Integrated Extravehicular Activity Human Research Plan: 2016

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Multiple organizations within NASA as well as industry and academia fund and participate in research related to extravehicular activity (EVA). In October 2015, representatives of the EVA Office, the Crew and Thermal Systems Division (CTSD), and the Human Research Program (HRP) at NASA Johnson Space Center agreed on a formal framework to improve multi-year coordination and collaboration in EVA research. At the core of the framework is an Integrated EVA Human Research Plan and a process by which it will be annually reviewed and updated. The over-arching objective of the collaborative framework is to conduct multi-disciplinary cost-effective research that will enable humans to perform EVAs safely, effectively, comfortably, and efficiently, as needed to enable and enhance human space exploration missions. Research activities must be defined, prioritized, planned and executed to comprehensively address the right questions, avoid duplication, leverage other complementary activities where possible, and ultimately provide actionable evidence-based results in time to inform subsequent tests, developments and/or research activities. Representation of all appropriate stakeholders in the definition, prioritization, planning and execution of research activities is essential to accomplishing the over-arching objective. A formal review of the Integrated EVA Human Research Plan will be conducted annually. Coordination with stakeholders outside of the EVA Office, CTSD, and HRP is already in effect on a study-by-study basis; closer coordination on multi-year planning with other EVA stakeholders including academia is being actively pursued. Details of the preliminary Integrated EVA Human Research Plan are presented including description of ongoing and planned research activities in the areas of: physiological and performance capabilities; suit design parameters; EVA human health and performance modeling; EVA tasks and concepts of operations; EVA informatics; human-suit sensors; suit sizing and fit; and EVA injury risk and mitigation.

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Acronyms

ABF	=	Anthropometry and Biomechanics Facility
AES	=	Advanced Exploration Systems
CTSD	=	Crew and Thermal Systems Division
EMC	=	Evolvable Mars Campaign
EVA	=	Extravehicular Activity
HHP	=	Human Health and Performance
HITL	=	Human-In-The-Loop
HRP	=	Human Research Program
HUT	=	Hard Upper Torso
ISS	=	International Space Station
LCVG	=	Liquid Cooling and Ventilation Garment
LSAH	=	Longitudinal Survey of Astronaut Health
MDV	=	Mars Descent Vehicle
NASA	=	National Aeronautics and Space Administration
NEEMO	=	NASA Extreme Environment Mission Operations
NBL	=	Neutral Buoyancy Laboratory
PRR	=	Path to Risk Reduction
PXS	=	Prototype Exploration Suit
SMT	=	System Maturation Team

I. Introduction

NASA's 2014 Strategic Plan[1] identifies that "Our long-term goal is to send humans to Mars. Over the next two decades, we will develop and demonstrate the technologies and capabilities needed to send humans to explore the red planet and safely return them to Earth." Current spacesuits and EVA concepts of operations used on the International Space Station or used previously during the Apollo missions to the Moon are inadequate to support even the shortest possible Mars exploration missions. Many questions must be answered with respect to the ability of EVA systems and crewmembers to function safely, reliably, and effectively for missions lasting a year or longer in what will be the most hostile and challenging environment ever explored by humans. A variety of intermediate missions and destinations will precede humans setting foot on Mars, beginning with testing of exploration systems on the International Space Station (ISS), currently in low-earth orbit, followed by missions incrementally further from Earth. NASA's Evolvable Mars Campaign (EMC) team is studying a variety of pathways to Mars that include design reference missions to cis-lunar space, asteroids, Mars orbit, and the moons of Mars[2, 3], while the technology developments that are expected to enhance and enable such missions are tracked, prioritized, and published in NASA's Space Technology Roadmap[4]. Meanwhile, NASA's Human Research Program focuses on identifying, researching, and mitigating risks to astronauts' health and performance during exploration missions.

The primary purpose of the Integrated EVA Human Research Plan presented here is to improve multi-year coordination and collaboration among three of the primary participants in EVA research at NASA's Johnson Space Center; specifically, the EVA Office, the Crew and Thermal Systems Division (CTSD), and the Human Research Program (HRP). While these organizations work together successfully on EVA research projects on an almost continual basis, it was recognized that the multi-year planning and coordination of research activities could be improved. To this end, a formal framework of collaboration was established.

At the core of the framework is an Integrated EVA Human Research Plan and a process by which it will be annually reviewed and updated. The over-arching objective of the collaborative framework is to conduct multi-disciplinary cost-effective research that will enable humans to perform EVAs safely, effectively, comfortably, and efficiently, to enable and enhance human space exploration missions. Research activities must be defined, prioritized, planned and executed to comprehensively address the right questions, avoid duplication, leverage other complementary activities where possible, and ultimately provide actionable evidence-based results in time to inform subsequent tests, developments and/or research activities.

Multiple organizations within NASA and outside of NASA have been successfully conducting EVA research and development efforts since the 1960s. The Integrated EVA Human Research Plan currently reflects only a small subset of all stakeholders in the field of EVA and was intended primarily as an internal NASA creation; however, the preliminary version of the plan is presented here in recognition of the importance of coordination and collaboration with the broader NASA community and beyond. Furthermore, this plan is not intended to be exhaustive but rather aims to identify the Human-In-The-Loop (HITL) research tasks that will require more coordination in terms of personnel, budgets, facilities, and test hardware as well as tasks that may provide for opportunistic add-on objectives.

It is important to understand that, other than the studies that are already in progress, the other research tasks described in this plan are only proposed, and have not yet been formally reviewed or approved by the prospective funding organizations. This review and funding process differs among organizations; this plan is intended to assist with coordination of those decisions among the respective funding organizations.

The identification and organization of EVA research priorities is described in Section II, the technical content of the plan is described in Section III, and the process by which the plan will be maintained is explained in Section IV.

II. Identifying and Organizing EVA Research Priorities

A. EVA System Maturation Team (SMT) Gaps

Following the creation of NASA's Space Technology Roadmaps[4], the EVA Office and CTSD led the development of an EVA System Maturation Team (SMT) Gap List, the purpose of which was to identify EVA-relevant technology research and development priorities in more detail than is included in the Space Technology Roadmaps. The EVA SMT Gap List is used by the EVA Office and CTSD in identifying and prioritizing EVA research activities. A sub-set of SMT gaps most directly relevant to the human-suit interactions that are the focus of this plan is included as an appendix to this paper.

B. Human Research Program (HRP) EVA Risk and Gaps

HRP uses a well-defined and documented process for the formal identification, prioritization, researching, and mitigation of risks to astronauts. The gaps in knowledge or countermeasure technology necessary to mitigate each risk are also identified. All HRP-funded research activities must directly target one or more formally identified gaps. The *Risk of Injury and Compromised Performance Due to EVA Operations* and seven corresponding gaps are currently being tracked by HRP (Table 1). An additional gap, EVA 7B, identified during the development of this integrated plan, is being proposed to HRP: *How does EVA suit sizing and fit affect crew health, performance, and injury risk?*

Table 1. Current and proposed (*) Human Research Program EVA Gaps[5].

HRP Gap ID	Description
EVA 6:	What crew physiological & performance capabilities[1] are required for EVA operations[2] in exploration environments[3]?
EVA 7:	How do EVA suit system design parameters[4] affect crew health and performance in exploration environments[3]?
*EVA 7B:	How does EVA suit sizing and fit affect crew health, performance, and injury risk? [Note that this has not yet been approved as a new EVA Gap]
EVA 8:	What are the physiological inputs and outputs associated with EVA operations[2] in exploration environments[3]?
EVA 9:	What is the effect on crew performance & health of variations in EVA task design and operations concepts for exploration environments[3]?
EVA 10:	Can knowledge and use of real-time physiological and system parameters during EVA operations[2] improve crew health and performance?
EVA 11:	How do EVA operations[2] in exploration environments[3] increase the risk of crew injury and how can the risk be mitigated?
EVA 14:	What other EVA-related risks, developments and technologies exist that may affect EVA research?

[1]e.g. anthropometry, aerobic fitness, muscle strength & power; [2]acceptable functional performance of expected nominal and contingency suited tasks; [3]i.e. Moon, NEA, Mars, L2 and other deep space microgravity locations; [4](e.g. center of gravity, mass, pressure, mobility, joint characteristics, suit fit; includes suit, portable life support system, and other enabling equipment). Note: Numbering of HRP EVA Gaps is not sequential due, in part, to previous recategorization of decompression sickness gaps into a separate HRP risk (Risk of Decompression Sickness).

EVA is recognized as a distinct discipline by HRP. The HRP EVA Discipline is responsible for coordinating a "Path to Risk Reduction (PRR)"[5], which is a multi-year test plan that aims to close or mitigate the EVA-related risks and gaps to acceptable levels in time to enable human exploration missions. The HRP EVA Discipline also maintains an "EVA Evidence Report"[6], a publicly available document in which literature relevant to the EVA risks is reviewed and continually updated as more research studies are performed. All aspects of the HRP EVA risks, gaps, schedules, and evidence reports are reviewed annually by an external (non-NASA) review panel of experts. Additionally, proposals are submitted and externally peer-reviewed for all HRP-funded EVA studies. Studies are open to competition by industry and academia (i.e. non-NASA organizations) except where studies can only be performed using facilities, hardware and expertise available within NASA. Full details can be found on the publicly accessible HRP website, humanresearchroadmap.nasa.gov.

In the process of developing the Integrated EVA Human Research Plan described here, the HRP EVA aspects were reviewed and revised in collaboration between the HRP EVA Discipline, EVA Office, and CTSD. At the time of writing, the updated PRR has been submitted to HRP management for external peer review. The tasks planned for addressing the *Risk of Decompression Sickness* and the *Risk of Hypobaric Hypoxia* are not presented here; however, those tasks are also being coordinated with the EVA Office and CTSD.

Note that the numbering shown in Table 1 is not sequential due, in part, to restructuring the original gaps and the recategorization of decompression sickness and hypobaric hypoxia gaps into separate HRP risks (*Risk of Decompression Sickness* and *Risk of Hypobaric Hypoxia*). Gap EVA 14 is being proposed for closure as a consequence of this Integrated EVA Human Research Plan. The gap was intended to address the possibility of failure to adequately coordinate and communicate among the EVA research community, which is specifically what this plan is intended to avoid.

C. EVA Development Milestones

There is currently no over-arching program defining the schedule by which exploration EVA capabilities must be developed. For the purposes of this plan, notional steps required to enable Mars surface exploration missions in the 2030s are used as a basis for phasing and prioritization of EVA HITL research efforts. The notional EVA milestones, shown in Figure 1, assume that a next generation (NextGen, in this paper) spacesuit will be developed for microgravity operation on ISS with the goal of extensibility supporting exploration upgrades at a later date. Figure 1 also indicates specific products (and their respective HRP and SMT Gaps, in italics) that are expected to result from the Integrated EVA Human Research Plan and their relation to the notional EVA development schedule.

It should be noted that the extent to which aspects of the microgravity-focused NextGen suit will be extensible to planetary exploration is not yet understood. Additionally, the milestones in Figure 1 are provided as an example and will be updated with formal milestones in once those milestones are defined by NASA. The phasing and products of the planned research tasks will also be revised at that time.

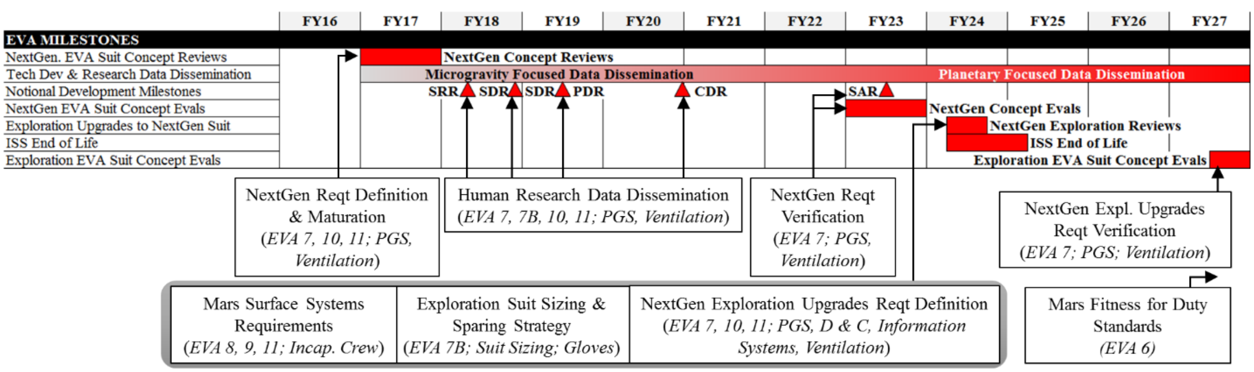

Figure 1. Notional EVA development milestones used for phasing and prioritization of EVA research by fiscal year (FY).

D. Organization of the Integrated EVA Human Research Plan

The HRP EVA Evidence Report[7] explains that review of the EVA Risk within the EVA research community and the NASA Human Systems Risk Board resulted in identification of 24 separate factors that contribute to the risk of injury and compromised performance due to EVA operations. These factors are separated into the interacting domains of Human, Suit, and Operations and are further grouped into categories of suit habitability, in-suit physical environment, EVA factors, crewmember physical state, and crewmember psychological state. The 3 domains, 5 categories, and 24 factors are shown in the EVA Risk Master Logic Diagram (Figure 2) and are described in the Evidence Report along with the an overview of the available evidence for each identified factor. The mapping of the HRP EVA Gaps (Table 1) to the contributing factors identified in Figure 2 is included in Appendix A of the HRP EVA Evidence Report[7].

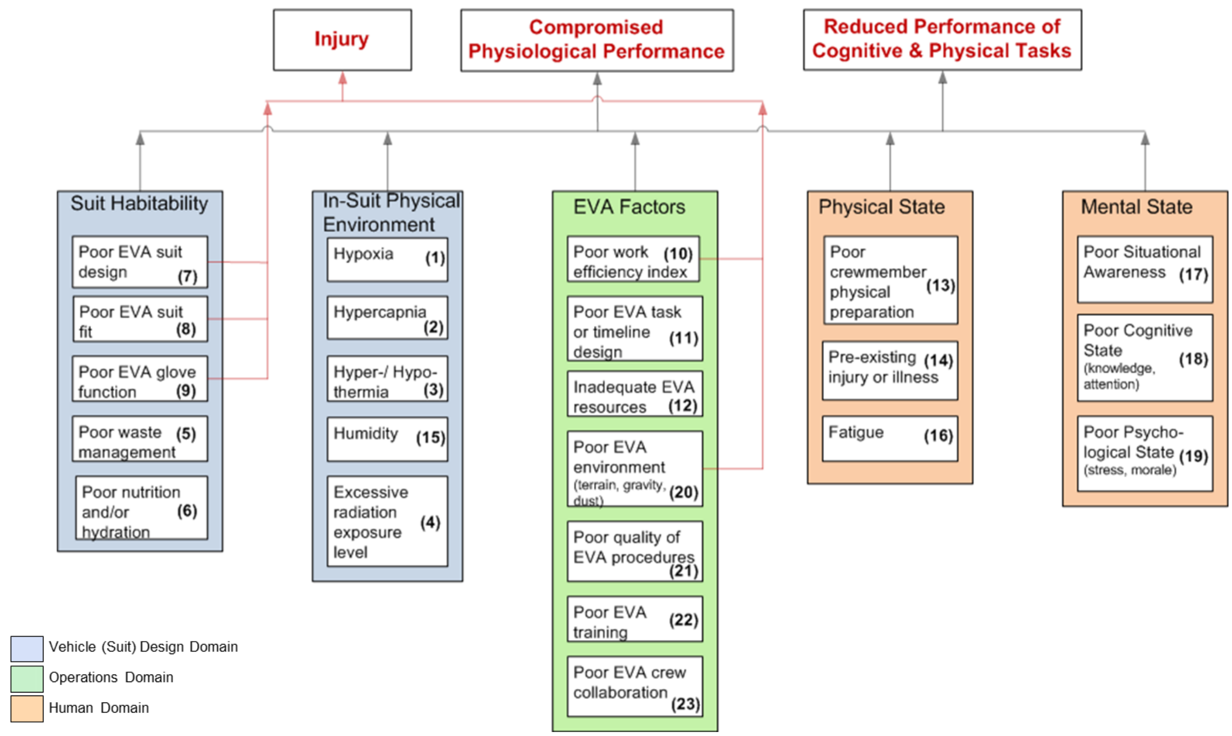

Figure 2. HRP EVA Risk Master Logic Diagram[7].

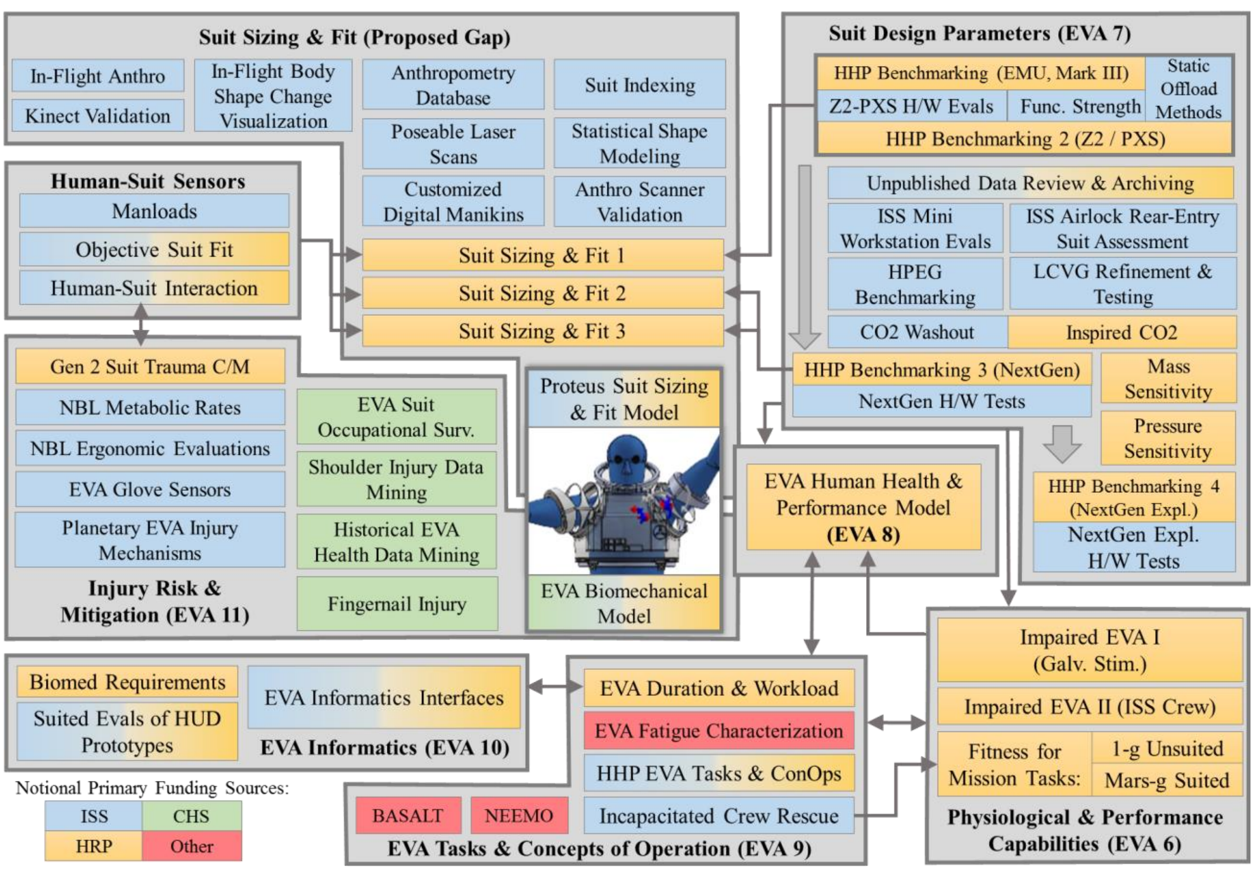

Figure 3. Organization of the Integrated EVA Human Research Plan.

By comparison, the EVA SMT Gaps are categorized primarily by different EVA systems such as Exploration EVA Avionics, Exploration EVA Tools, etc. Specific gaps are then identified within each system-level category. The different approaches reflect the different perspectives of the corresponding organizations and result in partial but not complete overlap between EVA SMT and HRP EVA Gaps.

For the purposes of organizing the Integrated EVA Human Research Plan, proposed tasks are grouped by functional areas that approximately map to the HRP EVA Gaps, as shown in Figure 3. All tasks are mapped to at least one HRP EVA Gap and/or an EVA SMT Gap and are briefly described in the following section. The intent of this document is to summarize the integrated plan rather than to provide significant detail on any specific study.

III. The Baseline Integrated EVA Human Research Plan

The tasks are not described in the chronological order in which they are expected to be performed. Instead, tasks are grouped into categories corresponding approximately to the HRP EVA Gaps that each would be primarily intended to address as summarized in Figure 3. The content is structured around the HRP EVA Gaps due to the human-centered focus of the plan; however, the relationship of the plan content to EVA SMT Gaps is also described, where applicable. The proposed sequencing of activities within the plan is shown in Figure 4.

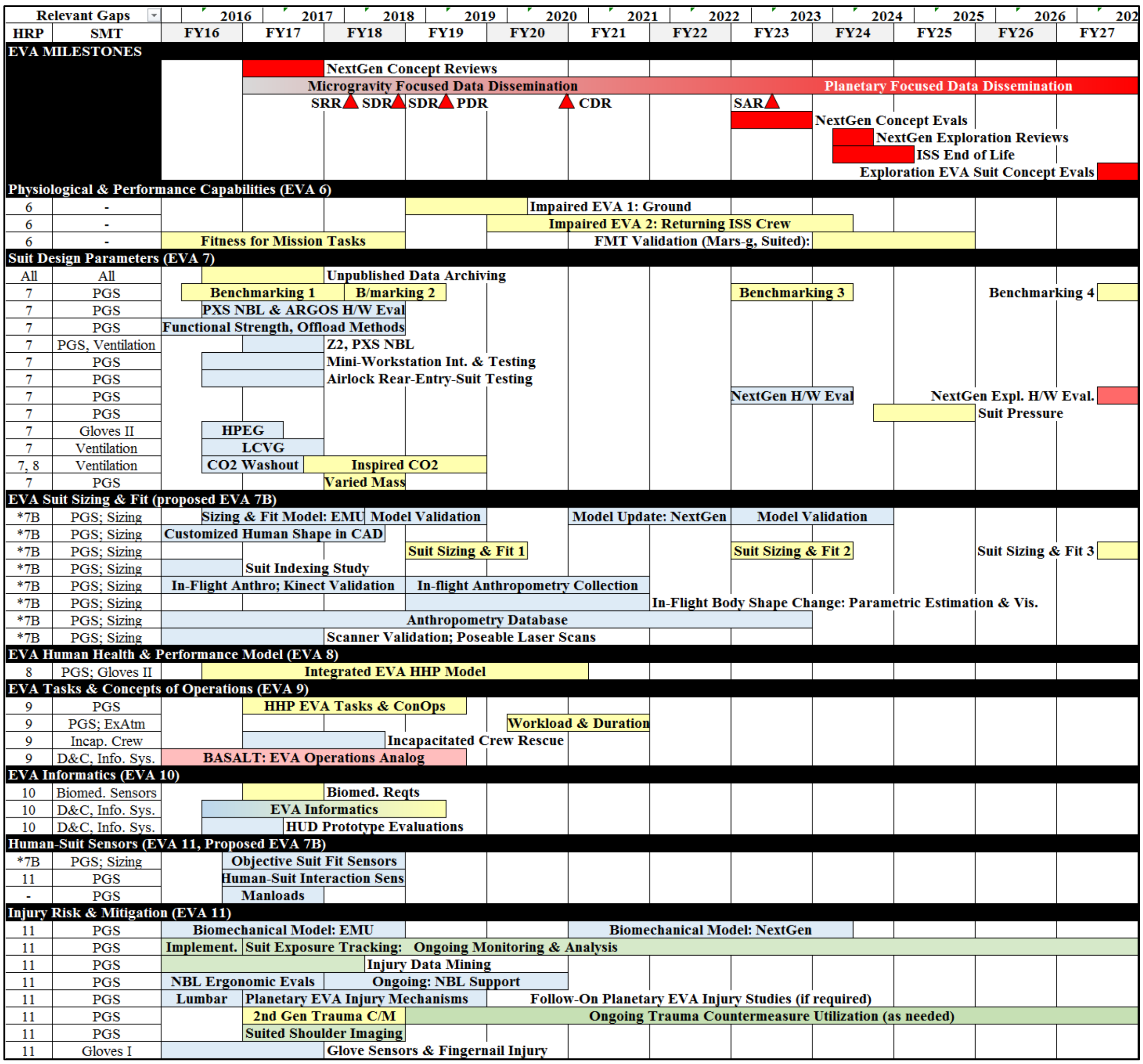

Figure 4. Proposed phasing of tasks in Integrated EVA Human Research Plan.

A. Physiological and Performance Capabilities

Tasks in this section are relevant primarily to HRP EVA Gap 6: *What crew physiological & performance capabilities are required for EVA operations in exploration environments?*

1. *Impaired EVA Performance*

Physiological adaptation to the microgravity environment during transit to Mars is likely to result in reduced functional capacity after landing on Mars' surface. While muscular and aerobic capacity may be preserved through inflight countermeasures, returning long-duration ISS crewmembers demonstrate significant decrements in functional performance upon return to a gravity environment due to neurovestibular / sensorimotor adaptation to microgravity that can take days or weeks from which to recover. The implications of such performance decrements are significant since they may require that the Mars Descent Vehicle (MDV) be capable of supporting astronauts for up to two weeks on Mars' surface to allow astronauts to rehabilitate before performing EVAs to egress the MDV and ingress a surface habitat or pressurized rover.

The purpose of the Impaired EVA Performance studies is to characterize suited health and performance outcomes in crewmembers as a function of vestibular / sensorimotor dysfunction during and after gravitational transitions, which will inform questions such as how long crew must remain in the MDV before they can go EVA after landing on Mars; which EVA tasks can be performed; and whether systems or operations can be modified to enable earlier post-landing EVA. The study is expected to consist of two parts.

The first study will be an unsuited ground study that begins with development of the method to simulate postflight vestibular disturbances using galvanic vestibular stimulation (GVS). This investigation will entail calibrating GVS intensity to match post-flight performance decrements and recovery profiles measured on functional task test and field test studies. The calibrated GVS will then be used on suited test subjects to assess suited functional performance outcomes for simulated vestibular disturbances in crewmembers during simulated planetary EVA. Functional performance outcomes will be based on the HHP Benchmarking methodology, but may be adapted to focus on the "First EVA on Mars" scenario.

The second part of the study will also involve measurement of functional EVA performance using the same simulated planetary EVA tasks and spacesuits; but instead of experiencing simulated vestibular disturbances, test subjects will be returning long-duration ISS crewmembers.

2. *Fitness for Mission Tasks Exercise Studies*

Two studies are currently funded by HRP to use unsuited 1-g testing of physically demanding critical misison tasks to establish aerobic and muscular fitness for duty standards. Three of the four tasks are EVA tasks and one of those tasks involves the rescue of an incapacitated EVA crewmember. The details of the EVA tasks that are to be simulated, and particularly the incapacitated crewmember rescue task, are not yet well defined and will be informed by the EVA Tasks and ConOps studies (Section III.D).

3. *Aerobic and Muscle Fitness for Duty Standards - Suited Validation Study*

Following completion of the 1-g Fitness for Mission Tasks Exercise Studies, aerobic and muscular fitness for duty standards will be recommended. These standards will also be informed by suited human performance results from the EVA Human Health and Performance (HHP) Benchmarking 1 study. However, validation of these standards will require a suited evaluation in which subjects both above and below the proposed fitness for duty standards will attempt to complete a set of functional EVA tasks in simulated Martian gravity. The tasks used will be based on the EVA Tasks and ConOps studies (Section III.D).

B. Suit Design Parameters

Tasks in this section are relevant primarily to the EVA SMT *Pressure Garment System (PGS)* Gap and the HRP EVA Gap 7: *How do EVA suit system design parameters affect crew health and performance in exploration environments?* These studies are also a primary source of data for the EVA HHP Model associated with EVA Gap 8: *What are the physiological inputs and outputs associated with EVA operations in exploration environments?*

1. *Review and Archiving of Unpublished EVA Test Data*

Human testing of EVA suits and suit prototypes has been ongoing for decades with many results published in conference papers, NASA technical reports, and peer-reviewed journal papers. However, results of many tests are not published or archived in a way that is readily searchable or accessible by anybody other than the person or people directly responsible for conducting the study. In many cases, the fact that the studies having even occurred is often known only by a small number of people, and many of the generation of scientists and engineers responsible for EVA testing in the 1960s and 1970s are now at or approaching retirement age. The purpose of this task is to update the HRP EVA Evidence Report and EVA Engineering archives with relevant findings from unpublished research studies that will be identified primarily through discussions and interviews with engineers in EVA Engineering and the EVA Office at JSC.

2. EVA Human Health and Performance (HHP) Benchmarking 1: EMU, Mark III

Suit performance is understood qualitatively from observation and subjective feedback and decades of effort has been spent attempting to quantify space suited performance with some methodologies resulting in more information than others. However, a rigorous and comprehensive characterization of the HHP implications of current and future EVA spacesuit designs does not yet exist. Standard methods for quantification of specific aspects of suited performance, such as metabolic expenditure, serve as tools in understanding and describing desired suited performance. Specifically, tools are helpful in providing insight into the performance of full-suit mobility architectures and of individual components, with the goal of aiding selection for specific missions and motions. In addition to informing suit design, standard methods are also necessary for many other tasks described in this plan, including the rigorous assessment of the effects of sensorimotor impairement, suit fit, aerobic fitness, strength, fatigue, and inspired Carbon Dioxide (CO_2) on suited human performance.

The aim of the EVA HHP Benchmarking study, initiated in early 2016, is to identify a standard set of tasks and metrics with known margins of error, to facilitate meaningful assessment and comparison of suit configurations and test conditions in current and future studies[8]. Through collaboration with the EVA community, the study will identify and develop a methodology to reliably characterize HHP metrics for individuals working inside EVA suits under realistic microgravity and planetary spaceflight conditions. Testing will involve a combination of static offloading and dynamic offloading using the Active Response Gravity Offload Simulator (ARGOS)[9]. The HHP benchmarking methodology will be used to characterize and compare existing spacesuits (Figure 5) and to statistically evaluate relationships between isolated joint performance and functional task performance. Test subjects will also complete tasks unsuited to provide a comparative baseline. In addition to involving collaborators from multiple JSC laboratories and engineering organizations, this study is being coordinated with several related tasks being funded by the EVA Office, described next.

Figure 5. Three spacesuits proposed for evaluation using the EVA HHP Benchmarking methodology. The Mark III suit, not shown, is also expected to be evaluated during the Benchmarking 1 study.

3. PXS Hardware Testing, Functional Strength, and Static Offload Methods

The EVA Office is directing preliminary evaluations of the PXS suit hardware using 1-g and static offload methods. In addition to providing assessment data for the PXS suit, some assessment strategies for the HHP benchmarking study of other suits are expected to be pilot tested. Specifically, strength, range of motion, reach envelopes, stability, subjective suit fit, and discomfort will be evaluated with repeated measures being used to assess reliability of each performance metric.

Reliable and verifiable testing of suited functional strength is the focus of another EVA Office funded task currently being conducted by the Anthropometry and Biomechanics Facility (ABF); this task will be used to evaluate test-retest reliability of the suited and unsuited functional strength measures that are being considered for inclusion in the HHP Benchmarking study.

A third task currently funded by the EVA Office will inform the static offload methods that will be used during the HHP Benchmarking Study. An ongoing study is comparing various data sets associated with suited performance when suited subjects are attached to a donning stand versus being suspended from a static overhead crane. Data collection includes pressure mats to measure shoulder-to-suit upper torso contact, subjective suit contact surveys, electromyography (EMG) for muscular effort, and motion capture. Results are expected to inform the selection of methods for the static offload portion of the HHP Benchmarking study.

4. Z-2 and PXS Neutral Buoyancy Laboratory (NBL) Mobility Testing and Worksite Assessments

NASA's EVA Engineering program is currently developing a new generation of 'Z-series' planetary EVA suits to test technologies for future EVAs, with the newest of these being the Z-2. These prototype suits will be assessed in a series of HITL evaluations over the next several years and are expected to include CO_2 washout testing followed by NBL testing with a particular focus on lower-body mobility requirements for the NextGen suit as well as analysis and HITL evaluation of ISS EVA worksite access. The PXS may also be included in FY17 NBL evaluations.

The scheduling of the Z-2 tests and the extent to which they may be combined with HRP-funded benchmarking studies will depend, in part, on when the Z-2 prototype is completed and certified for HITL evaluations, but NBL testing is currently proposed for FY17.

It is intended that the integrated data collection efforts supporting the NBL ergonomic and metabolic assessments, described in Section H.4, will be leveraged to enable support for planned Z-2 and PXS NBL testing. Additionally, options for NBL benchmarking tasks and performance metrics will be considered during the development of the HHP Benchmarking methodology so that HITL evaluations in the NBL will have a similar degree of rigor and consistency.

Testing of Z-2 and PXS hardware on ARGOS using the HHP benchmarking methodology is proposed as part of a Z-2 / PXS Hybrid study, described next.

5. EVA HHP Benchmarking 2: Suit Design Parameters

The Z-2 and PXS suits are designed for different EVA environments. The Z-2 spacesuit prototype includes a lower-torso assembly (LTA) designed for planetary ambulation. The PXS uses an LTA designed to meet microgravity EVA requirements. However, the Z-2 and PXS suits share several common interfaces that may allow for certain components of PXS and Z-2 suits to be combined into hybrid configurations. This capability, combined with the HHP benchmarking methodology would provide for the opportunity to systematically vary suit design features and rigorously assess their respective contributions to human health and performance outcomes. The aim of the second EVA HHP Benchmarking study is to use the benchmarking methodology to characterize and compare human health and performance outcomes for different suit configurations with the purpose of informing specification and design of the NextGen suit. The specific suit configurations to be tested will be discussed and agreed upon with Co-Investigators from CTSD and the EVA Office. As with the first HHP Benchmarking study, this second study is expected to complement ISS-funded hardware evaluations that are already planning for the prototype hardware.

6. Mini-Workstation Integration and Testing with Z-2 and PXS

This task will consist of pressurized suited evaluation of Z-2 and PXS suit designs with the ISS Mini-Workstation installed. The prototype suits were not required to be compatible with the mini-workstation, so design work will be performed to determine optimal method of mounting the mini-workstation followed by testing to validate.

7. ISS Airlock Rear Entry Suit Assessment

Donning and doffing rear entry suits on ISS is significantly different than the current waist entry suits. An analysis is required to assess whether existing EMU Don/Doff Assembly hardware can be used for ingress/egress of a rear entry suit. Also, a volumetric assessment of the airlock is required to ensure that two rear entry suits can be accommodated in the airlock during IVA and EVA operations. This assessment will determine if existing hardware will be sufficient or whether alternative methods and hardware must be assessed. This activity is expected to be completed in FY16.

8. NextGen Hardware Testing; EVA HHP Benchmarking 3 and 4

The results of the HHP Benchmarking studies will be used to inform the design and build of the NextGen suit. The aim of the HHP Benchmarking 3 and 4 studies will be to use the established HHP benchmarking methodology to characterize the human health and performance outcomes of human subjects using the NextGen suit for microgravity operations and planetary operatyions, respectively. Data will be compared with data collected from the EMU and other suits during the preceding HHP benchmarking evaluations. It is expected that this study will be performed in conjunction with ISS-funded HITL evaluations of the NextGen suit hardware.

9. Suit Pressure Study

The pressure at which EVA suits operate affects the resistance experienced by crewmembers at individual joints, which can affect the health and performance outcomes for those crewmembers. Lower suit pressure reduces suit joint torques but also increases the risk of decompression sickness. The purpose of this study is to use the EVA HHP Benchmarking methodology to quantify and compare health and human performance outcomes for human subjects operating in the spacesuit at a range of pressures from 24.1 kPa (3.5 psia) to 56.5 kPa (8.2 psia). While it is unlikely that this data will affect suit design, it is expected to inform the selection of suit pressure, which is a trade between decompression stress at lower suit pressures and increased joint resistance and fatigue at higher pressures.

10. High Performance EVA Glove (HPEG) Prototype Evaluations

The design and fit of EVA gloves affects performance of tasks requiring manual dexterity and gripping and also affects the risk of fingernail delamination and other hand and finger trauma[10]. Almost all EVA suits and EVA gloves are designed with a common glove attachment mechanism, meaning that most EVA gloves are interchangeable among different suits. Thus, the benchmarking of EVA gloves will be considered separately from the benchmarking of EVA suits, although testing will preferably be performed by subjects wearing a pressurized suit as opposed to a glovebox. The purpose of this study is to identify a standard set of tasks and metrics, with known margins of error, to facilitate meaningful assessment and comparison of human health and performance when using different EVA glove designs and configurations. This task is relevant to the *Gloves I* and *Gloves II* EVA SMT Gaps.

11. Liquid Cooling and Ventilation Garment Design Refinement and Testing

This task is expected to involve the development and testing of a liquid cooling and ventilation garment (LCVG), which may incorporate a redundant thermal loop. An existing LCVG prototype design developed for use with the PXS suit will serve as a prototype design for consideration during this design phase.

12. Carbon Dioxide Washout; Inspired Carbon Dioxide Requirement

Testing of the Z-2 prototype suit is planned during 2016 and 2017 and will include measurement of the efficacy with which expired CO_2 is washed out from the helmet of the suit. In addition to HRP EVA Gap 7, this work is also relevant to the EVA SMT *Ventilation* Gap. Testing will be performed at several different pressures to determine the effect of pressure on CO_2 washout. The Z-2 testing will also provide a test bed for finalizing the methodology for quantification of inspired CO_2 in EVA suits. The EMU will also be characterized using this methodology to provide a reference of current CO_2 washout capability.

The next step of this work will be to establish an evidence-based standard for inspired CO_2 during EVA. This will begin with an exhaustive literature search and, if necessary, unsuited testing using an environmental chamber to evaluate at functional impairment due to CO_2. Finally, CO_2-related performance decrements in suited subjects will be quantified using neurocognitive assessment and functional performance tasks from the HHP Benchmarking protocol.

13. Mass Sensitivity Study

The purpose of this study is to use the HHP Benchmarking methodology to evaluate the sensitivity of human health and performance measures to changes in simulated suit mass, center of gravity (CG), and gravity level. The range of masses and CGs evaluated will be based on the likely range of achievable masses and CGs anticipated for the NextGen planetary suit. Results of this study are expected to inform suit mass and primary life support system trades. For example, results may show that mass reductions beyond a threshold value yield negligible changes in human health and performance outcomes or that increases above a threshold value result in significant increases in workload and consumables usage. In addition, results could show that overall suited mass may affect performance in Mars gravity but that CG affects performance more in lower gravity. For these reasons, results will also directly inform the design of the Fitness for Duty Validation, EVA Workload and Duration, and Impaired EVA studies.

C. EVA Human Health and Performance Model

The EVA HHP Model is expected to address HRP EVA Gap 8: *What are the physiological inputs and outputs associated with EVA operations in exploration environments?* Specifically, the purpose of this task is to develop a parametric model for providing time-varying estimates of EVA translation distances, joint cycles, ground reaction force dose, decompression stress, workload, fatigue, and metabolic rates when given model inputs of suit mass, gravity level, and task type. Model outputs will inform fitness for duty standards, exercise prescriptions, prebreathe validation protocols, suit lifecycle information for certification profiles, EVA consumables sizing, and may also inform exploration concepts of operations, task design, and eventual exploration EVA planning.

The model will use a combination of data from analog field tests and pressurized suit testing. The model will begin with existing datasets from testing of the Mark III suit and will be incrementally updated and validated through prediction and incorporation of additional physiological datasets as they become available. Studies associated with HRP EVA Gaps 6, 7, and 9 will provide the primary sources of empirical data, but the EVA Biomechanical model may also eventually be capable of enhancing the predictive capacity of the EVA HHP Model.

D. EVA Tasks and Concepts of Operations

Tasks in this section are relevant primarily to HRP EVA Gap 9: *What is the effect on crew performance and health of variations in EVA task design and operations concepts for exploration environments?*

1. Human Health and Performance EVA Tasks and ConOps

The EVA research tasks described in this plan require definition of the assumed EVA tasks and ConOps during future mission architectures and, in some cases, results of these research tasks will, in turn, inform changes or add detail to those tasks, ConOps and even to overall mission architectures. This activity will serve as a focusing element to develop and maintain a single set of consistent assumptions with respect to EVA tasks and ConOps as they pertain to HHP.

While EVA ConOps documents are maintained for design reference missions by the EVA Office, in some cases they do not include the necessary detail to inform the design of HHP studies or they lack detail on expected human constraints and considerations that may affect architectural decisions. Through close coordination with the EVA Office and Human Architecture Team, existing ConOps documents will be supplemented with relevant HHP data and assumptions, including information such as estimated metabolic rates, ground reaction forces, task types and frequencies, and decompression profiles. The EVA HHP Model is expected to serve as the source of data in many cases. Through coordination with the Exploration EVA Working Group, this document will be developed and then periodically reviewed and updated based on results of research studies, architectural trade studies, and changes to design reference missions. A similar document was developed for lunar surface operations during the Constellation Program[11].

In addition to the documentation and assimilation of existing data sets made available from other studies, this study will use existing studies such as Biologic Analog Science Associated with Lava Terrains (BASALT), funded by the Science Mission Directorate (SMD), and possibly other SMD-funded analog studies, to collect task characterization data. At a minimum, data is expected to include the types, durations, and frequencies of tasks, distances and terrains traversed, and may also include perceived exertion, heart rate, joint kinematics, and even metabolic rate data, if possible. Although SMD-funded studies are unsuited and in 1-g, they represent real geological and biological exploration operations and therefore are reasonable approximations of what might be attempted during planetary EVAs as well as a physiological baseline against which to compare predicted planetary EVA workload. Data from 1-g unsuited exploration environments and data from suited, reduced gravity tests such as the benchmarking studies will then be combined within the EVA HHP Model.

2. EVA Fatigue Characterization

Prior to the EVA Workload and Duration Study, a reliable and proven methodology will be required for assessing physical and neurocognitive fatigue resulting from EVA performance. The purpose of this study is to evaluate different methods for assessing fatigue pre- and post-EVA operations while unsuited and also while in the suit, either as a standalone test or preferably as a method that could be used unobtrusively during normal EVA operations and other ground studies. This study is expected to complement the NBL Ergonomic Assessments and Metabolic Rates task.

3. EVA Workload and Duration Study

The human health and performance implications of current architectural assumptions of up to 24 hours EVA per person per week for long duration planetary missions have not been evaluated and may not be credible. The purpose of the EVA Workload and Duration Study will be to characterize suited health and performance outcomes as a function of EVA duration and frequency, up to 24 hours of EVA in a week. It is anticipated that multiple test subjects will perform up to 3 x 8 hour simulated planetary EVAs on ARGOS or NBL in a week. The circuit components of the HHP benchmarking methodology will be employed to periodically measure performance during the simulated EVAs. Criteria will be defined for ending EVAs given specific degrees of decrement in physical and/or cognitive performance. The types, frequencies, and durations of tasks performed during the EVA simulations will be based on the HHP EVA Tasks and ConOps as well as results of the HHP Benchmarking studies. The simulated suit mass will be informed by the Mass Sensitivity Study.

Opportunities to incorporate this study within end-to-end mission simulations such as HERA will be investigated since the pre- and post-EVA workload associated with maintenance and preparation of EVA hardware should also be considered. For best engineering data, this investigation would be performed with a high fidelity system requiring realistic maintenance to assess the success of efforts to ease and limit required maintenance.

4. Incapacitated Crewmember Rescue

The Incapacitated Crewmember Rescue EVA SMT Gap specifically identifies the need to develop methodology for transfer/transport of an incapacitated crewmember at each destination and how to transfer him/her onto the ingress/egress hardware or through side hatch, and doff suit. As described previously, the Fitness for Mission Tasks studies also plan use this task in determining fitness for duty standards. While previous studies have been conducted[12, 13], the limited fidelity and scope of those studies have precluded the establishment of a baseline protocol for this important contingency EVA task. The purpose of this study is to design, build, and test high-fidelity concepts for incapacitated EVA crewmember rescue. Test environments may include NASA Extreme Environment Mission Operations (NEEMO)[12], NBL, and/or ARGOS as well as 1-g testing. Results are expected to directly inform design features required to facilitate EVA rescue.

E. EVA Informatics

The tasks described in this section are relevant to HRP EVA Gap 10: *Can knowledge and use of real-time physiological and system parameters during EVA operations improve crew health and performance?* In addition, these tasks are relevant to several EVA SMT Gaps: Biomedical Sensors; Displays and Controls; and Information Systems.

1. EVA Biomedical Monitoring Requirements Definition

This task will involve coordination between the HRP EVA Discipline, Exploration Medical Capabilities (ExMC), Medical Operations, EVA Office, CTSD, Crew Office, and other stakeholders to seek consensus on the EVA biomedical monitoring requirements and operations concepts for exploration missions. Beginning with requirements and rationale developed during the Constellation Program, the multi-disciplinary team will consider which data are minimally necessary as well as whether data should be self-monitored, monitored by an IV crewmember, monitored by the ground, and/or monitored by an algorithm. This assessment will be achieved through one or more workshops involving all stakeholders and will conclude with updates to NASA Standard 3001 NASA Space Flight Human-System Standard and, depending on the recommended approach, may also include functional requirements for biomedical monitoring hardware, software, and operations. More specific knowledge gaps and associated tests may be identified if existing literature and experience are found to be inadequate to make specific recommendations.

2. EVA Informatics Interfaces

A human interface is required to navigate the non-critical informatics system. This technology would be required for full evaluation of the informatics system, since it is an integrated package with a menu-driven system that must be designed with the particular interface in mind. For example, a voice navigated menu would look different than a gesture driven system. This proposed task will develop and evaluate information systems and interfaces for processing, displaying, and interacting with physiological and system parameters during EVAs. The task is proposed as a collaboration with EVA Engineering, HRP EVA discipline, HRP Space Human Factors and Habitability element, and ExMC.

It is proposed that a packaged prototype of the interface system be designed and fabricated for integration into the Portable Life Support System (PLSS) prototype for evaluation in early FY18, or a component-level evaluation in FY17. Prototype systems may be evaluated during suited test opportunities such as the EVA Workload and Duration study to determine the acceptability of user interfaces as well as the utility of the physiological and system data in improving crew health and/or performance. Dedicated testing may be necessary to provide controlled comparisons in which case those tests will be designed to use other tests in the Integrated EVA Human Research Plan as the control condition.

Opportunities for unsuited assessment of EVA Informatics in operational field (i.e., non-laboratory) environments such as the BASALT project will also be sought. Indeed, a central component of the BASALT project is the development and assessment of exploration information system capabilities and EVA operations concepts. Previous work performed by the Space Human Factors and Habitability element in collaboration with engineers at NASA Glenn Research Center as well as HRP-funded work on a bioadvisory algorithm, and BASALT-funded work on exploration information systems will be leveraged.

3. Suited Evaluation of Heads-Up Display Prototypes

Pressurized suited evaluation of an externally-provided Heads-Up Display prototype and an existing PXS display concept are proposed for FY16. Results and relevant technologies will be incorporated into the EVA Informatics and Testing task.

F. Human-Suit Sensors

The tasks described in this section are all relevant to the EVA SMT *Pressure Garment System* Gap. Additionally, the Objective Suit Fit Sensors task will be relevant to the Suit Sizing & Fit Gap that will be proposed to HRP as a new EVA Gap, while the Human-Suit Interaction Sensors will be relevant to EVA Gap 11: *How do EVA operations in exploration environments increase the risk of crew injury and how can the risk be mitigated?* The proposed phasing of studies is shown in Figure 4.

1. Human-Suit Interaction Sensors Assessment

Understanding the interaction between the human and the spacesuit is necessary for both identifying and improving the interrelated determinants of suit fit, suited performance, and suit injury risk. Much of what is known today comes from valuable subjective data provided by test subjects and crewmembers and incorporating sensor technology to measure human-suit interactions (i.e., forces and pressures) could provide a valuable objective complement to the subjective data[14]. In particular, ergonomic suit design could be informed by improved understanding of where the human drives the suit, the contact forces required to drive the suit, and the resulting forces and pressures experienced by the human. However, many technical challenges remain, including the possibility that sensors inside the suit will themselves affect fit, discomfort, and injury risk, and the ability of the crewmember to perform EVA tasks, all of which could confound the primary test objectives.

The objective of this task is to identify technologies and techniques that provide valid and reliable quantification of human-suit interactions that can be related to specific locations on the human and the suit. If a valid and reliable approach is identified, it will be incorporated into the Suit Sizing and Fit Study to measure human-suit interactions as a function of suit fit and tasks and to identify and mitigate potential mechanisms of suit trauma and injury. The approach will also be used in the assessment of Second Generation Suit Trauma Countermeasures.

2. Objective Suit Fit

A separate but related task will aim to complement subjective ratings of suit fit with objective measures of critical suit fit dimensions. While the Human-Suit Interaction Sensors will quantify forces and pressures between the human and suit, this task will attempt to quantify offsets between the human and the suit in critical dimensions; for example, offsets between joint centers. If successful, the Objective Suit Fit methodology will be employed during the Suit Sizing and Fit Study during which the statistical reliability of objective and subjective suit fit measures may be calculated and compared. Depending on the overhead and efficacy of the Objective Suit Fit methodology, it may also be used routinely during suit fit checks for objective verification of acceptable fit. Alternatively, if the comparison of objective and subjective suit fit assessment methods during the Suit Sizing and Fit Study shows close agreement between methods, then the simpler subjective approach may be adequate in most cases. Any approach to assessment of suit fit must allow for the possibility that multiple acceptable suit sizing approaches may exist for subjects.

3. Manloads Testing

The forces exerted by the human into the axial restraint system of the suit are referred to as manloads[15] and must be measured so that appropriate conservatism is incorporated into the suit structure design, ensuring that the suit cannot be damaged by the movement of the human. The manloads input to suit structure is suit design dependent and, as such, the test set up is specific to the suit load path and suit hardware being evaluated. Measured manloads are also dependent on suit sizing and fit; in most cases, a subject wearing a tighter fitting suit (fingertip-to-fingertip, heel-to-shoulder, crotch-to shoulder) will induce greater manloads than a subject wearing a loosely fitting suit.

The manloads associated with the Z-2 suit mobility architecture will be measured during this study using on-suit axial sensors. Options for combining aspects of manloads testing with the Suit Sizing & Fit Study will be investigated, potentially providing the opportunity to characterize manloads for a range of suit sizes and fits in multiple test subjects.

G. EVA Suit Sizing & Fit

Tasks in this section are relevant to the EVA SMT *Pressure Garment System* Gap and also HRP EVA Gap 7: *How do EVA suit system design parameters affect crew health and performance in exploration environments?* However, while suit fit is a function of suit system design, fit is also dependent on how the suit is sized as well as the anthropometry of the human. And while there exists universal recognition of the importance of suit fit, there is currently no established method for fit quantification or definition of acceptable suit fit. As such, a new EVA Gap is proposed: *How does EVA suit sizing and fit affect crew health, performance, and injury risk?*

1. "Proteus" Suit Sizing and Fit Model

The end product of the tasks described in the Suit Sizing and Fit section will be a predictive model that, given inputs of an individual's anthropometric dimensions and a spacesuit's geometry and adjustability features, will provide a quantitative estimate of suit fit for that individual in each of the critical dimensions, as well as recommended suit sizing parameters. For the critical dimensions, ranges within which fit has been shown to be associated with decreased performance or increased injury risk will be provided. Predictions of suit fit changes in critical dimensions due to in-flight anthropometry changes will also be provided. In addition to providing individual predictions of suit fit, the model will enable population analysis, providing estimates of the proportion of the general population or the astronaut population that would be accommodated with acceptable suit fit by different suit design and sizing strategies. The model will be developed and validated using data from Suit Sizing and Fit studies in combination with customized digital manikins and computer models of EVA suits (Figure 6), described later in this section.

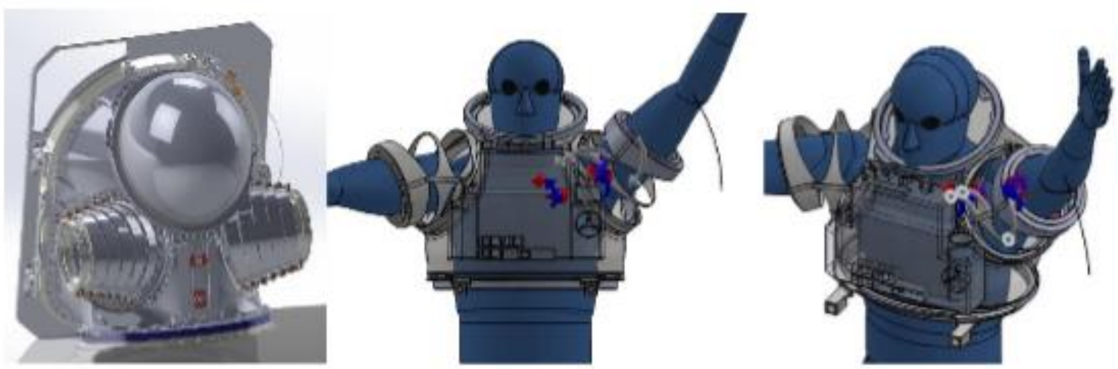

Figure 6. Screenshots taken from prototype version of the future *Proteus* Suit Sizing and Fit Model.

Validation of predicted changes due to in-flight anthropometry changes may be possible once the NextGen suit is flown on ISS, although subjective rather than objective in-flight suit fit assessments may be required.

The Suit Sizing and Fit Model development is expected to be complementary to the aforementioned EVA HHP Model and, particularly, the EVA Biomechanical Model, as described in the Injury Risk and Mitigation section.

2. Customized Digital Manikins; Statistical Body Shape Modeling

Customized Computer-Aided Design (CAD) models of human body shape (manikins) are a critical component of the *Proteus* Suit Sizing and Fit Model as well as the EVA Biomechanical Model. However, current modeling tools use generic "average" or "boundary" manikins rather than representing the actual anthropometry of individual astronauts or test subjects. This task will develop capacity for CAD manikins to represent a specific person's body shape and anthropometry measurements. Scanned body shapes from the Astronaut Anthropometry Database will be summarized by a vector of principal components, which can quantitatively characterize and categorize a person's body shape. Computational mapping between the principal components and CAD manikin geometry will then be defined, enabling reconstruction of CAD manikins from the anthropometry of individuals in the Astronaut Anthropometry Database.

3. EVA Suit Sizing and Fit Studies

It is understood that the sizing of certain critical dimensions of EVA suits relative to critical anthropometric dimensions of the human inside the suit will affect the fit of that human in that suit. During development of the Space Suit Assembly Enhancements, crewmembers reported sensitivities to changes in arm length of 6 mm (1/4 inch); changes in sizing smaller than that were not discernable by the crew. Suit fit sensitivity is also likely to differ between microgravity and planetary EVA environments. However, the sensitivity of suit fit with respect to suited health and performance outcomes has not been systematically characterized for microgravity or planetary environments. This data is necessary to inform the degree of customization that must be provided by spacesuits, including spares, to ensure that inadequate suit fit will not affect human health and performance outcomes, including accommodation for the potential impact of in-flight anthropometric changes. Suit fit sensitivity characterization will also enable definition of test subject selection criteria to mitigate suit fit as a potentially confounding factor in EVA research studies for which a very limited degree of suit sizing is typically available. An accurate model may also reduce the fit check iterations necessary to obtain an acceptable suit fit.

This study will use the benchmarking methodology and a repeated-measures study design with varied suit sizing. The same test subjects will perform the same benchmarking tasks in the same suit, but with the variable that the suit will be sized differently on each occasion, with sizing being initially based on predictions from the Suit Sizing and Fit Model. Suit fit will be assessed for the suit's critical suit fit dimensions (e.g., heel-to-shoulder, crotch-to-shoulder, etc.) using the Objective Suit Fit methodology and subjective suit fit ratings, while performance decrements will be assessed using the benchmarking methodology. Data will be used to validate the Suit Sizing and Fit Model and will enable definition of the range of values for critical suit fit dimensions that provide acceptable suited health and performance outcomes. All primary testing is expected to occur in 1-g and ARGOS with a subset of validation data points collected during NBL and parabolic flight testing, if available.

Human-Suit Interaction Sensors as well as manloads sensors will also be incorporated into testing, if practical, which would enable characterization of the relationship between suit fit, performance, injury/trauma risk, and manloads.

Up to three Suit Sizing and Fit studies are proposed. The first is proposed in the FY19 timeframe, using the existing EMU, which would ensure that the *Proteus* Suit Sizing Model and the Objective Suit Fit methods have been developed to enable prediction and quantification of suit fit for test subjects. Results are expected to precede the NextGen suit Critical Design Review by 1-2 years. A second study will be conducted following delivery of the NextGen suit, results of which are expected to inform the quantities and sizes of suit components and spares necessary to support ISS and future exploration missions. The second study will also evaluate suit sizing and fit sensitivity for a prototype planetary suit configuration and is expected to be followed by a third study after delivery of the NextGen-2 planetary suit.

4. Suit Indexing Study

When there is a large interior gap between an individual and the suit they are wearing, subjects report difficulty in performing certain tasks. In this pilot study, currently underway, pads of custom size and shape are used to index subjects within an EVA suit and the efficacy of the indexing is evaluated through objective measurements such as mobility and stability, and subjective assessment of discomfort and fit as they complete a variety of functional tasks. Results of this study are expected to inform the Second-Generation Suit Trauma Countermeasures study and the Suit Sizing and Fit study.

5. In-Flight Anthropometry Changes, Body Shape Visualization, and Kinect Validation

Changes in anthropometry occur during spaceflight due to fluid shifts, spinal elongation, and changes in body composition. These changes are known to affect suit fit, and on-orbit fit checks are required prior to EVAs on ISS to ensure acceptable fit. Ensuring acceptable suit fit during all phases of exploration missions requires that anthropometric variability be predicted and accommodated within the suit design and sizing strategy.

A study titled Body Measures is currently underway onboard ISS that measures in-flight changes in anthropometry using one-dimensional measurements of critical suit sizing parameters. This study will continue, and a validation study will also be conducted to investigate the possibility of expediting and expanding in-flight data collection using Microsoft Kinect™ sensor technology. The statistical body shape modeling approach described above will also be applied to reconstruct 3-D body shape changes parametrically from the in-flight measurements, which will provide for visualization of 3-D body shapes for in-flight crewmembers without the need for 3-D body scanning.

Pre-flight, in-flight, and post-flight anthropometry data from the Body Measures study, as well as the corresponding 3-D body shape estimates will be incorporated into the *Proteus* Suit Sizing and Fit Model. Although no data exists for anthropometric changes in lunar or Martian gravity, it is expected that earth gravity and microgravity represent the two bounding cases.

6. Astronaut and Test Subject Anthropometry; Scanner Validation; Poseable Laser Scans

As the Consolidated Center for Astronaut Anthropometric Data, the ABF is responsible for extracting all vital and critical anthropometric measurements that are necessary for vehicle, suit, Soyuz, EMU, glove design, verification purposes, and other analyses and data requests. The ABF will continue to scan and process the anthropometric and volumetric data of crewmembers and test subjects and fulfill data requests for anthropometric data and population analyses.

A scanner system based on photogrammetry will replace the laser scanners previously used by the ABF, which is anticipated to expedite the collection and post-processing of anthropometric data. Prior to implementation, the processes for data collection will be developed and results compared with the existing laser-based methods.

Further improvements in the data collection and post-processing methods, which increase the utility of anthropometric data, may be possible through a collaboration with a private company that has developed a technique for fitting poseable manikins from 3D body scan images. These manikins are expected to expedite extraction procedures by requiring the use of fewer scanning postures to extract the necessary postures and anthropometry.

H. Injury Risk & Mitigation

Tasks in this section are relevant primarily to the EVA SMT *Pressure Garment System* Gap and the HRP EVA Gap 11: *How do EVA operations in exploration environments increase the risk of crew injury and how can the risk be mitigated?*

1. EVA Biomechanical Model

The EVA Biomechanical Model will combine suit geometry and customized anthropometric manikins from the Suit Sizing and Fit Model, while also incorporating musculoskeletal modeling and finite element modeling (FEM) to predict human-suit interaction forces, pressure distributions, manloads, bearing loading, and crewmember injury risk for different combinations of subjects, tasks, suit designs, and suit sizes. Initially, the model is expected to assist with identification and mitigation of injury mechanisms for the EMU, including development of the *Second Generation Suit Trauma Countermeasures*; application will also extend to informing development and operation of the NextGen suit. For example, the effects of bearing torques on lower-body kinematics may be estimated, optimized, and fed back into suit design.

This study will seek to leverage and complement ongoing work at JSC and in academia and will use data collected during the *Human-Suit Interaction Sensors Assessment* study to validate model predictions. Once available, the comprehensive human-suit interaction data set from the *Suit Sizing and Fit* study will be used to validate the biomechanical model for the NextGen suit.

2. EVA Suit Occupational Surveillance

A critical element in future EVA risk and injury mitigation efforts is the systematic collection and archiving of suit occupational surveillance data. Specifically, data regarding the suit used, how it was sized, assessment of suit fit, tasks performed, the person using the suit, any existing health conditions, and any discomfort, trauma, or injuries that result from suit exposure. This data has been collected with varying levels of consistency in prior years. Previous data mining efforts have provided valuable insights[10, 16], but have been limited by inconsistent and incomplete datasets. A task is currently underway to implement a standard tracking questionnaire, database, and process for the systematic collection of this data for all EVA suit exposures including testing, training, and flight EVAs.

The data collected will be continually analyzed, and in conjunction with the EVA Biomechanical Model and the other studies listed in this section, will be used to identify potential injury mechanisms and predictors of negative health consequences. Over time, the data will also be used to assess the efficacy of countermeasures as they are implemented in the form of modifications to hardware, training, and/or operations.

3. Historical EVA Health Data Mining

A study currently underway is using existing data on EVA-related injuries and suit trauma from the Longitudinal Survey of Astronaut Health (LSAH) and combining that data with anthropometry, shoulder anatomy, strength, and range of motion data, where available. The focus of the current study is limited to predictors of EMU shoulder injury, but it is expected that the scope will increase to look at a broader dataset in the future. Specifically, collaboration with the LSAH project is expected to result in the systematic review and compilation of medical records associated with up to 12,500 EVA training sessions since 1981. Descriptive data on the training sessions that have already been compiled include name, sex, event date, event name, hard upper torso (HUT) type, HUT size, facility, and estimated run time. In some cases, data also include actual run time, time inverted, waist bearing type, shoulder harness, shoulder pads, and Teflon™ inserts. Shoulder and hand injury reports have previously been extracted from medical records; the proposed study will extract all relevant suit exposure and injury outcome data followed by a comprehensive data mining effort to identify predictors of health outcomes based on EVA hardware, training operations, and subject characteristics.

4. NBL Ergonomic Assessments and Metabolic Rates

Ergonomists began conducting subjective assessments of ergonomic risk factors during a limited number of NBL training runs in 2015. The ergonomic assessments are continuing in 2016 and are expected to additionally include quantitative metrics of crew performance including pre- and post-NBL run measures of mobility, strength, and rate of perceived exertion. Metabolic rate data is also routinely collected by the EVA Physiology Laboratory during NBL training runs as a requirement for EVA medical monitoring, and this data will be combined with the other ergonomic assessment data. A third phase of this study is expected to begin in FY2017 during which in-water assessment of functional strength and other measures will be added (Figure 7).

In addition to reducing injury risk during NBL training, it is intended that the integrated data collection efforts supporting the ergonomic and metabolic assessments will be leveraged to enable support for planned Z-2 NBL testing that is expected in FY2016 or FY2017.

Figure 7. Example of in-water assessment of functional strength at the NBL.

5. Planetary EVA Injury Mechanisms

Although there is some familiarity with the type of injuries that occur during microgravity EVA, there is limited knowledge of how operation in a planetary suit may expose a crewmember to injury risk. This study, in conjunction with the suit trauma countermeasures development task, will attempt to anticipate the types of injuries that may result from planetary EVA through a combination of occupational surveillance data mining, ergonomic assessments, and predictions from the EVA Biomechanical Model. Depending on the nature of any potential injury mechanisms that are identified, additional tasks may be defined to conduct follow-up investigations and seek mitigation strategies if warranted. For example, low back injury risks may warrant the assessment of lumbar kinetic and kinematics.

6. Second-Generation Suit Trauma Countermeasures

HRP solicited for proposals to develop and a test a second generation suit trauma countermeasure in a 2015 Human Exploration Research Opportunities (HERO) announcement (NNJ15ZSA001N-FLAGSHIP). It is expected that the work will be performed during FY2017 and FY2018 and that the task will involve the design, build, and test of a garment that is intended to improve health and comfort outcomes for EVA crewmembers during training and flight without unacceptable decreases in functional performance. The content of the project has the potential to leverage and complement multiple other studies described in this plan. No further details are available until the recipient of the research award is announced.

7. Glove Sensors and Fingernail Injury

Hand discomfort and trauma such as fingernail delamination are often observed following EVA training in the NBL[10]. Hypothesized mechanisms include a combination of high temperatures, high humidity, and high fingertip contact forces; however, conditions inside EVA gloves have not been measured during NBL training. The purpose of this task is to use a sensor glove developed over the past several years to assess forces on the hand and nails, temperature, blood perfusion and humidity of EVA gloved hands in the NBL environment. Results will be used in combination with data from the Fingernail Injury study to determine the potential contributions of each variable to hand injury and thus inform the design of gloves as well as possible changes to cooling and ventilation hardware.

The Fingernail Injury study will evaluate fingernail mechanics during finger pressing (Pad, Tip, between) under a range of temperature and humidity conditions, including conditions consistent with those measured using the sensors inside the EVA gloves. This task is relevant to the Gloves I EVA SMT Gap.

IV. Maintaining and Executing the Plan

The Integrated EVA Human Research Plan presented here is intended as a tool to facilitate collaboration and coordination on human-in-the-loop EVA research. Representation of all appropriate stakeholders in the definition, prioritization, planning and execution of research activities is essential to accomplishing the over-arching objective. Coordination with stakeholders outside of the EVA Office, CTSD, and HRP is already in effect on a study-by-study basis; however, closer coordination on multi-year planning with other EVA stakeholders, including academia, is being actively pursued.

Given the dynamic nature of NASA organizations, budgets, and priorities, it is understood that this plan must be continually reviewed and revised in order to remain useful. As specified in the formal framework of collaboration that led to creation of this plan, representatives of the EVA Office, HRP EVA Discipline, and CTSD will review the plan on an annual basis and make updates as necessary. The plan will also directly inform budget planning and prioritization for the respective organizations. Although not required, it is intended that updates to the plan be made publicly available each year, either through publication on a NASA website and/or through publication and presentation at a national or international conference.

External peer-review panels will continue to review and provide input to the multi-year plan for HRP-funded EVA research (the "Path to Risk Reduction"), and detailed proposals associated with each individual HRP-funded study described in the plan will also be submitted and subjected to external peer-review. Studies that require the unique facilities and expertise available at NASA JSC, as determined by HRP management, will be performed as directed studies, meaning that they will be led from JSC but will still allow for external collaborators and will still be subject to external peer review prior. All other HRP-funded studies will be competed through research announcements.

As studies are performed, updates will be made to the EVA Evidence Report, results will be presented to NASA's Human Systems Risk Board (HSRB), EVA Configuration Control Board, and to external review panels during annual reviews. Updates will be made to the EVA risk classification via the HSRB where results are determined to have reduced or closed knowledge gaps.

Appendix

SMT Gap Name	Description
Pressure Garment System (PGS)	Need new lightweight pressure garment for walking and other exploration tasks. Need new pressure garment to accommodate full 5th to 95th percentile anthropometric range while having adequate space for inherently required services (PPRV, Purge Valve, DCU mounting, Umbilical Attachment, etc.). Need new pressure garment which is designed to latest understanding of crew injury data (glove and shoulder are greatest concerns). Need new pressure garment which is compatible with frequent ingress/egress method (i.e., pressurized donning and 8 psi compatible, e.g., suit port). Need new pressure garment which is cut and puncture resistant and/or which can self-heal after sustaining damage. Need a pressure garment which is designed to function in the relevant environments (gravity, dust, radiation, thermal, plasma, etc.). Need durable pressure garment to meet DRM EVA models. Need durable boot design which can accommodate dust and integrates ankle/hip bearings to accommodate walking. Frequently solutions for one gap tend to negatively impact other areas.
Ventilation	Need an improved helmet vent inlet that washes CO_2 from the oral/nasal area of the suited astronaut, resulting in possible reduction to fan speed and reduced power which would result in mass savings and/or longer duration EVAs.
Anthropometry – Minimum suit size	Need a suit that accommodates fifth percentile crewmember dimensions (minimum) and still accommodates all system required services (purge valve, umbilical services, display/control unit, positive pressure relief valve, etc.).
Gloves I	Need improved moisture removal from glove region to improve comfort and reduce finger & hand trauma. Need Cut and puncture resistant gloves. Abrasion resistant surfaces need longer life cycle than current. Glove is susceptible to cuts, need restraint and bladder materials which can self-heal after being cut or punctured. Need hand heating that covers a more appropriate region of the hand (current heaters are fingertip only). Need glove with more thermal protection for wider range thermal environment at each destination without compromising mobility.

Gloves II	Need glove design that minimizes impact on hand strength and mobility (phase VI glove reduces both by 75%). Need improved glove fit and design to increase flexibility of the metacarpal joint. Loss of mobility is measured by glove sweep volume. Need glove design for fine motor tasks.
Hydration	Need a reusable drink bag that is not susceptible to biological build-up and that requires limited maintenance between EVA uses, to decrease the amount of logistics during long duration missions.
Biomedical Sensors	Need a radiation hardened, wearable biomedical system that does not require the crew to shave or crew time to don.
Displays & Controls; Information Systems	Need a radiation tolerant graphical display that is compatible with the suit (either 100% O_2 compatible and inside the PGS –OR- compatible with the helmet & visors). Need to develop an informatics storage/processor system to provide the information to the display. Desire a hands-free user input device to control the informatics system. This device could consist of a speech recognition system with a minimum of 95% accurate word identification. Integration: Need to integrate all of the above into a system.
Incapacitated Crewmember Rescue	Integration, Need to develop methodology for transfer/transport of an incapacitated crewmember at each destination and how to transfer crewmember onto the ingress/egress hardware, or through side hatch, and doff suit. Knowledge: Rescue protocol has not been identified for each destination. Determine how to address rescue of incapacitated crewmember on single person EVA scenarios. How does a 5th percentile strength crewmember rescue a 95th percentile mass crewmember?
Suit Sizing	Knowledge: Need program and mission definition to determine PGS sizing strategy (ISS style suit resizing vs custom suit for each CM).

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