ISS)-like modules: Diameter≈4m, Length≈5m) from the solar cosic rays (SCRs) at all energies and the reduction by a factor > 2 of the galactic cosmic ray (GCR) flux.

Capability State of the Art: Demonstrated for small magnetic fields and volumes, scaling up remains problematic and protection from higher energy particles has not been demonstrated.

Parameter, Value:
Physical properties and performance under various conditions; supporting system mass and power requirements.

Capability Performance Goal: Cryogenic coolers and support system safe to crew and systems from confining field’s effects.

Parameter, Value:
System masses less than the corresponding passive system.

Power requirements not prohibitive.

Protects the ‘living’ modules (ISS-like modules: Diameter≈4m, Length≈5m) from the SCRs at all energies and the reduction by a factor > 2 of the galactic cosmic rays (GCRs) flux.

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 8a Crewed Mars Orbital	Enabling	2033	--	2027	12 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	12 years

6.5 Radiation
6.5.3 Protection Systems

6.5.3.7 Integrated Design Tool

TECHNOLOGY

Technology Description: Integrate multidisciplinary modeling. Includes physics, systems analysis, vehicle design, and biological models. Validated analysis tools for vehicle design. Vehicle design optimization and mission planning. Performance: efficiency and fidelity of model.

Technology Challenge: Integration of tools from different disciplines.

Technology State of the Art: On-Line Tool for the Assessment of Radiation In Space (OLTARIS) can be used to assess the protection provided by complex vehicle architectures for exploration missions. This tool set can be expanded to support multidisciplinary (radiation, thermal, structural) analysis and optimization. Integration of this tool with emerging human risk models is needed. There are also current development efforts to create vehicle radiation assessment capabilities that utilize Monte-Carlo transport algorithms.

Parameter, Value:

Parameter: computation time, accuracy.

Value: computation time ranges from minutes to days, depending on the complexity of the vehicle architecture for OLTARIS.

Uncertainty estimates range from 15% to 100%, depending on the source of the estimate and the mission/vehicle details.

TRL
3

Technology Performance Goal: An integrated, multidisciplinary vehicle architecture assessment capability, enabling multidisciplinary optimization.

Parameter, Value:

Parameter: computation time, accuracy. Value: computation time fast enough to support multidisciplinary optimization of vehicle architecture.

Uncertainty: < 15% details.

TRL
6

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

CAPABILITY

Needed Capability: Radiation protective systems.

Capability Description: Advancements in the design of integrated radiation protection shielding technologies are needed that extend mission duration for missions beyond low-Earth orbit (LEO) to greater than 60-90 days, within the scope of reasonable vehicle design and mass. It is generally accepted that shielding cannot completely protect against galactic cosmic ray (GCR) and that biological countermeasures and a drastic reduction in the uncertainty associated with radiation risk assessment will need to be developed for missions.

Capability State of the Art: Limited shielding options currently used since missions are in LEO. Radiation shielding plan for Orion consists of rearranging movable components to create a shield. On the International Space Station (ISS), some polyethylene shielding has been added for solar particle event (SPE) crew shielding if needed. No long-term shielding of GCR available.

Parameter, Value:

Parameter: days in space without exceeding permissible exposure limits (PELs).

Value: ~100 days in free space (GCR + SPE) without exceeding PELs in vehicle without parasitic shielding mass.

Capability Performance Goal: An integrated multidisciplinary vehicle architecture assessment capability, enabling multidisciplinary optimization that extend mission duration beyond LEO to greater than 60-90 days, within the scope of reasonable vehicle design and mass.

Parameter, Value:

Reduction in computation time with high accuracy.

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 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

6.5 Radiation
6.5.3 Protection Systems

6.5.3.8 Uncertainty Models for Thick Shielding

TECHNOLOGY

Technology Description: Analysis codes to assess the effect of thick shielding on radiation exposure. Performance: uncertainty reduction.

Technology Challenge: An analytical method for quantifying uncertainty in thick shield exposure predictions, using limited measurement data and code benchmarks.

Technology State of the Art: A number of radiation transport codes exist that could be used to calculate astronaut exposure behind thick shielding, but only limited verification/validation has been performed for thick shields. Recent transport calculations suggest that there may be a local minimum near 40 g/cm^2. This would be very important for minimal mass vehicle design. Validation and models for quantifying the uncertainty in galactic cosmic ray (GCR) exposure predictions for thick shields are needed.

Parameter, Value:

Parameter: accuracy.

Uncertainty estimates range from 15% to 100%, depending on the source of the estimate.

TRL 2

Technology Performance Goal: Assessing the uncertainty associated with thick shield radiation exposure analyses.

Parameter, Value:

Parameter: accuracy.

Uncertainty: < 15% details

TRL 6

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

CAPABILITY

Needed Capability: Radiation protective systems.

Capability Description: Advancements in the design of integrated radiation protection shielding technologies are needed that extend mission duration for missions beyond low-Earth orbit (LEO) to greater than 60-90 days, within the scope of reasonable vehicle design and mass. It is generally accepted that shielding cannot completely protect against GCR and that biological countermeasures and a drastic reduction in the uncertainty associated with radiation risk assessment will need to be developed for missions.

Capability State of the Art: Limited shielding options currently used since missions are in LEO. Radiation shielding plan for Orion consists of rearranging movable components to create a shield. On the International Space Station (ISS), some polyethylene shielding has been added for solar particle event (SPE) crew shielding if needed. No long-term shielding of GCR available.

Parameter, Value:

Parameter: days in space without exceeding permissible exposure limits (PELs).

Value: ~100 days in free space (GCR + SPE) without exceeding PELs in vehicle without parasitic shielding mass.

Capability Performance Goal: Assessing the uncertainty associated with thick shield radiation exposure analyses needed for missions beyond LEO to greater than 60-90 days, within the scope of reasonable vehicle design and mass.

Parameter, Value:

Parameter: accuracy.

Uncertainty < 15% details

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	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	10 years

6.5 Radiation
6.5.3 Protection Systems

6.5.3.9 Active Shielding Modeling Tool Set

TECHNOLOGY

Technology Description: Combined analysis toolset to analyze and assess active shielding protection. Performance: efficiency and fidelity of model.

Technology Challenge: Monte Carlo transport codes can be used to calculate the effects of magnetic fields on the radiation environment, but these calculations are computationally intensive, and the incorporation of even moderately complex vehicle geometry is very challenging and time intensive. Faster methods and uncertainty quantification are needed.

Technology State of the Art: Tools currently used to assess the protection provided by active shielding technologies rely on rough approximations or take a very long time to perform. Tools are needed for the rapid assessment of the combined effects of active and passive shielding systems.

Parameter, Value:

Parameter: computation time, accuracy.

Value: computation time and accuracy. Very little or no ability to perform calculations for complex vehicle architecture.

TRL

2

Technology Performance Goal: Tools for the rapid assessment of the combined shielding effects of active and passive shielding for complex vehicle architecture.

Parameter, Value:

Parameter: reduced computation time, greater accuracy.

TRL

6

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

CAPABILITY

Needed Capability: Radiation protective systems.

Capability Description: Advancements in the design of integrated radiation protection shielding technologies are needed that extend mission duration for missions beyond low-Earth orbit (LEO) to greater than 60-90 days, within the scope of reasonable vehicle design and mass. It is generally accepted that shielding cannot completely protect against galactic cosmic ray (GCR) and that biological countermeasures and a drastic reduction in the uncertainty associated with radiation risk assessment will need to be developed for long-duration missions.

Capability State of the Art: Limited shielding options currently used since missions are in LEO. Radiation shielding plan for Orion consists of rearranging movable components to create a shield. On the International Space Station (ISS), some polyethylene shielding has been added for solar particle event (SPE) crew shielding if needed. No long-term shielding of GCR available.

Parameter, Value:

Parameter: days in space without exceeding permissible exposure limits (PELs).

Value: ~100 days in free space (GCR + SPE) without exceeding PELs in vehicle without parasitic shielding mass.

Capability Performance Goal: Rapid assessment of the combined shielding effects of active and passive shielding for complex vehicle architecture for missions beyond LEO to greater than 60-90 days, within the scope of reasonable vehicle design and mass.

Parameter, Value:

Parameter: high accuracy.

Value: uncertainty < 15% details. Reduced computation time.

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 8a Crewed to Mars Orbital	Enabling	2033	--	2027	12 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	12 years

6.5 Radiation
6.5.4 Space Weather Prediction

6.5.4.1 Tool for All-Clear Forecasting of Solar Particle Event Onset

TECHNOLOGY

Technology Description: Technology to indicate "all clear" or no event expected solar conditions. All clear should be given in multiple time windows (e.g., hours or days).

Technology Challenge: Mission operators currently function by reacting in real-time to adverse space weather conditions. This limits mission efficiency and could increase the likelihood of damaging vehicle systems and increasing astronaut radiation exposure. Of primary concern for future long-duration missions outside of low-Earth orbit (LEO) are Solar Energetic Proton (SEP) events, i.e., the transient increase in energetic protons levels, and large coronal mass ejections (CMEs). There is no current ability to predict the onset, intensity and evolution of SEPs and CME arrival time. Although SEP exposure can theoretically be mitigated by passive shielding, vehicle mass constraints limit the degree of mitigation for any future long-duration mission. It is thus vital that tools for forecasting occurrence and magnitude be developed for future exploration to alert flight control teams and crews of impending adverse conditions. The objective of these tools would be to provide forecasts on time windows from days to weeks with high confidence and low false alarm rates.

Technology State of the Art: Probabilistic models, such as magnetogram forecast (MAG4), that provide statistical information about pending solar eruptions.

Parameter, Value:

Correct "yes/no" forecasts for major events given selected statistical decision threshold.

TRL: 9

Technology Performance Goal: Accurate forecast of all clear SPE conditions.

Parameter, Value:

Forecast skill score hgh with no false alarm.

TRL: 6

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

CAPABILITY

Needed Capability: Space weather forecasting.

Capability Description: Current operations and mission planning efforts are limited to responding to current solar activity, which limits efficiency. Predictive capability could significantly increase capability. Potential models vary from purely empirical to detailed multiphysics models that include eruptions from sun and propagation through interplanetary space. Advance warning system required to minimize and monitor exposure during missions.

Capability State of the Art: No ability to predict onset and evolution of SPE. Data sets exist but need to develop forecasting models.

Parameter, Value:

Reliability, time to warning.

Capability Performance Goal: Advance warning system required to minimize and monitor exposure during missions. Forecasting the occurrence and magnitude of event. Forecasting all clear periods.

Parameter, Value:

Time: mission duration

High confidence

Score of 0-1.0

0% false alarms

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

6.5 Radiation
6.5.4 Space Weather Prediction

6.5.4.2 Tool for Forecasting Solar Particle Event Intensity and Evolution

TECHNOLOGY

Technology Description: Technology to forecast the dynamic evolution of solar particle events (SPEs). This includes forecasting of time profile of appropriate SPE fluxes.

Technology Challenge: Mission operators currently function by reacting in real-time to adverse space weather conditions. This limits mission efficiency and could increase the likelihood of damaging vehicle systems and increasing astronaut radiation exposure. Of primary concern for future long-duration missions outside of low-Earth orbit (LEO) are Solar Energetic Proton (SEP) events, i.e., the transient increase in energetic protons levels, and large coronal mass ejections (CMEs). There is no current ability to predict the onset, intensity and evolution of SEPs and CME arrival time. Although SEP exposure can theoretically be mitigated by passive shielding, vehicle mass constraints limit the degree of mitigation for any future long-duration mission. It is thus vital that tools for forecasting occurrence and magnitude be developed for future exploration to alert flight control teams and crews of impending adverse conditions. The objective of these tools would be to provide forecasts on time windows from days to weeks with high confidence and low false alarm rates.

Technology State of the Art: None

Parameter, Value:

Forecast skill score, false alarm rate

TRL: None

Technology Performance Goal: Technology to forecast the dynamic evolution of SPEs. This includes forecasting of time profile of appropriate SPE fluxes.

Parameter, Value:

Forecast skill score high, false alarm rate low.

TRL: 6

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

CAPABILITY

Needed Capability: Space weather forecasting.

Capability Description: Current operations and mission planning efforts are limited to responding to current solar activity, which limits efficiency. Predictive ability could significantly increase capability. Potential models vary from purely empirical to detailed multiphysics models that include eruptions from sun and propagation through interplanetary space. Advance warning system required to minimize and monitor exposure during missions.

Capability State of the Art: No ability to predict onset and evolution of SPE. Real–time monitoring should be adequate for large events, since doses are small in first hour for 99% of historical SPEs. Data sets exist but need to develop forecasting models.

Parameter, Value:

Reliability, time to warning.

Capability Performance Goal: Space weather forecasting occurrence and magnitude of event. Forecasting all clear periods.

Parameter, Value:

Time: mission duration

High % confidence

Score of 0-1.0

0% false alarms

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

6.5 Radiation
6.5.4 Space Weather Prediction

6.5.4.3 Probabilistic Models (Tools) of Solar Particle Event Spectral Characteristics and Astronaut Risks

TECHNOLOGY

Technology Description: Models that calculate risk from solar particle event (SPE) exposure for a given mission duration, including variation in possible SPE events.

Technology Challenge: Not available.

Technology State of the Art: None

Parameter, Value:
None

TRL
None

Technology Performance Goal: Models that calculate risk from SPE exposure for a given mission duration, including variation in possible SPE events, with risk to astronauts.

Parameter, Value:
Time: mission duration
High % confidence
Score of 0-1.0
0% false alarms

TRL
2

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

CAPABILITY

Needed Capability: Space weather forecasting.

Capability Description: Current operations and mission planning efforts are limited to responding to current solar activity, which limits efficiency. Predictive capability could significantly increase capability. Potential models vary from purely empirical to detailed multiphysics models that include eruptions from sun and propagation through interplanetary space. Advance warning system required to minimize and monitor exposure during missions.

Capability State of the Art: No ability to predict onset and evolution of SPE. Real-time monitoring should be adequate for large events since doses are small in first hour for 99% of historical SPEs. Data sets exist but need to develop forecasting models.

Parameter, Value:
Reliability, time to warning.

Capability Performance Goal: Probabilistic Solar Energetic Proton (SEP) spectra modeling to include astroanaut risk over mission durations from weeks to years.

Parameter, Value:
Time: mission duration
High % confidence
Score of 0-1.0
0% false alarms

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

6.5 Radiation
6.5.4 Space Weather Prediction

6.5.4.4 Ensemble Coronal Mass Ejection Forecasting for Mission Impact Assessment

TECHNOLOGY

Technology Description: Technology to carry out ensemble coronal mass ejection (CME) predictions (locations impacted, the time of impact) throughout the solar system.

Technology Challenge: Mission operators currently function by reacting in real-time to adverse space weather conditions. This limits mission efficiency and could increase the likelihood of damaging vehicle systems and increasing astronaut radiation exposure. Of primary concern for future long-duration missions outside of low-Earth orbit (LEO) are Solar Energetic Proton (SEP) events, i.e., the transient increase in energetic protons levels, and large CMEs. There is no current ability to predict the onset, intensity and evolution of SEPs and CME arrival time.

Technology State of the Art: Ensemble CME prediction system implemented at Community Coordinated Modeling Center at NASA.

Parameter, Value:	TRL
Forecast skill score, false alarm rate and percent uncertainty in arrival times.	3

Technology Performance Goal: Ensemble CME predictions (locations impacted, the time of impact) throughout the solar system.

Parameter, Value:	TRL
Low false alarm rates and low uncertainty in arrival times with high forecast skill score.	6

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

CAPABILITY

Needed Capability: Space weather forecasting.

Capability Description: Current operations and mission planning efforts are limited to responding to current solar activity, which limits efficiency. Predictive capability could significantly increase capability. Potential models vary from purely empirical to detailed multiphysics models that include eruptions from sun and propagation through interplanetary space. Advance warning system required to minimize and monitor exposure during missions.

Capability State of the Art: No ability to predict onset and evolution of solar particle event (SPE). Data sets exist but need to develop forecasting models.

Parameter, Value:

Reliability, time to warning.

Capability Performance Goal: CME predictions that includes occurrence, magnitude of event, and all-clear periods.

Parameter, Value:

Time: mission duration

High % confidence

Score of 0-1.0

0% false alarms

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

6.5 Radiation
6.5.4 Space Weather Prediction

6.5.4.5 High-Performance Computing Architecture that Supports Real-Time Implementation of Operation Forecasts

TECHNOLOGY

Technology Description: Technology that enables use of large-scale, state of the art, physics-based models for space weather forecasting.

Technology Challenge: Mission operators currently function by reacting in real-time to adverse space weather conditions. This limits mission efficiency and could increase the likelihood of damaging vehicle systems and increasing astronaut radiation exposure. Of primary concern for future long-duration missions outside of low-Earth orbit (LEO) are Solar Energetic Proton (SEP) events, i.e., the transient increase in energetic protons levels, and large coronal mass ejections (CMEs). There is no current ability to predict the onset, intensity and evolution of SEPs and CME arrival time. Models with detailed multi physics that include eruptions from sun and propagation through interplanetary space are needed to run in real time.

Technology State of the Art: Real-time space weather simulations carried out at the Community Coordinated Modeling Center and other relevant NASA facilities.

Parameter, Value: Ability to run moderately large space weather simulations in real-time.

TRL: 3

Technology Performance Goal: High-resolution latest coupled physics-based space weather models in real-time for forecasting purposes.

Parameter, Value: Operationally timely.

TRL: 6

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

CAPABILITY

Needed Capability: Space weather forecasting.

Capability Description: Current operations and mission planning efforts are limited to responding to current solar activity, which limits efficiency. Predictive capability could significantly increase capability. Potential models vary from purely empirical to detailed multiphysics models that include eruptions from sun and propagation through interplanetary space. Advance warning system required to minimize and monitor exposure during missions.

Capability State of the Art: No ability to predict onset and evolution of solar particle events (SPEs) and CME arrival time. Data sets exist but need to develop forecasting models.

Parameter, Value:

Reliability, time to warning.

Capability Performance Goal: High-performance computing architecture that supports real time operation forecasting of the occurrence and magnitude of an event as well as all-clear periods.

Parameter, Value:

Time: mission duration

High % confidence

Score of 0-1.0

0% false alarms

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

6.5 Radiation
6.5.5 Monitoring Technology

6.5.5.1 Active Personal Dosimetry for Intravehicular Activities and Extravehicular Activities

TECHNOLOGY

Technology Description: Real-time individual dosimetry monitors that can be worn by each astronaut for intravehicular activities (IVAs) and extravehicular activities (EVAs).

Technology Challenge: The major technical challenge is in the development of a low-power, low-heat-producing, active dosimetry monitor in a small form factor. Additional challenges involve integration of the monitor with power and wireless communication in a package that can be worn on the body indefinitely without causing discomfort or impeding other activity.

Technology State of the Art: Current personal dosimetry is passive. Existing active dosimetry is too big, does not have the necessary battery technology, and cannot communicate with vehicle systems wirelessly.

Parameter, Value:

Power/battery life, size

TRL: 3

Technology Performance Goal: Real-time individual monitors that can be worn by each astronaut.

Parameter, Value:

Size: Blackberry/pocket size. Power/battery life: life of mission or rechargeable for life of mission. Measurement: current is dose, expand to dose equivalent.

TRL: 9

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

CAPABILITY

Needed Capability: Monitoring technology.

Capability Description: The ability to monitor astronaut exposure to space radiation.

Capability State of the Art: Currently, astronaut exposure is monitored through passive personal dosimeters. A variety of other measurement devices have also been used on the International Space Station (ISS), which measure output dose, dose equivalent, or particle fluence. These devices are not integrated into ISS systems and therefore require astronaut time.

Parameter, Value:

Parameters: mass, power required, measured quantity, and for personal dosimetry: battery life and wireless capability.

SOA for personal dosimetry (thermoluminescence dosimeters (TLD)): passive only, very small (~8 cm^3), very light (~8 g).

SOA for dose area monitoring (Luilin): ~ size and mass of a Blackberry (~100 cm^3, 125 g). Most of the mass is the battery.

SOA for active dose equivalent monitoring (Intra-Vehicular Tissue Equivalent Proportional Counter, or IV TEPC): ~0.03 m^3, ~10 kg.

SOA for active particle spectrometers (Mars Science Laboratory Radiation Assessment Detector, or MSL RAD): ~2,500 cm^3, 1.56 kg, 4.2 W.

Only crude capability for biological dosimetry currently exists.

Capability Performance Goal: Lightweight, low-power devices for monitoring astronaut radiation exposure are needed, including active personal dosimetry, biological dosimetry, monitoring devices that can be integrated into vehicle architecture, and particle spectrometers for charged particles and neutrons.

Parameter, Value:

Mass, power required, measured quantity, and for personal dosimetry: battery life and wireless capability.

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	Enhancing	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

6.5 Radiation
6.5.5 Monitoring Technology

6.5.5.2 Compact Biological Dosimetry (Biodosimetry)

TECHNOLOGY

Technology Description: Dosimetry for non-invasive (spit or blood drop) radiation diagnostics. Compact biological dosimetry technologies that can be used in flight on long-duration missions. Diagnostic tool for damage done by radiation. Biomarkers to track risks; dosimetry tracks damage.

Technology Challenge: Biomarkers to track risks, dosimetry tracks damage.

Technology State of the Art: Some crude dosimetry exists. Some instrumentation parts are high Technology Readiness Level (TRL), but the ability to look for biomarkers is low TRL. Not miniaturized. Not stand alone unit.

Parameter, Value:

Size, number of biomarkers.

TRL 1

Technology Performance Goal: Dosimetry for non-invasive (spit or blood drop) radiation diagnostics.

Parameter, Value:

Number of biomarkers can detect with ability to grow as needed.

TRL 6

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

CAPABILITY

Needed Capability: Monitoring technology.

Capability Description: The ability to monitor astronaut exposure to space radiation.

Capability State of the Art: Currently, astronaut exposure is monitored through passive personal dosimeters. A variety of other measurement devices have also been used on the International Space Station (ISS), which measure output dose, dose equivalent, or particle fluence. These devices are not integrated into ISS systems and therefore require astronaut time.

Parameter, Value:

Parameters: mass, power required, measured quantity, and for personal dosimetry: battery life and wireless capability.

SOA for personal dosimetry (thermoluminescence dosimeters (TLD)): passive only, very small (~8 cm^3), very light (~8 g).

SOA for dose area monitoring (Luilin): ~ size and mass of a Blackberry (~100 cm^3, 125 g). Most of the mass is the battery.

SOA for active dose equivalent monitoring (Intra-Vehicular Tissue Equivalent Proportional Counter, or IV TEPC): ~0.03 m^3, ~10 kg.

SOA for active particle spectrometers (Mars Science Laboratory Radiation Assessment Detector, or MSL RAD): ~2,500 cm^3, 1.56 kg, 4.2 W.

Only crude capability for biological dosimetry currently exists.

Capability Performance Goal: Lightweight, low-power devices for monitoring astronaut radiation exposure are needed, including active personal dosimetry, biological dosimetry, monitoring devices that can be integrated into vehicle architecture, and particle spectrometers for charged particles and neutrons.

Parameter, Value:

Mass, power required, measured quantity, and for personal dosimetry: battery life and wireless capability.

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	Enhancing	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

6.5 Radiation
6.5.5 Monitoring Technology

6.5.5.3 In-Situ Active Warning and Monitoring Dosimetry

TECHNOLOGY

Technology Description: Proton event warning system.Compact, dose-equivalent area monitors for missions beyond low-Earth orbit (LEO).

Technology Challenge: Size, power, integration with vehicle systems, and reducing the technology to the size of a Blackberry (or smaller device) are challenges.

Technology State of the Art: Hybrid Electronic Radiation Assessor (HERA) currently being developed and tested at NASA.

Parameter, Value:
Size, power

TRL
5

Technology Performance Goal: Active area dosimeters that can be distributed throughout the spacecraft and integrated into the vehicle monitoring systems.

Parameter, Value:
Low power and be small (Blackberry size or smaller)

TRL
9

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

CAPABILITY

Needed Capability: Monitoring technology.

Capability Description: The ability to monitor astronaut exposure to space radiation.

Capability State of the Art: Currently, astronaut exposure is monitored through passive personal dosimeters. A variety of other measurement devices have also been used on the International Space Station (ISS), which measure output dose, dose equivalent, or particle fluence. These devices are not integrated into ISS systems and therefore, require astronaut time.

Parameter, Value:

Parameters: mass, power required, measured quantity, and for personal dosimetry: battery life and wireless capability.

SOA for personal dosimetry (thermoluminescence dosimeters): passive only, very small (~8 cm^3), very light (~8 g).

SOA for dose area monitoring (Luilin): ~ size and mass of a Blackberry (~100 cm^3, 125 g). Most of the mass is the battery.

SOA for active dose equivalent monitoring (Intra-Vehicular Tissue Equivalent Proportional Counter, or IV TEPC): ~0.03 m^3, ~10 kg.

SOA for active particle spectrometers (Mars Science Laboratory Radiation Assessment Detector, or MSL RAD): ~2,500 cm^3, 1.56 kg, 4.2 W.

Only crude capability for biological dosimetry currently exists.

Capability Performance Goal: Lightweight, low power devices for monitoring astronaut radiation exposure are needed, including active personal dosimetry, biological dosimetry, monitoring devices that can be integrated into vehicle architecture, and particle spectrometers for charged particles and neutrons.

Parameter, Value:

Low mass and power required, measured quantity, and for personal dosimetry: battery life and wireless capability.

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	Enhancing	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

6.5 Radiation
6.5.5 Monitoring Technology

6.5.5.4 Miniaturized Low-Power Charged-Particle Spectrometers with Active Warning

TECHNOLOGY

Technology Description: Compact, low-power, charged-particle spectrometers that can be used during missions beyond low-Earth orbit (LEO). Measures radiation environment.

Technology Challenge: Expanding measurement capability to broader energy ranges is a challenge.

Technology State of the Art: Mars Science Laboratory Radiation Assessment Detector (MSL RAD) currently working on Mars on Curiousity; International Space Station (ISS) Radiation Assessment Detector (RAD) near completion.

Parameter, Value: Size, power, MSL RAD: ~2,500 cm^3, 1.56 kg, 4.2 W.

TRL: 8

Technology Performance Goal: Charged-particle spectrometers.

Parameter, Value: No bigger than the current MSL RAD and be able to measure the particles and energy ranges at least as broad as those measured by MSL RAD.

TRL: 9

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

CAPABILITY

Needed Capability: Monitoring technology.

Capability Description: The ability to monitor astronaut exposure to space radiation.

Capability State of the Art: Currently, astronaut exposure is monitored through passive personal dosimeters. A variety of other measurement devices have also been used on the ISS, which measure output dose, dose equivalent, or particle fluence. These devices are not integrated into ISS systems and therefore, require astronaut time.

Parameter, Value:

Parameters: mass, power required, measured quantity, and for personal dosimetry: battery life and wireless capability.

SOA for personal dosimetry (thermoluminescence dosimeters): passive only, very small (~8 cm^3), very light (~8 g).

SOA for dose area monitoring (Luilin): ~ size and mass of a Blackberry (~100 cm^3, 125 g). Most of the mass is the battery.

SOA for active dose equivalent monitoring (Intra-Vehicular Tissue Equivalent Proportional Counter, or IV TEPC): ~0.03 m^3, ~10 kg.

SOA for active particle spectrometers (MSL RAD): ~2,500 cm^3, 1.56 kg, 4.2 W.

Only crude capability for biological dosimetry currently exists.

Capability Performance Goal: Lightweight, low power devices for monitoring astronaut radiation exposure are needed, including active personal dosimetry, biological dosimetry, monitoring devices that can be integrated into vehicle architecture, and particle spectrometers for charged particles and neutrons.

Parameter, Value:

Mass, power required, measured quantity, and for personal dosimetry: battery life and wireless capability.

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	Enhancing	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

6.5 Radiation
6.5.5 Monitoring Technology

6.5.5.5 Miniaturized Low-Power Neutron Spectrometers with Active Warning

TECHNOLOGY

Technology Description: Measure neutron spectrum on long-duration crewed missions outside low-Earth orbit (LEO) to meet operational requirements and determine exposure contribution to crew during the mission.

Technology Challenge: Neutron detection is inherently difficult because of the nature of the particles. An operational neutron spectrometer must provide a reliable measure of the neutron spectrum in a complicated mixed field of all radiation types where the potential for misidentification is significant and can substantially impact the assessment of the radiation environment for crews.

Technology State of the Art: A number of neutron detection techniques have been utilized on past science missions (Boron-10, He-3). To date, no spectrometer has been adopted for operational needs. A new lithium-based neutron spectrometer has demonstrated improvements over SOA techniques in ground based testing.

Parameter, Value:

Energy range: 1 to 10 MeV.

Resources: 15 Watts, 5 kgs.

Misidentification of neutrons < 10^{-4} probability.

TRL

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Technology Performance Goal: Improve neutron spectral measurements to cover a broader energy range and reduce susceptibility to false identification of neutrons in mixed radiation fields. Design for operational modes that ensures safe data storage, active alarming, and meets resource limitations.

Parameter, Value:

Measure neutron spectrum from 0.5 to 50 MeV.

Measure fluence of thermal and epi-thermal neutrons.

Identify neutrons with a reliability of > 95% in mixed radiation fields.

Implement operational features to ensure crew safety, store data and alarm.

TRL

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

CAPABILITY

Needed Capability: Compact, low-power, neutron spectrometer that can function on missions beyond LEO.

Capability Description: Measure the energy spectrum of neutrons in crewed quarters and provide alarming capability.

Capability State of the Art: Measures the energy spectrum of neutrons on the International Space Station (ISS) using boron-doped plastic scintillator. It is integrated with an area monitor for ionizing radiation and gamma rays. Measures neutron energies from 1 to 7 MeV.

Parameter, Value:

Energy range 1-7 MeV.

Reliability of identifying neutrons > 80% (background dependent).

Capability Performance Goal: Miniaturized low-power neutron spectrometers with active warning for operational modes that ensures safe data storage, active alarming, and meets resource limitations.

Parameter, Value:

Measure neutron spectrum from 0.5 to 50 MeV.

Measure fluence of thermal and epi-thermal neutrons.

Identify neutrons with a reliability of > 95% in mixed radiation fields.

Implement operational features to ensure crew safety, store data and alarm.

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
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Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	5 years