NASA Crew Health & Performance Capability Development for Exploration: 2021 to 2022 Overview

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Radiation, reduced gravity, distance from earth, isolation and confinement, and habitation within artificially created and controlled life support environments are hazards that present risk to human space explorers. In many cases, research is required to characterize those risks and help identify risk mitigation strategies. Where new capabilities are necessary to maintain crew health and performance (CHP) during future missions, a multi-step process is followed: 1) a *capability gap* is defined; 2) a plan or "roadmap" to develop that capability is established based on agency priorities and anticipated mission development timelines; and 3) work defined on the roadmap is then initiated as resources allow, with the objective that the capability will be available in time to support the future mission. Over the past year, significant progress has occurred in CHP technology development, ground testbed development, ground-based testing, and in preparations for International Space Station (ISS) technology demonstrations. This paper provides a development update in the following capability areas: crew health countermeasures, spacesuit physiology and performance, food and nutrition, and exploration medical capabilities. Project overviews will include descriptions of CHP development activities over the past year, the human system risks and capability gaps being targeted, as well as planned follow-on activities and anticipated program infusion points.

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Nomenclature

AMIS = automated medical inventory system
APACHE = assessments of physiology and cognition in hybrid-reality environments
ARGOS = active response gravity offload system
CO_2 = carbon dioxide
CHP = crew health and performance
CHP-IDA = crew health and performance integrated data architecture
CSRM = crew state & risk model
DCS = decompression sickness
ECLSS = environmental control and life support systems
EHR = electronic health record
EVA = extravehicular activity
GHBMC = global human body models consortium
HMD = helmet mounted display
HRP = Human Research Program
HSRB = human system risk board
IMEA = injury modes and effects analysis
ISS = International Space Station
MIM = multifunctional integrated medical
NBL = neutral buoyancy laboratory
O_2 = oxygen
PersEIDS = personalized EVA informatics and decision support
SCLT = systems capability leadership team
TRL = technology readiness level

I. Introduction

NASA is developing concepts for long duration, deep space missions including cislunar, human lunar surface, Mars transit, and human Mars surface operations. Increasingly, each of these missions will require crew to be more independent of Earth while at the same time extending their exposure to the hazards of spaceflight. New technologies, procedures, and standards are needed to enable crew autonomy and mitigate the risks to the human system inherent in the deep space environment. NASA's Environmental Control and Life Support Systems (ECLSS) and Crew Health and Performance (CHP) Systems Capability Leadership Team (SCLT) has worked to identify many of these technology needs in the form of capability gaps and to develop strategic plans in maturing the capabilities needed to close those gaps. The SCLT serves to coordinate between evolving exploration mission characteristics to provide strategic advisement in a range of technology development programs. The intent is to ensure a safe, reliable, and habitable environment and provide technologies allowing the crew to maintain their health and performance so they can accomplish the missions' objectives. The SCLT capability areas are broadly grouped into ECLSS and CHP, see Figure 1. Each 'Capability Area' (e.g., 'Life Support') is composed of 'Capabilities' (e.g., 'Atmosphere Management').

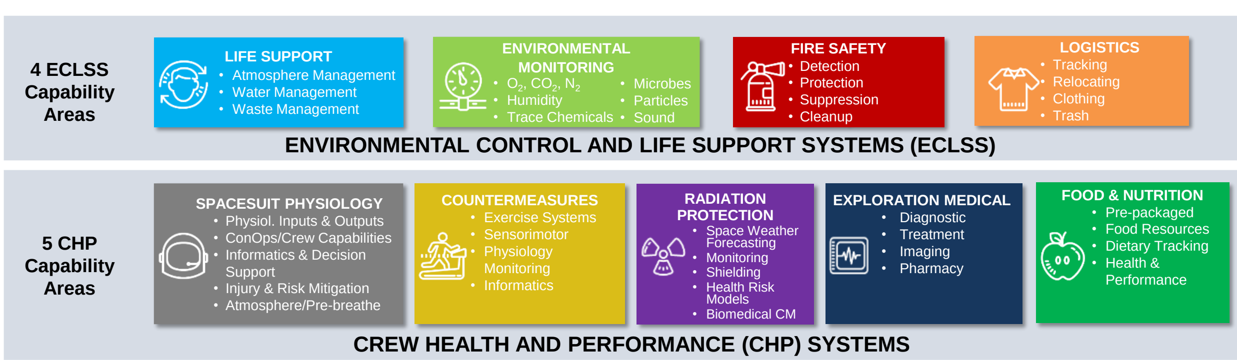

Figure 1. ECLSS-CHP SCLT Capability Areas.

This paper describes Strategic planning and integration activities which seek to ensure alignment between research-focused and technology-focused strategic roadmaps within the agency. Additionally, this paper reviews recent progress in CHP technology development, ground testbed development, ground-based testing, and preparations for International Space Station (ISS) technology demonstrations. Technical updates are provided in the areas of Spacesuit Physiology and Performance, Crew Health Countermeasures, Food Systems, and Medical and Behavioral Health Systems. Recent advances within the ECLSS capability areas are described in a companion paper. [1]

II. Human System Capability Gaps

NASA's Human System Risk Board (HSRB) maintains a set of twenty-nine Human System Risks to aid in identifying and prioritizing human research needs. [2] Subject matter experts from across the agency provide regular updates to the estimated likelihood and consequence associated with each risk for a set of generic design reference missions. The Human Research Program (HRP) has historically used these risk classifications as a primary basis for identifying and prioritizing their research investments, and they maintain a Human Research Roadmap* which is a strategic plan that identifies research activities aimed at improving NASA's ability to characterize and/or mitigate the respective human system risks.

In many cases, human research is necessary but not sufficient to adequately address a human system risk; technology development is required to mature required countermeasures or other capabilities to a Technology Readiness Level (TRL) at which they can be incorporated by flight programs without introducing significant cost, schedule, and/or technical risk to the program. As an example, research studies are being conducted by HRP to identify evidence-based standards for contingency CO_2 exposure during EVAs, currently a knowledge gap. Depending upon the outcome of the research studies, new technology development may be required to ensure those standards are achievable in future EVA spacesuits. While the HRP also conducts technology development in some instances, it is a research program, and HRP strategic roadmaps have typically focused on HRP-funded research and development activities. By comparison, the SCLT's role is to continually evaluate the capability needs of the evolving exploration mission architectures and ensure appropriate prioritization of NASA's technology investments across the agency. Close coordination between the SCLT and HRP is essential to ensure appropriate alignment and prioritization of CHP-related research and technology development to enable NASA's future exploration missions.

Where a capability is identified as being required for a future mission, but it does not yet exist, these are referred to as capability gaps. [3] A primary function of the ECLSS-CHP SCLT is to continually identify, review, and update capability gaps relevant to ECLSS-CHP disciplines and to establish and oversee multiyear strategic roadmaps aimed at guiding NASA's technology development priorities in these areas. These roadmaps are intended to be agency-wide and independent of any program, directorate, or other organization within NASA.

During 2021, the SCLT and HRP collaborated to establish a set of Human System Capability Gaps (Appendix A), which establish a formal linkage between the capability gaps used to prioritize investments across much of NASA, and the Human System Risks that are primarily used to inform and prioritize human research. This set of twenty-eight gaps was developed by subject matter experts, each gap mapped to the primary associated Human System Risks. The gaps and risk mapping were then formally reviewed and approved via the HSRB and submitted via the agency-level capability gap update process. This integration effort enables development of fully integrated SCLT-HRP roadmaps with activities that are formally linked to agency-recognized capability gaps and Human System Risks.

III. Spacesuit Physiology & Performance

NASA identifies four enabling Human System Capability Gaps associated with spacesuit physiology and performance [4] and this section provides a summary of recent progress associated with each gap as well as in the development of multiple complementary simulation environments that are required for the successful closure of these gaps. The capabilities currently being developed are "suit agnostic" meaning that they are generalizable capabilities being developed and matured so that they can later be applied and tailored to aid in the design and eventual verification and operation of specific spacesuits and other related systems. This same approach was used in the development and certification of multiple aspects of the Orion and Commercial Crew Program spacecraft and spacesuits.

A. Simulation Development

Recent progress in this area includes the definition of a common set of methods, mockups, metrics, and other simulation infrastructure for the assessment of crew health and performance during suited activities. This standardized

* https://humanresearchroadmap.nasa.gov

approach, referred to as Physical And Cognitive Exploration Simulations (PACES), allows for aggregation and comparison of data sets between different tests and even different simulation environments, which is essential for the development of the Crew State and Risk Model (see Section C, below). These methods have been developed and deployed during pressurized suit testing in the Neutral Buoyancy Laboratory (NBL) and Active Response Gravity Offload System (ARGOS) in 2020-21, which also included significant progress in achieving lunar gravity offloads. An updated ARGOS gimbal and definition of a methodology for characterizing and adjusting the center of gravity of the suited test subject has improved the repeatability of the lunar gravity simulation in both ARGOS and NBL; however, comparison with parabolic flight test data is required to validate the accuracy of the offload and its effect of suited workload and controllability. This testing is targeted for 2023.

Pressurized suited testing is necessary to understand factors such as human-suit interaction, suit fit, injury modes, metabolic energy expenditure, thermal regulation, and inspired CO_2, all of which must be characterized to ensure suited health and performance. For test objectives requiring a higher fidelity approximation of the operational environment and associated cognitive workload, or where the integration of prototype sensors or other hardware into the suit system is prohibitively expensive, alternative simulations are desirable.

A custom unpressurized spacesuit simulator is being developed to provide an adjustable physical workload approximation while ensuring compatibility with VR hardware, physiological sensors, galvanic stimulation hardware, display prototypes, and an overhead fall restraint system. The spacesuit simulator will be used in field analogs as well as in a hybrid reality environment called APACHE (Assessments of Physiology And Cognition in Hybrid-reality Environments), which is being developed for CHP-focused testing and potentially future crew training. A public crowd-sourcing challenge is underway in 2022 to develop additional simulation content for APACHE, and this will be the primary environment used for development and testing of technologies associated with the Spacesuit Bioinformatics & Decision Support capability gap.

Development and validation of decompression sickness (DCS) models and countermeasure protocols requires human testing at reduced pressures, with specific atmospheric compositions, and while performing physically representative tasks, because physical workload significantly affects DCS risk. An existing 3-story, 8,090 ft^3, hypobaric chamber at Johnson Space Center has been outfitted and certified to operate at up to 34% O_2 / 66% N_2 and as low as 29.6 kPa (4.3 psi) with breathing masks delivering up to 100% O_2 to simulate EVA conditions. [5]

The facility also includes custom-built equipment for full-body EVA workload simulations as well as Doppler and ultrasound equipment for subject monitoring. [6] Furthermore, because prebreathe protocol validation for atmospheres other than 1 ATA requires multiple day studies at the appropriate atmospheres, the chamber provides all necessary habitability accommodations for up to 8 people to live and sleep in the chamber for up to 11 days at a time.

B. Spacesuit Fit & Injury

Injury prediction, monitoring, and mitigation technologies are required for planning, training, operations, and system design for all suited mission phases and for all anticipated crewmember anthropometries.

Suited injury incidence during Apollo as well as in the current spacesuit used on the ISS suggests that musculoskeletal injuries affecting mission objectives, and potentially long-term health, are not only possible but likely during these types of long-duration surface missions unless improved fit and injury capabilities are developed and implemented. [7] [8] Future spacesuits must ensure that male and female astronauts of all shapes and sizes are not only accommodated by the suit but can perform all necessary mission tasks without discomfort or increased injury risk. Changes in anthropometry that occur during spaceflight must also be identified and accommodated. [9]

An Injury Modes and Effects Analysis (IMEA) aims to systematically identify all possible suited injury modalities then assign likelihood and consequence estimates to each, thus enabling identification and prioritization of specific capabilities necessary to characterize and mitigate suited injury risk. The IMEA was established in 2021 and early 2022 with input and vetting from stakeholders across NASA and outside experts and will now be used to prioritize subsequent activities as well as to provide a framework for tracking progress on gap closure.

In parallel with the development and vetting of the IMEA, a suite of suited injury models is being developed including finite element, ergonomic, musculoskeletal, and anthropometric models, each of which has potential application to the characterization and mitigation of different injury modes. In all cases, existing human injury models such as Global Human Body Models Consortium (GHBMC) are being adapted and integrated with models of generic high mobility spacesuits. Initial versions of several integrated models were completed in 2021, and initial validation was performed; however, significant additional work remains to validate these models. Prioritization of that work will be based on the IMEA and will require use of parabolic flight testing as this is the only terrestrial analog in which the weight of the human inside the suit is realistically simulated.

While significant work remains to close the Suit Fit & Injury capability gap, early work has already resulted in implementation of a suit-specific ergonomics training class given to users of prototype planetary spacesuits. And because systematic tracking of suited injuries is an essential component of the integrated strategy, a Suited User Injury Tracking System (SUITS) is being developed and has already been deployed to enable tracking of human health outcomes for all flight and ground-based suited human events (whether injurious or not). Further development will enable integration of SUITS with the Electronic Medical Record as well as incorporation of suit fit data.

C. Crew Capabilities & Constraints

Crewmember physical and cognitive state monitoring and prediction technologies are required for EVA planning, operations, system design, and decision support systems. Uncertainty and variability in which functions each astronaut will be capable of performing at any given point in a mission presents many challenges, compounded by uncertainty in the exact physical and cognitive demands and cost associated with many of those functions when performed in the lunar or Mars environment. Several related efforts are ongoing in this area:

- A 2022 study will use the APACHE environment and suit simulator to evaluate physical and cognitive performance during a simulated 1-hour emergency scenario at different levels of inspired CO_2; this will be used to inform the acceptable levels of inspired CO_2 under emergency scenarios for future spacesuits.
- A multi-year study initiated in 2021 measures the performance of astronauts performing simulated Mars EVA tasks on ARGOS before and at set time intervals immediately after long-duration missions to ISS; results will inform the time required for crewmember sensorimotor readaptation prior to performing EVAs after landing on Mars.
- Other suited ARGOS testing initiated in 2021 is quantifying the metabolic, thermal, and human factors implications of performing different tasks in prototype spacesuits in simulated lunar gravity; results will reduce uncertainty about the health and performance impacts of the heavier and higher-mobility suits expected to be used in future missions.

Because the PACES methodology enables aggregation of data across tests and environments, results from each of these studies are integrated into a Crew State and Risk Model (CSRM), which aims to provide individualized prediction of multiple important health and performance parameters such as metabolic, thermal, fatigue, CO_2 dose, and decompression stress. Where available, archived flight and training data is also being used to build the CSRM.

D. Spacesuit Bioinformatics & Decision Support

Ground-based and in-flight EVA technologies are needed to maintain EVA crew health and performance monitoring and decision making during increasingly Earth-independent operations. The unavoidable communications latency between Earth and Mars will require that many of the EVA medical monitoring and other functions currently provided by the Mission Control Center (MCC) team on Earth be performed by astronauts and their spacesuits or spacecraft. This paradigm shift will require a significant evolution of technology, training, and operations and will significantly increase the cognitive workload for IVA and EVA crewmembers. The individualized physical and cognitive state prediction capability provided by the CSRM will have to integrate with life support system models and purpose-built operational EVA planning, execution, and decision support tools that protect and provide for health and performance during all phases of EVAs. This integrated suite of capabilities is referred to as Personalized EVA Informatics & Decision Support (PersEIDS).

Recent PersEIDS progress includes assessment of metabolic rate biofeedback and other data visualizations provided in real-time to simulated IV crewmembers and to astronauts via a voice-controlled helmet-mounted display (HMD) during ISS training runs in the NBL. Significant progress has also been made on an electronic procedure authoring and execution tool, Maestro, which has been integrated with the PACES data collection methodology and the NBL informatics testbed to enable real-time visualization of procedural information via the HMD and in APACHE. The automated synchronization and association of an individual's health and performance data with their task data is an important step in creation of the CSRM.

Related progress includes the prototyping of a tool that provides real-time visualization of predicted (based on CSRM) versus actual metabolic rates and inspired CO_2 as a function of EVA tasks, incorporating projected violations of crew constraints (i.e., CO_2 limits). CSRM is also being integrated with digital elevation models of potential Artemis lunar landing sites to provide GIS visualizations that reflect crew capabilities and constraints and their implications on achievable exploration ranges.

As with Suit Injury & Fit, the scope of the challenge requires a framework to enable the identification and prioritization of development and testing efforts, as well as for the tracking of progress in terms of gap closure. Initial efforts are primarily focused on hazards and operational implications associated with crew overexertion including hypercapnia and excessive heat storage. An approach similar to the IMEA will help prioritize follow-on work.

E. Decompression Sickness

Decompression stress (DCS) prediction and mitigation technologies are needed to enable EVA planning, training, operations, and system design for planetary surface missions where existing microgravity decompression sickness countermeasures are not applicable. DCS risk models are also required in the design of spacecraft feed-the-leak capabilities and spacesuit operating pressures to protect against DCS in the event of a cabin depressurization.

Apollo missions used a 100 percent O_2 cabin atmosphere, effectively eliminating risk of DCS during EVA on the moon. NASA's future missions to the moon and Mars are expected to use nitrox gas mixtures of up to 34 percent O_2, 66 percent N_2; this will reduce flammability risk compared with Apollo but will necessitate oxygen prebreathe prior to EVA to reduce DCS risk to acceptable levels. [10] Prebreathe protocols used on the space shuttle and ISS are validated for microgravity EVAs, but the significantly increased risk of DCS during equivalent ambulatory EVAs makes these protocols inapplicable to planetary EVA. [11]

An "exploration atmosphere" of 56.5 kilopascals (kPa) (8.2 psia), 34 percent O_2 and 66 percent N_2, has been recommended by NASA as a compromise that balances prebreathe duration, hypoxia, and flammability risk, assuming a 29.6 kPa (4.3 psi) spacesuit. However, this atmosphere may not be used for vehicles that do not support frequent EVA. With commercial and international providers expected to deliver landers, pressurized rovers, habitats, and spacesuits, different combinations of vehicle and spacesuit atmospheres are possible and will each require validated prebreathe protocols. A validated DCS risk prediction tool, encompassing the range of potential spacecraft and spacesuit pressures and atmospheres, will enable risk-informed development and operation of all future spacecraft and spacesuit operations, including contingency scenarios such as cabin depressurizations.

Human testing using the hypobaric facility described in section III.A is required to validate prebreathe protocols and DCS risk models. This testing began with 1- to 3-day tests in early 2022 in preparation for 11-day tests, planned to begin Summer 2022. [5]

IV. Crew Health Countermeasures

The Crew Health Countermeasures (CHC) capability area involves identification and development of the countermeasure technologies needed to enable and optimize astronaut health and performance during exploration missions and to ensure long-term health. There is a risk of loss of mission objectives, injury, long-term health impacts, or even loss of life if crew's ability to perform mission critical tasks (e.g., vehicle landing, egress, and surface EVA) is not protected, and a multi-faceted approach to countermeasure hardware, software, and protocol development will be required to achieve this.

Eleven human system capability gaps have been identified in this capability area. While the current suite of ISS countermeasures is largely effective in protecting crewmembers during missions in low earth orbit (LEO), the hazards and constraints of exploration missions beyond LEO mean that existing countermeasure capabilities are neither directly applicable nor sufficient for meeting exploration mission needs. Further, the rigidity of the ISS data architecture does not allow for new software systems and informatics needed to integrate physiological, vehicle system, and operational parameters to inform countermeasures use in near real-time to the onboard crew or ground support crew. These systems are necessary to meet the need for increased crewmember autonomy to self-assess and self-administer using the exploration tools.

CHC exploration gaps must address the need to (1) reduce mass and volume, (2) reliably maintain and monitor fitness in-flight to enable unassisted landing, egress & EVA, and (3) validate lunar and Mars fitness standards. As such, novel exploration-forward assessment tools, countermeasures, and informatics tools are needed to protect physical performance capabilities and long-term health during exploration missions.

The organization of the CHC capabilities and tasks to date is based on the 11 identified capability gaps, several of which are discussed below and shown in Figure 2. In the future, these capabilities will be examined in a more integrated fashion, from the perspective of both how one capability impacts multiple risks [12] or how multiple disciplines contribute to one capability. [13]

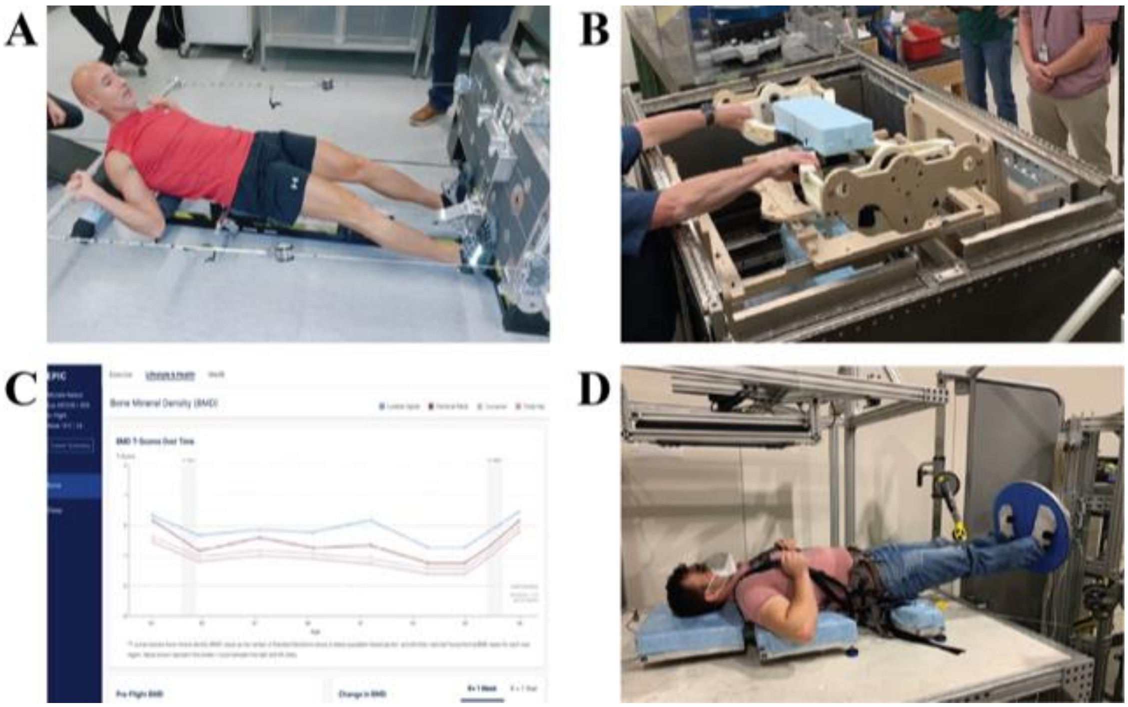

Figure 2. Overview of key CHC capability area developments. *A. E4D testing at the Danish Aerospace Company in Denmark, B. E4D VIS under development by JSC Engineering Division, C. EPIC sample user interface displays, D. Sensorimotor balance trainer for use during bed rest.*

A. Exercise Countermeasures

Exercise countermeasures and assessment tools are needed to maintain and monitor physical health and enable performance of critical exploration mission tasks. The ISS suite of exercise devices provides the current state of the art countermeasure against physical deconditioning during long duration spaceflight. **[14] [15]** A new multi-function fitness machine called the European Enhanced Exploration Exercise Device, or E4D for short, is being developed by the Danish Aerospace Company on behalf of ESA. The E4D was selected to be evaluated on ISS for efficacy, acceptability, and feasibility of use for exploration missions. Current efforts support the continued development, testing, and verification of E4D hardware and software in both 1-G and on ISS for crew acceptance, feasibility of use, and efficacy of the device to maintain multi-system health and performance of mission critical tasks.

ISS missions longer than 45 days have always had treadmill exercise capabilities, the current T2 treadmill representing the state of the art. Understanding the specific physiological and psychological benefits associated with treadmill exercise is critical in defining exploration exercise hardware requirements. A current flight study (Zero-T2) is underway in which crewmembers are asked to not use the T2 during the duration of their mission and participate in a battery of testing to evaluate the efficacy of exercise using only ARED (Advanced Resistive Exercise Device) and CEVIS (Cycle Ergometer with Vibration Isolation and Stabilization System). Participants in this study will eventually be asked to use the E4D as an inflight validation. Pre-, in-, and post-flight assessments of aerobic fitness, muscle strength, and functional mobility similar to those used during previous investigations are an important component of these studies. **[16] [17]**

B. Exercise Vibration Isolation and Stabilization (VIS) System

Vibration isolation and stabilization (VIS) systems are needed to protect the spacecraft and provide sufficient stabilization for the exerciser during performance of critical exercises. The current effort includes development of a VIS to support E4D use on ISS and to collect data to inform exploration VIS requirements. The VIS must attenuate exercise-induced accelerations transmitted to the spacecraft structure and payloads to within acceptable limits. Future exploration VIS systems must provide this within the volume and mass constraints of the exploration vehicles and with the reliability to maintain this capability during long duration transit times. Given the changes that unstable surfaces may have on exercise performance, [18] an important aspect of this capability is to ensure the VIS permits the full range of exercise needed to mitigate physical deconditioning.

C. Crew Health & Performance Countermeasure Informatics

Ground-based and in-flight informatics tools, utilizing a Crew Health & Performance Integrated Data Architecture (CHP-IDA, see Section VI), are needed to monitor and optimize crew health and performance via improved use of exploration countermeasures during increasingly Earth-independent, resource-constrained, and long-duration mission operations. The Exercise Performance and Information Console (EPIC) integrates data from a variety of different countermeasures systems, vehicle systems, and human physiological data that allows for smart data handling and human systems interfaces. Algorithms utilizing this aggregated data can then be used as tools to inform crewmembers and the flight medical operations community of health status, predict changes in crew health and performance capabilities (e.g., EVA readiness), and provide guidance on adjustments in countermeasures use (e.g., exercise prescription updates). Development, testing, and validation of EPIC's algorithm-based tools is planned in 1-G analogs and onboard ISS. The end product will provide timely and actionable information for optimization of human health and performance and countermeasure use. Current tasks include integration with medical data systems, data visualizations, and metrics of user acceptability during beta testing.

D. Sensorimotor Countermeasures

Sensorimotor assessment and countermeasure tools are needed to enhance preflight training, maintain inflight conditioning, and accelerate recovery following transitions between gravity environments. Current efforts include augmenting the conditioning and assessment tools used by the Astronaut Strength and Conditioning Rehabilitation (ASCR) specialists to optimize sensorimotor adaptation. [19] The use of Galvanic vestibular stimulation is being explored to provide a portable spatial disorientation training capability that could be used for piloting or recovery operations. [20] Current efforts also include the development of inflight training to keep the proprioceptive and tactile systems tuned to respond to balance challenges in a partial gravity environment and thus improve post-flight balance and mobility to perform capsule egress and EVAs. [21] The first trainer is being developed using an air bearing horizontal surface for a Head Down Bedrest validation study. Future technology demonstrations are planned for parabolic flight and on the ISS. Individual health assessments will be required during exploration missions to account for variability in neurosensory adaptation and task readiness for early EVAs. Unobtrusive monitoring of head and body motion is under development to provide a capability for in-mission assessments of crew mobility to perform EVAs. [22] This same tool will provide feedback of self-administered rehabilitation exercises that will be used on the planetary surface to enhance adaptation to the novel gravitational environment.

E. Cardiovascular Countermeasures

Cardiovascular deconditioning can result in low blood volume, cardiac atrophy, vascular dysfunction, orthostatic intolerance, and reduced work capacity, affecting an astronaut's ability to perform work during and immediately after spaceflight. [23] Countermeasures and assessment tools are therefore needed to mitigate the long-term health and operational risks associated with cardiovascular structural and functional changes during and following long-duration and reduced-gravity exploration missions. Fluid loading is an integral part of the countermeasures against orthostatic intolerance upon landing; [24] however, the current protocols using salt tablets and water are not well-tolerated and need to be optimized for exploration missions. A task has been initiated which will determine the efficacy of an alternative solution to expand plasma volume without the gastrointestinal distress. This task also includes the development of a standardized test protocol for comparison of fluid loading protocols in practice.

F. Future CHC Capabilities

While the CHC capability area has prioritized the need for exploration exercise, the scope is broadening to align with countermeasure development associated with additional human safety risks. For example, countermeasures such as bisphosphonates [25] are needed to mitigate the risks of fracture and irreversible skeletal changes associated with spaceflight-induced changes in bone mass and structure that resistive exercise alone does not protect against. Inflight bone heath assessment tools are currently lacking. Countermeasures and assessment tools are being developed to detect and mitigate neuro-ocular changes related to Spaceflight Associated Neuro-ocular Syndrome or SANS. [26] Countermeasures and assessment tools will also be needed to mitigate the long-term health effects (Cancer, CNS damage, etc.) of exposure to space radiation during deep space exploration missions as well as mitigate and monitor immune system dysfunction and microbially induced disease. [27] [28]

V. Food Systems

Food is critical for multiple crew health countermeasures in long duration missions. Food also is the largest crew consumable mass. As such, understanding the food system stability, its close relationship to crew performance, the impact of life support hardware, and monitoring the crew's in-flight consumption of food nutrients are all important aspects for technology development. Food system efforts are focused on five high-level gaps.

A. Safe, Acceptable, and Nutritious Food

First, the food system must be safe, nutritious, and acceptable to support crew health and performance throughout increasingly long-duration and Earth-independent missions. The current shelf life of shelf-stable foods ranges from 1 to 3 years, but a shelf life of at least 5 years will be required for missions to Mars. A 5-year shelf-life brackets two mission scenarios. Mars surface missions may have crew consumables delivered to the Mars surface prior to crew departure for Mars, adding two years due to infrequent earth-Mars launch opportunities. Second, for the Mars crewed transit phase, Earth food preparation and launch will be at least a year-long activity for the quantity of food required. The Mars transit vehicle will require multiple elements and outfitting missions in cis-lunar orbit, and it is generally assumed the large quantity of food required may be built up in the year before earth-departure. Both mission cases require food shelf life in the 5-year timeframe.

One project funded by HRP is evaluating different formulation, processing, packaging, and storage combinations to determine potential methods to achieve a 5-year quality and nutritional shelf life for a range of food types. Although cold storage can increase shelf life, both passive and active refrigeration methods would require additional mission resources. Cold storage is an active area where resource reduction solutions are needed.

Variety and choice can be as important as nutrition, but they are likely to be restricted or unavailable on long duration missions due to limited food system upmass and potential prepositioning. If the food within a closed and limited system is not acceptable to all crew it will not be consumed in adequate amounts, potentially leading to weight loss and nutritional deficiency. Similarly, if a crewmember avoids certain foods and consumes more of other foods, imbalances may be created in what all crew have access to consume, again possibly leading to weight loss and nutritional deficiencies. [29] [30]

Determining methods to provide a high quality, safe, and nutritious variety of foods that meet long-duration requirements is a critical task. Although the food system has historically consisted of shelf-stable foods, in-flight production, such as crop growth, can be considered. However, any in-flight production must produce an acceptable product, include an acceptable and resource efficient process, and ensure food safety. Crew on exploration missions will be very busy with other tasks, and meal preparation should only include tasks that the average busy person would find acceptable and efficient in their own kitchens. [29] In addition to determining shelf-stable foods, current work in this area includes developing plant growth infrastructure and capabilities to support salad crops as a supplement to the shelf-stable diet on ISS and Mars missions.

B. Food Resources

Second, the food system must fit within resource constraints. New food system technologies must maintain or improve reliability while reducing mass, volume, power, crew time, and other resource requirements. Food system resources include, but are not limited to, water, power, mass, volume, volatile impacts to vehicle systems, cleaning and sanitation, food safety testing, and crew time required for both the food and preparation infrastructure. [31] Work in this area includes assessing the potential to reduce the water content and maintain acceptability of the shelf-stable food system, assessing resource impacts and trades of new plant growth technologies, and determining low-resource refrigeration strategies for food preservation. These tasks also support technology gaps related to water system closure and vehicle infrastructure.

NASA is developing more mass efficient microgravity crop production systems to provide crew with supplemental nutrition and increased food variety. Production systems focus on food output for crew consumption with repeated growth cycles in a mission rather than extensively instrumented and variable environmental conditions utilized in research plant facilities on ISS. NASA is developing a roughly half rack sized crop production facility, named Ohalo, that will provide lighting, water, and nutrients to a crop watering and growth module provided by a competitive development process from a mix of academic and commercial providers.

C. Low-Hydration Food

Third, related to food resources, the water content of launched prepackaged food is an important parameter. Water in launched food is effectively water resupply to the life support systems. As the carbon dioxide removal and reprocessing systems increase from their current ISS efficiency of ~47% to the target of >75% oxygen recovery, there is a substantial decrease in the need for water resupply. Electrolysis of water is used to produce oxygen. The hydrogen from electrolysis is used to break down the carbon dioxide to water, which is then used for crew consumption and oxygenation. Currently the food water content is ~47% by mass for the standard ISS food items. It is desired to reduce the water content of launched prepackaged food to <30% to fully take advantage of improvements in carbon dioxide reduction/oxygen recovery in the life support systems. NASA has initiated efforts to reformulate a few food items each year. It is not as simple as just dehydrating food, as nutrient content can be changed, palatability, and shelf-life can all be impacted. All those potential impacts can decrease the overall effectiveness of the food system's ability to be an effective countermeasure. ISS crew members have commented that the variety from different types of foods is important to prevent menu fatigue and maintain intake, health, and performance. The retort thermostabilized foods that do not require rehydration are especially critical when crew time for food preparation/rehydration is limited. The impact of reducing these options on overall intake and resulting health and performance is currently unknown and would have to be assessed. [32] Note that *Low-Hydration Food* is an ECLSS capability gap rather than a Human System Capability Gap and therefore does not appear in the Appendix.

D. Food Impacts to Health and Performance

Fourth, any potential space food system must demonstrate the ability to support crew health, and physical, cognitive, and behavioral performance over long-durations with mission relevant conditions and tasks. ISS and ground analogs are used to determine dietary intake associations with health and performance outcomes according to food provisioning scenarios. This information is necessary to inform trades between health and performance risks and food resource availability, ultimately informing provisioning requirements. Current work in this area includes evaluation of the relationship between a Mars realistic food system and crew health and performance in a series of three one-year Mars surface ground analogs at a facility being built up at Johnson Space Center (CHAPEA-Crew Health and Performance Exploration Analog). CHAPEA will provide an integrated evaluation of nutritional intake, crew performance, cognition, and behavioral and health outcomes from astronaut-like participants over a year given a Mars-mission relevant food system, resource constraints, and schedule. Given the outcomes, mission resources can be allocated to best support crew health and performance, and therefore mission success. Additionally, if CHAPEA shows a significant benefit of the addition of some crops, that would provide a basis for prioritization of related projects such as Ohalo.

E. Food Intake Tracking

A fifth capability gap is associated with the need to accurately track food intake. Once the relationship between health and performance and food intake from a realistic Mars food system is established, an effective food intake tracking system will be needed to monitor compliance and guide maintenance of health and performance within each food provisioning scenario throughout the duration of Earth-independent exploration missions.

VI. Medical and Behavioral Health Systems

The Exploration Medical capability area focuses on identifying gaps in medical capabilities for exploration, detailing a roadmap for closing those gaps, and developing technologies to be able to be used operationally in the spaceflight environment. Areas of focus include medical imaging; diagnostics; treatment technology; medical decision support and informatics; medical simulation; safe and effective pharmaceuticals; behavioral health and performance; and medical risk modeling and trade space analysis. The current projects within this capability area are detailed below.

A. Intravenous Fluid Generation (IVGEN) Mini

Future exploration missions to Mars have increased medical risk and need for intravenous (IV) fluids. However, expiration dates of commercially available IV fluids are currently shorter than the duration of a planned mission to Mars. Thus, prepositioned IV fluids would expire during the mission. The ability to produce sterile, medical grade IV fluids in-situ from the potable water supply of a vehicle or habitat would reduce medical risk and the mass/volume of the overall medical system. The first IVGEN experiment successfully demonstrated this capability aboard the ISS in 2010 during ISS Expedition 23. However, this demonstration used a large prototype that was intended for future miniaturization.

The IVGEN Mini project will focus on a development effort with the goal of miniaturization of the previously flown IVGEN system and upgrades to make the system more reliable and easier to use. A technical demonstration of the miniaturized system is targeted for ISS in the 2024 timeframe to increase the IVGEN TRL and demonstrate its suitability for long-duration missions beyond LEO.

B. Crew Health and Performance Integrated Data Architecture (CHP-IDA)

CHP related data on ISS is downlinked in a manual manner that requires both crew and ground team time. Data lives in separate locations and databases that do not allow for real-time integration and advanced analytics. Exploration missions will require increased crew autonomy which would benefit from such advanced analytics and data integration. Prior efforts have been made to advance the concept of an integrated data architecture, including HRP's Medical Data Architecture (MDA) project. Whereas the MDA project focused on aggregation of medical data, there is a need to expand this scope to include all relevant CHP-related data (e.g., exercise performance data, EVA physiological data, spacecraft environmental data, timeline and task data, nutritional intake, sleep, etc). This need is captured in the cross-cutting Human System Capability Gap 5.1 (see Appendix): *Data architecture integrated across all crewmembers, vehicle systems, and mission phases to enable multi-system crew health and performance assurance (e.g., monitoring, decision support, data collection, analytics, visualization, etc.).*

User-facing software developments such as PersEIDS (Section III) and EPIC (Section IV) will require a back-end data architecture to provide synchronized data sources for subsequent processing and decision support. The CHP-IDA aims to provide this backend data architecture to allow for the seamless collection, storage, processing, display, and utilization of CHP-related data for exploration missions. In FY22, the CHP-IDA project completed SRR and is being developed with the vision of an integrated fully ground-based demonstration followed by a hybrid demonstration using ground-based hardware and software with real mission data from ISS. Future work includes flight demonstration and implementation during cis-lunar Artemis missions.

C. Automated Medical Inventory System (AMIS)

The current inventory of medical equipment and supplies onboard ISS is maintained in a very manual manner. As pharmaceuticals or supplies are used, ground teams rely on crew reporting their use. The Health Maintenance System (HMS) team then manually adjusts the existing inventory database. Over time, the inventory of medical equipment and supplies including pharmaceuticals becomes increasingly inaccurate. An automated solution such as the AMIS would allow for minimal crew interaction to maintain an accurate inventory of medical equipment and supplies. Such a capability is particularly important for exploration missions requiring increased crew autonomy. High level concept of operations development and a market survey has been performed in this arena. Further development of the AMIS is targeted to begin in FY24.

D. Exploration Electronic Health Record (xEHR)

Currently, only Flight Surgeons on the ground have access to the Electronic Health Record (EHR). After Private Medical Conferences are completed, the Flight Surgeon must input the encounter into the EHR. Crew onboard the ISS do not have access to their own medical record, nor does the Crew Medical Officer (CMO) have access to such data. Exploration missions will require increased crew autonomy in the provision of medical care. As such, there is a need for an Exploration Electronic Health Record (xEHR) that will be available in-mission to the CMO. Additionally, it will provide crewmembers limited access to their own medical information similar to a patient portal. The xEHR will also be accessible to ground medical personnel such as Flight Surgeons so that they may review care provided in-mission and provide additional guidance as needed. High level concept of operations and functional requirements have been developed for the xEHR. Development work on xEHR is targeted to begin in FY23.

E. Multifunctional Integrated Medical Device

Exploration missions innately involve greater medical risk due to the longer transit times (and thus environmental exposures), longer mission durations, and inability for realistic evacuation or resupply. Despite this increased medical risk, mass and volume constraints will be significantly limiting for the overall medical system. Currently, the ISS medical system involves multiple separate devices to cover the desired capabilities provided. For exploration missions, Multifunctional Integrated Medical (MIM) Devices that optimize the number of medical capabilities provided while minimizing mass and volume are desired. In collaboration with HRP, commercially available MIM devices are being evaluated in ground testing and ISS flight testing to assess their utility for future exploration missions. Future work will also include the integration of MIM data products with the CHP-IDA.

F. Pharmacy

Exploration missions will involve increased medical risk and therefore increased need for pharmaceuticals to manage this risk. These missions will also involve increased environmental exposures of pharmaceuticals to things like radiation. The impact on the safety and efficacy of these pharmaceuticals is currently not well understood. Additionally, many medications will expire during exploration mission to Mars. The safety and efficacy of these medications beyond their expiration dates is not well described. There is a need to identify an exploration formulary of medications that will be both stable and effective for crewmembers on exploration missions.

VII. Conclusion

Significant new research and technology developments are essential to ensuring crew health and performance during future space exploration missions. The focus of this paper is on recent CHP technology developments, primarily those funded by the Exploration Capabilities Program, and it was not feasible to describe all relevant activities within the page limitations. Readers are therefore encouraged to review the references for further details on the activities outlined in this paper. Most of NASA's human research investments are coordinated through HRP and are well documented via journal publications, the publicly available Human Research Roadmap website, and at the annual HRP Investigators Workshop.

Recent coordination efforts have further improved the ability to identify, prioritize, and coordinate necessary CHP investments across NASA and its stakeholders, including commercial and international partners, academia, and other government agencies. Notwithstanding the global COVID-19 pandemic, advances in CHP technologies inside and outside of NASA in 2020 and 2021 have made steady progress at closing capability gaps for both near term and longer-range exploration missions. In addition to maintaining the cross-agency coordination of CHP technology development, a near-term strategic priority for the ECLSS-CHP SCLT is to ensure efficient and effective mechanisms for infusion of new capabilities into future missions including those involving commercially provided services.

It is important to recognize that the identification and eventual closure of Human System Capability Gaps does not in itself assure the health and performance of crewmembers in future spaceflight missions. The capability gaps and associated roadmaps provide a framework for the ongoing identification and prioritization of NASA's investments in technology development. Even where technological solutions have been identified, developed, and demonstrated, future programs must implement these solutions as part of an integrated CHP system. In the same way that an exploration ECLS system must be designed, built, tested, and operated as an integrated system, so too must the CHP system. The CHP system must be formulated to ensure the health and performance of the crewmembers, from pre-flight, to launchpad, to landing, to post-flight – through all flight phases and across all vehicles and spacesuits. And as with ECLSS, the reliability of the CHP system must be characterized and improved so that the probability of sufficiency (POS) is known and acceptable.

While it is beyond the scope of the SCLT to define the integrated CHP system, it is important that the interdependencies and opportunities among the CHP capabilities be considered not only by exploration programs, but also in the ongoing development and prioritization of the SCLT's CHP roadmaps. The purpose of these roadmaps is to ensure that at least one mature technological solution is available, when it is needed, for every enabling capability. And these various technological solutions need to – at a minimum – be compatible with each other. Ideally, the solutions are complementary. As an example, physiological sensors or imaging devices required for health monitoring or performance assessment during EVA, countermeasure use, or research studies would also be usable for medical diagnostics and vice-versa. Informatics tools supporting medical decision making would be seamlessly integrated with the tools used to inform countermeasure utilization, nutritional intake tracking, and EVA decision support. Integrated ground and flight testing of CHP capabilities is important but not sufficient to ensuring this integrated CHP system. Cross-agency discussion and documentation of CHP system integration is one of the SCLT's top, near-term priorities.

Appendix

Human System Capability Gaps and Risk Mappings

1 Medical and Behavioral Health Systems

1.1 Medical Risk Model and Trade Space Analysis Tools

Quantitative medical risk models and trade space analysis tools that utilize up to date terrestrial and spaceflight medical evidence databases to inform mission-specific medical concept of operations, system design, and system optimization and enable increasingly Earth-independent operations.

<u>Primary associated Human System Risks:</u> Medical Conditions, Behavioral Med.

1.2 Medical Concepts of Operations

Development of mission specific medical concept of operations and evidence-based medical standards to inform required medical capabilities for increasingly Earth-independent operations.

Primary associated Human System Risks: Medical Conditions, Behavioral Med.

1.3 Medical Imaging, Diagnostics, and Treatment Technologies

Flight-tested medical imaging, diagnostic, and treatment technologies necessary to effectively manage medical conditions relevant to exploration missions that meet constraints (e.g., mass, volume, power, data, etc.), integrate with medical decision-support tools, and enable increasingly Earth-independent operations.

Primary associated Human System Risks: Medical Conditions, SANS

1.4 Operational Medical Decision Support Software & Informatics

In-flight medical decision support software that guides crew through diagnosis and treatment as well as medical informatics such as an electronic health record and inventory tracking capability all of which utilize a Crew Health and Performance Integrated Data Architecture to enable data-driven medical decision making during increasingly Earth-independent operations.

Primary associated Human System Risks: Human Systems Integration Architecture (HSIA), Pharm, Medical Conditions, Behavioral Med.

1.5 Integrated Medical Simulation Technologies

Integrated medical ground simulation capabilities incorporating medical hardware- and software-based diagnostic and treatment aides to enable development of crew procedures and training protocols that decrease reliance on ground support and enable increasingly Earth-independent medical operations.

Primary associated Human System Risks: Medical Conditions, Behavioral Med., HSIA

1.6 Semi-autonomous Behavioral Health and Performance Technologies

Semi-autonomous behavioral health diagnosis, treatment, and support tools that decrease reliance on real-time ground support to enable behavioral health and performance during increasingly Earth-independent operations.

Primary associated Human System Risks: Behavioral Med., Sleep Loss, Team Risk

1.7 Safe and Effective Pharmaceuticals

Capability to maintain medication safety and effectiveness over the course of all exploration mission concepts despite increased exposure to environmental stressors including deep space radiation.

Primary associated Human System Risks: Pharm

2 Crew Health Countermeasures

2.1 Exercise Countermeasures

Exercise countermeasures and assessment tools to maintain and monitor physical health and enable performance of critical exploration mission tasks during microgravity and reduced-gravity exploration missions.

Primary associated Human System Risks: Muscle, Aerobic, Sensorimotor, Cardiovascular, Immune, Behavioral Med., Medical Conditions, Bone Fracture

2.2 Exercise Vibration Isolation and Stabilization System

Exploration forward VIS systems to protect the vehicle and provide sufficient stabilization for the exerciser during performance of all critical exercises.

Primary associated Human System Risks: Muscle, Aerobic, Sensorimotor, Cardiovascular, Immune, Behavioral Med., Medical Conditions, Bone Fracture

2.3 Bone Countermeasures

Countermeasures and assessment tools to mitigate the risks of fracture and irreversible skeletal changes associated with spaceflight-induced changes in bone mass and structure during increasingly longer-duration exploration missions.

Primary associated Human System Risks: Bone Fracture, Renal Stones

2.4 Sensorimotor Countermeasures

Sensorimotor countermeasures and assessment tools that enhance preflight disorientation training, maintain inflight physical performance, and accelerate recovery following transitions between gravity environments, enabling performance of critical exploration mission tasks during long-duration and reduced-gravity exploration missions**.**

Primary associated Human System Risks: Sensorimotor

2.5 Cardiovascular Countermeasures

Countermeasures and assessment tools to mitigate the long-term health and operational risks associated with cardiovascular structural and functional changes during and following long-duration and reduced-gravity exploration missions.

Primary associated Human System Risks: Cardiovascular

2.6 Neuro-ocular Countermeasures

Countermeasures and assessment tools to detect and mitigate neuro-ocular changes during and following long-duration exploration missions.

Primary associated Human System Risks: SANS

2.7 Biomedical Radiation Countermeasures

Biomedical countermeasures and assessment tools to mitigate the long-term health effects (Cancer, CNS damage, etc.) of exposure to space radiation during deep space exploration missions.

Primary associated Human System Risks: Radiation Carcinogenesis, Behavioral Med., Cardiovascular

2.8 Probabilistic Radiation Risk Models

Predictive models of crew health risks to inform the development of integrated radiation protection strategies and exploration mission design.

Primary associated Human System Risks: Radiation Carcinogenesis

2.9 Immune Countermeasures

Immune countermeasures and assessment tools to mitigate and monitor immune system dysfunction during increasingly Earth-independent, resource-constrained, and long-duration exploration missions.

Primary associated Human System Risks: Immune, Medical Conditions

2.10 Microbially-Induced Disease Countermeasures

Countermeasures and assessment tools against microbially induced disease to maintain crew health and performance during increasingly Earth-independent, resource-constrained, and long-duration exploration missions.

Primary associated Human System Risks: Microhost, Medical Conditions

2.11 Crew Health & Performance Countermeasure Informatics

Ground-based and in-flight informatics tools, utilizing a Crew Health & Performance Integrated Data Architecture, to monitor and optimize crew health and performance via improved use of exploration countermeasures during increasingly Earth-independent, resource-constrained, and long-duration mission operations.

Primary associated Human System Risks: HSIA, Muscle, Aerobic, Sensorimotor, Cardiovascular, Behavioral Med., Medical Conditions, Bone Fracture

3 Food Systems

3.1 Safe, Acceptable, and Nutritious Long Duration Food System

Food system containing adequate variety for prevention of menu fatigue and inadequate caloric intake as well as adequate nutrition and quality to support crew health and performance throughout the duration of increasingly long-duration and Earth-independent missions (~5-year shelf life).

Primary associated Human System Risks: Food and Nutrition, Medical Conditions

3.2 Food Impacts to Health and Performance

Determination of food system/dietary intake associations with health and performance outcomes as a crew health and performance countermeasure to better inform provisioning and tracking requirements during increasingly long-duration and Earth-independent exploration missions.

Primary associated Human System Risks: Food and Nutrition, Behavioral Med.

3.3 Food Intake Tracking

Food intake tracking capability, compatible with the exploration Food System, to monitor compliance with food intake requirements, which is necessary to maintain crew health and performance during increasingly long-duration and Earth-independent exploration missions.

Primary associated Human System Risks: Food and Nutrition

3.4 Food System Efficiency and Resource Requirements

Food system maintaining safety, acceptability, nutrition, and reliability while reducing mass, volume, power, crew time, and other resource requirements to enable increasingly Earth-independent, resource-constrained, and long-duration mission operations.

Primary associated Human System Risks: Food and Nutrition

4 Spacesuit Physiology and Performance

4.1 Space Suit Fit and Injury

Injury prediction, monitoring, and mitigation technologies to enable planning, training, operations, and system design for all suited mission phases (EVA and IVA) and for all anticipated crewmember anthropometries.

Primary associated Human System Risks: EVA, Dynamic Loads

4.2 EVA Crew Capabilities and Constraints

Crewmember physical and cognitive state prediction technologies to enable EVA planning, operations, system design, and decision support systems based on crewmember capabilities and constraints.

Primary associated Human System Risks: EVA, Behavioral Med.

4.3 EVA Bioinformatics & Decision Support

Ground-based and in-flight EVA decision support technologies, utilizing a Crew Health & Performance Integrated Data Architecture, to enable EVA crew health and performance monitoring and decision making during increasingly Earth-independent operations.

Primary associated Human System Risks: EVA, HSIA

4.4 Decompression Stress Prediction and Mitigation

Decompression stress prediction and mitigation technologies to enable EVA planning, training, operations, and system design for planetary surface missions where existing microgravity DCS countermeasures are not applicable.

Primary associated Human System Risks: DCS, Hypoxia, EVA

5 Cross-Cutting Crew Health and Performance Systems

5.1 Crew Health & Performance Integrated Data Architecture

Data architecture integrated across all crewmembers, vehicle systems, and mission phases to enable multi-system crew health and performance assurance (e.g., monitoring, decision support, data collection, analytics, visualization, etc.).

Primary associated Human System Risks: HSIA, Medical Conditions, Behavioral Med., Muscle, Aerobic, Sensorimotor, Cardiovascular Bone, Fracture, EVA

5.2 In-situ Biological Sample Storage, Processing & Analysis

Technologies to store, process, and analyze a variety of biological samples in-situ to enable human and biological research and operations for exploration missions with limited sample return capability.

Primary associated Human System Risks: HSIA, Medical Conditions, Muscle, Aerobic, Sensorimotor, Cardiovascular, Food and Nutrition

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