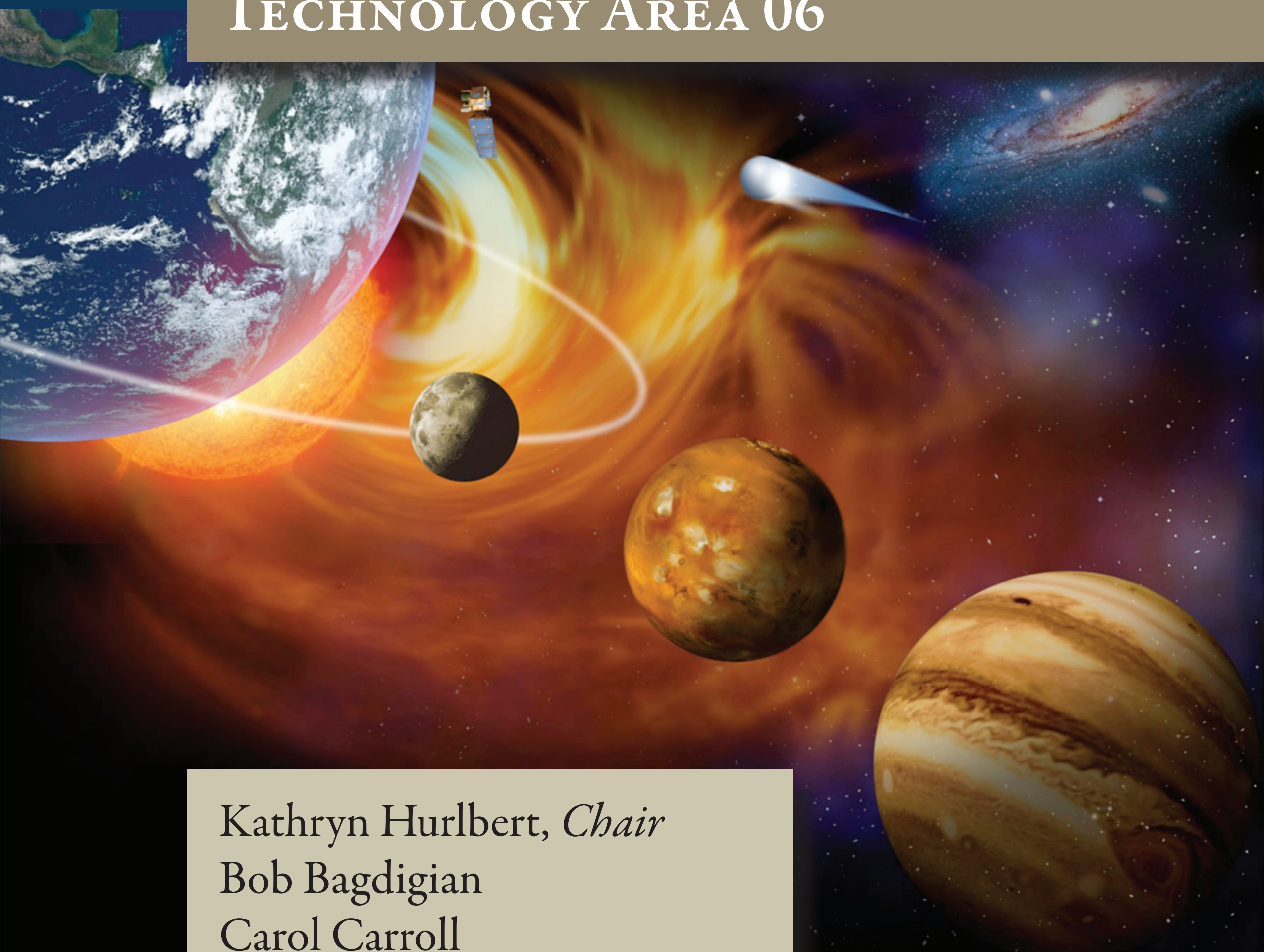
National Aeronautics and Space Administration

DRAFT Human Health, Life Support and Habitation Systems

Technology Area 06



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FOREWORD

NASA's integrated technology roadmap, including both technology pull and technology push strategies, considers a wide range of pathways to advance the nation's current capabilities. The present state of this effort is documented in NASA's DRAFT Space Technology Roadmap, an integrated set of fourteen technology area roadmaps, recommending the overall technology investment strategy and prioritization of NASA's space technology activities. This document presents the DRAFT Technology Area 06 input: Human Health, Life Support and Habitation Systems. NASA developed this DRAFT Space Technology Roadmap for use by the National Research Council (NRC) as an initial point of departure. Through an open process of community engagement, the NRC will gather input, integrate it within the Space Technology Roadmap and provide NASA with recommendations on potential future technology investments. Because it is difficult to predict the wide range of future advances possible in these areas, NASA plans updates to its integrated technology roadmap on a regular basis.

EXECUTIVE SUMMARY

This roadmap provides a summary of key capabilities in the domain of TA06, Human Health, Life Support and Habitation Systems (HLHS), necessary to achieve national and agency goals in human space exploration over the next few decades. As an example, crewed missions venturing beyond Low-Earth Orbit (LEO) will require technologies with improved reliability, reduced mass, self-sufficiency, and minimal logistical needs as an emergency or quick-return option will not be feasible. The sub-technology areas (sub-TAs) included in the roadmap are Environmental Control and Life Support Systems (ECLSS) and Habitation Systems; Extra-Vehicular Activity (EVA) Systems; Human Health and Performance (HHP); Environmental Monitoring, Safety, and Emergency Response (EMSER); and Radiation.

Shown on the next page is an overview roadmap (called the Technology Area Strategic Roadmap (TASR)), which includes planned, predicted, and new proposed missions and milestones at the top. Examples of the planned and predicted missions are human missions to LEO (e.g., International Space Station (ISS)) and Near-Earth Objects (NEOs). More detail on these "pull" missions and milestones is given in Section 1.3. In addition, new "push" missions and milestones are proposed, and represent key events that would advance or validate technologies to a point where they would be available to implement into future missions at low risk. An example "push" mission is the extension of ISS operations beyond 2020, to allow for continued and sustained testing and advancements related to space-environment effects on humans.

The lower portion of the TASR is populated with technology milestones and activities for each of the sub-TAs, as recommended to allow significant advancements to support the missions and milestones identified. The icons are designated in the legend at the bottom, and distinguish between "pull" that directly tie to a mission, activity or milestone, versus "push" where there is no direct link but a recommendation/path to support future needs. Also, distinction is made for ground versus flight activities, and cross-cutting technologies are identified. Notably, some technologies in the roadmap are currently at a low Technology Readiness Level (TRL), but could provide significant advancement in the current State-of-the-Art (SOA) and/or drive new approaches or techniques in accomplishing mission implementation. The subject matter experts authoring this roadmap believe that each activity or milestone represented in the TASR does indeed have a technology solution to pursue at the present time, or will have within the timeframe shown. Each sub-TA portion of the roadmap is detailed in Section 2, providing further explanation of the sub-TA as well as a summary table of the priority technologies and/or system functional areas of interest, the current SOA, the major challenges for advancement, and the recommended milestones/activities to advance to a TRL-6 or beyond (i.e., demonstration in a relevant mission environment or simulation thereof), which correlates with the TASR content. Section 2 also provides some example technological solutions, but these should not be considered all-inclusive or decisive without rigorous survey of SOA and proposed technologies and further review/study. Some major technical challenges identified for each sub-TA are presented in Section 1.4, for periods spanning the next two decades.

As can be seen in the TASR, milestones are aligned to minimize the number of necessary flights to progress the technologies and maximize the use of integrated ground tests/demonstrations of new technologies for reduced risk. The 'flight campaigns' serve as validation beacons to project managers of future missions. It is recognized that validation to TRL-6 should occur by the Preliminary Design Reviews (PDRs) of these missions; PDR is targeted for no later than three years before launch readiness, and more often desired five to six years before human missions.

The primary benefit of investment in technology development for the HLHS domain is the ability to successfully achieve human space missions to LEO and well beyond, as described in Section 1.2. At the same time, significant potential exists for improvements in the quality of life here on Earth and for benefits of national and global interest. Section 4 provides an extensive description of how investment in HLHS can provide technologies for climate change mitigation, emergency response, defense operations, human health, biological breakthroughs, and more.

The OCT Roadmapping activity is intended to identify overlaps across TAs, and for the topical areas of TA06, HLHS, many such overlaps exist. Notably, the greatest overlap occurs with TA07, Human Exploration and Development of Space (HEDS). Delineation exists in that the focus of HLHS is specific to the human element, including technologies that directly affect crew needs for survival, human consumption, crew health and well-being, and the environment and/or interfaces to which the crew is exposed. Alternately, HEDS focuses on the global architecture and overall infrastructure capabilities to enable a sustained human presence for exploration destinations. More detail on HLHS relationships to the other TAs is included in Sections 2.0 and 3.0.

1. GENERAL OVERVIEW

1.1. Technical Approach

This roadmap provides a summary of key capabilities, including game-changing or breakthrough items, within the domain of TA06, HLHS, necessary to achieve predicted national and agency goals in space over the next few decades. As an example, crewed missions venturing beyond LEO will require technologies for high reliability, reduced mass, self-sufficiency, and minimal logistical needs, as an emergency or quick-return option will not be feasible. Human space missions include other critical elements such as 1) EVA systems to provide crew members protection from exposure to the space environment during planned and contingency/emergency operations; 2) crew health care to address physiological, psychological, performance and other needs in-situ; 3) monitoring, safety, and emergency response systems such as fire protection and recovery, environmental monitoring sensors, and environmental remediation technologies; and 4) systems to address radiation health and performance risks, and shielding and other mitigations.

The TASR provides a top-level overview of the roadmap content herein. The missions shown include those to LEO (e.g., ISS) and other potential destinations beyond (e.g., NEO). In addition, "push" missions and milestones are recommended for consideration, which represent key events for advancement or validation of technologies and/or a point where the technologies could be available to implement for future missions. An example "push" mission is the extension of ISS operations beyond 2020 to allow for continued and sustained testing and advancements related to space-environment effects on humans. Notably, some technologies in the roadmap are currently at a low TRL, but could provide significant advancement in the SOA and/or drive new approaches or techniques in accomplishing mission implementation.

The HLHS sub-TAs detailed in the roadmap content herein are ECLSS and Habitation Systems; EVA Systems; HHP; EMSER; and Radiation. Section 2 details each sub-TA, including proposed technologies as well as associated milestones and missions correlating to the TASR. Also, the TASR milestones are aligned to minimize the number of necessary flights to progress the technologies and maximize the use of integrated ground tests/demonstrations for reduced risk. The 'flight campaigns' serve as validation beacons to project managers of future missions. It is recognized that validation to TRL-6 should occur by the Preliminary Design Reviews of these missions; PDR is targeted for no later than three years before launch readiness, and more often desired five to six years before human missions.

1.2. Benefits

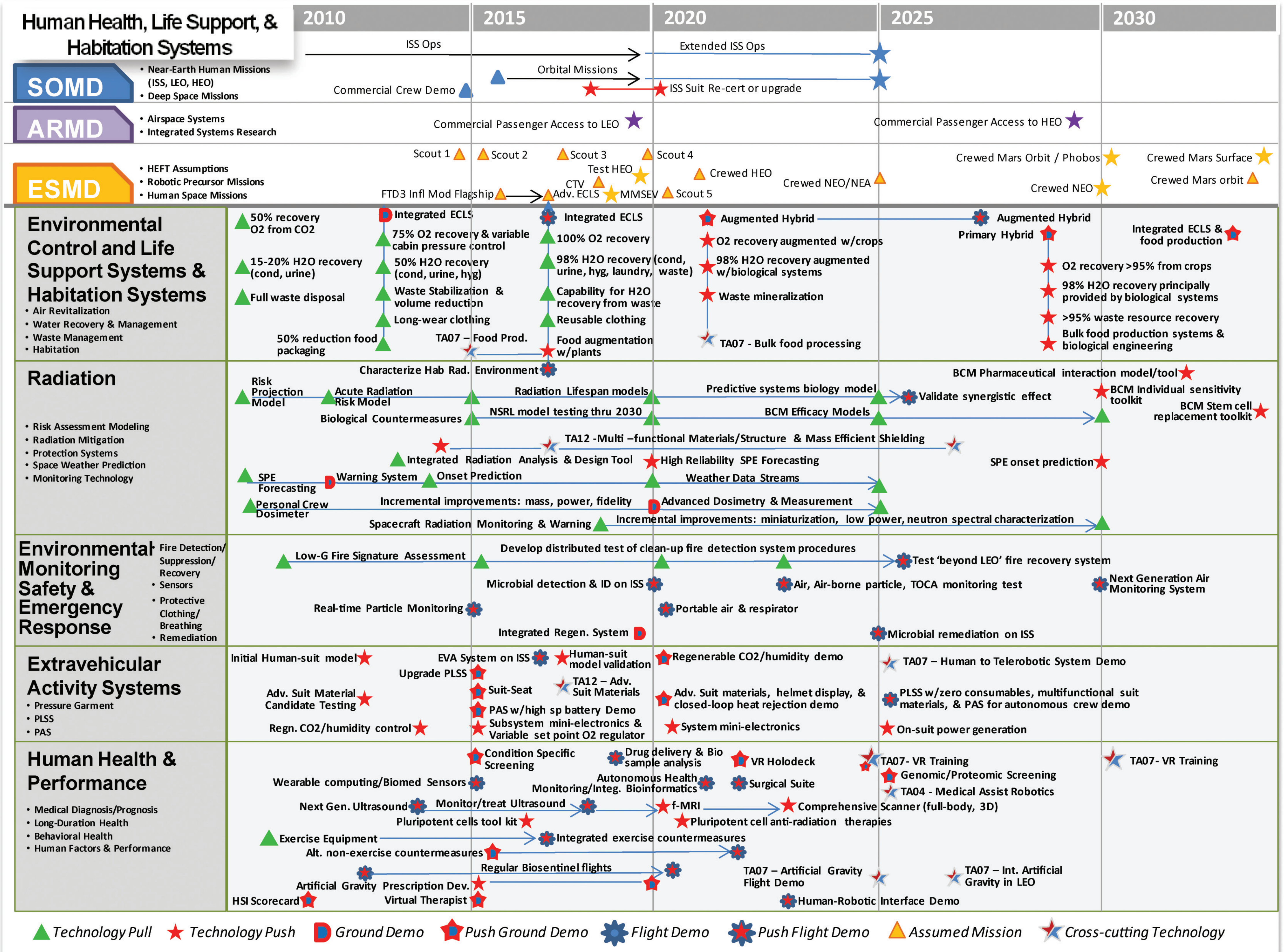
The primary benefit of significant technology development for the HLHS domain is the ability to successfully achieve affordable human space missions to LEO and well beyond. Continued ISS operation and missions will directly contribute to the knowledge base and advancements in HLHS in the coming decade, as a unique human-tended test platform within the space environment. Either extension of ISS operations, or using an alternative permanent or semi-permanent in-space facility would facilitate sustained research/testing and associated advancements into the following decade as well, in preparation for missions beyond LEO. In-space test beds will be crucial to the development and validation of technologies needed for those bold space missions, such as a NEO, currently under consideration.

The proposed roadmap includes many suggested in-flight and ground test activities for pre-flight evaluation and augmented research/testing of recommended technologies, which will regularly and efficiently provide advancements during the development phases. More details on the benefits for each entry are defined in subsequent sub-TA sections. Additionally, Section 4 provides an extensive description of how investment in HLHS technologies can lead to improvements in the quality of life here on Earth and create benefits of national and global interest. Examples include, but are not limited to, technologies related to climate change mitigation, emergency response, military operations, human health, and biological science breakthroughs.

1.3. Applicability/Traceability to NASA Strategic Goals, AMPM, DRMs, DRAs

The process to develop the TASR included 1) initial consideration of the overall agency goals, outcomes, and objectives as "pull" missions for the technology content and milestones; and 2) incor-

Figure 1: *Human Health, Life Support and Habitation Systems Roadmap*



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poration of the NASA Mission Directorate and NASA Centers needs and focus within the sub-TAs. While the strategic plan for the agency, and therefore its strategic goals, specific missions, etc., is currently being finalized, the top portion of the roadmap does include the proposed agency-level major missions and milestones derived from the drafted FY11 Agency Mission Planning Manifest (AMPM)[1] ; an example is the planned ISS operations through 2020. In addition, some content related to Design Reference Missions (DRMs) were based on Design Reference Architectures (DRAs) evaluated as a part of the Human Exploration Framework Team (HEFT) activity[2] ; an example is the assumed human missions beyond LEO, such as the mission to a NEO/Near-Earth Asteroid (NEA), within the 2025 timeframe. An attempt was also made to consider the relevant missions and milestones included on TA07, Human Exploration and Development of Space (HEDS), Roadmap, as considerable potential overlap with this technology area (TA) exists; however, the distinction is that TA06, HLHS, is specific to the human element, including technologies that directly affect crew needs for survival, human consumption, crew health and well-being, and the environment and/or interfaces to which the crew is exposed. For the TA06, HLHS, drafted roadmap herein, some "push" missions and milestones are also recommended for consideration, like extended operation of the ISS. It should be noted that alternative platforms might serve this purpose as well, such as commercial or joint space stations/vehicles, if available and appropriate for the proposed technologies.

The proposed roadmap provides time phasing that would allow infusion of technologies or capabilities to support planned, predicted, and new proposed agency missions and/or milestones. Once the agency direction and authorization for FY11 and beyond is finalized, the roadmap should be re-evaluated.

1 *Agency Mission Planning Manifest. Draft internal NASA document. 2011.*

2 *Human Exploration Framework Team (HEFT) DRM Review - Phase 1 Closeout, September 2, 2010.*

1.4. Top Technical Challenges

The table below summarizes some major technical challenges that will be faced in the continua-

Table 1. *Major Technical Challenges*

Present – 2016
Integrate fundamental research results on radiation environment biological effects, and including other effects from space exposure, into damage/risk model(s) and consolidate and interpret databases of major signaling pathways causative of cancer from space exposure and other damage
Stabilize liquid and solid wastes to recover water and to control pathogens, biological growth and gas/odor production
Achieve high reliability and reduce dependence on expendables over existing SOA systems that recover O_2 from CO_2 and H_2O from humidity condensate and urine
Develop advanced screening technologies, to detect and/or predict subclinical malignancies, subclinical cataracts, individual susceptibility levels to space exposure (e.g., radiation) and carbon dioxide exposures, osteoporosis, oxidative stress, renal stone formation, anxiety, and depression
Demonstrate EVA technologies that could be used to extend EVA capability on ISS beyond 2020. These technologies include advances for on-back regenerable CO_2 and humidity control, advanced suit materials, and more capable avionics
Demonstrate real time airborne particle monitoring on the ISS
2017 – 2022
Develop radiation risk model(s) as a predictive systems biology model approach for space radiation, including development of experimental methods/techniques and models to verify integrated risk and understand synergistic effects of other spaceflight stressors (microgravity, reduced immune system response, etc.) combined with radiation
Validate physiological and psychological countermeasures for long-duration missions, which can include any combination of exercise, non-exercise (e.g., pharmacological) and/or advanced techniques (e.g., Virtual Reality technologies such as a "Holodeck", artificial gravity)
Close high-reliability ECLSS more fully, with >95% O_2 and H_2O recovery from an integrated mission perspective
Implement bulk food processing in-flight and augmentation of food supply with plants
Advanced EVA technologies to enable missions to NEOs, which includes suits that incorporate advanced materials and component demonstrations of life support technologies that reduce consumables
Complete development of a distributed hybrid fire-detection system for space missions
2023 – 2028
Demonstrate hybrid physical/chemical and biological ECLSS with >95% recovery of O_2 and H_2O with bulk food production
Develop and validate a non-ionizing, full body, dynamic, 3-D imaging with in-situ diagnosis and treatment capabilities (e.g., renal stone ablation)
Validate real-time monitoring and forecasting space weather model(s), to include prediction of onset and evolution of Solar Particle Events (SPEs) as well as all clear periods
Flight demonstration of an advanced EVA system, including suits that utilize multifunctional materials, a portable life-support system (PLSS) with no consumables, on-suit power generation, and avionics that enable the crew to operate autonomously
Complete integrated system testing of portable, non-solvent-based microbial remediation on ISS

tion and progression of human spaceflight, especially for crewed missions beyond LEO. The listing was determined by reviewing the recommended content for each sub-TA for the time period specified, and selecting one or two technologies and/or priority system functions within that domain for a balanced representation of HLHS. The table specifies technologies that are a low TRL and require extended development time to be ready for future missions, those that may significantly impact mission implementation (e.g., high reliability, reduced logistics, decreased mass, high efficiency power systems, etc.), and/or those that are critical to human safety and well-being. An example is that top priorities for ECLSS include maturing technologies for high reliability and reduced logistics, as supported by the recent HEFT activity[3] . The recommended activities and milestones related to the challenges listed below, and those in the Section 2 tables for each sub-TA, are directly correlated to the TASR content. The TASR also shows when the milestones and activities related to the challenges are intended to be met.

3 *Ibid.*

2. DETAILED PORTFOLIO DISCUSSION

This document provides a summary of key capabilities in the TA06, HLHS, domain, recommended to achieve predicted national and agency goals in space over the next few decades. The sub-TAs, illustrated in Figure 2, are described in more detail in subsequent sections. Notably, for TA06, HLHS, the greatest TA interdependency is with TA07, HEDS. Substantial delineation between the two TA scopes does exist. HLHS concentrates specifically on the human element, whereas HEDS focuses on the global architecture and overall infrastructure capabilities to enable a sustained human presence for exploration destinations. The HLHS domain includes technologies that directly affect crew needs for survival, human consumption, crew health and well-being, and the environment and/or interfaces to which the crew is exposed. An example is water technologies, which are needed for direct human water intake, but also for hygiene and humidity control. This is distinguished from HEDS, for which the water focus is on extraction from in-situ materials for use in vehicle systems, or optimal placement of storage tanks to maximize radiation shielding

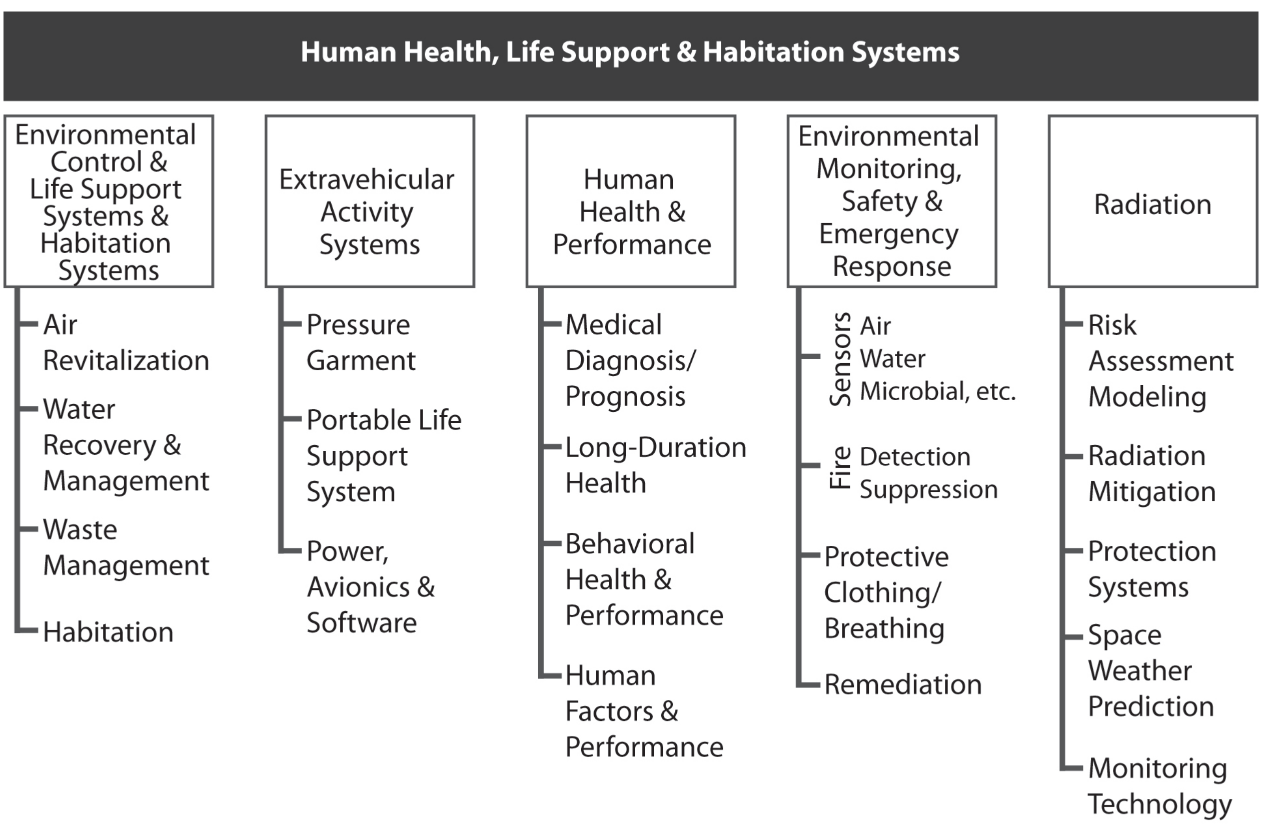

Figure 2. *Technology Area Breakdown Structure (TABS)*

without affecting the functional architecture. Another example is that for HLHS, the EVA systems are those that directly interface to the human and provide the life support, such as the suit itself and the support systems. Conversely, in HEDS, for the EVA systems include the mobility technologies needed to interface to the vehicles/systems at the exploration site(s) and to the components, in order to conduct human mission operations; examples include a suitport and/or suitlocks, rovers, tools and translation aids. Another area of potential overlap for both TAs is food preparation and production, but this too has been resolved: for HLHS, food is a critical consumable for humans and provides a future interface to the life support system for carbon dioxide scrubbing. For HEDS, the primary concentration is on production and preservation of food for in-transit space and destinations, to minimize human-specific logistics and, therefore, support self-sufficiency for remote missions beyond LEO. Overlaps with other TAs are described briefly in Section 3.

2.1. Environmental Control and Life Support Systems (ECLSS) and Habitation Systems

The main objective 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 includes four functions, each of which is described below.

Air Revitalization – The overarching function of this element is to maintain a safe and habitable atmosphere within a spacecraft, surface vehicle, or habitat. This is achieved through the removal of carbon dioxide, trace volatile organic compounds, and particulates that are released into the atmosphere from crew member and vehicle sources. Oxygen and nitrogen are added to the atmosphere in controlled manners to maintain cabin pressures and composition, and to make-up for metabolic consumption and loss. Ventilation mixes atmospheric constituents and transports sensible and latent heat loads to rejection devices. In long-duration missions, oxygen and carbon can be recovered from carbon dioxide and recycled to reduce mission life-cycle costs and upmass.

Water Recovery and Management – This element provides a safe and reliable supply of potable water to meet crew consumption and operational needs. Short-duration missions often can be executed by using launched water supplies combined with disposing wastewater via overboard venting or de-orbiting in spent resupply vehicles. Longer-duration missions demand that reusable water be recovered from wastewater in order to reduce or eliminate the need for Earth-based resupply. Short- and long-duration missions typically also require some degree of wastewater stabilization to protect equipment and facilitate potable water disinfection for storage.

Waste Management – The objective of this element is to safeguard crew health, increase safety and performance, recover resources, and protect planetary surfaces, all while decreasing mission costs. Key technology gaps to be addressed for future missions include waste/trash volume reduction and stabilization, water recovery from wastes, and ultimately a high-percentage recovery of H_2O, O_2, N_2, CO_2, and minerals. Additional technology gaps include waste collection, disposal and containment technologies, and source odor/contaminant control.

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. Other habitation functions such as deployable crew volumes, habitation analogs, lighting, housekeeping tools, and noise mitigation are addressed in TA07, HEDS.

2.1.1. Approach and Major Challenges

The basic human metabolic spacecraft requirements of oxygen, water, and food have been well characterized, and these requirements have largely been met for short-duration missions (from Project Mercury to the Space Shuttle) with open-loop life support systems using expendables.

For the ISS, continual operational costs of a conventional open-loop system are prohibitive. Accordingly, the ISS life support systems process condensate and urine into potable water. An upcoming technology demonstration will also enable recovery of half of the oxygen available in carbon dioxide. This approach is a significant advance over previous systems, but many of the technical solutions to human life support for the ISS depend upon reliable system operation and timely logistical support from Earth.

As NASA looks toward human missions beyond LEO, two key distinctions exist from all crewed space missions to date: 1) human beings will spend significantly longer periods of time farther from reliable logistics depots, and 2) an emergency quick-return option will not be feasible.

Accordingly, to sustain life on long-duration missions beyond LEO, high reliability will become an increasingly dominant design driver. Therefore, the ECLSS and Habitation Systems technical area must develop and mature technologies that emphasize 1) high-reliability processes and integrated systems that employ autonomous monitoring and control systems and that are easily maintained by the crew; 2) increased self-sufficiency, enabled by highly reliable means of recovering life-supporting commodities such as oxygen, water, and food; and 3) minimized logistics supply to diminish overall mass of spares, maintenance equipment, clothing, food containers, and other items requiring stowage mass and volume.

Reliability, logistics, and loop closure all contribute to overall mission life-cycle costs. As capabilities to recover and produce life support consumables (O_2, H_2O, food) are added to a launch vehicle, initial mass may be increased for additional system hardware, spare parts, and expendable supplies. Depending on the mission duration and operations concept, these initial penalties need to be justified by the resultant long-term consumables savings. Architectural trades uncover which combinations of capabilities yield the lowest life-cycle cost for a given mission duration and concept. A representative break-even comparison of this type is shown in Figure 3. The goal of life support and habitation architecture is to select the capabilities with the optimal combination of mass, size, reliability, logistics, and loop closure characteristics that will best support the given mission scenario.

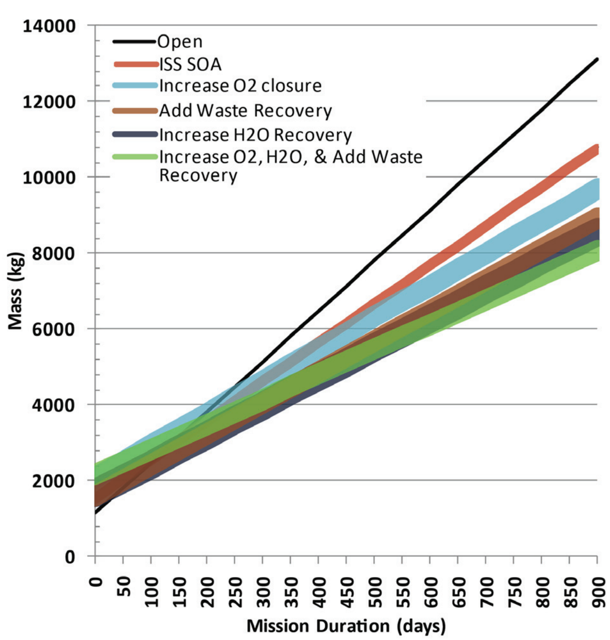

Figure 3. *Representative Comparison of Life-Cycle Mass Predictions, Candidate ECLSS Architectural Approaches*

In maturing these technologies, life support and habitation systems for missions beyond LEO will need to address both the technological shortcomings and the functional integration inefficiencies of existing systems. Further reduction of life-cycle costs and closure of life support systems is paramount, including focus on the key challenges summarized in Table 2.

Air revitalization is typically achieved by the combined operation of many individual equipment items, each optimized to perform one or two functions[4] . Utilization of multifunctional materials and processes can reduce system size and operational complexity, regardless of mission duration. Such multifunctional systems must be developed to avoid burdensome maintenance or repair. Although air revitalization life-cycle costs for long-duration missions are dominated by the degree of oxygen recovery, system reliability and utilization of expendables also contribute substantially to mission economics and probability of success. Reliability drivers include dynamic electromechanical devices (valves and valve position indicators, compressors, etc.) as well as components often considered "static" due to material attrition and loss of critical properties over time (sorbents, heat exchanger coatings, membranes, etc.). Operating equipment and airflows produce substantial acoustic emissions that dominate the cabin environment and require system size increases to accommodate marginally-effective acoustic treatments. Overboard venting of process gases as well as residual atmosphere constituents during airlock operations may require substantially greater controls on planetary surfaces than has been historically required in LEO in order to meet planetary protection requirements. Mission concepts that require the recharge of oxygen accumulators drive the need to reliably generate or compress gaseous oxygen to high pressures or liquefy it to achieve high storage densities.

Similar to air revitalization, life-cycle costs for water recovery and management are dominated by the degree of water recovery, system reliability, and utilization of expendables. As in air revitalization, reliability drivers include both dynamic

4 Perry, J., Bagdigian, R., and Carrasquillo, R., 2010, "Trade Spaces in Crewed Spacecraft Atmosphere Revitalization System Development." Paper presented at 40th International Conference on Environmental Systems, Barcelona, Spain, July 11-15.

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Table 2. *ECLS and Habitation Technical Area Details*

Function	Current SOA/Practice	Major Challenge(s)	Milestones/Activities to Advance to TRL-6 or beyond
Air Revitalization	CO_2 removal via expendable lithium hydroxide and regenerable molecular sieves [TRL-9] and amines [TRL-6] O_2 supply via compressed gas delivery, scavenging of cryogenic fuel cell reactant boil-off, consumption of expendable perchlorate candles, and water electrolysis 50% O_2 recovery from CO_2 [Sabatier TRL-7] Trace contaminant removal via catalytic oxidation and expendable sorbents Particulate filtration Ducted fans Air/liquid heat exchangers (condensing, non-condensing)	Attain high reliability Reduce utilization of expendables Reduce power and equipment mass and volume Increase recovery of O_2 from CO_2 Reduce acoustic emissions Control environmental mass exchanges to ensure planetary protection System impacts of cabin atmospheres with reduced total pressures and elevated oxygen concentrations Develop and validate complex models and simulations (e.g., Computational Fluid Dynamics (CFD), human metabolic models, chemical and microbial processes)	**2011-14:** 75% O_2 recovery **2011-14:** Variable cabin pressure control **2015-19:** 100% O_2 recovery **2020-24:** O_2 recovery augmented by crop systems and life-supporting materials **2025-29:** O_2 recovery principally provided by crop systems and life supporting materials
Water Recovery and Management	H_2O recovery from humidity condensate and urine only (representing only 15-20% of the anticipated wastewater load for exploration missions)	Attain high reliability Reduce utilization of expendables Reduce power and equipment mass and volume Reduce acoustic emissions Recover water from additional sources, including hygiene and laundry Increase overall water recovery percentage Stabilize wastewater from multiple sources in manners that are compatible with processing systems Disinfect and maintain microbial control of potable water by means that protect crew health and provide reliable monitoring	**2011-14:** 40-55% H_2O recovery (condensate, urine, hygiene) **2015-19:** 98% H_2O recovery (condensate, urine, hygiene, laundry, waste) **2020-24:** 98% H_2O recovery augmented by biological systems (condensate, urine, hygiene, laundry, waste, In-Situ Resource Utilization (ISRU)-derived) **2025-29:** 98% H_2O recovery principally provided by biological systems
Waste Management	Single-use supplies and return of all wastes to Earth for disposal	Attain high reliability Reduce utilization of expendables Reduce power and equipment mass and volume Stabilize wastes to control pathogens, biological growth, and gas/odor production Resource Recovery – recover H_2O and other resources (O_2, CO_2, N_2, minerals, clothing radiation shielding, and fuel) Planetary Protection compatibility	**2011-14:** Waste stabilization and volume reduction **2015-19:** H_2O recovery from wastes **2020-24:** Waste mineralization **2025-29:** >95% waste resource recovery
Habitation	Limited clothing reuse prior to disposal (0.38 kg/crew-day) – no in-flight laundry capability All ISS food requires ground resupply – zero-g plant growth demonstrated	Odor/microbial control for multiple uses – limiting impact on wastewater processor Simplified bulk food preparation and continuous low-energy and low-volume food production Laundry systems	**2011-14:** Long-wear clothing; 50% less food packaging **2015-19:** Reusable clothing; fresh food augmentation **2020-24:** Bulk food processing **2025-29:** Bulk food production systems **2025-29:** Biological engineering for food production

electromechanical devices (valves, pumps, centrifugal gas/liquid separators, etc.) and "static" materials (sorbents, catalysts, membranes, etc). The physical, chemical, and microbiological complexity and variability of wastewaters necessitate that they be stabilized to protect equipment from biological and chemical fouling-induced failure and gaseous contaminant release (e.g., ammonia). Recovered potable water must be disinfected to ensure safe storage with biocides that don't pose long-term crew member health risks. The capability to recover water from a wider range of potential wastewater sources can contribute to lower life-cycle costs, particularly by enabling clothes laundering and reducing dependence on expendable wipes for crew hygiene.

Solid waste management systems for missions to date have been limited to a "cradle-to-grave" approach, consisting of a one-time use of supplies followed by storage and return to Earth. Beyond hand compression of trash prior to containment, no processing is conducted. Biological growth and concomitant odor production continue during storage, and are managed using closed or vented storage containment. While this strategy has sufficed for past missions, including frequent downmass return to Earth, it will not satisfy the requirements of future long-duration missions.

Enabling long-duration missions will require establishing an integrated "cradle-to-cradle" strategy that employs resource retrieval and reuse via water recovery, air revitalization, and other subsystems. Further gains can be realized by deliberate selection of mission consumables, packaging plastics, and spacecraft materials that facilitate direct reuse or serve as feedstock for in-situ manufacturing of valuable products such as radiation protection, spares and fuel. Such processing will, by default, 1) provide mass and volume savings; 2) enhance mission sustainability; and 3) reduce the amount of waste that requires safe handling, storage and disposal. Extensive waste reuse also decreases the amount of waste that requires processing to satisfy potentially restrictive planetary protection requirements. Widespread use of specifically-designed biodegradable materials, including bioplastics, can dramatically increase resource recovery and reduce residue proportions.

Habitation engineering is a distinct TA directly applicable to vehicle success, but an area that historically has been inadequately addressed in initial vehicle system design. Current habitation capabilities were designed for LEO missions and are not optimized for resupply, reliability, mass, volume, and autonomy requirements which will be design drivers for deep-space missions.

Habitation cleaning, clothing, and consumables are currently all open-loop systems, and portions of the loops must be closed for long-duration missions beyond LEO. Several habitation systems have considerable interface with Air Revitalization, Waste Management, and Water Recovery systems, and require improved capabilities as stated in the paragraphs below. Other habitation systems are detailed in TA07, HEDS.

Improved means of food preparation, rehydration, water dispensing, and galley architecture concepts are needed. A significant reduction of food packaging via new materials, bulk food preparation, and on-orbit food production capabilities is also required for future missions. Advances in biology have the potential to revolutionize food production in space through genetic engineering of plants to increase harvest index, protein and vitamin content, and growth rate, and create shorter, more volume-efficient crops. A key challenge for food production will be developing energy-efficient lighting technologies, including electrically driven devices such as Light-Emitting Diodes (LEDs) or the use of captured solar light.

Hygiene systems include partial-body cleaning (hand washing, wipes), full-body cleansing (showers), and metabolic waste collection interfaces (fecal, urine, menstrual, emesis). Urine pretreatment and hygiene cleansers/chemicals must be compatible with water recovery technologies, and the human waste collection interface must facilitate processing and stabilization of feces. Necessary housekeeping improvements include trash/debris collection, surface cleaning systems, advanced consumables stowage (packaging material development), antimicrobial/antiseptic recovery control, and post-fire cleanup.

Deep-space missions will require the ability to launder clothing in space. Both body hygiene and laundry typically utilize water and a cleaning surfactant to remove salts, body oils, and dander. Recovery of this high Total Organic Carbon (TOC) wastewater is important to closing the water balance. A laundry system that requires minimal surfactants to clean clothing is desirable. Additional key challenges include developing light-weight, quick-dry fabrics for crew clothing and repeated-use antimicrobial wipes that require only negligible cleaning.

Re-purposing of stowage containers has been proposed to minimize mass and allow reuse via conversion into crew items and acoustic/radiation blankets. Alternate approaches include reduction in volume for disposal, or conversion to solid plastic bricks by heat melt compaction for use as radiation shielding.

The major challenges of each sub-element, as well as efforts required to overcome the challenges to develop and demonstrate the technology to TRL-6, are listed in Table 2.

2.2. Extra-Vehicular Activity (EVA) Systems

EVA systems are critical to every foreseeable human exploration mission for in-space microgravity EVA and for 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. An EVA system includes software and hardware 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. AIAA publications[5,6,7], provide further details of the current SOA of the EVA technology and challenges necessary to advance this TA to conduct NASA's planned missions safely, affordably, and sustainably. The complete EVA system includes three functions, each of which is described below.

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 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 the nominal and off-nominal environments (e.g., gravitational, sound, chemical) encountered during launch, entry and landing.

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 environment, and removing products of metabolic output such as CO_2 and H_2O.

Power, Avionics, and Software (PAS) – The PAS system is responsible for power supply and distribution for the EVA system, 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 to enable crew members to perform their tasks with more autonomy and efficiency.

2.2.1. Approach and Major Challenges

The current suit development process is hampered by a lack of analytical modeling to predict combined body-suit dynamics, effects of body parameters, and suit size. A high-fidelity integrated model will allow computer simulations leading to decreased development time and cost while providing better-performing suits. This capability could also potentially lead to preventing crew injury during mission phases that require suited operations.

Extending these capabilities to include the ability to model the LEA suit-seat interface and predict crew injuries during vehicle landing will enhance crew safety and survivability. New suit materials could potentially perform multiple functions that may include power generation, heat rejection, communication, dust protection, injury protection, reduced risk of electrical shock hazards (e.g., due to plasma charging), radiation protection, and enhanced crew survivability. New materials should continually be identified, evaluated in coupon-level testing, and then integrated into suit components. Once they have been proven as a viable, effective suit component via a pressurized suit test in a relevant environment, they will be considered TRL-6. Advanced suit tests in the Neutral Buoyancy Laboratory (NBL) at JSC are an appropriate environment for microgravity mobility evaluations. Other reduced-gravity testing simulators exist and can be used when appropriate. Vacuum chamber tests may also be relevant environments for suit demonstrations of concepts that use advanced materials. These innovations should lead to game-changing suit configurations and architectures with decreased mass, improved mobility, self-sizing capabilities, and/or increased life. Improved materials may also lead to advances in mobility elements such as gloves, shoulders, bearings, and other joints.

LEA suits could benefit from many of these types of advances in suit materials. They could be donned extremely quickly in the event of an emergency, which could provide crew protection for more vehicle failure scenarios. Integrated crew-escape or crew-survival hardware would be beneficial as well. New designs that better integrate the suit, restraints, supports, and the vehicle seat could greatly increase the safety of crew members. Technology solutions to enable long-duration suited

5 *Chullen, C., and Westheimer, David T., 2010, "Extravehicular Activity Technology Needs." Paper presented at AIAA Space 2010 Conference, Anaheim, California, August 30-September 2.*

6 *Conger, B., Chullen, C., Barnes, B., Leavitt, G., 2010, "Proposed Schematic for an Advanced Development Lunar Portable Life Support System (AIAA-2010-6038)." Paper presented at 40th International Conference on Environmental Systems, Barcelona, Spain, July 11-15.*

7 *Malarik, D., Carek, D., Manzo, M., Camperchioli, W., Hunter, G., Lichter, M. and Downey, A., 2006, "Concepts for Advanced Extravehicular Activity Systems to Support NASA's Vision for Space Exploration (AIAA-2006-348)." Paper presented at 44th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, January 9-12.*

operations, as in the case of a cabin depressurization event, could resolve technical challenges associated with long-duration waste management, provision of food and water, and administering medication. Emergency breathing systems incorporating oxygen generation, rebreathers, or filtration systems would be beneficial for emergency scenarios with smoke or the release of toxic chemicals.

The PLSS is a prime candidate for infusion of new technologies to significantly reduce consumables, improve reliability, and increase crew performance. Regenerable technologies for removing moisture and CO_2 from the suit lead to reduced consumables and mass requirements. Amine swing bed technology, currently being developed, can be proven via a test on ISS in the 2016 timeframe. Additional advances could include 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. This would help close the loop for water and oxygen on a mission level. These advances could be made with technologies such as zeolites, nano-porous beds, or wash-coated foams. The crew member is cooled using a water loop that passes through a liquid cooling garment and also an evaporative cooling device that vents to a space vacuum. Innovations to make this water loop robust to chemical, particulate, or microbial contamination are critical to providing reliable, long-lasting systems. In addition, non-venting heat rejection technologies would lead to significant reduction in mission consumables. Compact, low-mass, reliable, and efficient technologies need to be developed that can reject heat to the spectrum of thermal environments of expected exploration missions. A variable set-point oxygen pressure regulator would provide new capabilities to decrease pre-breathe time, treat in-suit decompression sickness, and interface with a wide number of vehicles that may operate at different atmospheric pressures. Optimization of inhalation/exhalation/ventilation architecture could provide potential benefits for umbilical-based EVA scenarios. Because the PLSS is such a highly integrated system, it is necessary to perform system demonstrations to evaluate the combined performance of advanced technologies. A PLSS human vacuum chamber test will be needed to bring technologies to a maturity level that allows for a flight demonstration in the 2016 time frame. Another PLSS vacuum chamber test should be performed to evaluate the technologies developed to reduce PLSS consumables. Testing of an integrated PLSS on ISS provides the ultimate validation of a microgravity suit.

PAS has significant opportunities to realize dramatic increases in capabilities over the current SOA. Key hardware constraints include mass, power, volume, and performance of existing radiation-hardened electronics. As such, there are many dependencies on other TASRs. For example, significantly increased bandwidth and processing requirements will exist for communications systems. These will include a radio with networking capabilities and data rates that support the transmission of high-definition (HD) video. Integrating speakers and microphones into the suit will improve crew comfort and the reliability of the communications system. Information systems and displays have tremendous possibilities for greatly improving crew autonomy and efficiency, and advancing the SOA. The future caution and warning system will have to obtain, process, and visually display the affected crew member's individual caution and warning telemetry, and that of other crew members. An integrated sensor suite including 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. Also, dramatic increases in the specific energy of future power systems are needed. PAS system demonstrations should be performed to mature selected technologies. An initial demonstration needs to be performed around 2016 to support EVA flight demonstrations and validate the maturity of technologies that could be used to support future ISS EVA activities. Additional demonstrations on ISS in the 2020-25 timeframe need to be performed to show that technologies can provide the crew with the autonomy needed to perform missions farther and farther away from Earth.

The major technical challenges for each sub-element, as well as efforts required to overcome the challenges to develop and demonstrate the technology to TRL-6, are listed in the following text and summarized in Table 3.

2.3. Human Health and Performance (HHP)

The main objective 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 in-

Table 3. *EVA Systems Technical Area Details*

Sub-Element	Technology	Current SOA/Practice	Major Challenge(s)	Recommended Milestones/ Activities to Advance to TRL-6 or beyond
Pressure Garment	Multifunctional suit materials development	Suits comprised of multiple layers of materials that independently provide functions such as structural support, thermal insulation, or atmosphere containment	Materials that can serve multiple functions including eliminating suit-induced injury, protecting from electric shock, saving mass, and improving suit mobility	**2013:** coupon-level demo **2020:** suit-level capability **2025:** multifunctional materials with increased capabilities
	Suit modeling tool development	No integrated modeling capability exists to evaluate suit sizing, mobility, or human-suit kinetics Tests with human subjects and their qualitative assessment is used	Optimize suit design using combined body and suit modeling to predict dynamic interactions between the limbs and the suit Provide capability to evaluate multiple suit architectures prior to finalizing design and fabrication	**2013:** initial capability **2018:** validated model
	Improved suit-seat interface design	Crew members are restrained in their seats with a harness that is applied over the suit Personal aviation and auto racing industry advances have not yet been incorporated into space applications	Develop options for restraining and protecting crew members during violently dynamic mission events	**2015:** Integrated suit-seat demo
PLSS	On-back regenerable CO_2 and humidity control	Suits use Lithium Hydroxide (LiOH), which is not regenerable, or Metal Oxides, which are heavy and require a power intensive bake-out	In–situ regenerable technologies that will allow on-back regeneration and enable sustained EVA	**2014:** TRL-6 component demo **2020:** CO_2/H_2O capture for in-vehicle recovery
	Closed-loop heat rejection system with zero consumables	Water evaporation is vented to space – for missions with many EVAs this is a significant impact to the vehicle life support system	Heat rejection systems with no consumables to eliminate water loss for cooling and decrease total mission mass	**2020:** component ground demo **2025:** PLSS demo
	Variable Set-point Oxygen Pressure Regulator	Suit pressure regulators have two mechanically-controlled set points	Capability to treat decompression sickness in the suit, allow for rapid vehicle egress, and provide flexibility for interfacing the suit with multiple vehicles that may operate at different pressures	**2015:** component ground demo
PAS	Miniaturized Electronic Components Demonstrated	Suits use limited electronics	New techniques to miniaturize electronics that enable decreased on-back mass while increasing the performance of suit avionics Components need to be radiation-hardened or radiation-tolerant and cost-effective to produce	**2015:** subsystem capability **2020:** system capability demo
	Advanced Displays and Enhanced Information Systems	Laminated data sheets and voice communications from the ground or IVA crew members	Enhanced on-suit displays, tactile data entry, voice commanding, integrated sensors suite, and on-suit systems to optimize crew performance, mission planning, and system control based on telemetry	**2020:** helmet display **2025:** information system
	On-suit Power Systems	The silver-zinc battery provides approximately 70 Wh/kg	Low-mass, high-capacity energy storage to meet EVA power and mass budgets (1,100 Wh with less than 5 kg of mass (> 220 Wh/kg))	**2016:** battery demo **2025:** advanced power system

cludes four functional focus areas as shown below.

Medical Diagnosis/Prognosis – The objective of this functional area is to provide advanced medical screening technologies for individuals selected to the astronaut corps and prior to crew selections for specific missions; this is a primary and resource-effective means to ensure crew health.

Long-Duration Health – The focus here is providing validated technologies for medical practice to address the effects of the space environment on human systems. Critical elements include research and testing, including innovative use of test platforms such as Biosentinels and micro and nano satellites, and the development of countermeasures for many body systems.

Behavioral Health and Performance – The objective in this topical area is to provide technologies to reduce the risk associated with extended space travel and return to Earth. Technology advancements are needed for assessment, overall prevention, and treatment to preclude and/or manage deleterious outcomes as mission duration extends beyond six months.

Human Factors and Performance – This element focuses on technologies to support the crew's ability to effectively, reliably and safely interact within the mission environments. Elements here include user interfaces, physical and cognitive augmentation, training, and Human-Systems Integration (HSI) tools, metrics, methods and standards.

2.3.1. Approach and Major Challenges

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 mission safety and success before, during, and after flight.

Medical systems for Exploration missions will be pursued based on spaceflight medical evidence generated to date, as well as research and analog populations. For each Exploration DRM, a list of medical conditions that have high likelihood and/or high crew health consequences to mission success will be generated. Astronauts currently undergo medical screening before they are selected to the astronaut corps and before they are chosen for specific missions. This is currently the primary, and most resource-effective, means to ensure crew health.

The on-going progress made in the field of genomics, proteomics (protein), metabolomics (metabolites), imaging, advanced computing and interfaces, microfluidics, intracellular Nanobots for diagnosis and treatment, materials, and other relevant technologies will significantly enhance addressing the medical needs of the human system.

Maintenance of HHP will require research before and during flight. 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. Other cross-cutting technologies provide significant value to other discipline teams – one example is artificial gravity, which is seen as a potential game-changing technology. Aside from being a promising countermeasure for many body systems, development would require a new approach to vehicle design and potentially revolutionize the way we explore space. The effect of microgravity and radiation on human systems will be ascertained using model systems (Biosentinels) such as cells, 3D-tissue, micro-organisms and small animals and these model systems will be evaluated using robotic precursor missions with platforms (including altered-gravity capabilities) planned at ISS, free-flyer-hosted payloads including micro and nano satellites (Edison) and Commercial or International collaborative missions such as Bions.

Missions beyond LEO will pose significant challenges to astronauts' psychological health, including confined living quarters with a small crew, delayed communications, no view of Earth, and separation from loved ones. 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 BHP risks associated with space travel, exploration, and return to terrestrial life. These technologies include 1) prevention technologies like reliable, unobtrusive tools that detect biomarkers of vulnerabilities and/or resiliencies to help inform selection recommendations; 2) assessment technologies for in-flight conditions such as high CO_2 levels, high air pressure, noise, microgravity, and radiation that may exacerbate risk; and 3) countermeasures aimed to prevent behavioral health decrements, psychosocial maladaptation, and sleep and performance decrements; also, countermeasures aimed to treat if decrements are manifested.

A successful human spaceflight program heavily depends on the crew's ability to effectively, reliably and safely interact with their environments. HFP represents a commitment to effective, efficient, usable, adaptable, and evolvable systems to achieve mission success, based on fundamental advances in understanding human performance (perception, cognition, action) and human capabilities and constraints in context. The most critical elements of the HFP roadmap are 1) user interfaces such as multimodal interfaces and advanced visualization technologies; 2) physical and cognitive augmentation such as adaptive automation based on in-situ monitoring of work activity; 3) training methods/interfaces; and 4) Human-Systems Integration (HSI) tools, metrics, methods and standards, such as those being developed by other government agencies, NASA HSI assessment tools, and human performance tools such as the development of human readiness level and related concepts for fitness-for-duty.

Table 4 identifies the essential function/technology relevant to the four sub-elements identified, current SOA/practice for the near-term planned missions, major challenges to mature the technology and the potential development activity needed for future missions and the time-line to elevate the potential technology, as envisioned today, to TRL-6.

Table 4. *Human Health and Performance Technical Area Details*

Technology	Current SOA/Practice	Major Challenge(s)	Recommended Milestones/Activities to Advance to TRL-6 or beyond
Condition Specific Screening Technology	Astronauts are screened for physical and psycho-logical conditions	Conditions exist that current medical technology cannot detect far enough in advance	**2012-20:** Early screening technologies for dental emergencies, subclinical medical conditions including malignancies, cataracts, individual susceptibility levels to radiation and carbon dioxide exposures, osteoporosis, oxidative stress and renal stone formation, sleep disorder, anxiety and depression. In a phased-fashion, the development in the identified areas will be implemented
Genetic/Phenotypic Screening	Not in practice for selections	Ethically acceptable screening technologies	**2015-25:** Screening technologies to personalize in-flight medical planning and care
Autonomous Medical Decision	Screen-shots of paper procedures	Lack of standards in data output from various medical instrumentation	**2012-20:** Handheld, smart device that integrates with vehicle, hardware, patient, care giver and Mission Control
Integrated Biomedical Informatics	Separate systems that do not seamlessly interface	Integrated standards	**2012-20:** Integrated electronic medical records, medical devices, inventory management system, procedures and utilizes a medical hardware communication standard
Virtual Reality Patient Simulator and Trainer	Does not exist for space-flight	Modular embedding of the technology	**2015-25:** Capability for crew members to practice just-in-time medical training on a system that accurately represents a patient's body in microgravity
Medical Assist Robotics	Does not exist for space-flight	Automated laproscopic surgery; advise physician of treatment options	**2015-25:** Capability to develop Medical Assist Robotics
Biomedical Sensors	Wet-electrodes; multiple systems for EVA, exercise and medical	Interference from multiple systems; Signal sensitivity	**2012-20:** Minimally-invasive diagnostic sensor suite that is easily donned/doffed (e.g. shirt). Systems to assess the physiology of the eye, skin, and brain non-invasively
Advanced Scanner	Ultrasound with guidance from the ground	Size, sensitivity and comprehensive nature	**2015-25:** Non-ionizing, full body, dynamic, three-dimensional (3-D) imaging with in-situ diagnosis and treatment capabilities (e.g., renal stone ablation)
Surgical Suite	Does not exist for space-flight	Logistics	**2015-25:** Sterile, closed-loop fluid and ventilation systems for trauma and other surgeries
Artificial Gravity	Does not exist for space-flight	Establishing ground analog study; Cost impact to develop space-flight systems	**2015-20:** Prescribed exposure to artificial gravity that may reduce or eliminate the chronic effects of microgravity **2020:** Ground Demo
Novel Drug Delivery Mode	Pills, injections, ointments	In-situ synthetic biology capability for less invasive and more efficient drug delivery	**2015-20:** Drug and Biomaterials manufacturing using synthetic biology
Portable In-flight Bio-sample Analysis	Dry chemical strips, portable clinical blood analyzer Samples returned to ground for analysis in labs	Biological sample collection; research-grade water; sample and reagent storage; integrated, portable, hand-held, in-flight bio-sample analysis (micro-fluidic flow cytometry; gene expression and proteomic analysis; microscopy; spectrophotometry/ fluorometry, mass spectrometry); real-time feedback on crew health status	**2012-16:** Miniaturized Analyzer **2014:** Research Grade Water **2016:** Miniaturized Microscopy Unit **2018:** Sample Processing and Storage **2014-19:** In-flight proteomic analysis **2016-21:** Mass spectrometry
Cell/tissue Culture, animal Models	Limited, primarily Experi-ment-Unique Equipment (EUE)	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	**2013/2016:** Bion M2/M3; 2012-2021 (ISS Annual): **2018** Biosentinels Flight Demo **2012-2018:** Biosentinels – 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 prior to or in conjunction with human DRMs
Induced Pluripotent Stem Cells (IPS)	Does not exist for space-flight	Individualized IPS based Stem cell replacement to enable longer mission duration Cost effective breakthroughs in anti-radiation therapies	**2012-16:** Individualized stem cell replacement tool kit for specific DRMs **2016-21:** IPS for anti-radiation therapies
Exercise Equipment and Methods	Uses large vehicle resources High crew time	Small, robust equipment. High efficacy with high return for long duration missions	**2012-2019:** Development of concepts and prototypes for integrated exercise-based countermeasure systems
Non-exercise counter-measures	Limited countermeasures	Robust, efficient and validated nutritional, radio-protective, and pharmacological countermeasures	**2012-19:** Pharmaceutical countermeasures **2012-15:** Nutritional countermeasures **2015-23:** Radio-protective countermeasures
Separation and isolation from home	Crew members call home, photograph Earth from ISS	Individual variation in response	**2023:** Virtual Reality technologies (i.e., "Holodeck") to provide "back-home" connection; Earth-like scenery

Technology	Current SOA/Practice	Major Challenge(s)	Recommended Milestones/Activities to Advance to TRL-6 or beyond
Lack of environmental control; stress/sleep loss	No continuous monitoring	Passive monitoring of crew health and performance (e.g., vital signs, exercise, waste products, sleep, exercise work-load)	**2015:** Sleep Monitoring detection system **2015-2019:** Interfaces with other measures to personalize aspects of habitat/vehicle such as lighting, noise, temperature
Depression, conflict, insomnia	Sleep medications, conference with Flight Surgeon and/or Psychiatrist	Identification of early symptoms	**2015-19:** Next-generation "Virtual Therapist" for autonomous missions to treat behavioral health, team cohesion, and sleep decrements and provide crew with surgeon's care
Advanced User Interface (UI) Concepts Displays and Controls (D&C) Smart Habitats Human-Robotic Interaction (HRI)	Interactive visualization, multimodal technologies (haptic, auditory, visual), intuitive wireless controls, HRI, smart habitats	Selection/ development of interfaces for unique spacecraft environment (e.g., high-g, low-g, zero-g, high vibration, pressurized and unpressurized suited) Effective, low cost/mass/volume/power integrated systems for human spaceflight Scalability to real-time scientific and engineering data	**2011-14:** Seamless human system interaction for NEO missions; Smart habitat interface concepts; Adaptive Habitat Design Tool for Human-in-the-Loop (HITL) evaluation; Proof-of-concept (PoC) for advanced HRI (robotic arm, rover) **2015-18:** Advanced UI for planetary; PoC for advanced HRI for aerial; Population analysis /Biomechanical countermeasures **2020-29:** Advanced HRI in-flight demo; Implementation (spin-offs) and augmentation as necessary augmented by crop systems
Physical, Cognitive and Behavior Augmentation (including Training and Maintainability) Tele-operations, remote operations	Radio Frequency Identification (RFID), motion tracking, wireless communication Wearable computing, adaptive training and decision support systems, tele-operations	Effective, low cost/mass/volume/power integrated systems for human spaceflight	**2011-15:** Wearable computing in-flight demo; Cognitive aids/adaptive automation in-flight demo; PoC tools for remote collaboration; just-in-time training **2012-16:** (NEO) / 2017-19 (planetary): Physical augmentation/ countermeasure technologies; Technology for sensorimotor augmentation, Habitability Rating Tool **2020-29:** Implementation (spin-offs) and augmentation as needed
Human System Integration (HSI) Tools, Methods, Standards	Other Governmental Agencies' activities NASA HSI Score Card; HSI Standards	Effective transfer/ evolution of other governmental agencies' approaches to a model effective to NASA environment and culture. Direct application of commercial tools and methods in space environment.	**2011-12:** HSI Scorecard Prototype for HSI cost & benefit assessment **2015:** HSI implementation and augmentation as needed within human spaceflight technology development programs/projects

2.4. Environmental Monitoring, Safety, and Emergency Response (EMSER)

The goals of the EMSER effort are to develop technologies to ensure crew health and safety by protecting against spacecraft hazards, and for effective response should an accident occur. This area includes four functions, which are further divided into sub-elements, as described below.

Fire Prevention, Detection, and Suppression – The goal of spacecraft fire safety is to develop technologies to 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. This is accomplished by addressing the areas of materials flammability in low- and partial-gravity, fire detection, fire suppression, and post-fire cleanup. These topics will be even more critical for long-duration exploration missions as 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.

Sensors – The focus of the sensors task is to provide future spacecraft with advanced, micro-miniaturized networks of integrated sensors to monitor environmental health and accurately determine and control the physical, chemical, and biological environments of the 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, and biological monitoring and advanced control must be assembled and must be tied synergistically to provide necessary technologies for future human space exploration. NASA and NRC documentation[8,9,10], , provide more de-

8 *Committee for the Decadal Survey on Biological and Physical Sciences in Space, Aeronautics and Space Engineering Board (ASEB), Division on Engineering and Physical Sciences (DEPS), National Research Council of the National Academies (NRC), 2010, "Life and Physical Sciences Research for a New Era of Space Exploration, An Interim Report," Washington, D.C.: The National Academies Press.*

9 *Committee to Review NASA's Exploration Technology Development Program, Aeronautics and Space Engineering Board (ASEB), Division on Engineering and Physical Sciences (DEPS), National Research Council of the National Academies (NRC), 2008, "A Constrained Space Exploration Technology Program: A Review of NASA's Exploration Technology Development Program," Washington, D.C.: The National Academies Press.*

10 *"Life Support and Habitations Systems (LSHS) Project Plan," Draft 2010.*

tails of sensor technology and challenges necessary to advance this technology area.

Protective Clothing / Breathing – The focus here is to provide crew 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, in which logistical resupply is not practical. Advancements are needed to reduce weight and cost, yet still provide effective protective clothing and breathing capabilities that may be deployed when needed.

Remediation – The focus of remediation is to provide crew the ability to clean the habitable environment of the spacecraft in the event of an off-nominal situation. Off-nominal events would include fire, an inadvertent chemical release, or microbial contamination. Advancements are needed to reduce weight and cost over current methods, yet still provide effective remediation capabilities that may be deployed when needed.

2.4.1. Approach and Major Challenges

The major challenge for fire research is predicting flammability in low-pressure and partial-g 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. Early fire detection improvements to minimize false alarms require both particulate and gaseous species detection, as well as distributed sensors. Reduced size and power consumption of both particulate and gaseous species sensors, as well as increased information content and sensor lifetime, are also required for this capability to be realized. Potentially, these fire detection systems could be combined with sensors to monitor post-fire cleanup, thereby reducing mass and simplifying crew emergency operations.

The approach to environmental monitoring sensor technology development is to leverage the rapidly advancing communities in microelectronics, biotechnology, and chem/bio terrorism defense. The focus will be on adapting for reliable long-term operation in the space environment, as well as reducing size and mass without sacrificing capability. In some cases, NASA-unique needs will require unique solutions. Leverage and overlap will exist with the space science instrument community. Challenges in the sensor area may be met by a combination of technologies. Differential Mobility Spectrometry (DMS) and miniaturized ion-trap mass spectrometry can potentially serve as the basis for environmental monitoring instrumentation. Because of their small size, low power requirements, and broad applicability, so-called "hyphenated analytical techniques", such as DMS-MS, electro-spray ionization (ESI)-MS, and even ESI-DMS-MS, can be realized for space applications. With a properly designed sample preparation/inlet system coupled to any one of these "hyphenated analytical techniques", it is highly possible to create a single "suite" of sensors applicable to atmospheric, water, and microbial monitoring. In all cases, space needs are more constraining than terrestrial needs in terms of mass/volume and long term reliability, including the need to stay in calibration.

The SOA in protective clothing/breathing and remediation technologies for in-flight off-nominal events relies heavily on the ability to resupply. Since resupply is highly unlikely, protective clothing/breathing and remediation technologies must be effective, regenerable (if applicable), and be able to be deployed by crew in various off-nominal situations. Typically, methods to regenerate current materials employ heat to desorb contaminants from the surface, thereby increasing power requirements. Metallocenes and hybrid organic-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 are representative of the type of development required for future missions. Improvements are needed to evolve coveralls and gloves that are resistant to fire, chemicals, and microbes.

The major challenges of each sub-element, as well as efforts required to overcome the challenges to develop and demonstrate the technology to TRL-6, are listed in Table 5.

2.5. Radiation

The radiation area is focused on developing knowledge and technologies to understand and quantify radiation health and performance risks, to develop mitigation countermeasures, and to minimize exposures through the use of material shielding systems. Possible other improvements

Table 5. *Environmental Monitoring, Safety and Emergency Response Technical Area Details*

Technology	Current SOA/Practice	Major Challenge(s)	Recommended Milestones/Activities to Advance to TRL-6 or beyond
Development of a predictive technology for low- and partial-gravity material flammability	Assessment of material flammability in normal-gravity at highest operational oxygen concentration	A low-g analog test and predictive capability must be defined and verified Verification of the flammability limit at length and time scales relevant for spacecraft	**2019:** Predictive ground-based low-g tests and modeling to evaluate material characteristics that lead to increased flammability hazards in low- and partial-gravity **2022:** Verification of the development and propagation of relevant-scale low-g fires
Hybrid gaseous and particulate fire detection and post-fire monitoring	Non-discriminate particulate detection; smoke filtering and dedicated instrument to monitor CO, CO_2, and HX during clean-up Realistic spacecraft fire and post-fire challenge does not exist	Development of small, low-power gas and particulate sensors for fire detection Realistic-scale fire scenarios and post-fire challenge for spacecraft	**2016:** Assessment of smoke and gaseous fire signatures from low-g fires **2021:** Development of a distributed hybrid fire detection system **2022:** Verification of the development and propagation of relevant-scale low-g fires
Autonomous 2-kg air Monitor for Trace Gases and Major Constituents	55-kg Major Constituent Analyzer 25 kg Vehicle Cabin Air Monitor (VCAM) Gas chromatography-mass spectrometry experiment) 3-kg Air Quality Monitor (gas chromatography-differential mobility spectrometry, trace gases only, ISS Detailed Test Objectives (DTO)), ground analysis of returned samples	Need ability to analyze complex mixtures capable of handling unknowns Need system to perform sample analysis and data analysis routinely, alerting crew only when necessary Size about 2 kg (i.e., 70-80% size reduction beyond SOA; life tested for Mars mission	**2020:** Flight test on ISS
Airborne Particle Monitoring	Ground analysis: 0.01 mg/m^3, integrated mass measurement for 0.3-10 micron particles	Real-time monitors with binning capability for fine (300 nm-10 microns) and ultrafine (30 nm-1 micron) particulates	**2020:** Flight test on ISS **2030:** Next Gen Tech Demo
Multi-analyte Technology for Stand-Alone Water Quality Measurements and TOC Monitoring	Cannot perform analysis in flight; currently perform Ground analysis of returned samples	Need sample processing and analysis system to extract, concentrate, and aerosolize samples and analyze complex unknown mixtures and alert crew only when necessary Need low mass, low power, and no consumables	**(2020):** Non-chromatographic method to speciate analytes **(2020):** Complementary non-mass spectrometric analysis capability **2030:** Flight test on ISS
Microbial Detection for Air, Water, and Surface	Flight analysis: Microbial Air, Water, and Surface Sampler Kits: Plate culture enumeration only (2-7 days), coliform test (2 days) Ground analysis of returned samples	<12 hour results equivalent to current culture methods; identify key organisms; lower mass; decreased crew time Need sample processing system for automated sampling and culturing	**2020:** Flight test on ISS – include sample preparation and molecular identification technology
Multi-Use/Multi-Function Respirator System and Mask	Ammonia / Fire Respirator Portable Breathing Apparatus delivering 100% O_2 for 15 minutes	Need respirator for first response to fire and chemical emergencies with communications and ability to plug into air source. Need multipurpose, regenerable, cartridge for fire and chemical response Need air masks with portable air supply	**2021:** Flight tests on ISS of candidate technology
Portable, Regenerable Air Remediation Technology	Activated Charcoal filters, High-Efficiency Particulate Air (HEPA) filters, and fan units	Need for portable, regenerable remediation system with high throughput	**2019:** Integrated Regeneration system testing in flight like conditions
Microbial Remediation Technology	Benzalkonium chloride wipes	Need for contingency, remediation method to ensure all affected areas are sufficiently cleaned	**2025:** Integrated system testing of portable, non-solvent-based microbial remediation system on ISS
Post-Fire Remediation and Recovery	LiOH cartridges; Ambient Temperature Catalytic Oxidizer; fan assembly; wipes; Monitor CO, CO_2, and HX (combustion products)	Need for portable, regenerable remediation system that can remove, combustion products and fire extinguishing material Identification and characterization of a relevant partial-g post-fire challenge Identification of gaseous and particulate species to monitor for post-fire cleanup	**2020:** Verification of post-fire challenge **2023:** Test of spacecraft post-fire environment and cleanup procedures at relevant scales **(2025):** Test a "beyond LEO" fire recovery system (separate from ECLSS)

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include combining shielding with biological countermeasures for enhanced effectiveness, development of higher-fidelity space radiation monitoring capabilities in the form of miniaturized active personal dosimetry, and to aid in crew selection and operations for long-duration, human missions beyond LEO.

Exposure to the space radiation environment poses both acute and chronic risks to crew health and safety that have clinically-relevant, lifelong implications. The major health and performance risks from radiation exposure 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 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, the need to proactively provide mitigation technologies (such as biological countermeasures and/or shielding) against GCR occurs beyond LEO for missions greater than ~90 to 100 days to remain below Space Radiation Permissible Exposure Limits (PELs)[11]. Exposure estimates for both short-stay (600 days) and long-stay (900 days) Mars missions 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 largely different from the damage caused by terrestrial radiation (such as x-rays or gamma rays), as it has significantly higher ionizing power and large associated uncertainties exist in quantifying biological response; and 2) shielding GCR is much more difficult than shielding terrestrial radiation, due to severe mass constraints and GCR ability 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 through technology maturation of 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 those related to radiation risk projection models using validated ground and flight data, radiation mitigation measures, space weather forecasting, radiation protection, and radiation monitoring. NASA has developed and operates the NASA Space Radiation Laboratory (NSRL) at Brookhaven to simulate GCR and SPEs. 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 ISS to NEO to Mars in order to achieve necessary technologies and to ensure crew safety factors. NASA and NRC documentation[12, 13, 14], provide more details of the Radiation technology and challenges necessary to advance this technology area.

2.5.1. Major Approach and Challenges

A major challenge for radiation will be to acquire sufficient ground and flight data on living systems exposed to the relevant space environment, in order to develop models to accurately predict radiation risks, identify genetic selection factors, and develop mitigation measures for remaining risks. A major advance is required to reduce the biological uncertainties associated with Radiation Risk Projection Models for both NEO and Mars missions so that an optimum use of shielding designs, mission length, crew selection and mitigation measures, such as biological countermeasures (BCM) can be developed. Research is on-going today and likely needs to continue for two more decades to gather sufficient data to develop these models with acceptable uncertainty levels. New molecular/genetic based systems biology approaches will be needed to achieve the uncertainty levels required for a Mars mission. Understanding the genetic/epigenetic factors for major risks such as lung cancer could substantially lower mission costs through crew selection or BCM design reducing shielding mass requirements. Significant advances are required to integrate fundamental re-

11 *"NASA-STD-3001, NASA Space Flight Human System Standard - Volume 1: Crew Health," 2007.*

12 *Committee for the Decadal Survey on Biological and Physical Sciences in Space, Aeronautics and Space Engineering Board (ASEB), Division on Engineering and Physical Sciences (DEPS), National Research Council of the National Academies (NRC), 2010, "Life and Physical Sciences Research for a New Era of Space Exploration, An Interim Report," Washington, D.C.: The National Academies Press.*

13 *Committee on the Evaluation of Radiation Shielding for Space Exploration, Aeronautics and Space Engineering Board (ASEB), Division on Engineering and Physical Sciences (DEPS), National Research Council of the National Academies (NRC), 2008, "Managing Space Radiation Risk in the New Era of Space Exploration," Washington, D.C.: The National Academies Press.*

14 *NASA Office of Program Analysis and Evaluation, 2006, "Report of the Radiation Study Team."*

search on the cell, molecular, and tissue damage caused by space radiation into modeling of major signaling pathways causative of cancer, CNS, and degenerative diseases.

Advancements in the design of integrated radiation protection systems will be needed and the goal is to optimize systems to achieve a 20% reduction in exposure to GCR. The types of materials that protect humans against radiation are well known but mission designers will need to take a cross-disciplinary, integrated systems approach to develop lightweight, cost effective multifunctional materials/structures that can minimize GCR exposure while providing other functionalities like thermal insulation and/or Micro-Meteoroid Orbital Debris (MMOD) protection. It is generally accepted that shielding cannot completely protect against GCR and that biological countermeasures will be need to be developed for long-duration missions. Further advancements in the design and development of miniaturized personal dosimeters for crew and small low-power active radiation instrumentation and advanced warning systems for spacecraft will also be needed to minimize and monitor exposures during operations. Also, insufficient knowledge exists about the amount of protection provided by the Mars atmosphere. The Mars radiation environment may be more severe than previously estimated due to the production and transport of neutrons, mesons, muons, and electromagnetic cascades. Effects of a mixed field environment (neutrons and charged particles) on radiobiological risks are unknown. Updates to transport codes and in-situ pre-cursor data are required to validate environmental models.

The major challenges of each sub-element, as

Table 6. *Radiation Technical Area Details*

Technology	Current SOA/Practice	Major Challenge(s)	Recommended Milestones/Activities to Advance to TRL-6 or beyond
Radiation Risk Assessment Modeling	Cancer models developed to date have 3.5-fold uncertainty No computational models exist to quantify CNS or degenerative tissue health and performance risks. No integrated mortality risk projection model exists. Relationship between radiation and other space stresses needs to be further clarified Current models predict organ exposures to +15% accuracy	Transition basis of radiation risk modeling from one based on terrestrial exposures (current SOA) to a predictive systems biology model approach for long-duration missions Need to reduce cancer uncertainty projections for NEO mission to 100% and for Mars to 50% uncertainty Integrate fundamental research on space radiation biological effects into model and data bases of major signaling pathways causative of cancer and other damage Need to develop new molecular/genetics-based systems biology approach to achieve <50% uncertainty levels required for a Mars mission Ground radiation facilities do not duplicate space radiation environment in terms of combination of energies and duration of exposure which indicates that flight tests are required to validate data Develop experimental methods/techniques and models to verify integrated risk and to Understand synergistic effects of other spaceflight stressors (microgravity, reduced immune system response, etc.) combined with radiation	**2020:** Utilize the ISS for groundbreaking studies on the whether the effects of radiation modified by microgravity on cellular and metabolic activities within relevant higher order biological organisms or systems **2020:** Perform ground based radiation biology research to develop and validate risk models **2030:** Identify need for countermeasures and/or selection of crew based on individual sensitivity **2025:** Flight demo to validate understanding of synergistic effect of spaceflight on integrated risk projections), including experiments on ISS and partnering on international flight opportunities such as **2013/2016:** Bion M2/M3; **2012-2021 (ISS Annual): 2018** Biosentinels Flight Demo
Radiation Mitigation/Biological Countermeasures	Radiation exposures exceed the NASA PELs by three to five times for 1,000-day Mars missions, and are exceeded for most NEO missions as well Some agents exist to protect against acute low LET radiation No countermeasures exist for chronic GCR or intermediate SPE dose rates	Need detailed understanding of the mechanisms that cause damage Need to develop breakthrough biological/pharmaceutical radio protective agents Need to verify extrapolation from models to humans Need to develop an individual sensitivity toolkit to optimize BCM and enable longer missions Need to understand interaction/impact of one BCM on other spaceflight risks	**2035:** Perform tests for a range of radiation qualities and mixed fields representative of GCR and SPE for sufficient number of biological models to extrapolate to humans **2035:** Drug discovery research **2035:** Develop databases and computer models to determine genetic sensitivity to radiation risks based on animal testing and modeling and extrapolate to crew selection and BCM optimization **2035:** Research individualized stem cell replacement therapies
Space Weather Prediction	No ability to predict onset and evolution of SPE Real–time monitoring should be adequate for large events since doses are small in first one hour for 99% of historical SPEs Data sets exist but need to develop forecasting models	Ensure data streams needed as input for forecasting models are provided Application of SPE research and transition of research models to real-time operational decision-making tools	**2030:** Development of real-time monitoring and forecasting space weather model(s), to include prediction of onset and evolution of Solar Particle Event as well as all clear periods **2030:** Develop forecasting tools to define 'all-clear' periods for EVAs and < 1 AU trajectories for missions

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Technology	Current SOA/Practice	Major Challenge(s)	Recommended Milestones/Activities to Advance to TRL-6 or beyond
Radiation Protection Systems	Radiation shielding systems must be developed to minimize mass for SPE and GCR shielding Shielding alone will not completely protect against GCR for long-duration missions	Optimize multifunctional shielding system to achieve a 20%-30% reduction in GCR exposure Integrated Systems approach to mass efficient SPE shielding Ultimate value of shielding material types and amounts require accurate risk projection models	**2014:** Development of an integrated systems approach to radiation shielding systems that implements a smooth transition from research to operations and lays the groundwork for an 'end-to-end' solution to radiation shielding **2016:** Development of miniaturized active personal dosimetry permitting measurement as a function of charge and energy **2017:** NSRL validation data for GCR simulations **2017:** Characterize the interior environment of habitat on Inflatable flagship mission technology demonstration **2025:** Continue development of material systems to provide maximum shielding possible
Monitoring Technology and Validation	Pre-flight and EVA crew exposure projections (passive detectors for individual astronaut dosimetry) Comprehensive crew exposure modeling capability Evaluation of radiological safety with respect to exposure to isotopes and radiation producing equipment carried on the spacecraft Large mass/volume instruments using to characterize and quantify the space radiation environment that utilize continuous vehicle power Laboratory based cytogenetic evaluations (chromosome aberrations) post flight	Active Personal Dosimetry and Monitoring for IVA and EVA operations. Miniaturization of electronics and sensor technologies required for compact, low power radiation dosimeters/monitors Compact, low power, charged particle and neutron spectrometers that can used on missions beyond LEO. Ruggedization, redundancy, and fail safe performance. Fail safe data storage and transmission for long term use without resupply or repair during missions In situ active warning and monitoring dosimetry, and passive, wherever there is a human presence beyond LEO. Improved battery technology for personal dosimeters that allow long wear periods without recharging Compact biological dosimetry technologies that can be used in-flight on long duration missions. Novel techniques to determine energy and charge of incident radiation fields in compact form factor Determination of relevant biomarkers/biodosimeters (HRP) for early and late radiation effects	ETDD Flight Demo for testing of miniaturized personal dosimeters **2017:** Inflatables Flagship Mission for testing of charged particle and neutron spectrometers and in situ warning dosimetry systems Development of measurement package to be used on robotic precursors mission to NEO, Moon, Mars ETDD Flight Demo for testing of miniaturized in-flight biodosimeters technologies

well as efforts required to overcome the challenges to develop and demonstrate the technology to TRL-6, are listed in Table 6.

3. INTERDEPENDENCY WITH OTHER TECHNOLOGY AREAS

The OCT Roadmapping activity is intended to identify overlaps with other TAs, and for the topical areas of TA06, HLHS, many such overlaps exist. Notably, the greatest overlap occurs with TA07, HEDS, and the reader is referred to the start of Section 2 for a detailed delineation between these TAs. The other priority crossover is with TA12, Materials, Structural and Mechanical Systems, and Manufacturing, as advanced materials for radiation protection, spacesuits, etc., are addressed there. Notably, it is a critical area for collaboration to ensure an integrated systems approach for radiation shielding and other HLHS technology developments and for their successful implementation. Further discussion and/or collaboration across the TAs is recommended.

4. POSSIBLE BENEFITS TO OTHER NATIONAL NEEDS

Many of the proposed technologies identified in the roadmap can lead to improvements in the quality of life here on Earth, creating benefits of national and global interest. First, life support and habitation technologies focus on developing reliable, closed-loop systems to minimize resources and energy use while maximizing self-sufficiency. These systems provide significant opportunity for knowledge transfer in numerous terrestrial areas including: climate change mitigation, emergency response, military operations, energy efficient buildings and “cradle-to-cradle” manufacturing. One example is the potential for complete wastewater recovery to potable standards for military, remote and water-scarce regions, and disaster relief, with the potential for simultaneous energy production. Additionally, technologies identified may provide 1) efficient methods for CO_2 capture, conversion, sequestration, and advanced contaminant removal/destruction and particulate

Table 7. *Technical Area Interdependencies*

Technology Area	Overlapping Technology Descriptions
TA02: In-Space Propulsion Systems	Tanks for high pressure gas storage and/or cryogenics; if tanks are "shared" then purity is an issue for ECLSS use For cryogenics, issues include zero-g or low-g management/boil-off control (*also overlap with TA03 and TA14)
TA03: Space Power and Energy Storage Systems	Tanks for high pressure gas storage and/or cryogenics; see description under TA2 (*also overlap with TA14) Low mass, high efficiency, long life, high reliability, etc. batteries for EVA/suits and/or human habitat/vehicle power systems High efficiency electrolyzers for production of O_2 and/or potable water
TA04: Robotics, Tele-robotics and Autonomous Systems	Human factors (e.g., immersive visualization) and human/robot interaction and automation systems (e.g., human-robot interfaces for remote operations) Medical-assist robotics Human safety enhancement (e.g., robotic surveying and remote operations)
TA5: Communication and Navigation Systems	Very high bandwidth communication systems (e.g., telemedicine, software uploads)
TA07: Human Exploration Destination Systems (HEDS)	Manufacture of components, tools, soft goods (e.g., o-rings, seals) etc/3D model Printing; see description under TA12 Research grade water production/recycle/reuse for research platforms/needs Integrated Habitat Systems (e.g., lighting, acoustics, advanced habitat materials) EVA mobility (e.g., rovers), interfaces (e.g., suitport/lock), and tools Virtual reality/Holodeck (e.g. STAR TREK) technologies for training, etc. Radiation protection materials and/or structures/architecture using in-situ resources (*also overlap with TA12) Contamination control and housekeeping (e.g., dust) Artificial gravity devices/architecture (e.g., rotating vehicle, centrifuge chair) In- situ or remote food production and processing
TA10: Nanotechnology	Nano-systems/sensors for non-invasive physiological monitoring of crew and/or medical treatment Advanced batteries for EVA suits (*also overlap with TA3) Nanoporous and/or other advanced nano-engineered materials/structures for ECLSS and/or other human-related applications (e.g., CO2 removal, water filtration, radiation protection, environmental and/or constituent sensors)
TA11: Modeling, Simulation, Information Technology and Processing	Human, environmental, subsystem and overall vehicle monitoring and data management systems Models and simulations/simulators for human and systems performance
TA12: Materials, Structural and Mechanical Systems, and Manufacturing	Materials compatible with future ECLS environment of 8 psi (reduced pressure) and 32% O_2 (enriched oxygen) Multifunctional materials and/or structures, including combined structural and radiation protection, microbial control (e.g., materials and/or coatings), and other examples: • The "water wall" concept envisions incorporating water required for life support into the vehicle structure to eliminate the extra mass of water tanks and provide additional radiation shielding in specific locations (e.g., crew quarters, storm shelter) • The idea is to build spacecraft internal structures (struts, secondary structure, avionics boxes, seat cushions, etc) out of materials that can, for example, absorb CO_2. If enough of the materials could be incorporated into the spacecraft and preserved throughout ground processing (or "regenerate" its capacity prior to launch), then for short missions the spacecraft structures could absorb all the CO_2 from the atmosphere Manufacture of components, tools, soft goods (e.g., o-rings, seals) etc./3D model printing; in space for increased reliability, to reduce spares, etc., similar to a STAR TREK replicator (*also overlap with TA7) Materials Flammability associated with advanced materials testing, and update(s) to MSFC-HDBK-527, Materials Selection List for Space Hardware Systems
TA14: Thermal Management Systems	High-efficiency, non-degradable condensing heat exchangers and lightweight radiators Non-venting, closed heat rejection system with no consumables for EVA/suits Tanks for high pressure consumables and/or cryogenics, including issues include zero-g or low-g management/boil-off control (*also overlap with TA02 and TA03)

management for climate change mitigation, mine safety, enclosed spaces, military applications and synthetic fuel production; 2) advanced controlled agriculture systems, which minimize energy, water use and growing area, can contribute significantly to future global food production needs; 3) lightweight, deployable, inflatable, interior structures provide rapid shelter construction for military deployments, disaster response, and temporary remote science lab operations; and 4) advanced strategies for waste minimization, "cradle-to-cradle" manufacturing and reuse, hazard reduction and energy recovery to decrease use of natural resources and landfills

Previous and recent space suit technologies have provided materials and manufacturing techniques that have led to significant improvements in commercial products, like athletic shoes, and specialized items that benefit many, like efficient manufacture of pharmaceuticals. Other examples include therapeutic suits for people with medical needs, protective suits like those for race car drivers and firefighters, life-saving gas and chemical masks, lighter-than-air (LTA) vehicles. It is anticipated that the spacesuit technologies identified herein could have similar impacts as well.

Technologies for HHP may lead to smaller portable analysis and imaging units that could be used in austere/harsh environments, or even in rural settings without access to large medical facilities. Also, countermeasures developed for space are likely to impact clinical practice by providing a better understanding of how the body works, and new tools to influence both wellness, and treatment of diseases. Technologies for enhanced crew interfaces and autonomy will have the potential for use in extreme environments.

Any biological innovations or breakthroughs would also be of interest to the National Institute of Health (NIH), having the potential to significantly improve life on Earth. Technologies for radiation may help cancer patients suffering from radiation treatments, and increase understanding of early onset of diseases of old age and provide preventive measures to delay or block their appearance.

Other example benefits are for environmental monitoring, where technological advances can improve fire detection and are relevant to homeland security for detection of hazardous aerosols. Also, the development of microbial and chemical sensors can easily translate to multiple applications, such as analysis of water sources for potability in remote locations (such as rural America), medical analysis of military personnel and the general public, submarine air/water monitors, and rapid identification of bio-terrorist attacks on the military and general public.

ACRONYMS

3-D	Three Dimensional
AMPM	Agency Mission Planning Manifest
ANC	Active Noise Control
BCM	Biological Countermeasures
BHP	Behavioral Health and Performance
CFD	Computational Fluid Dynamics
CNS	Central Nervous System
D&C	Display and Controls
DMS	Differential mobility spectrometry
DRA	Design Reference Architecture
DRM	Design Reference Mission
DTO	Detailed Test Objective
ECLSS	Environmental Control and Life Support Systems
EHS	Environmental Health System
ER	Environmental Monitoring, Safety, and Emergency Response
ESI	Electro-spray ionization
EUE	Experiment-Unique Equipment
EVA	Extra-Vehicular Activity
GCR	Galactic Cosmic Radiation
HD	High-Definition
HEDS	Human Exploration and Development of Space
HEPA	High Efficiency Particulate Air
HFP	Human Factors and Performance
HHP	Human Health and Performance
HITL	Human-in-the-Loop
HLHS	Human Health, Life Support, and Habitation Systems
HRI	Human-Robotic Interaction
HIS	Human System Integration
IPS	Induced Pluripotent Stem Cells
ISRU	In-Situ Resource Utilization
ISS	International Space Station
JSC	Johnson Space Center
KSC	Kennedy Space Center
LEA	Launch, Entry, and Abort
LED	Light-Emitting Diode
LEO	Low-Earth Orbit
LST	Life Support Technologies
LTA	Lighter-than-Air
MMOD	Micro-Meteoroid Orbital Debris
MS	Mass spectrometry
MSFC	Marshall Spaceflight Center
NASA	National Aeronautics and Space Admin.
NBL	Neutral Buoyancy Laboratory
NEA	Near-Earth Asteroid
NEO	Near-Earth Objects
NIH	National Institute of Health
NSRL	NASA Space Radiation Laboratory
OCT	Office of Chief Technologist
PAS	Power, Avionics, and Software
PEL	Permissible Exposure Limits
PLSS	Portable Life Support System
PoC	Proof-of-concept
RFID	Radio Frequency Identification
SOA	State-of-the-Art
SPE	Solar Particle Events
TA	Technology Area
TABS	Technology Area Breakdown Structure
TOC	Total Organic Carbon
TRL	Technology Readiness Level
UI	User Interface
VCAM	Vehicle Cabin Air Monitor

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