NASA/TP-20205007604

# Crew Health and Performance Extravehicular Activity Roadmap: 2020

*Andrew F. J. Abercromby*[1]
*Omar Bekdash*[4]
*J. Scott Cupples*[1]
*Jocelyn T. Dunn*[4]
*E. Lichar Dillon*[2]
*Alejandro Garbino*[3]
*Yaritza Hernandez*[4]
*Alexandros D. Kanelakos*[1]
*Christine Kovich*[5]
*Emily Matula*[6]
*Matthew J. Miller*[7]
*James Montalvo*[6]
*Jason Norcross*[4]
*Cameron W. Pittman*[7]
*Sudhakar Rajulu*[1]
*Richard A. Rhodes*[1]
*Linh Vu*[8]

[1]*NASA Johnson Space Center, Houston, Texas*
[2]*University of Texas Medical Branch, Galveston, Texas*
[3]*GeoControl Systems Inc., Houston, Texas*
[4]*KBR, Houston, Texas*
[5]*The Aerospace Corporation, Houston, Texas*
[6]*Stinger Ghaffarian Technologies (SGT) Inc., Houston, Texas*
[7]*Jacobs Technology, Inc., Houston, Texas*
[8]*MEI Technologies, Inc., Houston, Texas*

National Aeronautics and
Space Administration

*Johnson Space Center*
*Houston, Texas 77058*

---

October 2020

## The NASA STI Program Office ... in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Report Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at *http://www.sti.nasa.gov*

- E-mail your question to help@sti.nasa.gov

- Phone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Information Desk
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

NASA/TP-20205007604

# Crew Health and Performance Extravehicular Activity Roadmap: 2020

*Andrew F. J. Abercromby*[1]
*Omar Bekdash*[4]
*J. Scott Cupples*[1]
*Jocelyn T. Dunn*[4]
*E. Lichar Dillon*[2]
*Alejandro Garbino*[3]
*Yaritza Hernandez*[4]
*Alexandros D. Kanelakos*[1]
*Christine Kovich*[5]
*Emily Matula*[6]
*Matthew J. Miller*[7]
*James Montalvo*[6]
*Jason Norcross*[4]
*Cameron W. Pittman*[7]
*Sudhakar Rajulu*[1]
*Richard A. Rhodes*[1]
*Linh Vu*[8]

[1] *NASA Johnson Space Center, Houston, Texas*
[2] *University of Texas Medical Branch, Galveston, Texas*
[3] *GeoControl Systems Inc., Houston, Texas*
[4] *KBR, Houston, Texas*
[5] *The Aerospace Corporation, Houston, Texas*
[6] *Stinger Ghaffarian Technologies (SGT) Inc., Houston, Texas*
[7] *Jacobs Technology, Inc., Houston, Texas*
[8] *MEI Technologies, Inc., Houston, Texas*

National Aeronautics and
Space Administration

*Johnson Space Center*
*Houston, Texas 77058*

---

October 2020

Available from:

NASA STI Program
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161

This report is also available in electronic form at http://www.sti.nasa.gov/ and http://ntrs.nasa.gov

# CONTENTS

## TABLES

## FIGURES

## ACRONYMS and DEFINITIONS

ABF = Anthropometry and Biomechanics Facility
AIS = Abbreviated Injury Scale
ANSUR = U.S. Army Anthropometry Survey
APACHE = Assessments of Physiology and Cognition in Hybrid-reality Environments
ARGOS = Active Response Gravity Offload Simulator
CAD = Computer Aided Design
CG = Center of Gravity
CHAPEA = Crew Health and Performance Exploration Analog
CHP = Crew Health and Performance
$CO_2$ = Carbon Dioxide
CTSD = Crew and Thermal Systems Division
D&C = Displays and Controls
DAVD = Diver Augmented Vision Device
DCS = Decompression Sickness
DEXA = Dual-Energy X-ray Absorptiometry
DRATS = Desert Research and Technology Studies
DSS = Decision Support Systems
ECLSS = Environmental Control and Life Support Systems
ECS = Environmental Control System
EIS = Exposure Incidence System
EMR = Electronic Medical Record
EMU = Extravehicular Mobility Unit
EMSS = EVA Mission Systems Software
EVA = Extravehicular Activity
FMT = Fitness for Mission Tasks
FOD = Flight Operations Directorate
FY = Fiscal Year
GHBMC = Global Human Body Models Consortium
GUI = Graphical User Interface
H-3PO = Human Physiology, Performance, Protection, and Operations
HERA = Human Exploration Research Analog
HERO = Human Exploration Research Opportunities
HH&P = Human Health and Performance
HHPD = Human Health and Performance Directorate
HIDH = Human Integration Design Handbook
HITL = Human-In-The-Loop
HLS = Human Landing System
HMD = Helmet-Mounted Display
HRP = Human Research Program
HSRB = Human System Risk Board
HUT = Hard Upper Torso
IARV = Injury Assessment Reference Value
IMU = Inertial Measurement Unit
ISS = International Space Station
IV = Intravehicular
JARVIS = Joint Augmented Reality Visual Informatics System
LCVG = Liquid Cooling and Ventilation Garment
LTA = Lower Torso Assembly
MDV = Mars Descent Vehicle
MHz = Megahertz
mmHg = Millimeters of Mercury
NASA = National Aeronautics and Space Administration
NBL = Neutral Buoyancy Laboratory
NBP = Neutral Body Postures

NEEMO = NASA Extreme Environment Mission Operations
NRA = NASA Research Announcement
$N_2$ = Nitrogen
$O_2$ = Oxygen
OCAD = Operational Control Agreement Database
OFV = On-Orbit Fit-Checks
PACES = Physical and Cognitive Exploration Simulations
PGS = Pressure Garment System
$PiCO_2$ = Inspired Partial Pressure of Carbon Dioxide
PLSS = Portable Life Support Subsystem
PSTAR = Planetary Science and Technology from Analog Research
RD&T = Research, Development, and Testing
SCLT = System Capability Leadership Team
SHyRE = Scientific Hybrid Reality Environments
SME = Subject Matter Expert
SMT = System Maturation Team
VGE = Venous Gas Emboli
WBH = Waist Bearing Hip
xEMU = Exploration Extravehicular Mobility Unit

# EXECUTIVE SUMMARY

**Multiple organizations within NASA, as well as industry and academia, fund and participate in research related to extravehicular activity (EVA). In October 2015, representatives from multiple organizations across NASA Johnson Space Center agreed on a formal framework to improve multiyear coordination and collaboration in EVA research. At the core of the framework is an integrated plan and a process by which it is periodically reviewed and updated. The integrated plan has previously been published as the Integrated EVA Human Research and Testing Plan, and is now referred to as the Crew Health and Performance (CHP) EVA Roadmap. The overarching objective of the collaborative framework is to conduct multidisciplinary, cost-effective, and targeted work that will enable humans to perform EVAs safely, effectively, comfortably, and efficiently, as needed to enable and enhance human space exploration missions. Activities on the roadmap 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 and products in timeframes that support NASA's missions. Representation of all appropriate stakeholders in the defining, prioritizing, planning, and executing of research activities is essential to accomplishing the overarching objective. A review of the roadmap is conducted annually. Details of the roadmap include description of ongoing and planned research, development, and human-in-the-loop testing activities in the areas of: physiologic and performance capabilities; suit design parameters; EVA consumables and life support parameters; EVA tasks and concepts of operations; EVA informatics and decision support systems; human-suit sensors; anthropometry and suit fit; EVA injury risk and mitigation; hardware evaluations and requirements verification; and decompression sickness risk mitigation. On March 26, 2019, the Vice President of the United States announced that the first woman and next man would be sent to the surface of the moon by 2024. Accordingly, the 2020 version of the CHP EVA Roadmap incorporates schedule and content updates in support of this policy direction. This includes closer coordination with more tactical team members, including the Flight Operations Directorate.**

# 1 INTRODUCTION

On March 26, 2019, the Vice President of the United States announced that the first woman and next man would be sent to the surface of the moon by 2024 with the long-term goal of sending humans to Mars [1]. Current space suits and extravehicular activity (EVA) concepts of operations used on the International Space Station (ISS) or during the Apollo missions to the moon are inadequate to meet the mission objectives associated with extended stays on the surface of the moon and even the shortest possible Mars exploration missions. Many technologic and knowledge gaps exist with respect to the ability of EVA systems and crewmembers to function safely, reliably, and effectively for missions that may last a year or longer in the most hostile and challenging environments ever to be explored by humans.

A significant step toward returning humans to the surface of the moon was taken in the initiation of the Exploration Extravehicular Mobility Unit (xEMU) project in 2018. Scope for this new EVA suit includes an initial ISS demonstration followed by full development to support lunar surface missions beginning in 2024. Further development will be required for a Mars surface EVA suit.

The Crew Health and Performance (CHP) EVA Roadmap presented here is the fourth such release, with previous versions being published in 2016, 2017, and 2019 [2-4]. The previous release of this document was titled “Integrated EVA Human Research and Testing Plan.” The title of the 2020 integrated plan has been updated for consistency with other CHP planning documents, which are referred to as “roadmaps.” The purpose of the document is to describe plans, priorities, and brief status reports related to the CHP EVA gaps while ensuring multiyear coordination and collaboration among the primary participants in EVA research at NASA Johnson Space Center (JSC). The document serves as a core component of a collaborative framework, the purpose of which is to conduct multidisciplinary, cost-effective research, development, and testing (RD&T) that will enable humans to perform EVAs safely, effectively, comfortably, and efficiently, to enable and enhance human space exploration missions. The RD&T activities must be defined, prioritized, planned, and executed to comprehensively address the right questions, avoid unnecessary duplication, leverage other complementary activities where possible, and ultimately provide actionable evidence-based results in time to inform subsequent developments and/or tests.

Multiple organizations within NASA and outside of NASA have been successfully conducting EVA RD&T efforts since the 1960s. The CHP EVA Roadmap reflects only a subset of all stakeholders in the field of EVA and is primarily an internal NASA creation; however, the plan is published 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 of all relevant EVA activities but rather aims to identify the human-focused 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 or partnerships with non-NASA organizations.

The identification and organization of EVA research priorities is described in Section 2, the technical content of the roadmap is described in Section 3, and the process by which the roadmap is maintained is explained in Section 4.

# 2 IDENTIFYING AND ORGANIZING CREW HEALTH AND PERFORMANCE EXTRAVEHICULAR ACTIVITY PRIORITIES

As in previous years, the gaps around which this plan is organized are formally recognized and documented by multiple organizations:

- EVA System Maturation Team (SMT) (via EVA Office's "Gap Tool")
  CHP-ECLSS (Environmental Control and Life Support Systems) SCLT (System Capability Leadership Team) – includes what was formerly CHP SMT
- Human Health and Performance Directorate's Human System Risk Board (HSRB)
- Human Research Program

By design, NASA uses a consistent set of gaps with only minor variations in wording according to the respective focus or convention of each organization, rather than using duplicative or inconsistent gap definitions across the different organizations. The gap titles, gap numbers (as cataloged in the EVA Office's EVA Gap Tool), and gap wording are shown in Table 1.

**Table 1. CHP EVA Gaps**

| CHP Gap Title | CHP EVA Gap ID | EVA SMT Gap # | CHP EVA Gap Wording |
|---|---|---|---|
| EVA Crew Required Capabilities | CHP.EVA. CREW | EVA-Gap-88 | Fitness for Duty standards that enable crew health and performance while accounting for the limitations, deconditioning, and impairment of crewmembers with respect to sensorimotor, aerobic, strength, cognitive, and immunologic function. |
| EVA Suit Design for Health and Performance | CHP.EVA. SUIT | EVA-Gap-89 | EVA spacesuit hardware (incl. mass, center of gravity, pressure, human-system interfaces, Portable Life Support Subsystem capabilities, cooling, ventilation, and Pressure Garment System design characteristics) that is within applicable CHP EVA standards for microgravity, lunar surface, and Mars surface exploration missions. |
| EVA Suit Sizing and Fit | CHP.EVA. FIT | EVA-Gap-90 | EVA suit sizing and fit methods and hardware that is within applicable CHP EVA standards for microgravity, lunar surface, and Mars surface exploration missions. |
| EVA Physiologic Inputs and Outputs | CHP.EVA. PHYS | EVA-Gap-91 | Predictive estimates of individualized crew health and performance state* associated with anticipated EVA tasks during lunar surface, Mars transit, and Mars surface exploration missions. **CHP state to include 1) Metabolic Rates, 2) decompression sickness (DCS) risk, 3) Inspired* $CO_2$*, 4) Heat Storage, 5) Hydration, 6) Physical and Cognitive Fatigue.* |
| EVA ConOps for Health and Performance | CHP.EVA. CONOPS | EVA-Gap-92 | EVA tasks and concepts of operation (ConOps), and mission designs that are within applicable CHP EVA standards for microgravity, lunar surface, and Mars surface exploration missions. |
| EVA Injury Risk and Mitigation | CHP.EVA. INJURY | EVA-Gap-94 | EVA injury risk estimates and mitigation strategies for exploration EVAs, training, and ground testing. |
| EVA Exploration Prebreathe | CHP.EVA. DCS | EVA-Gap-95 | Validated and efficient DCS risk estimates and mitigation strategies for lunar and Mars surface exploration missions. |

## 2.1 EXTRAVEHICULAR ACTIVITY SYSTEM MATURATION TEAM GAPS

Following the creation of NASA's Space Technology Roadmaps [5], the EVA Office and the Crew and Thermal Systems Division (CTSD) at JSC led the development of an EVA 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 Office and CTSD uses the EVA SMT Gap List to identify and prioritize EVA developmental research activities. A subset of SMT gaps most directly relevant to crew health and performance was included in previous releases of the Integrated EVA Human Research and Testing Plan.

## 2.2 CREW HEALTH AND PERFORMANCE SYSTEM – ENVIRONMENTAL CONTROL AND LIFE SUPPORT SYSTEMS CAPABILITY LEADERSHIP TEAM GAPS

The ECLSS SCLT absorbed the CHP SMT scope in 2019. Responsibilities of the ECLSS-CHP SCLT include:

- Identify capability gaps to advance agency objectives and develop strategies and roadmaps
- Make recommendations on ECLSS and CHP technology development efforts and investments
- Establish key performance parameters and participate in key program and project reviews
- Analyze budget, skills, facilities, and other assets required to execute ECLSS and CHP capability advancement and recommend acquisition strategies in concert with agency investment and partnership goals, leveraging and acting as the steward of NASA's critical capabilities in ECLSS and CHP, and providing input into the agency planning, programming, and budgeting execution cycle
- Examine and maintain cognizance of state of ECLSS and CHP
- Coordinate with commercial and international partners to identify areas of mutual interest and cooperation
- Support future human exploration architecture studies
- Maintain cognizance of relevant national and international technology activities in government, industry, and academia, specifically emerging innovations and technologies, and identifying trends and opportunities

The CHP-ECLSS SCLT is organized into multiple capability areas, each of which has a designated lead and specific gaps associated with it; these gaps in knowledge and/or technology must be closed to enable NASA's future exploration missions. Multiyear roadmaps are defined for each capability area, identifying the specific RD&T activities necessary to ensure closure of the associated gaps. Roadmaps aim to capture all relevant work, regardless of funding source or location.

The 2019 Integrated EVA Human Research and Testing Plan met the roadmap criteria and was adopted as initial version of the roadmap for the EVA Physiology and Performance Capability Area. This document represents the 2020 version of the roadmap.

During the review of EVA SMT gaps in 2019, it was recognized that the existing EVA SMT gaps covered some but not all of the open technical and knowledge gaps with respect to crew health and performance during EVA. As such, eight EVA SMT gaps were created, which exist within both the EVA SMT and the CHP-ECLSS SCLT gap structures. These gaps, shown in Table 2, also correspond directly to the existing EVA Human System Risks and Gaps, described next, and also include an exploration prebreathe gap. As such, the new gaps provide a direct and consistent mapping between existing Human System Risk gaps, EVA SMT, and CHP-ECLSS SCLT while ensuring that the full scope of crew health and performance gaps are adequately captured.

## 2.3 HUMAN SYSTEM EXTRAVEHICULAR ACTIVITY RISK AND GAPS

NASA's Health and Medical Technical Authority, primarily through the Human Health and Performance Directorate (HHPD) and specifically the HSRB, uses a well-defined and documented process for the formal identification and prioritization of safety and health risks to astronauts [6]. The gaps in knowledge or technology necessary to mitigate each risk are also identified. Within the scope of managing all risks of astronauts, the HSRB is concurrently tracking the *Risk of Injury and Compromised Performance Due to EVA Operations*, often referred to as the "EVA Risk," and seven corresponding gaps (Table 2).

**Table 2. Human Systems EVA Risk and Gap Structure [7]**

| EVA Gap ID | Description |
|---|---|
| EVA 6: | What crew physiologic and 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? |
| EVA 8: | What are the physiologic inputs and outputs associated with EVA operations[2] in exploration environments[3]? |
| EVA 9: | What is the effect on crew performance and health of variations in EVA task design and operations concepts for exploration environments[3]? |
| EVA 10: | How can knowledge and use of real-time physiologic 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? |

[1]e.g., anthropometry, aerobic fitness, muscle strength and 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 Human Systems EVA Gaps is not sequential starting from 1 due, in part, to previous gap reorganization and the recategorization of decompression sickness and hypoxia gaps into separate risks (Risk of Decompression Sickness and Hypobaric Hypoxia).

Extravehicular activity is recognized as a distinct discipline by the Human Research Program (HRP), and has provided intermittent funding for activities in the CHP EVA Roadmap. The 2020 CHP EVA Roadmap includes current and potential future HRP-funded activities. In November 2018, the HRP announced the selection of the *Impaired EVA Performance* study (see Section 3.1.1, now referred to as *Egress Fitness*), which was submitted as a proposal in response to an HRP solicitation (Human Exploration Research Opportunities Solicitation: 80JSC017N0001-BPBA Appendix C). Human injury modeling also is being considered for future funding by HRP at the time of writing.

Additional details of HRP's risks, gaps and related activities can be found on the publicly accessible HRP website, https://humanresearchroadmap.nasa.gov.

## 2.4 HUMAN SYSTEM RISKS OF DECOMPRESSION SICKNESS AND HYPOBARIC HYPOXIA

In addition to the aforementioned EVA Risk, two additional risks that are closely associated with EVA are the *Risk of Decompression Sickness* [8] and the *Risk of Hypobaric Hypoxia* [9]. The primary tasks associated with defining an exploration DCS risk mitigation strategy, including validation of exploration prebreathe protocols, are included in this roadmap. The strategy for mitigation of DCS during exploration missions has multiple implications for the development and operation of exploration EVA space suits and host vehicles. The risk of hypobaric hypoxia is bounded by the risk associated with hypoxic exposure during staged decompression strategies used to mitigate DCS and therefore requires a very limited research scope.

## 2.5 EXPLORATION EXTRAVEHICULAR MOBILITY UNIT TESTING AND DEVELOPMENT MILESTONES

The most significant updates arising since the previous (2019) release of this document are those associated with the directive that NASA will put the first woman and next man on the moon by 2024 under the Artemis program [10]. Although the 2024 date for a return to the moon is aggressive, development of the next generation space suit was already well underway, being organized under the xEMU project. The xEMU project team continues to develop a demonstration exploration space suit (xEMU Demo) that will be delivered to the ISS in 2023 while concurrently working on a lunar version of the xEMU space suit that will enable the Artemis lunar missions. The xEMU development milestones are shown in Figure 1. The activities and anticipated products described in the 2020 CHP EVA Roadmap align with these milestones.

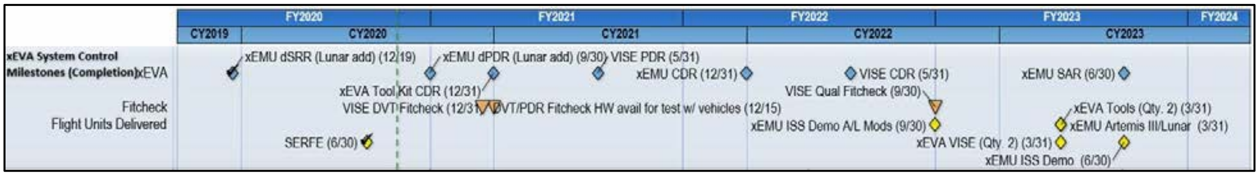


**Figure 1. xEMU development schedule.**

## 2.6 MARS APPLICABILITY OF LUNAR EXTRAVEHICULAR ACTIVITY

Previous versions of this roadmap assumed that most activities would at least attempt to conduct testing under both lunar and Martian gravity simulation conditions. However, the aggressive schedule for xEMU development and for the Artemis program overall, in combination with the understanding that the xEMU and Mars EMU may differ significantly, have made it more practical to focus on lunar-specific testing and development activities.

Table 3 describes the extent to which the lunar-focused activities that are the current focus of most CHP EVA Roadmap tasks are expected to be applicable to Mars EVA.

The 2020 CHP EVA Roadmap identifies some specific Mars-focused future activities, which are likely to be required to enable Mars missions; however, the exact scope and timing of these tasks should be considered notional at this time.

**Table 3. Mars Applicability of Lunar-focused CHP EVA Roadmap Tasks**

| GAP AREA | MARS APPLICABILITY |
|---|---|
| Prebreathe protocols and DCS Models | No difference expected for Mars (assuming vehicle and suit atmospheres are the same as lunar or within model range). |
| Crew Required Capabilities | No difference for Mars – tasks are already primarily Mars-focused and must be continued at the current time to utilize returning long-duration ISS crewmembers as analogs for deconditioned Mars crewmembers. |
| Suit Sizing and Fit | No significant difference expected for Mars; possible increase in in-flight anthropometry changes. |
| Human Health & Performance (HHP) Model | HHP EVA Model architecture and integration with EVA Mission Systems Software (EMSS) and EPIC will be applicable. Physiologic and cognitive data will differ. |
| EVA Injury | Injury mechanisms, models and countermeasures likely applicable to Mars but with additional injury mechanisms possible due to different suit, ConOps, and gravity level. May have different risk acceptance and treatment options for Mars. |
| Informatics and Software | Will build on lunar informatics but need for significantly increased crew autonomy; goal is to develop and test this on the moon. |
| ConOps | Physical and Cognitive Exploration Simulations (PACES) project simulations and performance assessment methods largely applicable to Mars. Different science and exploration objectives, communication latency, and possibly decreased crew work capacity (due to mission duration, increased EVA physical and cognitive workload) will drive different ConOps. |
| Suit Design | Likely to build on xEMU design but increased gravity, changes to $CO_2$ removal technology, and different mission requirements will affect CHP-related aspects of suit design. |

## 2.7 ORGANIZATION OF THE CREW HEALTH AND PERFORMANCE EXTRAVEHICULAR ACTIVITY ROADMAP

The HRP EVA Evidence Report [11] explains that review of the EVA risk within the EVA research community and the NASA Human Systems Risk Board resulted in the identification of 23 separate factors that contribute to the risk of injury and compromised performance because of 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 Human Systems EVA Gaps (Table 2) to the contributing factors identified in Figure 2 is included in Appendix A of the HRP EVA Evidence Report [11].

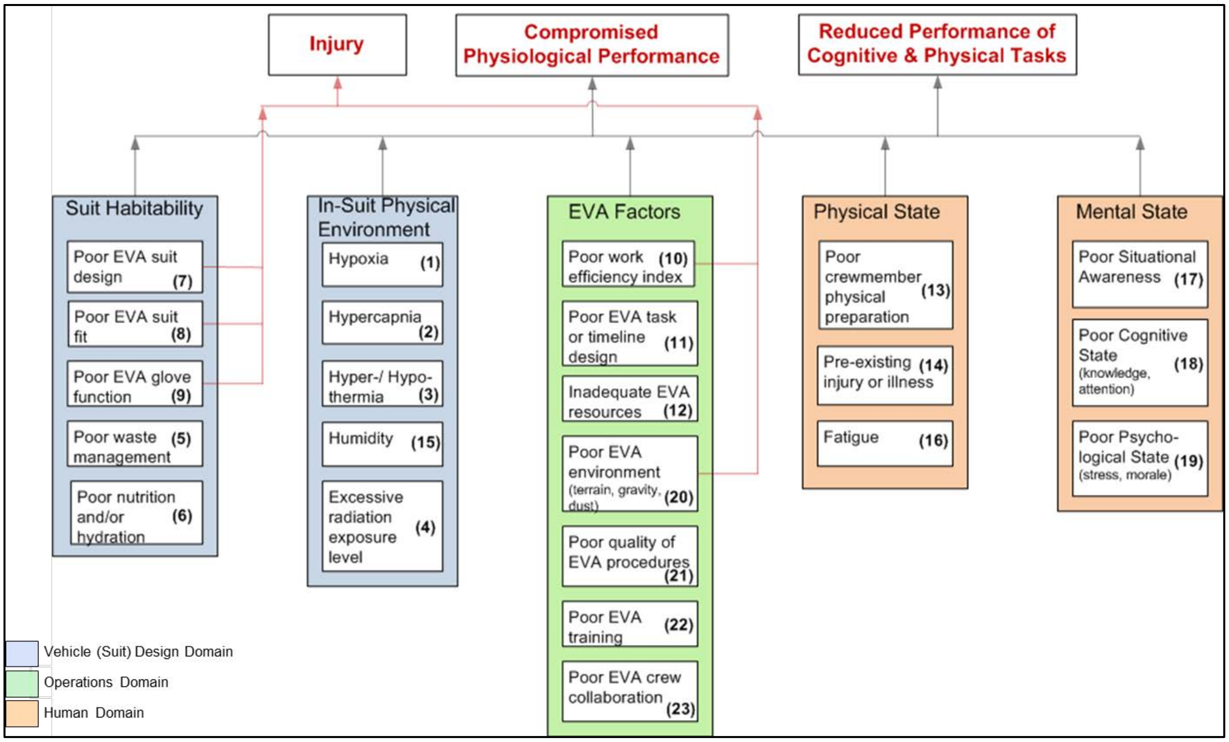


**Figure 2. HRP EVA risk master logic diagram [11].**

For the purposes of organizing the CHP EVA Roadmap, activities are grouped by the gaps that they most directly address and are briefly described in Section 3. The intent of this document is to summarize the roadmap rather than to provide significant detail on any specific activity. Many activities map to more than one gap but are only shown under one gap.

The initial release of the Integrated EVA Human Research and Testing Plan was presented and published as a conference paper in 2016 [2], with subsequent updates being published via a public NASA website in 2017 [3], via presentations at the 2017 and 2018 NASA EVA Technology Workshops, and as a publicly available NASA Technical Report in 2019 [4].

## 2.8 CREW HEALTH AND PERFORMANCE EXTRAVEHICULAR ACTIVITY STANDARD MEASURES

The gaps defined in Section 2 of this roadmap require that EVA hardware, software, operations, and human operators be rigorously characterized and, in some cases, evaluated with respect to various aspects of health and performance. Previous versions of this roadmap have included a Planetary EVA Standard Measures task, the purpose of which was to provide a reliable and valid methodology to evaluate the extent to which a suited test condition provides adequate mobility, dexterity, and tactility to enable crewmembers or test subjects to accomplish suited tasks within acceptable physical and cognitive workload, fatigue, and comfort limits. The CHP EVA Standard Measures task described here is an extension of that work, wherein applicable standard measures will be identified or created for all aspects of each CHP gap defined in this roadmap. Standard measures are expected to include:

- Identification of construct being measured
- Definition of specific data parameter(s)
- Evidence or basis for inclusion as a standard measure
- Necessary conditions under which data must be collected (i.e., simulation fidelity)

- Applicable data processing methods (e.g., signal processing, identification of outliers, etc.)
- Considerations regarding numbers of subjects (e.g., minimum number of subjects)
- Test subject inclusion and exclusion criteria (e.g., level of training, anthropometry, aerobic fitness, etc.)
- Criteria for acceptance (e.g., threshold values as defined in NASA-STD-3001)

Identification, selection, and interpretation of appropriate standard measures depends on multiple contextual factors such as tasks, operations, and human-system interactions. Although many crew performance measures exist, there is a need for a framework consisting of a common set of measures that characterizes individual performance and total system performance. A more structured methodology for measuring crew and system performance can monitor and address on-going as well as real-time performance gaps.

Wherever possible, applicable measures as defined within NASA-STD-3001 will be used and directly applied. For example, the inspired partial pressure of $CO_2$ ($PiCO_2$) quantification methodology identified in [12] and documented in [13] will be applied to the assessment of $CO_2$ washout performance within the CHP.EVA.SUIT Gap (Table 1). In many cases, existing standards are either unavailable or are defined at a high level within NASA-STD-3001 and must be tailored to the relevant gaps. Where no applicable standards currently exist, new validated standards will be developed and documented within the CHP EVA Standard Measures document, and will be proposed for inclusion in future updates to NASA-STD-3001 (as was the case with the Spacesuit $PiCO_2$ methodology).

Another source of standard measures is expected to be the Human Integration Design Handbook (HIDH), NASA/SP-2010-3407, which serves as a resource document to NASA-STD-3001, Volume 2, Human Factors, Habitability and Environmental Health. The handbook provides guidance for writing and implementing human interface requirements and helps guide the development of designs and operation for spacecraft human interfaces. The document serves as valuable technical resource supplemental to the NASA Systems Engineering Processes and Requirements, NPR 7123.1C and Human-Rating Requirements for Space Systems, NPR 8705.2C documents.

Standard measures will not necessarily be the only data collected during a test, and not all tests will necessarily include all applicable standard measures, due to logistical or other considerations. However, the intention is that all relevant standard measures will be incorporated into a test to the extent that it is practical to do so. Physical And Cognitive Exploration Simulations (PACES), described in Section 3.3.1, is expected to incorporate multiple CHP EVA Standard Measures while also ensuring appropriate simulation fidelity to enable meaningful assessment of the constructs being evaluated. Indeed, the express purposes of the PACES methodology is to provide consistent and comparable CHP-relevant data across multiple tests and test environments, while minimizing confounding variables, and utilization of standard measures is a core component of that approach.

In addition to providing consistent and comparable methods by which to assess and compare CHP across different tests, the measures will be used as criteria to track progress being made with respect to gap closure. Gaps will be considered closed if associated study/task/project outcomes are demonstrated to be within applicable CHP EVA standards. Key performance parameters for each gap will be developed based on the extent to which applicable standards have been identified and met. As a notional example, if 80% of anticipated lunar EVA tasks have been evaluated and demonstrated to be within applicable CHP EVA Standards, the CHP EVA ConOps (reference

Table 1) gap would be considered 80% closed for lunar exploration. Or if 80% of anticipated lunar EVA tasks had been evaluated but were found to be within only 50% of applicable CHP EVA standards, the gap would be considered (80% × 50%) 40% closed.

Status: A consolidated document of CHP EVA Standard Measures is expected to be baselined in fiscal year (FY)21 with periodic updates as required.

# 3 THE CREW HEALTH AND PERFORMANCE EXTRAVEHICULAR ACTIVITY ROADMAP

The content is structured around the CHP EVA Gaps. In many cases, tasks are associated with more than one gap but are only shown once. The sequencing of tasks within the roadmap is shown in Figure 3.

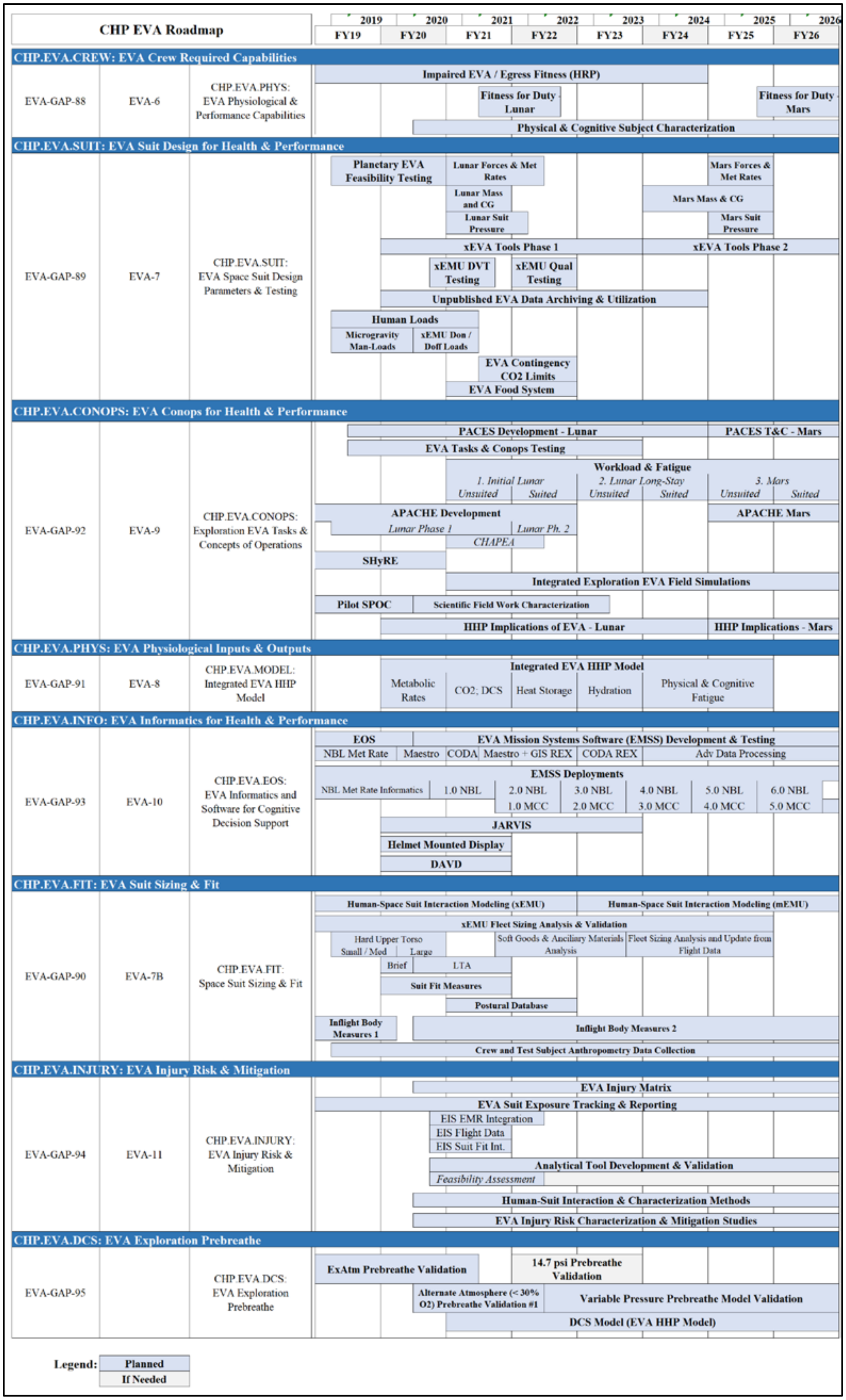


**Figure 3. Planned phasing of tasks in CHP EVA Roadmap.**

## 3.1 CREWMEMBER PHYSIOLOGIC AND PERFORMANCE CAPABILITIES

Tasks in this section are relevant primarily to the Table 1 CHP.EVA.CREW Gap: *Fitness for Duty standards that enable crew health and performance while accounting for the limitations, deconditioning, and impairment of crewmembers with respect to sensorimotor, aerobic, strength, cognitive, and immunologic function.*

### 3.1.1 IMPAIRED EVA PERFORMANCE AND FITNESS FOR MISSION TASK VALIDATION (IMPAIRED EVA / EGRESS FITNESS)

Physiologic adaptation to the microgravity environment during transit to Mars is likely to result in reduced functional capacity that will hinder the ability to perform tasks after landing on Mars' surface. While most ISS crew maintain muscle strength and aerobic capacity within 10% of pre-flight levels [14] with robust exercise countermeasure systems, there are currently no countermeasures for protection of neurovestibular/sensorimotor capabilities. As evidence, 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 [15]. The implications of such performance decrements are significant since they may affect the ability to perform nominal or contingency EVAs immediately post-landing, potentially requiring increased automation and teleoperation of surface systems. Performance decrements also may necessitate that the Mars Descent Vehicle (MDV) be capable of supporting astronauts for up to 2 weeks on Mars' surface to allow astronauts to rehabilitate before performing EVAs to egress the MDV and ingress a surface habitat or pressurized rover. Although the focus of this study is primarily to inform Mars exploration, it is unknown to what extent the transition into lunar gravity after an extended microgravity exposure may have similar concerns. Apollo missions were all direct flights to the moon and future lunar missions may be staged from the Gateway after an extended duration in microgravity.

The purpose of the Impaired EVA Performance study is to characterize suited health and performance outcomes in crewmembers as a function of muscular, aerobic, and vestibular/ sensorimotor dysfunction after gravitational transitions, which will inform questions such as how long crew must remain in the MDV before they are able to safely perform EVAs 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 will utilize functional EVA performance outcomes based on the "First EVA on Mars" scenario. Test subjects will be returning long-duration ISS crewmember wearing prototype planetary space suits under simulated reduced-gravity conditions shortly after returning to Earth. Additional non-EVA functional performance testing also will be performed including performance of simulated telerobotic tasks.

Status: In progress. Selected for funding via NASA Research Announcement (NRA) Human Exploration Research Opportunities (HERO) Solicitation: 80JSC017N0001-BPBA Appendix C. Title: Validation of Fitness for Duty Standards Using Pre- and Post-Flight Capsule Egress and Suited Functional Performance Tasks in Simulated Reduced Gravity. PIs: J. Norcross and M. Rosenberg.

### 3.1.2 FITNESS FOR DUTY STANDARDS DEVELOPMENT (FITNESS FOR DUTY – LUNAR; FITNESS FOR DUTY – MARS)

Muscle strength and aerobic fitness standards for NASA astronauts are currently based on 0*g* EVA (or “spacewalk”) metabolic requirements and maintaining muscle strength and aerobic fitness within preflight thresholds that will help facilitate rapid return to preflight levels. The physical and cognitive demand associated with partial gravity EVAs is expected to be higher compared to ISS EVAs. These exploration performance requirements necessitate an update to the current aerobic fitness and muscle strength standards to protect crew health and performance on future missions.

Simulation of exploration tasks and decrements in physiologic performance capabilities associated with spaceflight (e.g., reduced gravity levels, movement within a spacesuit and the spacesuit microenvironment, and multi-system physiologic deconditioning) will be difficult. Given these limitations, a well-thought-out approach to developing these standards using spaceflight data and high-fidelity ground-based analogs is needed. The proposed approach to developing partial gravity EVA standards is outlined in Table 4.

**Table 4. Proposed Approach to Developing Partial Gravity EVA Standards**

| STEP | DESCRIPTION |
|---|---|
| 1: Literature Based Metabolic Upper Bound | Evaluate literature to determine max. sustainable (6-8 hour) physical workload without significant physical and/or cognitive performance decrements (estimate 30% to 40% $VO_2pk$) |
| | Calculate corresponding absolute metabolic rates for astronaut population |
| | Identify percentage of population exceeding current xEMU capabilities |
| 2: xEVA task strength and metabolic characterization | Characterize metabolic rates (relative to body weight and absolute) and force required for discrete tasks in xEVA ConOps using suited reduced-gravity testing (e.g., ARGOS, NBL) |
| | Identify percentage of crew population for which xEVA task demands may exceed sustainable workload or absolute strength requirements for completing a discrete task. |
| | **If** FMT study met rates align with xEVA suited reduced-gravity met rates, use FMT-based models to identify FFD standard recommendations [16, 17] |
| Step 3: FFD standard recommendations | Use high fitness/strength and low fitness/strength subjects (based on Egress aerobic fitness and muscle strength standard thresholds) in EVA Workload and Fatigue Study |
| | Quantify performance during 6-hour simulated planetary EVAs using xEVA tasks and ConOps |
| | **If** acceptable* sustained EVA performance at low fitness/strength level → use egress-based FFD standards |
| | If unacceptable* performance decrements during sustained EVA among low fitness cohort → additional testing to identify fitness/strength level at which sustained performance is acceptable. |

*Based on CHP EVA Standard Measures

### 3.1.3 PHYSICAL AND COGNITIVE SUBJECT CHARACTERIZATION

This activity will provide systematic collection of physical and cognitive characterization data from EVA crewmembers and test subjects participating in the various human-in-the-loop (HITL) activities on the CHP EVA Roadmap, wherever possible. These data are expected to include, at a minimum:

- Muscle Performance Test Battery [18]
- Aerobic Fitness characterization ($VO_2pk$)
- Cognition Battery

- 3D anthropometric laser scan
- Body mass

In addition to including these data within the HHP EVA Model, these data will enable generalizable assessments of the impact of physical and cognitive capabilities and characteristics on EVA crew health and performance, including the development of Fitness for Duty standards with respect to muscle strength and aerobic fitness.

## 3.2 SUIT DESIGN PARAMETERS

Tasks in this section are relevant primarily to the Table 1 CHP.EVA.SUIT Gap: *EVA spacesuit hardware (including mass, CG, pressure, human-system interfaces, Portable Life Support Subsystem (PLSS) capabilities, cooling, ventilation, and PGS design characteristics) that is within applicable CHP EVA standards for microgravity, lunar surface, and Mars surface exploration missions.* These studies are also a primary source of data for the EVA HH&P Model associated with CHP.EVA.PHYS Gap (reference Table 1).

### 3.2.1 EVA TASK STRENGTH AND METABOLIC CHARACTERIZATION (LUNAR FORCES AND MET RATES 1 AND 2; MARS FORCES AND MET RATES)

Metabolic data from Apollo EVAs are lower than metabolic rates during similar tasks performed in prototype high-mobility planetary EVA suits under simulated reduced gravity, by as much as double in some cases [19-21]. The reason(s) for these differences are not fully understood, but may include the limited mobility of the Apollo suit, increased work capacity enabled by higher mobility space suits, comparison of nonequivalent flight and ground-test tasks, compensation for the reduced-gravity simulation environments, and/or other factors. It is important that the xEMU be capable of supporting the anticipated metabolic work rates of crewmembers during planetary EVA and that crewmembers be capable of performing for extended periods at the work rates expected to be required when working in the xEMU. It is therefore also important to accurately predict anticipated metabolic rates during future planetary EVAs.

This study will enable estimates for metabolic rate profiles for expected planetary EVA tasks, based on analysis of existing data sets and collection of new data sets in ARGOS and possibly Neutral Buoyancy Laboratory (NBL) environments. Initial estimates (*Lunar Met Rates 1*) will be made based on testing with the Mark III space suit in ARGOS and testing of the Z-2 space suit in the NBL in simulated lunar gravity. Estimates will be updated in FY21 based on testing with the xEMU DVT space suit (*Lunar Met Rates 2)* and using an updated ARGOS gimbal and PLSS mass simulator.

ARGOS is designed to simulate any reduced-gravity environments, such as lunar, Martian, or microgravity, using a robotic system similar to an overhead bridge crane. The facility provides several advantages over other partial gravity analogs (e.g., POGO, NBL, parabolic flight) including, full X, Y, Z translational DOF, a precise control of the offload, and active control of all translational axes to reduce the system inertial effects on the subject. Despite these advantages over previous or other partial-gravity simulation environments, ARGOS still has limitations on freedom of movement within the gimbals, volume to perform tasks, and height of the structure for inclusion of large scale mock-ups.

In addition to metabolic workload requirements, the physical strength requirements associated with planetary EVA tasks will also be evaluated, results of which will feed into the Fitness for Duty Standards development, described in the previous section. Estimation of forces and torques is expected to be achieved primarily through simulation and HITL testing of discrete EVA tasks or even subtasks, as well as through computational modeling (Section 3.7.4); however, inclusion of force measurement within the metabolic characterization testing will also be investigated.

This activity was combined with planetary EVA Standard measures in the 2019 roadmap; the 2020 roadmap separates the standard measures component from metabolic task characterization and distinguishes between lunar and Mars metabolic task characterization, with the latter activity being added as a separate, follow-on activity later in the roadmap ("Mars Met Rates").

Status: Lunar Met Rates 1 is in progress. Significant testing was undertaken during the first half of FY20 on "feasibility testing" using ARGOS and the Mark III spacesuit, the purpose of which was to evaluate the simulation quality of the integrated spacesuit-gimbal-ARGOS system. As a result of this testing, design and fabrication of a new gimbal and a PLSS mass simulator was initiated, which aim to improve the realism of the lunar gravity simulation.

### 3.2.2 Mass and Center of Gravity Acceptability (Lunar Mass and Center of Gravity; Mars Mass and Center of Gravity)

The mass and center of gravity (CG) of space suits affects the ability of suited crewmembers to perform mission tasks during planetary EVA [22]. However, existing data are inadequate to accurately predict acceptable mass and CG combinations for the xEMU. The primary objective of this study is to develop an adjustable mass and CG simulation and evaluate the acceptability of the proposed mass/CG of the xEMU for performance of planetary EVA tasks using the *EVA Standard Measures*. Because crewmember anthropometry, strength, and aerobic fitness also affect EVA performance, test subjects for this study will be selected to ensure acceptability for the lower percentiles of the crew population.

NASA developed an integrated CG suit model using the 3D models of suit components and reported mass of each suit component. Additionally, human body manikins (CG derived from individual body segments) can be aligned inside the CG suit model to provide an overall CG location, which can be projected onto a virtual force plate (Figure 4). The overall CG location will automatically update based on the size and shape of the human manikin.

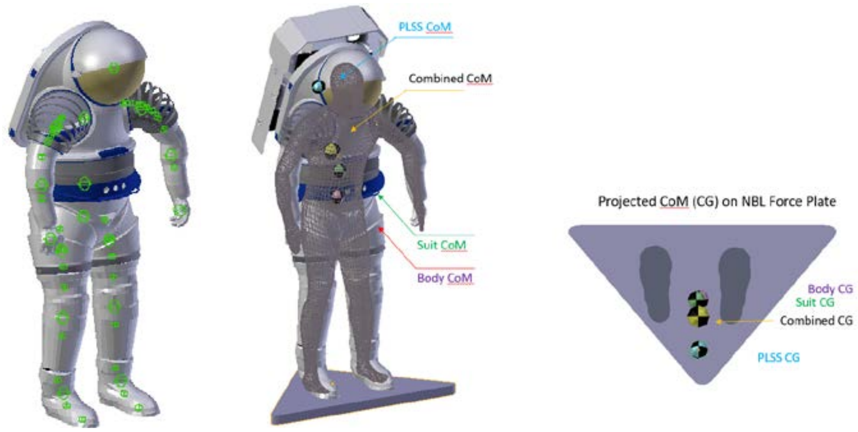


**Figure 4. Segmented suit geometry with part-wise CG (left) and virtual overlay of suit geometry over the body scan for center of mass (CoM).**

This virtual model is being validated through testing at ARGOS using force plates. This model was also incorporated into software tool to assist the NBL in their planetary EVA simulations. A realistic CG is needed to improve simulation task quality and perform accurate ergonomic and task assessments. The tool was created to provide weigh-out assistance to the dive support team. Further model refinement and additional CG validation testing is ongoing.

Status: CG model development ongoing; testing planned in late FY20.

### 3.2.3 SUIT PRESSURE (LUNAR SUIT PRESSURE; MARS SUIT PRESSURE)

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 DCS. The purpose of this study is to use the *EVA Standard Measures* methodology to quantify and compare health and human performance outcomes for human subjects operating in the space suit at 4.3 psia, 5.0 psia (to be confirmed) and 8.2 psia; these pressures represent anticipated pressure set points for the xEMU during initial lunar missions.

The duration of testing will be adequate to identify fatigue effects. It is not expected that these data will affect suit design, because it is currently assumed that the Pressure Garment System (PGS) for exploration missions will be capable of operating at each of these set points; however, results of this study are expected to inform the selection of suit operating pressure(s) used during EVAs, which is a trade between decompression stress at lower suit pressures and increased joint resistance and fatigue at higher pressures. Findings of acceptable health and performance outcomes during extended operations at higher suit pressures could lead to the development of shorter prebreathe protocols, if EVAs are to be performed at higher suit pressures, especially for spacecraft that are unable to operate at the Exploration Atmosphere [23].

Status: Testing is targeted to begin in late FY20 or early FY21 using the Z-2.0 space suit, MK III, and possibly glovebox testing, with more comprehensive testing planned using the xEMU DVT space suit in FY21. Initial testing may be performed as part of Lunar Met Rates 1, with subjects performing their training runs at elevated pressure of 5.0 psid. Subjects will perform a glove dexterity and comfort testing protocol as outlined by the High Performance EVA Glove study, in addition to several PACES tasks. Representative test durations will be important to evaluate fatigue effects. This will provide discrete performance data from functional glove tasks in addition to in context feedback from the subjects during flight-like activities (e.g., geology sample collection and preparation; ambulation; working in and around landers; etc.).

### 3.2.4 XEVA TOOLS

The xEVA Tools Team is responsible for the design, development, manufacturing, assembly, testing, and certification of the Artemis xEVA tools. They are expected to include tools to support standard EVA operations, geology, dust mitigation, construction, incapacitated crew rescue, and maintenance.

In FY20, the xEVA Tools team has been tasked with starting the “Baseline Artemis Geology Tools.” While the Artemis ConOps is still being developed, this small suite of geology sampling tools is expected to be required regardless of the specific science objectives. Those tools include a hammer, scoop, rake, extension handle, tongs, sample bag, Drive Tube, contingency sampler, and the US flag. Examples are shown in Figure 5.

**Figure 5. xEVA geology tools prototypes.**

Work on dust mitigation tools and techniques also has been initiated. Existing hardware is being evaluated with respect to potential use singularly or in combination with one another to remove regolith from the xEMU before ingressing the Human Landing System (HLS) vehicle. The overall dust mitigation requirement will be controlled by more than just the xEVA tools team, but the tools will be one of the first lines of defense.

In addition, the xEVA Tools team has started work on the xEMU to tools interfaces. These interfaces will allow the crewmembers to carry tools on the suit without holding them in their hands. Early testing should determine whether the interfaces will be incorporated into the xEMU Environmental Protection Garment, if they will be manufactured and certified separately and installed on the xEMU, or some combination of the two.

Tool development, testing, and deployment is expected to continue throughout the 2020s to support all of the Artemis Phase 1 and Phase 2 objectives.

Status: Ongoing.

### 3.2.5 xEMU HARDWARE EVALUATIONS

Several xEMU requirements derived in part or in whole from NASA-STD-3001 point to the need to verify the acceptability of the xEMU Demo and subsequent xEMU planetary space suits with respect to human health and performance. Details of these future verification and validation tests will be developed in collaboration between the EVA Office, engineering, and HH&P. The scope of the integrated human-system performance testing throughout the hardware development life-cycle process will ensure that xEMU Demo and subsequent xEMU space suits provide mobility, dexterity, and tactility to enable crewmembers to accomplish suited tasks within acceptable physical workload, fatigue, and comfort limits for all microgravity and partial-gravity EVA scheduled and contingency mobility tasks. The testing also will ensure that the cognitive performance capabilities, workload productivity, and safety shall be accommodated in the human-system interfaces for all levels of crew capability and all levels of task demands. It is anticipated that the accommodation of cognitive capabilities will be demonstrated, in part or in whole, through the acceptable performance of simulated EVA tasks using the tasks and assessment methods being developed for PACES. Evaluations will be used to describe and establish workload and other human-system performance criteria during all crew operations.

The xEMU hardware evaluations also will include characterization of $CO_2$ washout performance, results of which will verify compliance with the associated xEMU requirements, and also will be incorporated into the EVA Human Health and Performance model.

Data collection, analysis, and detailed test results will be documented and used to understand risks and uncertainties while potentially influencing human-system design and supporting operational performance across missions.

Status: Planned to begin in FY20.

### 3.2.6 xEMU SATELLITE HANDLING HUMAN LOADS (AKA "MANLOADS") TESTING

The forces exerted by the human into the axial restraint system of the suit are referred to as manloads [24] 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 setup is specific to the suit load path and suit hardware being evaluated. Measured manloads also are 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.

Testing of the Space Shuttle EMU indicated that satellite handling manloads impart higher loads into the suit than the so-called isometric manloads that occurred during normal or exaggerated motions in the suit. These satellite handling manloads were used as inputs to the Z2 structural design, but must be verified. Manloads distribution throughout a suit's components is geometry dependent, therefore the actual magnitudes and locations of maximum manloading must be evaluated for the new suit design.

Status: Ongoing. Funded by the EVA Office and led by the Anthropometry and Biomechanics Facility (ABF) and CTSD. Completion of this task is expected in 2020. The manloads associated with the Z-2 suit mobility architecture were measured during this study using on-suit axial sensors, during HITL testing on the ARGOS. In this test series, the subject was asked to lie prone on an air bearing cart that slid with minimal friction on a smooth aluminum plate as shown in Figure 6. The subject was asked to firmly grip an EVA handrail, which was then pulled away at one of two speeds: slow (0.83 cm/s) and fast (8.23cm/s). Test conditions included an inline loading condition (direction of pull perpendicular to the foot restraints) and an off-axis loading condition (direction of pull a 60-degree angle to the foot restraints). These loads are currently being analyzed, and results will be included in a final report on the study.

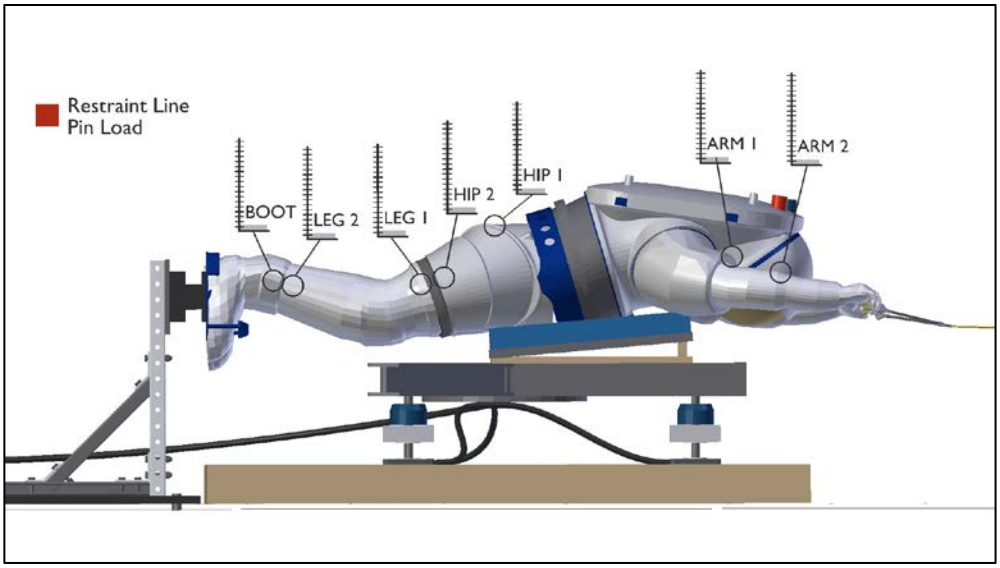


**Figure 6: Diagram of manloads test (MK III model used as surrogate for Z-2 in illustration).**

### 3.2.7 xEMU Donning and Doffing Loads

Donning and doffing a suit can be an aggressive endeavor, especially when the wearer is well indexed in the suit. This leads to concerns of overloading the suit components that must withstand loads applied via the don/doff maneuver. Previous testing on the EMU evaluated loads applied throughout the don/doff maneuver, including ingress of the suit and closure of the waist – both in 1*g* and microgravity conditions. However, the rear-entry configuration of the xEMU will lead to different loading patterns than the waist entry Space Shuttle EMU, and must therefore be verified (reference Figure 7). Testing to evaluate the loads into the suit and provide inputs to structural modeling is planned for 2020.

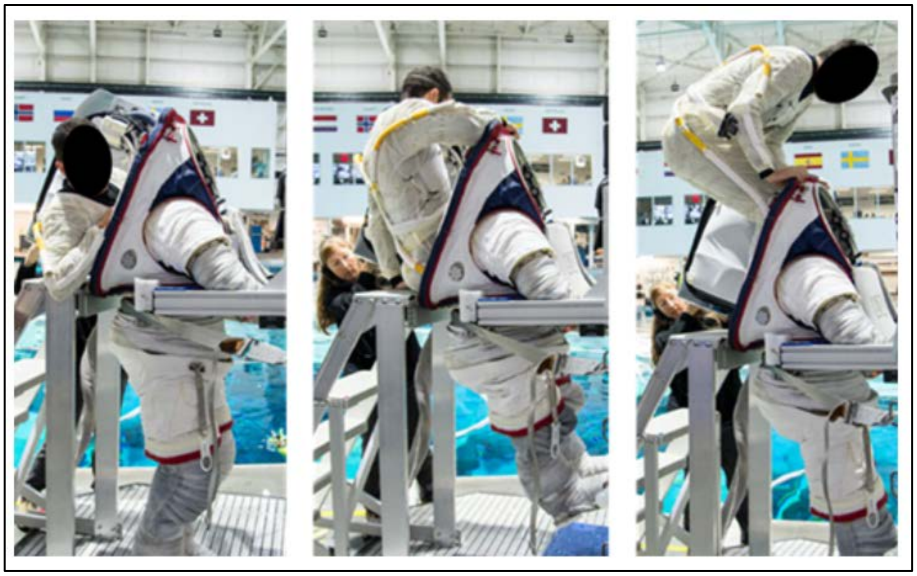


**Figure 7: Example doffing of a rear-entry configuration suit (the Z-2)**

Status: Ongoing

### 3.2.8 EVA CONTINGENCY $CO_2$ LIMITS

Previous versions of this roadmap described work on development of methods for the quantification of inspired $CO_2$ ($PiCO_2$) in spacesuits, as well as the definition of acceptable limits for future spacesuit designs. This work resulted in a standard test protocol for inspired $CO_2$ [13], an xEMU requirement for nominal inspired $CO_2$, and a NASA standard for nominal inspired $CO_2$, included in NASA-STD-3001 Volume 2, Rev B. However, neither the xEMU requirement nor NASA Standard apply to contingency scenarios in which higher levels of $PiCO_2$ may be permitted for brief periods of time. There is an absence of data associated with in-flight, acute, high $PiCO_2$ exposures in human subjects, so current contingency $CO_2$ requirements permit only minimal excursions above nominal limits.

The purpose of this task is to conduct in-flight testing on physiologic and cognitive responses to acute exposures to known levels of $PiCO_2$. In-flight testing may be necessary because of concerns that sensitivity to $CO_2$ may be significantly increased in spaceflight as compared with Earth-based exposures.

Status: A study design is being formulated for consideration by xEVA project and the Human Research Program.

### 3.2.9 EVA FOOD SYSTEM

To account for energy expenditure associated with extended duration EVA operations, NASA-STD-3001 Volume 2, outlines that daily provisions will account for the addition of 837 kJ (200 kcal) per surface (e.g., moon, Mars) EVA hour when these operations exceed 4 hours in duration (NASA-STD-3001). Furthermore, according to these requirements "the system shall provide a means for crew nutrition in pressure suits designed for surface (e.g., moon or Mars) EVAs." This approach is expected to provide additional benefits to physical and cognitive performance during and after EVA operations compared to an approach where additional nutrition is only available before and after EVAs. There are several physiologic, logistic, and engineering aspects of an EVA Food System that require a concerted effort from several technical disciplines to fully address the following questions:

- How much nutrition (e.g., kcals) must be provided/available in-suit and how much can be leveraged by supplementing pre- and post-EVA rations?
- What food formulations are appropriate and safe for extended in-suit operations (e.g., liquids, solids, palatability, low residue)?
- What are the limitations of the suit (e.g., suit volume, waste management, ports)?
- What are practices and preferences that astronauts commonly follow that should be considered (e.g., pre, post, NBL habits, eating, voiding).

The planned approach will provide recommendations on the caloric quantity and nutritional composition (protein, fat, carbohydrate) of nutrition for pre-, mid-, and post-EVA consumption based on review of relevant literature and anticipated energy expenditure associated with planetary EVA (provided by the EVA Metabolic Characterization study). Design solutions for meeting the recommendations then will be developed in coordination between food scientists, human factors engineers, xEMU project engineers, and the crew office. Suited and unsuited testing will be used to evaluate the human factors of the EVA food system prototype and to inform refinements as needed. The EVA Workload and Fatigue study will incorporate the expected EVA food system to the same extent that it is expected to be included in the Artemis II mission. If necessary, the EVA Workload and Fatigue study will be performed with and without the EVA Food System.

Status: Expected to begin in FY21.

## 3.3 EXTRAVEHICULAR ACTIVITY TASKS AND CONCEPTS OF OPERATIONS

Tasks in this section are relevant primarily to the Table 1 CHP.EVA.CONOPS Gap: *EVA tasks and concepts of operation, and mission designs that are within applicable CHP EVA standards for microgravity, lunar surface, and Mars surface exploration missions.*

### 3.3.1 PHYSICAL AND COGNITIVE EXPLORATION SIMULATIONS (PACES) DEVELOPMENT

The PACES (Physical and Cognitive Exploration Simulations) project is being developed as a complement of tasks, procedures, information systems, and standard measures that simulates realistic physical and cognitive workload under flight-like exploration scenarios and provides a standardized methodology by which to characterize and assess physiology, performance, and other human factors data. The PACES project will develop a catalog of representative exploration tasks and procedures, tailored to meet the constraints of analog test environments. These tasks are derived from the JSC EVA-EXP-0042 Document: Extravehicular Activity (EVA) Office Exploration EVA System Concept of Operations [25] that describes the possible types of EVAs that may be performed in missions beyond Earth orbit.

The development of technologies and operations concepts to enable safe, effective, and efficient exploration EVAs requires that candidate approaches be rigorously evaluated in operationally relevant environments. The ISS is a poor analog for exploration EVA research, and prototype space suits are limited in their availability, and are difficult to test under conditions that are representative of exploration EVA operations due to their excessive weight when used in Earth gravity. Laboratory testing of prototype exploration space suits is typically performed to evaluate physiology and biomechanics, and is conducted without the cognitive demands and constraints of a realistic operational environment. Meanwhile, analog testing during scientific field studies may be used to evaluate operations concepts and technologies, but are not physiologically representative of exploration EVA conditions and such tests generally include limited simulations of cognitive workload and little or no capacity to measure cognitive performance.

The PACES project is being developed such that most elements of the simulations, including the embedded physical and cognitive performance metrics, will be usable under shirt-sleeve, hybrid reality, and suited test conditions. For example, subjects will either be in a pressurized spacesuit under simulated reduced gravity or they will be outfitted with a spacesuit simulator so as to reproduce approximate physical workloads as measured during previous suit tests in reduced-gravity simulations. This approach means that testing of preliminary concepts or candidate technologies can be performed at relatively low cost and with larger sample sizes, with follow-on testing of down-selected concepts or with smaller sample sizes possible under suited conditions using comparable methods and metrics.

Cognitive workloads will be simulated through a combination of flight-like tasks including life support monitoring, timeline management, communication, navigation, and procedure execution. Performance on simulated cognitive tasks will be measured using a combination of subjective measures, explicit queries, and implicit performance measures such as task completion times, error rates, and deviation rates. Initially, PACES consists of one or two EVA test subjects and an intravehicular (IV) surrogate or test operator. It is planned that the simulation will later expand to include multiple IV crewmembers, as well as non-EVA scenarios, which will enable further evaluations of operational concepts, communication methods, and research questions of team dynamics and trust. “Modules” of exploration tasks (e.g., airlock egress and ingress, EVA maintenance task, instrument deployment task, etc.) are being developed that can be combined to enable multihour, end-to-end simulations.

The PACES is being developed such that the impact of changes to EVA design parameters such as displays, biosensors, informatics, and metabolic- and thermal-control algorithms, as well as different concepts of operation, can be evaluated using simulated EVA scenarios that accurately replicate the physical and cognitive workload of real EVAs, while also using quantitative and operationally-relevant metrics of physical and cognitive performance.

Task analysis is an activity that breaks a task down into its component levels. It involves (1) the identification of the tasks and subtasks involved in a process or system, and (2) analysis of those tasks (e.g., who performs them, what equipment is used, under what conditions, the priority of the task, dependence on other tasks). The focus is on the human and how they perform the task, rather than the system. Results can help determine the displays or controls that should be developed/used for a particular task, the ideal allocation of tasks to humans vs. automation, and the criticality of tasks, which will help drive design decisions.

The objective of the PACES task analysis is to document and track tasks in the PACES timelines. The task information is used to feed detailed design, databases, and models. Designers also can use the task analysis to design subsystems and components to accommodate crew tasks. Human Factors Engineers use the analysis to plan HITL evaluations and verifications in addition to operations personnel utilizing it for ConOps and crew procedures development.

Maintaining consistent nomenclature across the PACES project is also an integral component of ensuring commonality and efficiency of development across multiple personnel and organizations. PACES has structured the various levels of a mission timeline to the tasks performed to the actions needed to perform those tasks as follows and shown in Figure 8:

1. Procedure: Top level category, encompassing a single, complete EVA.
    - In graphical format, also referred to as the timeline.
    - Composed of a sequence of all PACES task and subtask instructions planned in the EVA day schedule.
2. Task: A discrete work objective in the EVA day.
    - (e.g., science instrument deploy, ingress, geology sampling)
    - Tasks are composed of steps
    - Some tasks include subtasks
3. Subtasks (optional): Discrete blocks of work to complete within a task (e.g., sampling, initialize geophone module, translate)
    - Subtasks are composed of steps
4. Steps: Individual instructions for completing the subtask procedure block
5. Substeps (optional): Some steps will have additional checks/actions/reminders to complete.
6. Functional Movement: Movement action required to complete the steps and/or substeps
    - (e.g., kneeling, walking, standing, etc.)

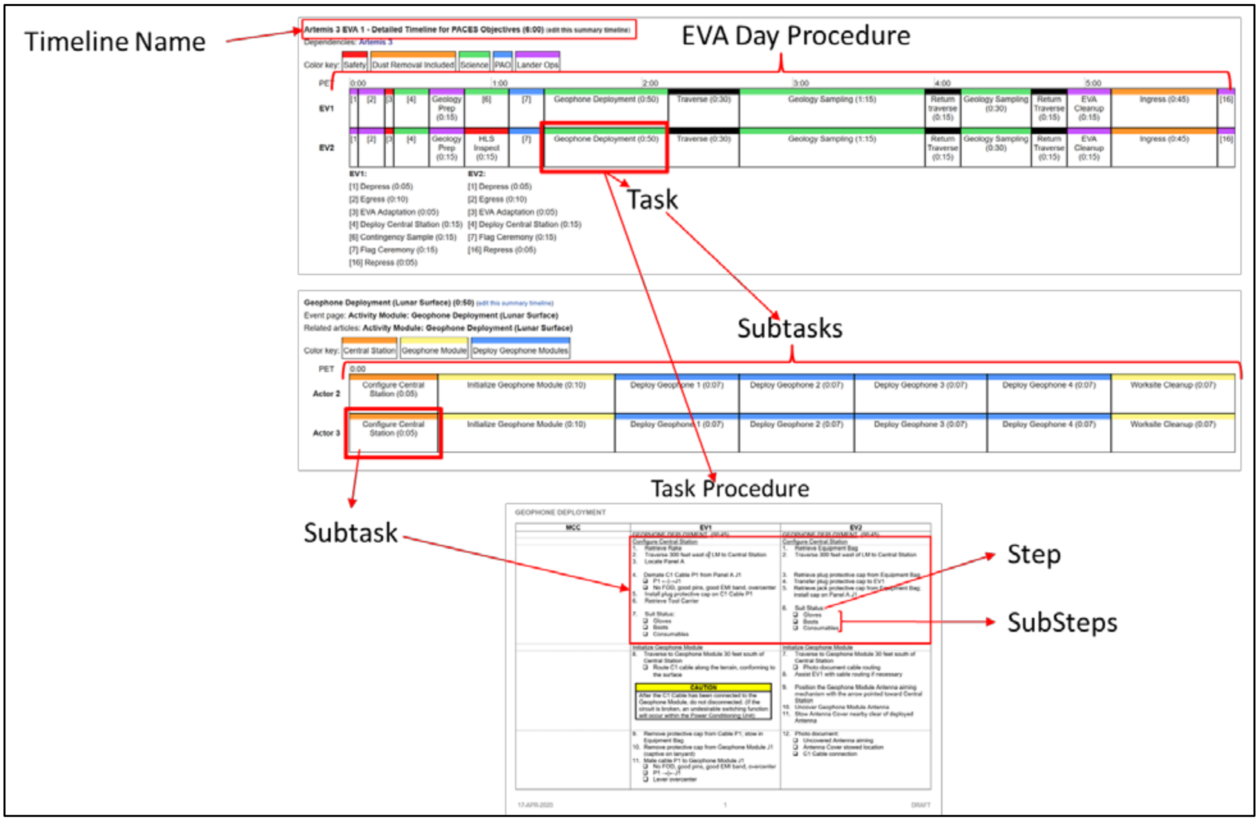


**Figure 8: EVA nomenclature.**

Status: Ongoing. The PACES Methods Development activity will continue throughout the multiyear development and maturation of xEVA systems, tasks, and ConOps to ensure frequent, user-centered testing in accordance with human systems integration best practices.

### 3.3.2 EVA TASKS AND CONOPS TESTING

Development of tasks under the PACES project will be done iteratively, following a circular design, build, and test philosophy to ensure that they are accurately reflecting the latest state of knowledge on planned exploration missions. Once a task is defined, H-3PO and CX3 personnel work with subject matter experts (SMEs) to develop and document task components: timelines, procedures, communication scripts, mock-up requirements, and measurement hardware. Following the first drafting of these PACES task products, iterative testing of procedures, timelines, task execution methods, mock-ups, simulation layouts, and data collection methods is performed shirt-sleeve in the H-3PO laboratory. This rapid prototype task test bed allows for iteration with low overhead and lower cost than performing developmental testing in a more advanced analog environment (e.g., NBL or ARGOS).

Integral to this shirt-sleeve testing is understanding the impact adding PACES measures may have on the exploration simulation quality, and development of data analysis methods and associated products. This process ensures that both the task design and subsequent products will generate reliable data and meet the needs of various stakeholders seeking to close gaps, mitigate risks, and train future lunar astronauts, design hardware, or conduct human performance centered research. Figure 9 illustrates how an exploration mission concept timeline can be reduced into the component tasks and then further reduced into individual tasks and procedures to be completed, as well as how those products are used to execute a PACES test.

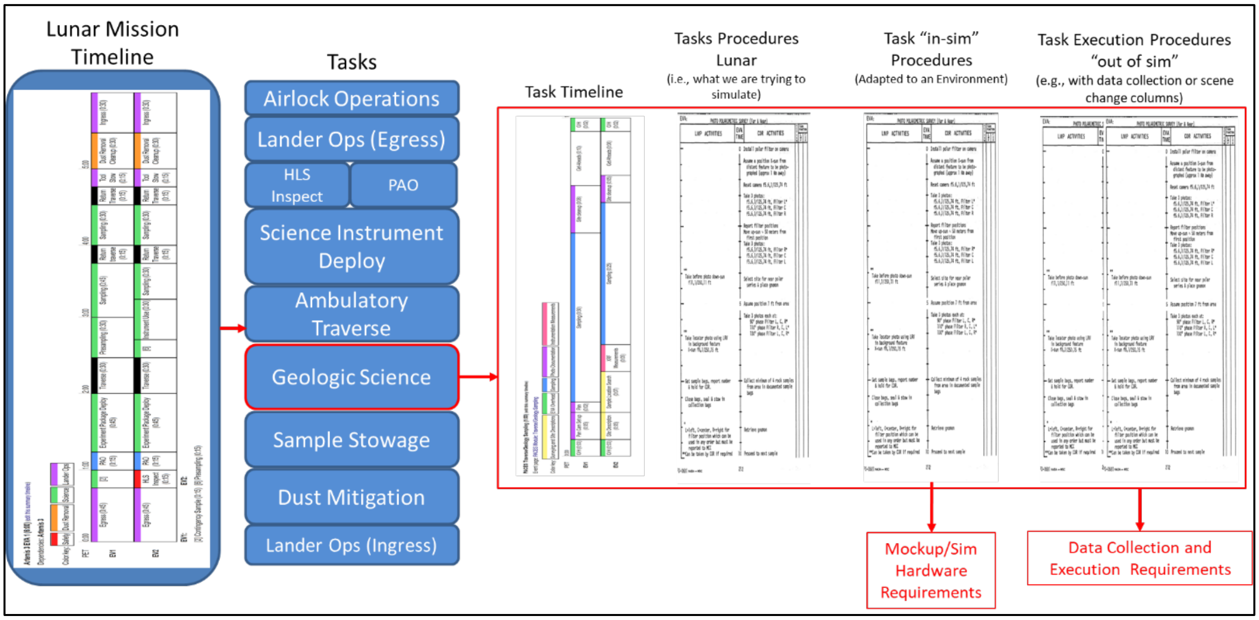


**Figure 9: PACES timeline, task, and procedure development.**

As components of the tasks are refined, requirements to adapt the modules to analog environments are developed in parallel where possible; however, formal testing in those environments occurs only after the module concept and associated elements are proven in the H-3PO shirt-sleeve environment. No single analog environment is able to fully simulate all aspects of exploration operations and multiple different test facilities are leveraged as part of the PACES methodology. In some cases, a task procedure or mock-up may need to be altered to execute the task in a specific analog environment. The degree to which the task can be changed without affecting the validity of the data is determined through this analog, environment-pilot-testing phase, and subsequent stakeholder review of data products. This testing in analog environments will focus primarily on simulation quality and feasibility of task execution to determine optimal analogs to perform tasks. These data will inform a growing list of tasks in the "PACES catalog" such that researchers can optimally select the correct task-analog implementation for their studies. Tasks are currently being developed for testing in the JSC Neutral Buoyancy Laboratory (NBL), the H-3PO Assessments of Physiology and Cognition in Hybrid reality Environments (APACHE) test bed, the ARGOS, and field testing at the JSC rock yard.

Once pilot testing in both shirt-sleeve and analog environments is complete, the development products are again vetted through the PACES stakeholder community for a final approval. This ensures that test execution documentation, mock-ups, hardware, tools, and data products are able to be optimally shared across stakeholder objectives and meet the needs of any planned studies. From this "catalog" of exploration tasks, multiple groups can then build integrated timelines to achieve specific study aims (e.g., build different simulated mission timelines for the EVA Workload and Fatigue study to look at effects of different EVA ConOps on performance) with consistent execution and data collection methods. This maximizes utility of data, cross-test comparisons, sharing of simulation elements (i.e., procedures and mock-ups used between analog environments), and improvements to execution are quickly distributed across stakeholders, reducing risk of repeated or out-of-sync development efforts.

The PACES tasks and associated procedures will be used for studies in the near term. This may require separate “simulation scripts” that compensate for a lack of a true flight environment with test execution controlled elements (e.g., pre-planned stops on a traverse to simulate crew making new discoveries). This is necessary from a research perspective to control the level of effort and simulation that each subject experiences to make accurate comparisons. However, over time, it is the goal that PACES tasks, which are initially scoped in reference to best effort understanding of what the real flight tasks that could be performed are, will evolve into the actual flight procedures, building upon all of the lessons learned and data products created through PACES development and testing. This will include the building and improvement of ground-based simulations and analog environment simulation facilities to support testing, flight crew training, and real lunar surface hardware evaluations.

Status: Ongoing.

### 3.3.3 EVA WORKLOAD AND FATIGUE

The human health and performance implications of mission designs that include up to 24 hours EVA per person per week have not been evaluated and may not be credible. The purpose of the EVA Workload and Fatigue study is to characterize and evaluate health and performance outcomes as a function of EVA duration and frequency, up to 24 hours of EVA in a week. During the Space Shuttle Program, there were occasions on which pairs of astronauts approached 24 hours of EVA in a week; however, those were microgravity EVAs and short-duration missions. Results of this study will inform Fitness for Duty standards (Section 3.1.2) and also may yield recommendations for changes to mission ConOps and task design.

Multiple test subjects with a range of anthropometries and fitness levels will perform up to 3 × 8 hour (or 4 × 6 hour) simulated planetary EVAs in a week using the PACES methodology to periodically measure performance during the simulated EVAs. Criteria will be defined and assessed 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 xEVA Concept of Operations for Artemis and will use the PACES methodology. Shirt-sleeve testing using the APACHE (see following section) will precede suited testing using ARGOS and possibly the NBL. Test subjects will be selected within targeted ranges of anthropometry and physical fitness to enable validation of Fitness for Duty standards.

Opportunities to incorporate objectives of this study within end-to-end mission simulations such as Human Exploration Research Analog (HERA), Crew Health and Performance Exploration Analog (CHAPEA) and the Exploration Atmosphere Prebreathe Validation study will be investigated. 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.

Status: Planned. Shirt-sleeve testing to begin in FY21.

### 3.3.4 ASSESSMENTS OF PHYSIOLOGY AND COGNITION IN HYBRID-REALITY ENVIRONMENTS (APACHE)

A primary test environment within which the PACES complement is being developed and will be utilized during future studies is APACHE. A hybrid-reality EVA environment as well as computer models of spacecraft systems already have been developed and are continuing to be evolved by internal NASA engineering collaborators. The purpose of APACHE is to adapt and implement NASA's existing hybrid reality capabilities in combination with dedicated development to create an integrated hybrid reality simulation, incorporating the full PACES complement of scenarios, tasks, procedures, sensors, information systems, displays, interfaces, and metrics. The APACHE is currently being developed within the hi-bay area of the Human Performance Laboratory (JSC's Building 21) and will provide a rigorous, repeatable, affordable, and readily available environment for PACES testing.

Status: Ongoing. The APACHE currently includes models of lunar landers (including combined physical/virtual interaction with airlock control panels, etc.), surface experiment packages, drive-able rovers and geological features. Environments near lunar equator as well as lunar south pole/Shackleton Crater rim can be used, which simulate the realistic lighting conditions of these locations. The simulation capabilities have recently been expanded to allow multiple EV crewmembers to see and interact with each other in the virtual reality environment, as well as the implementation of a lunar regolith simulant surface for subjects to walk on to further improve the simulation quality. Testing of the ambulation capability using a passive treadmill was conducted in Spring 2020 [26]. Development of the APACHE environment to support Artemis Phase 1 testing is currently ongoing and expected to continue in FY21.

### 3.3.5 SCIENTIFIC HYBRID REALITY ENVIRONMENTS (SHYRE)

The SHyRE (Scientific Hybrid Reality Environments) is a planetary-science focused hybrid-reality analog closely related to APACHE. The use of analog environments in preparing for future planetary surface exploration is key in ensuring we both understand the processes shaping other planetary surfaces as well as develop the technology, systems, and concepts of operations necessary to operate in these geologic environments. Although conducting fieldwork and testing technology in relevant terrestrial field environments is crucial in this development, it is often the case that operational testing requires a time-intensive iterative process that is hampered by the rigorous conditions (e.g., terrain, weather, location, etc.) found in most field environments. Additionally, field deployments can be costly and logistically challenging, typically limiting the testing opportunities to only once or twice per year.

To overcome these inherent challenges, SHyRE is a Planetary Science and Technology from Analog Research (PSTAR) funded, multiyear campaign aimed at developing a scientifically robust analog environment using hybrid reality setting that addresses these limitations [27, 28]. Hybrid reality is unique in that operators not only work within a virtual environment, but physical objects, advanced tracking systems, and various other technologies (e.g., procedure assistant, voice recognition, feature tracking, etc.) also are incorporated to create a highly realistic and immersive simulated environment.

To date, the SHyRE program has integrated handheld scientific instruments into a scientifically relevant geologic scene and developed a preliminary set of human planetary exploration testing scenarios. These scenarios include part-task training and procedure development of the scientific instruments as well as prototyped informatics displays to study in-situ data analysis and utilization. The application of this analog environment has immediate implications and opportunities to inform future planetary missions and science investigations by rapidly prototyping and testing new scientific instruments with relevant data processing activities (e.g., archiving and analysis) embedded within realistic/envisioned flight operational constraints. It is anticipated that relevant elements of the SHyRE environment will be incorporated as “modules” into future APACHE simulations and vice-versa, with significant overlap in personnel and technologies already existing between the projects.

Status: Ongoing [27, 28].

### 3.3.6 INTEGRATED EXPLORATION EVA FIELD SIMULATIONS

Integrated exploration EVA field simulations, similar to Desert Research and Technology Studies (DRATS) tests from 2008-2011, can serve as important opportunities to evaluate exploration ConOps, capabilities, and prototype technologies. These type of simulations can be conducted in environments that combine high-fidelity, flight-like operations; integration with multiple other systems; and include many of the other flight-like challenges associated with field environments such as dust, rough terrain, and communication challenges. In the past, such tests also have served as valuable focusing elements and milestones for multiple separate but interrelated projects.

The scope, location, and timing of these simulations have not been determined yet, but are expected to involve implementation and testing of the current exploration ConOps and surface system prototypes such as EVA tools and informatics. These tests may not include pressurized suit testing, because of the lack of a portable gravity offload system at this time, but they are expected to use prototype xEMU informatics in combination with the EVA Mission Systems Software (EMSS) (see Section 3.5.3).

Status. Planned to begin FY21.

### 3.3.7 TERRESTRIAL FIELDWORK CHARACTERIZATION

There remains a lack of understanding regarding the intrinsic operational challenges, success criteria, cadence, and behaviors that field scientists must overcome and exhibit to achieve their fieldwork objectives in present-day terrestrial settings, let alone hypothesized future spaceflight missions. This task aims to characterize the physical and cognitive demands associated with “Earth normal” scientific fieldwork, to inform the development and testing of ConOps, tools, technologies and techniques in laboratory environments, where the physical, cognitive, and operational constraints of spaceflight can be more realistically simulated as compared with field analogs.

Pilot work has been initiated to more directly study the rudimentary components of the scientific process within traditional terrestrial fieldwork. Using a combination of data collection methods that include audio, video, and motion-based wearable sensors such as inertial measurement units (IMUs), this work can characterize the work performed by field scientists to understand the moment-to-moment relationships between the cognitive challenges and physical behaviors demonstrated throughout their lunar-relevant field campaigns. These insights then can be integrated into ongoing complementary development and testing activities at NASA JSC that incorporate high-fidelity spaceflight constraints. As a result, this project will generate grounded work representations that span multiday, multisite fieldwork campaigns to better define spaceflight exploration concepts and technologies that account for realistic scientific fieldwork demands and productivity.

The Workload and Fatigue study, as well as future evaluations of EMSS and xEMU Informatics using PACES will utilize ConOps that are based on the results of these studies.

Status: Pilot work performed in FY19 and continues in FY20 with a NASA TRISH Post-Doctoral award

### 3.3.8 HUMAN HEALTH AND PERFORMANCE IMPLICATIONS OF EVA

Although EVA ConOps documents are maintained for design reference missions by the EVA Office (EVA-EXP-0042), in some cases they do not include the necessary detail to inform the design of HH&P studies or they lack detail on expected human constraints and considerations that may affect architectural decisions. Through close coordination with the EVA Office and the Flight Operations Directorate, existing ConOps documents will be supplemented with documentation of relevant HH&P data and assumptions, including information such as estimated metabolic rates, ground reaction forces, task types and frequencies, and decompression profiles. This task will ensure appropriate documentation and, where possible, publication of the results and outcomes of the activities described in the CHP EVA Roadmap.

Status: Ongoing. FY20 efforts are focused on publication of xEMU Inspired $CO_2$ requirements development including: EMU inspired $CO_2$ characterization; inspired $CO_2$ literature review; xEMU requirement development [29, 30]. Status: Ongoing. FY20 efforts are focused on publication of xEMU Inspired $CO_2$ requirements development including: EMU inspired $CO_2$ characterization; inspired $CO_2$ literature review; xEMU requirement development[13, 30].

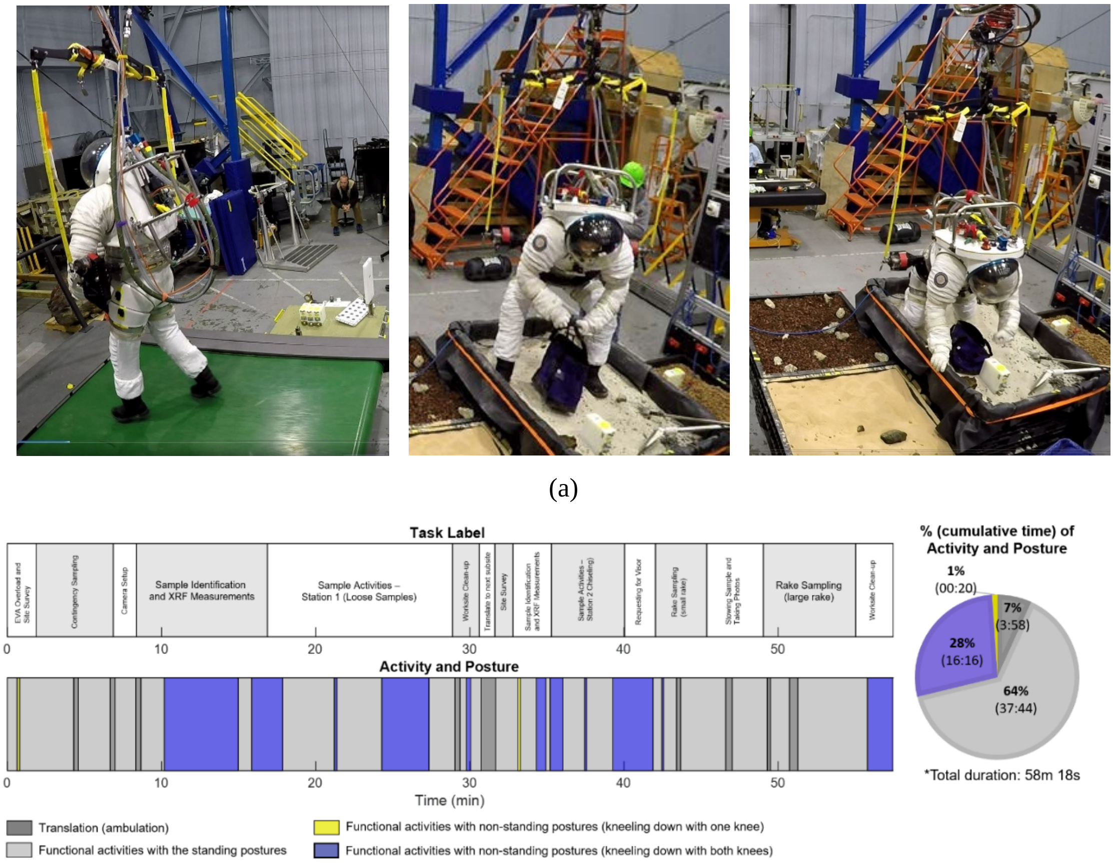
## 3.4 EXTRAVEHICULAR ACTIVITY HUMAN HEALTH AND PERFORMANCE STATE ESTIMATION

Tasks in this section are primarily associated with Table 1 CHP.EVA.PHYS Gap: *Predictive estimates of individualized crew health and performance state associated with anticipated EVA tasks during lunar surface, Mars transit, and Mars surface exploration missions.*

### 3.4.1 EVA HUMAN HEALTH AND PERFORMANCE MODEL

The EVA HH&P Model will be a model for providing time-varying estimates of EVA translation distances, joint cycles, ground reaction force dose, decompression stress, workload, physical and cognitive fatigue, hydration, nutrition, metabolic rates, heat storage, inspired $CO_2$ exposure, and consumables usage rates when given model inputs including suit mass, gravity level, task type, and other individualized health and performance predictors. Additional metrics determined through the EVA Standard Measures study may also prove valuable in this model as surrogates for values that cannot be directly estimated or measured, and data from the Workload and Fatigue study may also be used to incorporate fatigue-related effects. Model outputs will inform fitness for duty standards, exercise prescriptions, prebreathe validation protocols, suit lifecycle information for certification profiles, EVA consumables sizing and monitoring, and may also inform exploration concepts of operations, task design, and eventual exploration EVA planning. This model will also function as a core component of the EMSS, described in Section 3.5.3.

Mobility required of crewmembers to perform various EVA tasks is an important component of the EVA HH&P Model, as it has implications for fatigue, injury risk, and suit component cycling. IMUs on each segment of the spacesuit during ground testing can characterize the postures and activities of the astronauts. Currently, postures and activities evaluated with the IMUs include ambulation, standing, bending over, and kneeling. Figure 8 (a) shows examples of the postures and activities during EVA-like tasks, such as deploying science experiments on the lunar surface. The duration and percentage of each activity type classified by IMUs and their corresponding health and performance metrics can provide both quantitative and objective data for the model and work-domain characterizations. An example report is shown in Figure 8.


(a)

(b)

**Figure 8. (a) Examples of postures and activities: walking on the treadmill (left); standing with torso bent forward (middle), kneeling with both knees (right). (b) Example data representation of periods of functional movements performed by the crewmember.**

The model will use a combination of data from HITL testing, flight and training data, as well as physics-based models where available. The model will begin with existing datasets and physics-based models and will be incrementally updated and validated through prediction and incorporation of additional datasets as they become available. Studies associated with Human Systems EVA Gaps 6, 7, and 9 (reference Table 2) will provide the primary sources of empirical data, and the PACES methodology will ensure that data sets can be utilized from different tests, test subjects, and environments.

Status: Funded. This task was initiated in FY20 with an initial focus on modeling of metabolic rates.

### 3.5 EXTRAVEHICULAR ACTIVITY INFORMATICS AND DECISION SUPPORT SYSTEMS

Tasks in this section are relevant primarily to the Table 1 CHP.EVA.INFO Gap: *EVA operations software and informatics for ground controllers, IV crew, and/or EVA crew that enables effective and efficient awareness, prediction, and utilization of crew state information.*

The CHP EVA Roadmap includes tasks in the area of EVA Decision Support Systems (DSS). DSS can be thought of as a distinct class of work support tools that fit within a suite of operations systems that enable human spaceflight operations across all phases of a mission. Existing technology development roadmaps lack an overarching program that feeds directly to the design and development of software capabilities that support the volume and variety of work support needs to enable future spaceflight operations beyond ISS operations. This document does not address the broader DSS needs of future missions, but focuses on EVA DSS.

During ISS EVA operations, a fleet of ground support personnel use Microsoft Office products, custom console displays, mental calculations, and hand-written notes to manually monitor suit/vehicle systems as well as manually adjust timeline elements such as tasks and detailed procedures all while the crewmembers are actively engaged in manual tasks. More critically, solutions to issues/hazards such as hardware configurations, incorrect procedure execution, and life support system diagnosis are provided mostly in real-time, by ground support personnel[31]. While this has worked acceptably for ISS EVAs, lunar and Martian exploration EVAs will be more physically demanding, more frequent, more hazardous, less structured, and more autonomous than ISS EVAs, which are typically very well-rehearsed by all members of the flight and ground crew before execution. The inherently unpredictable nature of exploration EVAs in combination with the decreased communication bandwidths and increasing communication latencies between ground support teams and in-flight crewmembers will further necessitate the reallocation of system monitoring and decision-making responsibilities to the inflight crewmembers and their support systems.

There is a prevalent assumption that, by providing future crewmembers with all the available information on a helmet-mounted or arm-cuff display, they will be able to both manage the EVA timeline and systems all while actually executing the EVA tasks. Such an approach is not feasible without significant investment in decision support systems; the experience, cognitive capacity, and judgement of multiple expert EVA ground controllers cannot simply be replaced by provision of additional crewmember displays. Empowering crewmembers and ground controllers with the information they need, when they need it, is critical to enabling the increasingly autonomous operations required by Exploration-class missions.

Decision support systems for exploration will consist of suites of tools and capabilities for the creation, distribution, manipulation, and utilization of operationally relevant workflows and data. Tools and capabilities are expected to consist of sensors, displays, interfaces, models, and software distributed across vehicle, space suit, and ground control systems. In some cases, within- and between-individual differences in metabolic profiles, $CO_2$ production, aerobic capacity, muscle strength, task performance, cognitive and physiologic state, and other operationally relevant factors also may be incorporated to enable individualized decision support (as currently provided through ground-based flight surgeon judgement).

Applications of an EVA DSS capability will span all mission phases, including mission planning and development, training, mission execution, and post-mission analysis and archiving. Some specific design and development efforts that resemble this concept have occurred in recent years [32, 33] and more broadly to support EVA operations from an intravehicular operator position [34-37]. However, there remains the need for construction of an EVA DSS framework and strategy that encompasses the broad range of DSS capabilities to support the future exploration EVA work domain. Furthermore, to ensure DSS tool implementation and utility, DSS tools must be integrated from the beginning of the training flow, years ahead of the planned mission, to ensure these tools allow seamless use and interaction by crew during mission operations ("Train as you fly"). Tasks described in this section are intended to provide this framework and strategy.

### 3.5.1 EXTRAVEHICULAR ACTIVITY BIOMEDICAL MONITORING REQUIREMENTS DEFINITION

This task involved coordination between numerous EVA stakeholders to seek consensus on the biomedical monitoring requirements for exploration EVA missions. Beginning with requirements and rationale developed during the Constellation Program, the multidisciplinary team considered which data are minimally necessary. The final products were updates to NASA Standard 3001 Volume 2 [12] and the requirements documents for the xEVA System (SSP 51073, Exploration EVA Suit Systems Requirements Document [38]) and the xEMU (CTSD-ADV-1188 , Project Technical Requirements Specification for the Exploration Mobility Unit (xEMU) Project [39]). The final products were updates to NASA Standard 3001 Volume 2 [12] and the requirements documents for the xEVA System (SSP 51073, Exploration EVA Suit Systems Requirements Document) and the xEMU (CTSD-ADV-1188, Project Technical Requirements Specification for the Exploration Mobility nit (xEMU) Project).

Status: Complete. Although, the minimum set of requirements has been established, the concept of operations is still in work and will be defined in new Exploration programs and led by xEMU documentation. Other tasks including PACES, EMSS and xEMU Informatics Interfaces will further define these concept of operations. Open questions include whether data should be self-monitored, monitored by another crewmember, monitored by the ground, and/or monitored by an algorithm. More specific knowledge gaps and associated tests may be identified if existing literature and experience are found to be inadequate to make specific recommendations.

### 3.5.2 NEUTRAL BUOYANCY LABORATORY METABOLIC RATE INFORMATICS

The H-3PO Laboratory measures and records metabolic rates during EVA training runs at the NBL as part of a medical requirement for the ISS. These metabolic rate profiles provide flight surgeons, biomedical engineers, and EVA planners with important information regarding normal and expected metabolic rates for specific tasks, which can vary significantly from crewmember to crewmember. Metabolic rate feedback also has been requested by some crewmembers for situational awareness and use as a training aid, with lower metabolic rates often associated with improved task performance efficiency. The data also are valuable in investigating mishaps or anomalies that can occur during NBL training and testing.

In 2018, H-3PO was asked to begin collecting metabolic rates during all suited NBL runs, rather than the subset of runs that are requested for medical monitoring requirement. Additionally, the H-3PO team recognized opportunities to improve the efficiency with which metabolic rate data were both recorded and processed, as well as possibly improving the utility of the data to trainers and crewmembers by making it available immediately post-run, and possibly in real-time during runs.

In 2019, H-3PO upgraded the metabolic rate, data-collection hardware to transition to a sensor that requires only monthly, rather than daily calibration by H-3PO employees. The H-3PO has worked with NBL personnel to test this new system and then packaged the hardware into enclosures that are now mounted on the Environmental Control System (ECS) panels at the NBL. Six total, one for each NBL umbilical, are installed at the NBL, and each includes $CO_2$ sensors, cables for data transmission from ECS flowmeters, Raspberry-Pi-based data acquisition devices, Ethernet connection to a Lab DMZ subnetwork, and a touchscreen with a Graphical User Interface (GUI). This GUI enables ECS operators to start and stop data collection and to view/verify the metabolic rate data collection is working properly in real-time. This system has reached operational readiness as of March 2020.

The next phase of this project in 2020 is working on a web application to make the metabolic rate data available in real-time to trainers and other authorized personnel, and to begin expediting the process by which metabolic rate data reports are processed to provide individualized task-by-task metabolic rate estimates for each crewmember. The EVA HH&P Modeling team is currently working on task-based estimations, and future plans with the EVA Mission Systems Software team include automating this data analysis and report generation.

Status: Ongoing. Completion is expected in 2020. This is a component task of the broader EMSS, described next, as well as the EVA HH&P Model that was described earlier.

### 3.5.3 EXTRAVEHICULAR ACTIVITY MISSION SYSTEMS SOFTWARE

The EMSS is a team focused on integrating cross-organization software in the planning, training, execution, and exploration phases of ISS and Artemis EVA operations. EMSS has adopted the Plan-Train-Fly-Explore mantra as an extension of the Flight Operations Directorate's (FOD's) Plan-Train-Fly, emphasizing the importance of collecting and analyzing mission data during and after missions. The EMSS aims to dramatically reduce the effort to view and manipulate data from all Plan/Train/Fly/Explore phases, thereby reducing risk to crew, improving probability of mission success, reducing resources and time required during planning and training phases, and improving data collection for human performance and geologic analysis.

The EMSS produces a suite of decision support tools and capabilities for the creation, distribution, and utilization of operationally relevant EVA workflows and data. Tools and capabilities are expected to consist of sensors, displays, interfaces, models and software distributed across EVA systems, including not only EVA crewmembers and their space suits, but also IV crewmembers and Mission Control Center. Applications of EMSS span all EVA mission phases, including mission planning and development, mission execution, and post-mission analysis and archiving. The EMSS platform aims to iteratively prototype and evaluate potential EVA data streams, visualization tools, algorithms and interfaces within current operations and proto-flight testing environments with the purpose of meaningfully influencing and enhancing EVA operations and informatics.

The relevant communities of EVA stakeholders that EMSS aims to support include: EVA and Program Management, Engineering, Crew Health and Performance, Operations, Safety and Mission Assurance, and Researchers. Each of these EVA stakeholders all have specific EVA interests, needs, and desired contributions to the development of future EVA concepts to which EMSS can provide customized and extensible solutions to meet these users' needs. In doing so, specific capabilities that are demonstrated to meaningfully enhance EVA operations will be brought forward for consideration for flight implementation.

The EMSS platform enables users to prepare, live, and re-live EVA experience(s) to discover higher-level insights/structure whether it be within present-day EVA operations or for future Exploration EVA settings. Specifically, EMSS provides a suite of user-friendly tools to:

1. Reliably ingest relevant data sources into a platform for real-time operations support and post hoc research/analysis
2. Visualization tools for time series data to overcome challenges associated with multiple time series data streams collected from disparate data sources
3. Create reproducible and collaborative data archiving and analysis pipelines
4. Share data and processes with other EVA stakeholders

5. Interface with other Crew Health and Performance data systems (e.g., habitat, exercise, medical) to provide a comprehensive analysis of crew status

In summary, the EMSS platform enables a "practice like you play" approach to the EVA community to more appropriately discover and demonstrate the capabilities desired to support present-day and future EVA operations.

Figure 9 provides an example of users' needs related to the integration of physiologic and operational data. In the example, data that are collected during real and simulated EVA conditions can be automatically associated with tasks being performed using Maestro, EMSS' procedure authoring and execution tool. Task execution and physiologic performance data can be archived during EVA execution, generating an ever-increasing relational database of physiologic and life support data. These data then can be combined with physics-based and data-based models of life support systems, physiology, health, and performance, which together provide an extensible capacity to predict the capabilities and constraints of the EVA-human system to the resolution of specific crew and hardware. The intent here is that a priori EVA data can inform EVA operations and vice versa, thereby "closing the loop" between the EVA development, planning, execution, and analysis processes. Data can be visualized using CODA, EMSS' application for consolidating the context of missions, training, and testing into an easy to use platform to relive and revisit each moment.

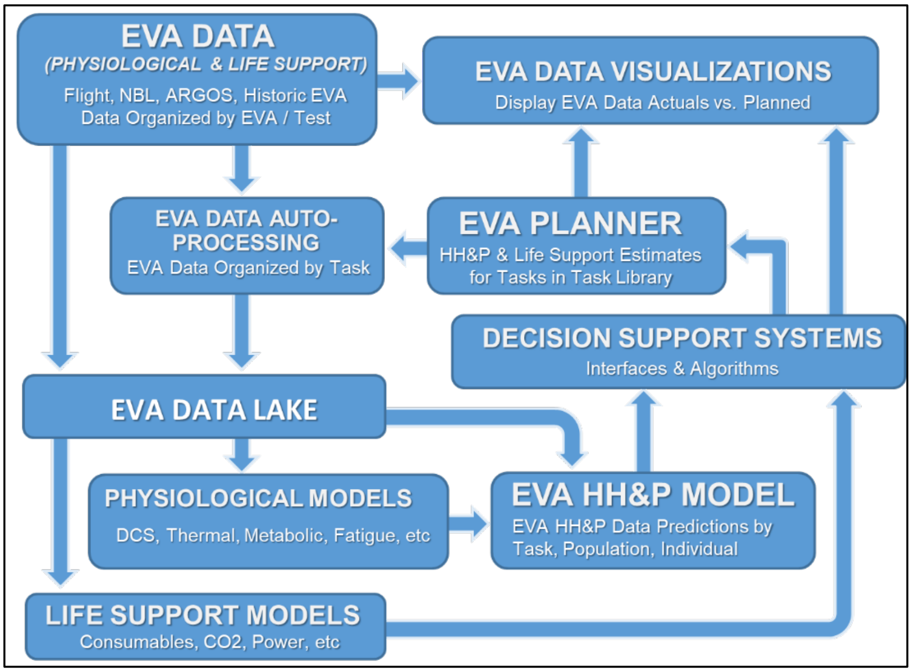


**Figure 9. Example of EVA data sources, models, and capabilities integrated to provide enhanced functionality. Note that this example is not encompassing of all anticipated EMSS functions and user cases.**

The EMSS will be iteratively developed, tested, and implemented across multiple laboratory, analog, training, and, ultimately, flight environments, using open source and existing software tools and teams wherever possible. Prototype EVA data streams, visualization tools, and algorithms will first be developed and tested within lab-based EVA simulation environments (e.g., APACHE) before being deployed to actual EVA training environments (e.g., NBL, ARGOS) for further evaluation and user feedback. Deployments into Mission Control and future spacecraft and potentially space suits for flight use will follow. Capabilities will be developed, tested, and deployed incrementally over multiple years. Maestro is currently in use for some NBL and simulation events, and will be deployed for development of ISS EVAs in late FY20. CODA is in early prototype phase, building upon previous CODA-like applications.

Where possible EMSS uses data to determine what to build and how to build it, but greater focus is put on building products and releasing new versions early and often to garner user feedback. Maestro was initially released as an alpha-quality product with known bugs, but was well received by members of the EVA community because of the problems it solves. Those users are providing frequent feedback to inform ongoing Maestro development.

Development, testing, and implementation within ground laboratory environments enables rapid and cost-effective design-build-test cycles. The utilization of analogs such as HERA and other settings may also be utilized on a case-by-case basis, depending on the specific capabilities being evaluated, compatibility with other analog mission objectives, and the availability of necessary data infrastructure. The NBL will be a valuable test environment on the path to flight due to the availability of space suits, EVA-trained astronauts, EVA flight-controllers and trainers, and a control room. In fact, the capabilities provided by EMSS are expected to provide direct benefit to the NBL training environment. Likewise, the NBL will be used as an analog environment to evaluate the utility of EMSS functions in current and future flight-like EVA simulations.

The EMSS products and capabilities developed initially for training and testing environments will be evaluated for use in mission environments where appropriate. For example, Maestro is currently in use to for developing training and test procedures, and is planned to be used in flight as early as 2021. NBL Helmet Mounted Display, however, is not planned to evolve into a flight product, but is intended as a low-cost solution to inform flight products like the non-EMSS “JARVIS” display. CODA may be developed for mission data first, due to the maturity of available APIs, and is expected to be functional for mission usage in 2021.

Status: EVA Mission Systems Software was created in April 2020 as a reorganization of the previous EVA Operations System (EOS) project. Where EOS was a project based in the HHPD, EMSS is a joint project between the following cross-directorate divisions:

1. SK: JSC’s HHPD, Biomedical Research and Environmental Sciences Division
2. XI: JSC’s Exploration Integration and Science Directorate, Astromaterials Research and Exploration Science (ARES) Division
3. CX: JSC’s Flight Operations Directorate, EVA, Robotics and Crew Systems Division

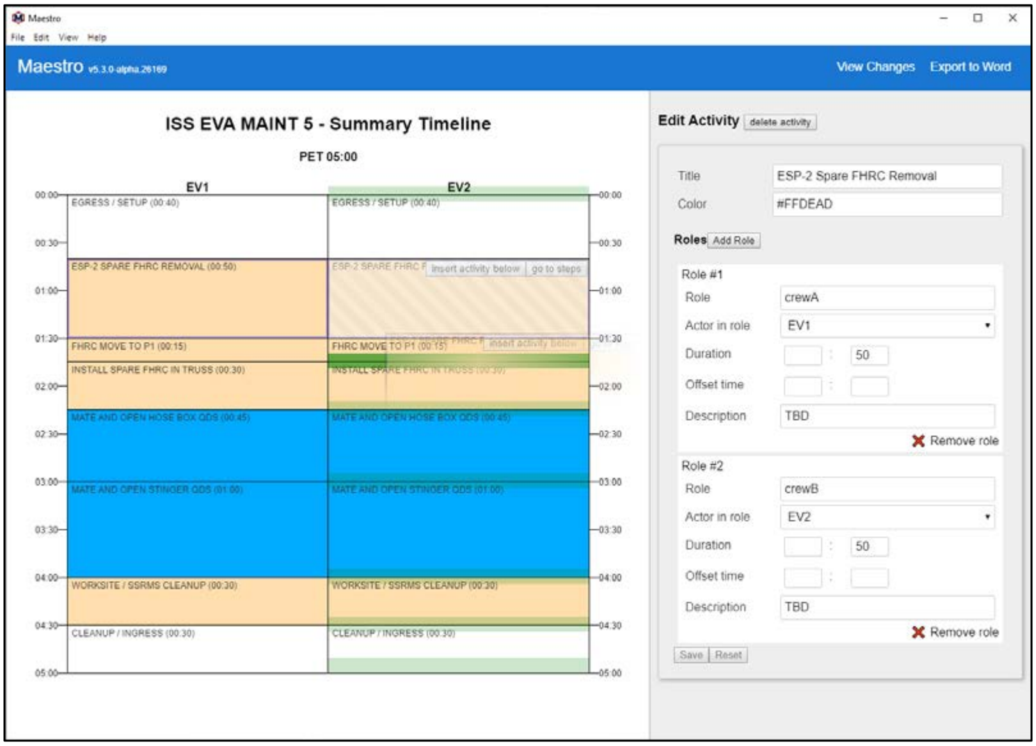
This reorganization creates an environment that leverages pre-existing software development efforts while avoiding duplication of effort. Furthermore, other organizations outside SK, XI, and CX also are working similar efforts, and by approaching those organizations as a collective rather than individual organizations there is greater likelihood of further collaboration.

The primary focus of EMSS for FY20 is the Maestro application. Maestro is designed to greatly simplify the process of authoring and maintaining EVA procedures, which have historically been very cumbersome. Since Maestro has been under EMSS direction, the following major improvements have been made:

1. Improved the ability to import existing EVA procedures in Microsoft Word format and non-EVA procedures in ISS "IPV" format.
2. Simplified editing experience, giving authors a cleaner user interface (Figure 10, Figure 11).
3. Created export formats to send Maestro content into Playbook and MediaWiki applications (Figure 12).

The remainder of FY20 will be focused on three goals:

1. Making Maestro able to fully develop EVA procedures for ISS EVAs and greatly improving the efficiency of EVA authors.
2. Allowing timestamped step completion tracking for export into HH&P databases, to correlate human performance data specific actions performed by EVA crewmembers.
3. Communicating step completion information in Maestro to Playbook



ISS EVA MAINT 5 - Summary Timeline

PET 05:00

| EV1 | EV2 |
|---|---|
| EGRESS / SETUP (00:40) | EGRESS / SETUP (00:40) |
| ESP-2 SPARE FHRC REMOVAL (00:50) | ESP-2 SPARE FHRC F |
| FHRC MOVE TO P1 (00:15) | FHRC MOVE TO P1 (00:15) |
| INSTALL SPARE FHRC IN TRUSS (00:30) | INSTALL SPARE FHRC IN TRUSS (00:30) |
| MATE AND OPEN HOSE BOX QDS (00:45) | MATE AND OPEN HOSE BOX QDS (00:45) |
| MATE AND OPEN STINGER QDS (01:00) | MATE AND OPEN STINGER QDS (01:00) |
| WORKSITE / SSRMS CLEANUP (00:30) | WORKSITE / SSRMS CLEANUP (00:30) |
| CLEANUP / INGRESS (00:30) | CLEANUP / INGRESS (00:30) |

**Edit Activity**

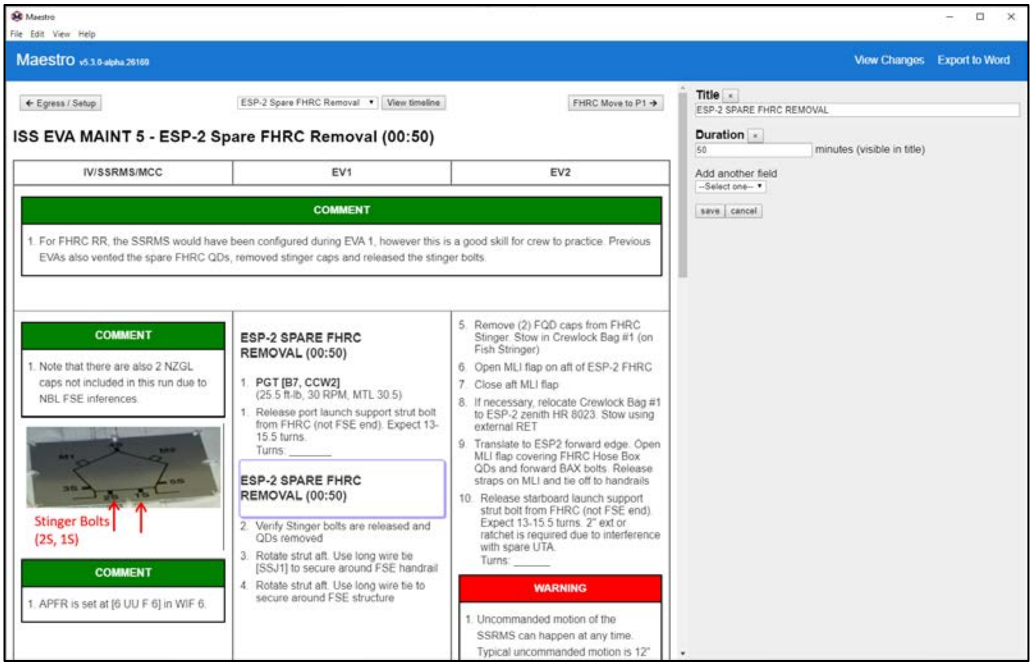
Title: ESP-2 Spare FHRC Removal
Color: #FFDEAD

**Roles**

Role #1
Role: crewA
Actor in role: EV1
Duration: : 50
Offset time: :
Description: TBD

Role #2
Role: crewB
Actor in role: EV2
Duration: : 50
Offset time: :
Description: TBD

**Figure 10. Dragging a task in summary timeline within Maestro.**



ISS EVA MAINT 5 - ESP-2 Spare FHRC Removal (00:50)

**COMMENT**

1. For FHRC RR, the SSRMS would have been configured during EVA 1, however this is a good skill for crew to practice. Previous EVAs also vented the spare FHRC QDs, removed stinger caps and released the stinger bolts.

**COMMENT**

1. Note that there are also 2 NZGL caps not included in this run due to NBL FSE inferences.

**COMMENT**

1. APFR is set at [6 UU F 6] in WIF 6.

**ESP-2 SPARE FHRC REMOVAL (00:50)**

1. **PGT [B7, CCW2]** (25.5 ft-lb, 30 RPM, MTL 30.5)
1. Release port launch support strut bolt from FHRC (not FSE end). Expect 13-15.5 turns.
   Turns: ______

**ESP-2 SPARE FHRC REMOVAL (00:50)**

2. Verify Stinger bolts are released and QDs removed
3. Rotate strut aft. Use long wire tie [SSJ1] to secure around FSE handrail
4. Rotate strut aft. Use long wire tie to secure around FSE structure
5. Remove (2) FQD caps from FHRC Stinger. Stow in Crewlock Bag #1 (on Fish Stringer)
6. Open MLI flap on aft of ESP-2 FHRC
7. Close aft MLI flap
8. If necessary, relocate Crewlock Bag #1 to ESP-2 zenith HR 8023. Stow using external RET
9. Translate to ESP2 forward edge. Open MLI flap covering FHRC Hose Box QDs and forward BAX bolts. Release straps on MLI and tie off to handrails
10. Release starboard launch support strut bolt from FHRC (not FSE end). Expect 13-15.5 turns. 2" ext or ratchet is required due to interference with spare UTA.
    Turns: ______

**WARNING**

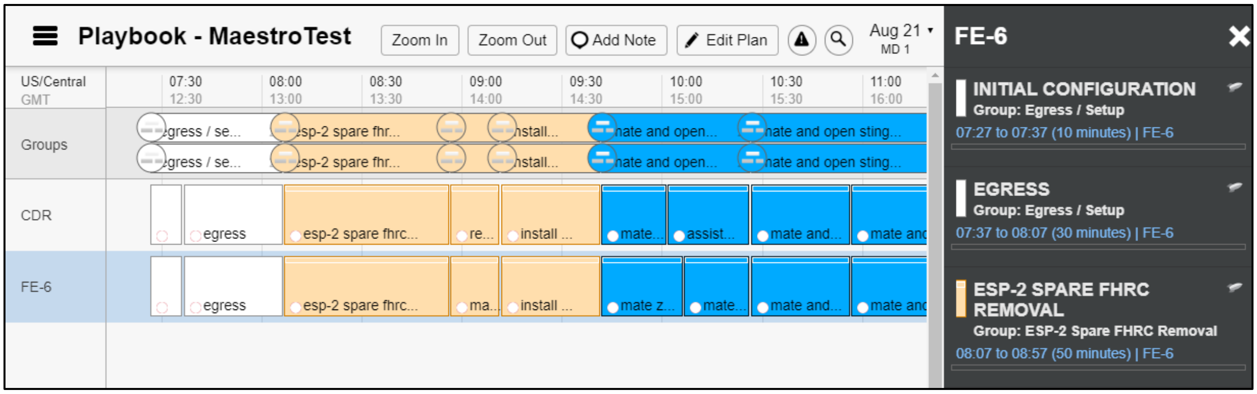
1. Uncommanded motion of the SSRMS can happen at any time. Typical uncommanded motion is 12"

**Title** ESP-2 SPARE FHRC REMOVAL

**Duration** 50 minutes (visible in title)

Add another field --Select one-- ▾

Figure 11. Step editing in Maestro.



**INITIAL CONFIGURATION**
Group: Egress / Setup
07:27 to 07:37 (10 minutes) | FE-6

**EGRESS**
Group: Egress / Setup
07:37 to 08:07 (30 minutes) | FE-6

**ESP-2 SPARE FHRC REMOVAL**
Group: ESP-2 Spare FHRC Removal
08:07 to 08:57 (50 minutes) | FE-6

Figure 12. Maestro procedure rendered in Playbook.

### 3.5.4 JOINT AUGMENTED REALITY VISUAL INFORMATICS SYSTEM (JARVIS)

The Joint Augmented Reality Visual Informatics System (JARVIS) is a heads-in display (HID) displays and controls (D&C) solution intended for the NASA's new spacesuit, known as xEMU. The overall goal of JARVIS is to enable crew autonomy during EVA by providing crewmembers direct access to the information necessary for them to accomplish their mission goals. The JARVIS is currently funded as an Early Career Initiative from the Science and Technology Mission Directorate with an infusion path intended for development toward D&C and accessory port interface requirements within xEMU. The JARVIS team is addressing three unique challenges: (1) solving the unique optics problem associated with having a near-eye display compatible with the xEMU helmet configuration, (2) integrating with the informatics systems currently employed in the xEMU design, and (3) demonstrating the utility and value of including the JARVIS display solution within the concept of operations of future EVA. Deliverables will reduce risk of the xEMU program not satisfying display requirements when they move from "deferred" status to "active."

Addressing the technology gaps regarding these display requirements now early within the life cycle of the xEMU project has the potential to increase display system technology readiness level leading up to 2024 while minimizing redesign, cost, and schedule impacts as xEMU evolves. The JARVIS will not initially be part of the xEMU Demo (ISS) or Lunar 2024 (Artemis III) missions, though scarring will exist that will enable JARVIS to be added to the xEMU for future missions.

Status: Ongoing.

#### 3.5.5 HELMET MOUNTED DISPLAY

The H-3PO, in collaboration with University of California-Davis, is developing the EMU Helmet-Mounted Display (HMD): an externally mounted display for the EMU helmet, consisting of a suit-side computing unit and a small display screen mounted to the outside of the EMU visor. This HMD project is enabling real-time metabolic rate data, phase elapsed time, and simulated data to be displayed to crewmembers during NBL training runs. The HMD is a low-tech, low-cost, and short timeline solution to introduce head/helmet display informatics to EVA training at the NBL. Initial ground testing will help the team refine the HMD design before utilization during suited NBL tests.

During both the ground testing and NBL testing, the team will receive feedback that will be used to improve this display and to provide input to the development of JARVIS and other xEMU informatics designs. Although the HMD is a technology demonstration and initial proof of concept for informatics displays in the NBL, the intent is that the NBL integration and operations practice, as well as HMD user feedback will help guide future implementation of more technologically advanced displays in the NBL and on future space suits.

Status: Ongoing. Data collection planned for Summer/Fall 2020. Crewmember interaction with the display will initially be voice-based; a wrist-mounted interface, possibly including an additional display, is currently being considered as an additional low-cost ground-based research platform.

#### 3.5.6 DIVER AUGMENTED VISION DEVICE (DAVD)

The Diver Augmented Vision Device (DAVD) aims to provide divers in the NBL with head-mounted-display content driven by topside support. The DAVD will be tested in the NBL for its viability as a platform that can be utilized to evaluate informatics capabilities that will be needed in the xEVA suit for Artemis Phase 2 (if not sooner). Tests with DAVD will help determine what kind of information is valuable to have displayed to the EVA crew and will inform development of the xINFO system of the xEMU. In addition, the DAVD tests in the NBL represent mutually beneficial cooperation with another agency, the U.S. Navy, as they continue to further develop this system for their divers, and possibly even assist with developing a Heads-Up Display for the xEVA suit.

Status: Initial testing was conducted in the NBL in fall 2020.

### 3.6 ANTHROPOMETRY AND SUIT FIT

Tasks in this section are relevant to the Table 1 CHP.EVA.FIT Gap. *EVA suit sizing and fit methods and hardware that is within applicable CHP EVA standards for microgravity, lunar surface, and Mars surface exploration missions.*

It is understood that certain critical dimensions of EVA suits relative to critical anthropometric dimensions of the human inside the suit can significantly affect the comfort and performance 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 also is 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 [40]. These data are necessary to inform the degree of customization that must be provided by space suits, including spares, to ensure that inadequate suit fit will not significantly impact crew health and performance during EVA, including accommodation for the potential impact of in-flight anthropometric changes. Suit-fit sensitivity characterization also will 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 and valid model also may reduce the fit check iterations necessary to obtain an acceptable suit fit.

### 3.6.1 Human - Space Suit Interaction Modeling

A simulation of human-suit interaction can help improve suit designs by developing optimized hardware solutions for human performance and anthropometric accommodation. Optimization of the bearing type, size, orientation, and location with respect to human-body joint centers of rotation may reduce the risk of injury, increase comfort, and increase human task performance capabilities. Computer models of the suit and its wearers (Figure 13) that can be repositioned and animated through different motions can be used to predict potential suit design issues and functional limitations, as well as aid in predicting suit sizing for a given individual. The goal is to develop a predictive model that, given inputs of an individual's anthropometric dimensions and a space suit's design features, will provide a quantitative estimate of performance aspects such as range of motion. Additionally, the model will be able to inform suit fit for specific individuals in each of the critical dimensions, which will require developing the criteria for permissible interaction forces as a function of location, as well as permissible misalignments between the human joint and the suit. In addition to individual predictions of suit fit, the model will be used to perform fleet sizing analyses, providing estimates of the proportion of the general or astronaut population accommodated with acceptable suit fit by different suit design and sizing strategies.

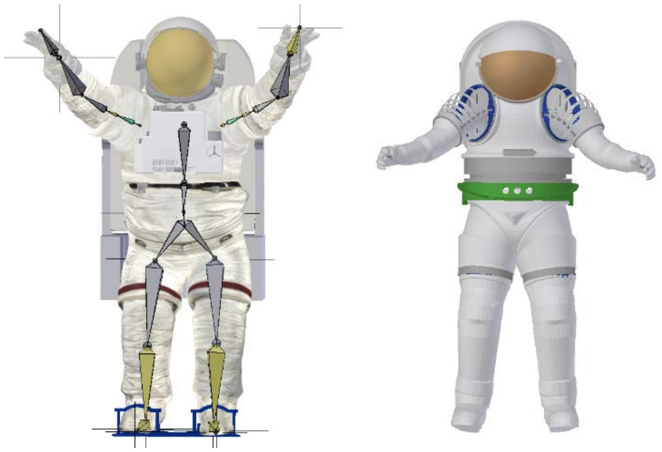


**Figure 13. Prototype versions of the EMU (left) and MK III (right) computer models showing the armature that is used to control the posture of the suit.**

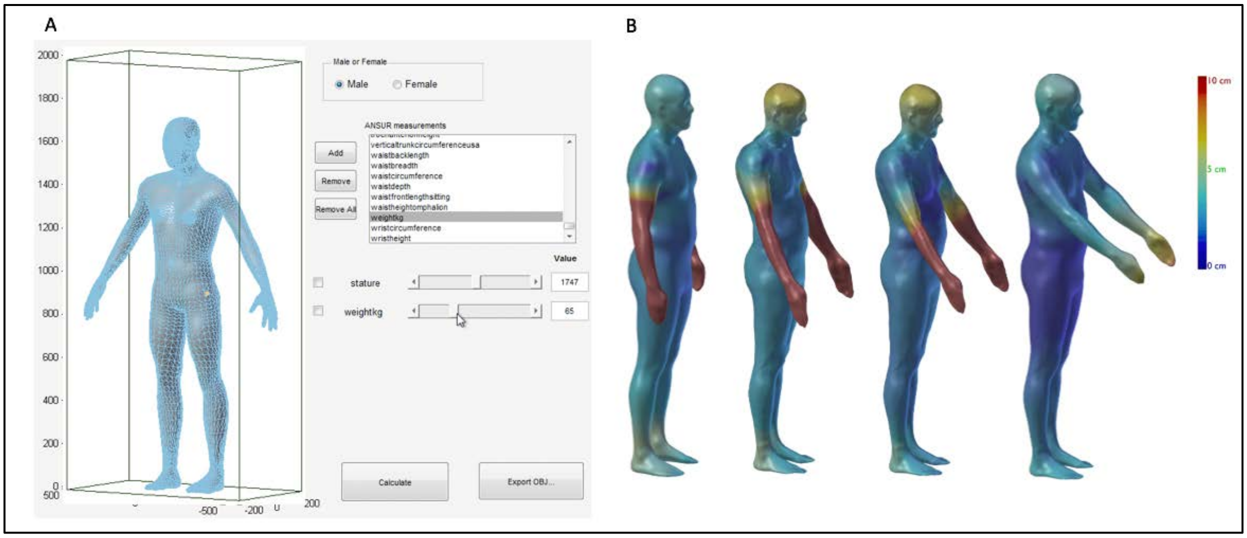
The focus of recent work on human-space suit interaction models was integration of a parametric human model with existing suit computer-aided design (CAD) models. This has improved upon previous efforts to model humans based on linear anthropometry by adding greater fidelity to the body shape represented for each individual that is modeled. Current work is focused on incorporation of soft goods suit components to more realistically constrain the human within the suit from head to toe. Interference detection mapping between the human and suit also is under current development that will further enhance understanding about fit in the suit.

Status: In progress. Project is currently funded by the EVA Office and led by the ABF.

### 3.6.2 VIRTUAL SUIT FIT ASSESSMENTS FOR xEMU FLEET SIZING

Customized models of human body shape (manikins) are a critical component of the Human-Space Suit Interaction Models. The ABF maintains a database of 3D scans collected from crewmembers and test subjects that can be used for predictive assessments. Although the database includes an extensive number of scans in multiple different poses, it may not represent the entire population of current and future crewmembers. Thus, when a body shape that does not exist in the current database has been needed for suit evaluations (e.g., extremely large or small size persons), the scan of the subject with closest anthropometry dimensions has been used in substitution.

A new technique was developed in which a statistical model was created based on the scans [41]. The scan geometry data were dimensionally reduced, and statistically predicted from the anthropometry dimensions critical to suit design, such as stature, shoulder width, etc. The new technique essentially enables scaling, interpolating, and extrapolating the scan dataset to approximate the body shapes that do not exist in the current database. The technique was developed into a software tool with a graphical user interface (Figure 14A). The user can enter the desired anthropometry dimensions and the tool can visualize and export 3D manikins in standard CAD formats. Larger 3D body databases, such as the U.S. Army Anthropometry Survey (ANSUR), also can be infused into the ABF database to expand the quantity of scan data. However, such databases often lack postures that are relevant to space suit or hardware evaluations. Thus, the scans in the external databases were transformed into the standard ABF postures relevant to suit fit evaluation. Using scans from multiple postures, the posture of these manikins was modeled and manipulated to better represent a specific work posture (i.e., hands projected slightly forward, feet together or apart). Realistic tissue deformation in different postures is difficult to reproduce, so future work is being performed to quantify and improve the accuracy across the deformation area. For example, the ANSUR scans in which the arms are down along the torso (Figure 14B leftmost manikin) were transformed through an iterative algorithm and the outcome is the ABF posture in which the arms are outstretched at 45° of forward flexion (Figure 14B rightmost manikin).



● Male ○ Female

☐ stature 1747

☐ weightkg 65

**Figure 14. A: Software tool for the statistical prediction of anthropometric body models. B: interactive posture transformation algorithm. Color represents the prediction error.**

Virtual fit assessment is the predictive evaluation of suit design for fit and performance. The assessment can be performed before building an actual suit or physical mock-up, thus substantially reducing the time and cost of iterative design modifications. Historically, virtual fit assessment has been performed using a limited number of boundary manikins representing the "worst case" conditions (e.g., the 99th percentile large or 1st percentile small persons). Then the selected body manikins are overlaid within a suit CAD model and the probability of fit is predicted from the suit-to-body clearance and overlap estimations. Although the boundary manikin technique provides a rough approximation of the accommodated population, the assessments using a limited number of worst case conditions do not reveal the specific characteristics of the body and suit geometry inducing fit or lack of fit ("unfit").

A Monte-Carlo technique was developed based on a large number of body shape models, which cover a large area of the target anthropometry space [40, 42]. Each body shape is automatically tested against the suit model and provides a "fit" or "unfit" decision (Figure 15A). Once fit is evaluated for each body shape, the proportion of accommodated population is explicitly counted. Compared to the previous boundary manikin technique, the Monte-Carlo technique has an advantage of identifying the marginally fitting cases (the border between the accommodated and unaccommodated segment in Figure 15B). The marginally fitting cases provide the critical anthropometry dimensions and specific body parts of persons related to suit fit. Furthermore, the boundary cases can help to identify the design issues, such as specific contours of the suit components that can lead to a restricted clearance or unwanted overlap. The Monte-Carlo assessment can be repeated for a set of proposed sizes or configurations of suits. The outcome of the multilayer analyses (i.e., fleet sizing evaluations) can quantify the specific directions and magnitudes of the changes in population accommodation. It is expected that the new technique will provide more direct assessments of suit fit and accommodation than traditional methods, and can be used for design improvements and decisions. A series of HUT fleet sizing analyses are currently underway at the time of writing, with HITL validation testing planned, as described following.

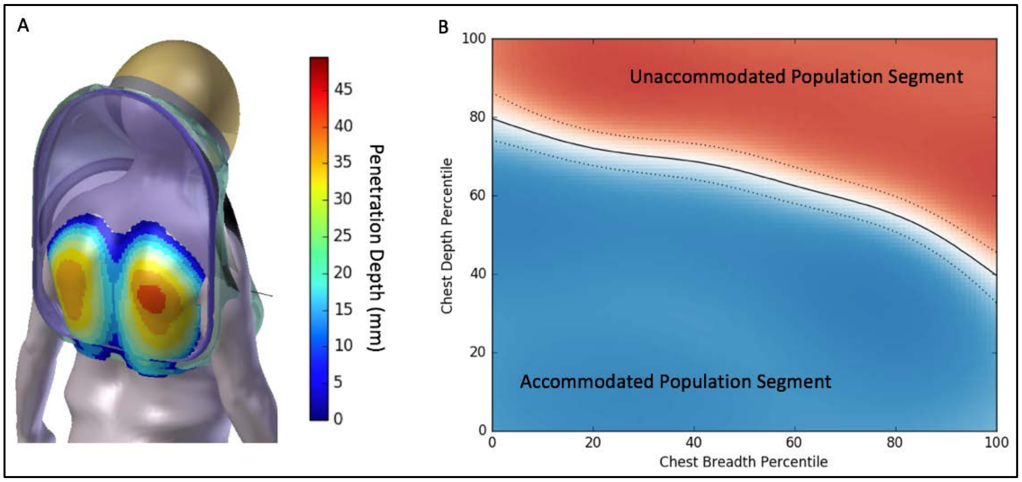


**Figure 15. A: Virtual assessment of suit-to-body overlap. B: Accommodated vs. unaccommodated population segments represented as a function of anthropometry dimensions.**

Status: Ongoing. In FY20, the virtual fit testing methodology was used to assess the hard components of the lower torso assembly (LTA) and a larger size of the hard upper torso (HUT). For the LTA, work focused on the waist bearing hip (WBH) assembly, which includes a brief, waist bearing, sizing rings and flex ring. Initial analysis was performed on the brief component, in the interests of optimizing the design before fabrication. A parametric model was developed of the brief, and fit checked with 3D scans from the ANSUR database (n=5, 6-2). Results of the virtual fit checks were used to modify the shape of the brief, to optimize the accommodation of the predicted user population [42]. This modified brief will be manufactured and included in the planetary LTA design.

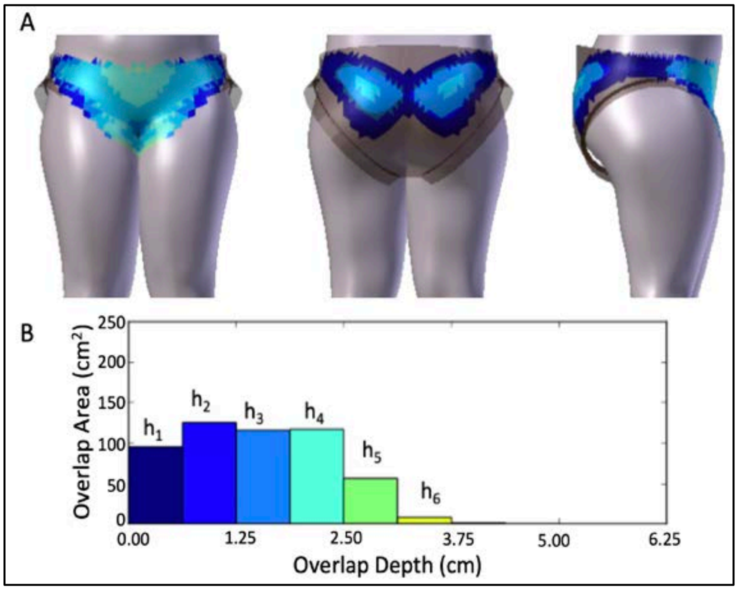


**Figure 16. A: Brief CAD model overlaid with body scan. B: Overlap area and depth histogram.** The overlap depths were color-coded as denoted in panel B. The illustration was made using a statistically synthesized body shape for anonymization.

Following assessment of the brief design, work was expanded to include the entire WBH assembly. The WBH was primarily analyzed for the overall height of the stack as it compared to the shoulder-to-crotch distance of the population. A model was developed to relate body manikin size and shape to an optimal spacing of the brief and HUT, which is achieved by adding sizing rings at the waist.

Also in FY20, virtual fit assessments were expanded to the larger size of the HUT. Following physical fit checks in a 3D-printed prototype and based on results of the virtual fit checking, some small changes were made to the large HUT geometry to improve accommodation. These changes will be evaluated via a new 3D-printed prototype later in 2020.

### 3.6.3 xEMU FLEET SIZING VALIDATION

Extensive work has been performed to model the fit interactions between the xEMU HUT and its intended wearer population. A HITL validation study is used to verify each of the xEMU Fleet Sizing analyses described previously. During these studies, test subjects are evaluated for their fit and performance in the xEMU, to validate the model and to determine whether additional metrics of suit fit should be incorporated. The subject pool has included large subjects who fall on the fit/non-fit boundary, as well as small subjects, who may easily don the suit hardware but may exhibit compromised performance. The utilization of 3D-printed mock-ups has allowed the testing of a much larger population of subjects than would ever be available in the full suit, given the logistics of pressurized suited testing and medical clearance restrictions associated with the pressurized suit.

Building on the EVA HH&P Benchmarking methods, and EVA Standard Measures in future studies, subjects' performance and discomfort will be measured on controlled isolated tasks such as maximal reach envelope, as well as functional tasks such as on-suit reaches and a bolt rotation task. Suited conditions will include initial fit and function assessments in 3D-printed hardware, as well as fully pressurized testing in the xEMU. Results from this test series will be used to distinguish the fit/non-fit boundary, as well as to fine tune the virtual fit model.

Status: In progress. HITL validation testing of the xEMU Medium HUT Fleet Sizing analysis was completed in 2019, followed by xEMU brief validation in early FY20. Large HUT Fleet Sizing validation is currently in progress, and further LTA Fleet Sizing verification is expected to be completed in FY20 – to include additional components of the LTA assembly (flex ring, waist bearing and sizing rings).

In FY19, 3D-printed prototype testing was initiated with the small-medium HUT. Twenty-five subjects were assessed for their ability to don the suit hardware, scanned to document hardware alignment on the body, and tested for functional capabilities such as reach. A contact mapping survey was also conducted. Data were collected in an unsuited condition, while wearing the liquid cooling and ventilation garment (LCVG), and while wearing the 3D-printed hardware.

In FY20, a quick-turnaround fit assessment was performed on the xEMU brief design to allow feedback on the design early in the prototype phase. Twenty-four subjects were assessed in the 3D-printed brief. Data included scans for hardware alignment (Figure 17), functional movement assessments, and contact mapping surveys. Results from these physical fit checks, combined with the virtual fit assessments, were used to modify the design of the brief to better match human contours and improve population accommodation.

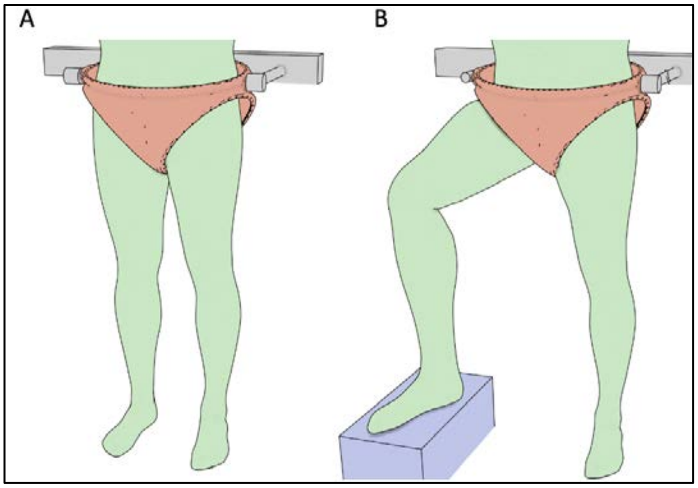


**Figure 17: Standard scan poses for physical fit checking.**

### 3.6.4 SUIT FIT MEASURES

A separate-but-related task will aim to complement subjective ratings of suit fit with objective measures of critical suit fit dimensions. The objective suit fit task is a counterpart to the subjective suit fit methodology developed under the EVA HH&P Benchmarking study and it is possible that elements of both objective and subjective suit fit assessment methodologies could be utilized during future studies. Although the Human-Suit Interaction and Characterization Methods will quantify forces, pressures, and kinematics 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, along with the subjective suit fit methodology, in Fleet Sizing Validation studies (Section 3.6.3) 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 also may 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.

Status: Limited work in FY20; further development of subjective suit fit methods is planned for FY21.

### 3.6.5 POSTURAL DATABASE

The suit exhibits unique work postures during different EVA tasks. Hardware and tool designs that do not account for these postures may compromise crew safety. Work is being done to quantify these postures and provide a digital library of suit poses, which can be used for designs or illustrations. The pose variations will be statistically parameterized by different task categories, workstation types, and crew anthropometry. The outcome will help to optimize habitat, hardware, and suit designs.

To build the database, suit postures and motions will be extracted from suit analog testing sessions and ISS archive videos. In addition to motion capture data, a machine learning algorithm will be developed to automatically assess suit poses from conventional photographs and videos to vastly expand the dataset. This algorithm will be trained using video and images from previous 1*g* suited test sessions and adapted for xEMU.

Once validated for the accuracy and reliability of the posture extractions, the machine learning system will also be deployed to estimate the EVA postures in current and future missions and analog training events. The framework will be applicable to NBL and ARGOS testing, which will help to optimize training procedures.

Status: Ongoing.

### 3.6.6 IN-FLIGHT ANTHROPOMETRY CHANGES (INFLIGHT BODY MEASURES)

Changes in anthropometry occur during spaceflight because of fluid shifts, spinal elongation, and changes in body composition. These changes are known to affect suit fit, resulting in the need to add the requirement to collected measurements during the on-orbit fit checks (OFV) before EVAs on the ISS to ensure acceptable fit. In the future, the measurements collected during OFV will help to reduce overall crew time before EVAs by using the change in measurements from preflight to help predict how the suit sizing will need to be adjusted. However, at this time there is insufficient information to fully predict suit sizing changes. 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.

An inflight study on the ISS, titled “Body Measures,” was completed. This study measured in-flight changes in anthropometry using measurements critical to suit sizing parameters. In-flight physical changes because of neutral body postures (NBP) and the associated spinal elongation effect on NBP during extended exposure to microgravity also were gathered. The study involved collecting anthropometric data using standard equipment (anthropometer, tape measure, weight scale), video imaging (digital still photographs and video), and a 3D whole-body scanner to measure changes in body shape, size, and posture during spaceflight.

The results from the study indicate that anthropometry changes throughout the duration of a mission with most changes occurring within the first 15 to 20 days of the mission except for some circumferences. After the initial period of significant changes, minor fluctuations were noted up until the end of the mission. For future planning, the suit needs to be adjustable based on the length of the mission. Future operations also may require prediction of anthropometry changes to ensure proper suit fit and if any additional sizing adjustments are necessary. To accomplish this objective, a portable and easily operable scanner may be required for future missions. The human-space suit interaction models and associated HITL testing may inform the extent to which in-flight anthropometry changes can be expected to affect suited comfort and performance.

Preflight, in-flight, and postflight anthropometry data from the Body Measures study were incorporated into the xEVA requirements (SSP 51073) [38] and flowed to xEMU (CTSD-ADV-1188 [39]). 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.

Status: Body Measures Study is complete but OFV still is measured (time permitting) in-flight for EMU operations. In-flight anthropometry changes were included in xEVA requirements document SSP 51073. Manuscript for Spinal Elongation was completed in FY19 [43]. Draft manuscripts for Body Measures will be completed in FY20.

### 3.6.7 CREW AND TEST SUBJECT ANTHROPOMETRY DATA COLLECTION

This activity involves the 3D anthropometric laser scanning of all astronauts and EVA suited test subjects. As the Consolidated Center for Astronaut Anthropometric Data, the ABF is solely 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 data collected allow the ABF to obtain and maintain an anthropometric database that can be used for population analyses, univariate and multivariate analyses, volumetric data analyses, and, when requested, in releasing data as per the guidelines set forth in the ABF IRB Master Protocol. Anthropometric data from this activity are combined/shared with the Physical and Cognitive Subject Characterization activity.

Status: Ongoing.

## 3.7 INJURY RISK AND MITIGATION

Tasks in this section are relevant primarily to the Table 1 CHP.EVA.INJURY Gap: *EVA injury risk estimates and mitigation strategies for exploration EVAs, training, and ground testing*

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. In addition to self-report of significant physical and cognitive fatigue, 9 injuries of varying severity were reported during the 14 total Apollo EVAs [44, 45], and future lunar and Martian missions are expected to involve significantly more EVA time per crewmember as compared with Apollo missions. Although still in the planning stages, estimates for planetary EVA consider 10 to 100 times more EVA than Apollo missions (EVA-EXP-0042).

The H-3PO and ABF laboratories initiated an EVA Injury Project in FY20, the purpose of which is to coordinate closely with the EVA community, inside and outside of NASA, to develop and implement a multiyear strategy for identifying and mitigating EVA injury-related risks. The goal of this effort is to identify and mitigate injury-related risks either through hardware design modifications, changes in task and ConOps design, and/or during training and operations. Characterization of injury risks may be accomplished using computational models, and work within this project will include adapting and validating models for suit-related injuries. This effort may require the development of probabilistic injury risk curves that are appropriate to the suited environment. Unique sensors that identify the motion, pressures, and forces that crew experience within the suit may need to be adapted to the environment both for validation of models, and as potential sources of feedback to the crew.

### 3.7.1 EVA INJURY MATRIX

The EVA Injury Matrix will document the types and causes of anticipated injuries that may result from planetary EVA. Specific known and hypothesized injury risks will be identified through a combination of occupational surveillance data mining, ergonomic and kinematic assessments, literature review, and predictions from a variety of suited human models. Injury cases will be identified, tabulated, and then assessed in terms of likelihood and consequence based on best available information. Supporting evidence for each injury risk will be gathered from the related activities described in this roadmap. Each risk will then be prioritized and dispositioned with respect to the risk acceptance, characterization, or mitigation strategy that will be pursued for each.

Potential EVA injury cases are being documented in the EVA Injury Matrix, currently in the form of a spreadsheet document. The document includes the following information for each potential injury case:

- Type and Context of Injury Risk: Describe the specific risk or precursor of event
- Injury Category: physical ergonomics, task and tool design, lunar task-based risk, hardware design, human factors, impact load
- Medical Operational Lunar Mission Concerns: Numbered 1-17, based on list of Medical Operational Lunar Mission Concerns
- Possible Injuries: Injury types/locations
- Mechanisms: Potential sources of injury
- Evidence or Basis for Risk: Why do we think this is a risk? Literature, flight data, ground data, SME predictions, model predictions, etc.
- Likelihood: Estimate for xEMU
- Consequence: Estimate for xEMU
- Mitigation/Characterization Strategies: What do we propose to do about it?
- Strategy Cost Estimate: 0-4 (N/A, low, medium, high)
- Strategy Benefit: 0-4 (N/A, low, medium, high)
- Strategy Schedule: Schedule for mitigation/characterization strategy
- Disposition: Closure Plan; how do we know we have mitigated this injury?

The EVA Injury Matrix, currently populated with 28 injury cases, will be further populated, peer-reviewed, and is expected to be periodically updated and published, possibly as an appendix in future releases of this roadmap document. The matrix will enable prioritization and tracking of injury-related roadmap tasks. The remainder of this section describes the specific injury-related tasks that are currently defined.

### 3.7.2 EVA SUIT EXPOSURE TRACKING AND REPORTING

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. Previous data mining efforts have provided valuable insights, but have been limited by inconsistent and incomplete datasets [46, 47]. A task is currently underway to implement a standard tracking questionnaire, database, and process for the systematic collection of these data for all EVA suit exposures including testing, training, and flight EVAs.

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

Three subprojects will further enhance the scope of the EVA Suit Occupational Surveillance project:

#### *3.7.2.1 Exposure Incidence System Integration with Electronic Medical Record*

The Exposure Incidence System (EIS) data collected through June 2020 has been without a consistent follow-up protocol that provides key information into how long it takes for suit-related issues to resolve completely. This has left gaps in understanding the full consequence of human and suit-related interactions. To address this gap in knowledge, there are two planned tasks. The first task has already started and is an automated follow-up process after the day of EVA to determine the duration it takes to resolve minor consequences. For issues that require medical follow-up, the system of records changes from the EIS to the NASA electronic medical record (EMR). The second task involves linking the EIS system with the EMR and ensuring that the EMR entries and follow-up care are related back to EVA exposures in general, but preferably to the EIS entry most related to the injury. Connecting the EIS to the EMR will help close the loop on the duration for injury resolution and the steps necessary to return to active duty, both of which are critical metrics with respect to operational and long-term health consequences. Because NASA is not the only possible provider of follow-up medical care, there will always be potential gaps in the data. Therefore, once the EIS to NASA EMR link is created, there may be a need to explore additional approaches to collect the same type of data from external care providers, especially for non-astronauts who may be more likely to seek care outside of NASA.

#### *3.7.2.2 Integration of Flight Data into Exposure Incidence System*

Current EIS data covers suited exposures during ground-based training and testing operations at JSC. Although similar data are collected during flight EVA, the data are not currently solicited and recorded in a way that is entirely consistent with the ground-based approach. To resolve this conflict, there will be two steps: The first is to transition to the use of the EIS as part of the pre- and post-EVA private medical conference with the flight surgeon. The second will be to migrate past records from pre- and post-private medical conferencs into the EIS system or, at a minimum, to complete an analysis designed to supply similar suit-related issue information as is provided by the EIS reports.

#### *3.7.2.3 Integration of Suit Fit Data into Exposure Incidence System*

As described in Section 3.6, suit fit is a critical metric to consider when discussing both human performance and injury risk. Although approaches to assessing suit fit are still underway and none are yet validated, there is need to at a minimum allow the suited subjects and if needed, the suit engineer to provide information on suit fit. Given the complexity of the topic, one solution is the inclusion of a subjective suit fit rating where the suited subject is able to rate their overall fit. In addition to subjective suit fit ratings, the suit engineer should provide information on that day’s sizing; for example, was it the nominal fit, off-nominal (by choice or by necessity) or have aspects of the fit recently changed.

Status: Ongoing. Yearly briefings began in FY20 to various NASA internal control boards. The format of the data reports and development of audience-specific briefings will be developed over the course of FY20 and will continue to iterate on a yearly basis. The three EIS subprojects are expected to continue into FY21.

### 3.7.3 EVA INJURY DEBRIEFINGS

As injuries arise either during training or in-flight, debrief sessions are planned. Key to this effort will be to identify and assemble the appropriate personnel and backgrounds necessary to support these debriefs. A standard survey will be developed such that comparisons can be made across all injuries. Video, sensor, or other data as available will be analyzed as part of this debrief process. Another aim of this effort beyond tracking is to bring a team together to help remedy and mitigate injuries in individual crewmembers as they appear using a personalized medicine approach. This may involve improvements to suit design, ergonomics of an activity, training, fitness training, alternative approaches to perform the task, etc.

### 3.7.4 ANALYTICAL TOOL DEVELOPMENT AND VALIDATION

#### *3.7.4.1 EVA Suited Human Dynamic Loads Model (Finite Element Model Based)*

The EVA Dynamic Loads Injury Model is expected to leverage existing human injury modeling capabilities such as those developed by the Global Human Body Models Consortium (GHBMC). However, the nature of the injury mechanisms for which existing human body models have been developed and validated are focused primarily around crash safety for the automotive industry. The purpose of this task is to develop human body models that allow for probabilistic injury risk estimates of dynamic EVA loading injuries. If successful, the resulting human body models will be incorporated into vehicle- and suit-specific injury models to improve injury risk estimates specific to the lunar lander design and operation as well as other dynamic environments such as rover operations.

To accurately predict acute dynamic load injury risk because of transient accelerations and inform suit and vehicle design, the GHBMC model will be used. Currently, the GHMBC model is limited to a few specific body shapes. To improve the subject-specificity of the model, scaling and body composition of the GHBMC model will be informed using whole body scans and dual-energy X-ray absorptiometry (DEXA) scans. A separate model will be developed that incorporates the 2D DEXA information such as bone lengths, joint locations, and tissue distribution into a 3D body scan. The composite 3D scan can be used to update the GHMBC model and provide greater fidelity for a specific crewmember or body shape of interest. This developed methodology is expected to be useful for a population analysis-based approach as different body shapes and body compositions can be tested iteratively using parametric body shape models.

Currently, the GHMBC does not incorporate any suit geometry in the analysis. Suit CAD and suit component materials and mobility properties can be incorporated into the GHMBC model for use during dynamic EVA tasks. Correct suit component sizing and placement can be determined using the suit fit and sizing models. Additional inputs from models such as the contact injury risk models can be used to improve load estimation accuracy and injury risk estimates.

The GHBMC model requires additional validation for spaceflight loading conditions including those expected during xEMU use. This validation is necessary to accurately predict injury risk in spaceflight loading conditions in body regions of interest. In the case of xEMU, accurate injury prediction to the lower extremities and spine while standing is a critical capability needed to protect the crew. In addition, closing-velocity injuries to the torso and head are of concern if the xEMU is not adequately restrained and the crewmember adequately restrained within the suit. This validation may be accomplished with existing human or post-mortem human surrogate data or may require additional data be collected depending on the available datasets.

#### *3.7.4.2 EVA Injury Scale Development*

One additional objective of this effort is to establish an EVA injury scale. A widely used injury scale in the automotive field is the Abbreviated Injury Scale (AIS). The AIS is a threat to life scale with 6 classification levels and is based in part, on car crash injuries where the occupant is not required to perform any actions post-crash and emergency medical personnel will arrive at the scene quickly. These assumptions do not apply to an EVA environment where emergency medical help is not nearby, and crew may be required to take actions following an injury to keep the severity from increasing or to maintain mission success. A similar scale that accounts for the need to take action and return to flight has been developed for crew in space capsule environments and will be leveraged to develop an EVA-unique scale [48].

### *3.7.4.3 Injury Assessment Reference Value Development*

Injury assessment reference values (IARVs) are limits that are defined to allow assessment of vehicle and suit designs against a specified injury risk. Because IARVs are dependent on the injury mechanism and body region, research is needed to relate injury risk to model responses related to loading and kinematics in the xEMU. In spaceflight applications, while injury mechanisms are unique, the crew become deconditioned over a mission and only low levels of injury risk are tolerable in the EVA environment, standard automotive-based IARV curves generally need to be modified. An example of an IARV that has been adapted to the space-capsule environment is shown in Figure 18 [49]. This example correlates a crash dummy (THOR) shoulder contact force with a probability of an AIS ≥2 shoulder injury. The IARV based on the GHBMC model will prove useful in determining both injury risk probabilities, and how changes in design, kinematics, and other xEMU aspects could affect the probability of injury. Based on the injuries expected during xEMU operations, IARVs will be developed to mitigate those injuries during dynamic phases of flight by matching injury outcomes with GHBMC model responses in identical loading conditions.

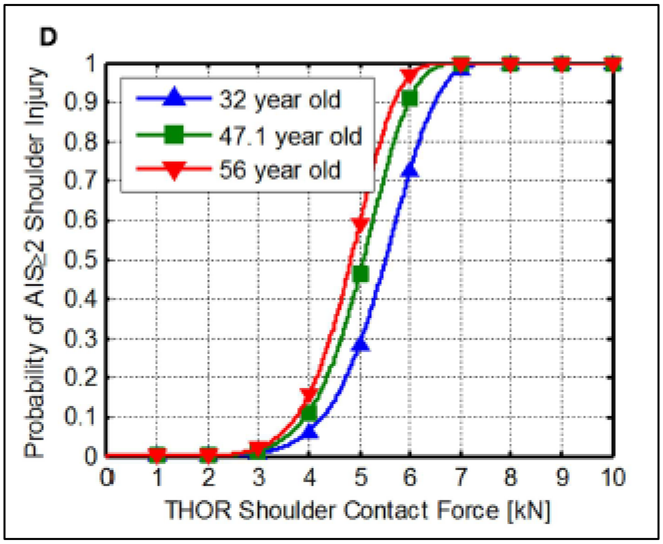


**Figure 18. Example injury assessment reference value curve.**

Status: A Suited Human Dynamic Loads Model feasibility study is expected to begin in FY21.

### *3.7.4.4 Rigidized Biomechanical Modeling*

For chronic, repetitive, or cumulative injury prediction capability, validation of appropriate biomechanical models such as OpenSIM, RAMSIS, Siemens Jack, Santos, or other similar biomechanics models will be required. These biomechanical models typically are used to predict joint torques and overall kinematics of the human body; however, use within the spacesuit and for predicting repetitive or cumulative injury mechanisms is a novel use that will require additional research and validation using rigorous step-by-step approach. This validation process is needed to fully understand the limitations and capabilities of each model. During each step, suit components (e.g., PLSS integration) will be incorporated into the model and validated with targeted tests. The feasibility of applying specific models to specific injury cases identified in the EVA Injury Matrix will be evaluated to confirm appropriate capabilities and functionality with existing suit models and numerical solvers.

Status: Planned. Feasibility study expected to begin in FY21.

#### *3.7.4.5 EVA (Sensor-Based) Ergonomic Modeling*

This task focuses on the forces, pressures, and kinematics between the human and suit for the primary purpose of identifying and mitigating injury risk. This task is closely related to the following tasks: contact injury risk model and sensor-based injury risk assessment. Understanding the interaction between the human and the space suit is necessary for both identifying and improving the interrelated determinants of suit fit, suited performance, and suit injury risk. The direct observations are extremely difficult for the body inside the spacesuit, so wearable sensor technologies have been proven effective and demonstrated usable outcome from previous testing.

For occupational ergonomic injury assessments, sensors-based ergonomic injury risk assessment models will be developed to understand the consequences of having to wear a bulky suit with potential interferences between the hardware components and the human. Existing finite element, musculoskeletal, and anthropometric modeling capabilities coupled with bone modeling will be incorporated with xEMU suit models and data. The models will be assessed for their current and possible future applicability to xEMU development, sizing, training, and operations. This will form the basis of an ergonomics-based occupation risk assessment model that would be tailored for specific EVA operational tasks and provide useful information for EVA mission planners. For example, low-back loading can be quantified across different EVA tasks. At the conclusion of the pilot phase, recommendations will be provided as to the focus and extent of follow-on work. In parallel, the EVA-suited dynamic loads model will focus primarily on understanding the dynamic loads during landing and launch operations. At the conclusion of the pilot phase, recommendations will be provided as to the focus and extent of follow-on work. In parallel, the EVA-suited dynamic loads model will focus primarily on understanding the dynamic loads during landing and launch operations.

Status: Planned to begin in FY21.

#### *3.7.4.6 Contact Injury Risk Model*

An anthropometry-based 3D shape model will be combined with DEXA scan data to enhance the quantifications of suit fit, contact loads, collision interference with hardware components. This modeling effort may improve the effectiveness of the anthropometry and suit fit task efforts. For more details regarding this model and validation efforts, please see the section titled, “xEMU Fleet Sizing Validation.”

Status: Pilot work being pursued in FY20. Anthropometry based 3D shape model will be infused with DEXA scan data to enhance the quantifications of suit fit, contact loads, and collision interference with hardware components.

### 3.7.5 HUMAN-SUIT INTERACTION AND CHARACTERIZATION METHODS

#### *3.7.5.1 Suited Human Motion Characterization*

Space suit fit at all points within the suit, and human motion within the suit during operations is not well understood, and is difficult to estimate from outside of the suit. Efforts will be made to identify sensors that could be used inside the suit to measure forces and kinematics. These sensors are targeted primarily for use in ground-based training and operations. However, if promising sensors do emerge, efforts may be pursued to incorporate them into the xEMU for in-flight operations.

A less complex approach for human movement tracking during in-flight EVA would be through externally mounted sensors. An IMU would provide useful information for impact events such as the lunar landing and rover operations. A suite of IMUs could relate information about exterior suit motion, and a transfer function could be developed relating external motion to internal human motion.

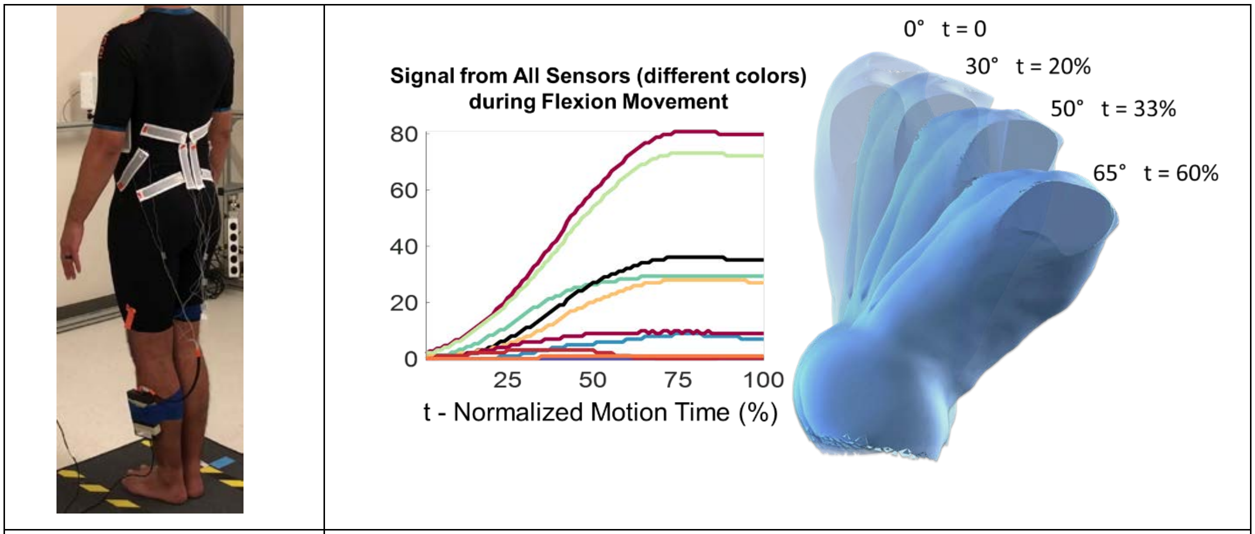
In our previous work, the difference between suit mobility and lower-limb motion has been quantified by using a knee joint angle in the sagittal plane via IMUs placed on the left/right tibia and left/right femur. In addition, it is important to understand how the mediolateral rotation of the hip joint of the suit would affect the lower-limb motion inside the suit during functional activities and ambulation. To the comparison, the unsuited ambulation trial on the ground (i.e., walk back and forth) with IMUs will be required. Differences in internal rotation angles between suited and unsuited walking may be important criteria for identifying crewmembers at risk of hip joint pain during long-time walking or kneeling down [50].

#### *3.7.5.2 Sensor-based Injury Risk Assessment*

Much of what is known today comes from valuable subjective data provided by test subjects and crewmembers; incorporating sensor technology to measure human-suit interactions (i.e., forces, pressures, and human/suit kinematics) could provide a valuable objective complement to the subjective data [51]. 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. These systems also may enable objectively quantifiable suit fit assessments. However, many technical challenges remain, including the possibility that sensors inside the suit will themselves affect fit, discomfort, injury risk, and the ability of the crewmember to perform EVA tasks; all of which could confound the primary test objectives.

A collaboration is in progress with the Wearable Technology Lab at the University of Minnesota to develop a system to measure the suit-to-body contact in the xEMU lower torso assembly. The objective of this task is to identify technologies and methods that provide valid and reliable quantification of human-suit interactions that can be related to specific locations on the human and the suit. This includes generating an understanding of the sensitivity of the measures to detect relevant effects and the specificity of the measures to identify the relevant cause in the context of general suit use. If a valid and reliable approach is identified, it will be incorporated into the xEMU fleet sizing validation studies and xEMU injury modeling efforts 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.

Status: Ongoing. In support of this overarching task, a wearable sensor garment that can estimate upper body kinematics and shape changes inside the suit was developed. The kinematic data can be combined with human-suit interaction sensors and suit hardware models to understand and quantify human movement inside of the spacesuit for ergonomic assessments. Because of volumetric constraints and ferrous magnetic interference in the suit, soft-body and low-profile strain sensors were used in the sensor garment. The strain sensors yields a capacitance measurement varying with the sensor elongation and have provided useful information on lumbar movement in previous studies. Thus, an array of the strain sensors were embedded into a tight-fitting garment in a specific pattern that would maximally respond to the wearer's skin deformation from motions (Figure 19A). The tight-fitting garment has been used as a test bed for the sensors and the sensors can be possibly embedded in the LCVG.



(A) (B)

**Figure 19. (A) Sensor garment. (B) Body shape prediction from sensor measurements during flexion movement.**

#### *3.7.5.3 Contact Injuries*

Similar to measuring human motion within the suit, it is potentially valuable to capture the magnitudes and locations of contact loading between the human and the suit. These data may prove valuable in development and validation of EVA suit fit and injury models and during specific injury-related studies such as the lunar falling task, described later in this section.

Status: Work in this area is currently being pursued by A. Anderson and Y.Y. Shen at CU Boulder.

### 3.7.6 INJURY RISK CHARACTERIZATION AND COUNTERMEASURE STUDIES

As mitigation and characterization strategies are identified within the EVA Injury Matrix, additional targeted tasks and studies will be initiated, many of which will employ the aforementioned model- and sensor-based methodologies. Ongoing and anticipated characterization and countermeasure tasks are described in the following subsections.

#### *3.7.6.1 Lunar Fall Injuries*

Falls and slips while ascending or descending a ladder or a crater, contusions or fracturing during sudden falls or impacts against hard and sharp objects such as rocks are all potential injury mechanisms during lunar operations. To mitigate the risk of injury HITL testing will be conducted during the early part of design evaluations to ensure that the suits are provided with protective mechanisms to minimize the effects of such anticipated injuries. A review of literature will be performed to identify and quantify the types of relevant injuries observed in non-EVA occupational contexts performed at a comparable frequency and physical demands, such as soldiers, wildland firefighters, field scientists, and commercial divers using atmospheric diving suits, along with a review of Apollo astronaut fall cases. Analyses using the xEMU Injury Model will be performed, if and when the model is sufficiently developed and validated.

Status: Ongoing

#### *3.7.6.2 Landing Injuries*

Landing while in a standing posture has the potential to injure crew, especially given the xEMU design. The mass of the xEMU has the potential to overload the legs and lumbar spine, while the fit of the HUT could result in closing velocity injuries. These injuries may be exacerbated by improper restraint of the suit in the lander design. To address these concerns and inform design and operation of the lunar lander designs, the EVA Suited Human Dynamic Loads Model will be employed to assess landing cases to inform design trades as well as evaluate proper restraint concepts in the design process. As the design matures, the model will be used to verify that the final design will minimize injury potential.

Status: Planned to begin in FY21.

#### *3.7.6.3 Rover Injuries*

Because the suited crewmembers may account for half of the total mass of the rover system, coupled loads analysis of the rover system with the suited crewmembers is required. The crew dynamic responses may contribute to the overall dynamics of the system. Given the reduced lunar gravity, coupled with a high center of gravity (CG) (because of the crew standing), the vehicle/crew system could become unstable when striking terrain obstacles. In addition, minimal restraint of the crew is desired, to improve ingress and egress efficiency and to avoid fault cases where the crewmember may not be able to disengage restraints. Assessment of potential driving cases for crew safety would be conducted using the EVA Suited Human Dynamic Loads Model to assure the design and ConOps are sufficient to protect the crew over the expected terrain.

Status: Planned.

#### *3.7.6.4 Incapacitated Crewmember Rescue*

The Incapacitated Crewmember Rescue EVA SMT Gap identifies the need to develop methodology for transfer/transport of an incapacitated crewmember at each destination and how to transfer them onto the ingress/egress hardware or through side hatch, and doff suit. This EVA SMT Gap also relates directly to the CHP.EVA.INJURY Gap (Table 1).

While previous studies have been conducted [52, 53], the limited fidelity and scope of those studies have precluded the establishment of a baseline protocol for this contingency EVA task. The purpose of this study is to identify credible cases for incapacitated crewmember rescue and – if directed by the xEVA project – to design, build, and test high-fidelity concepts for incapacitated EVA crewmember rescue. Test environments may include NASA Extreme Environment Mission Operations (NEEMO) [52], NBL, and/or ARGOS as well as 1*g* testing. Results are expected to directly inform design features required to facilitate EVA rescue.

Testing will include task analysis as well as standalone evaluations of prototype rescue hardware, and integrated testing following the PACES methodology. Stand-alone testing will provide data on the general designs to inform a down select process of candidate systems following which crew operation of the systems will be evaluated while working within the physical and cognitive constraints of a flight-like environment. For instance, a design may be acceptable in an isolated test, where subjects are not fatigued and can compensate for any deficiencies, but totally unacceptable if performed at the end of a 6-hour EVA where the likelihood of cognitive or physical fatigue-borne error is potentially higher.

Status: Analysis of credible cases ongoing in FY20. Additional development and testing, as required, planned for FY21.

#### *3.7.6.5 Suit Donning and Doffing Injuries*

For the current EMU, suit donning and doffing in 1*g* during training have resulted in injury. Although the xEMU is rear-entry suit, donning and doffing may have the potential for injury to the crew in both 1*g* training and surface operations. During extended stays on the planetary surfaces, crewmembers will be expected to don and doff the suit for normal operations as well as during any emergency operations. Thus, the frequency of donning and doffing the suit may increase the risk of injury to the crewmember because of the complexity involved in such tasks. This task will use HITL testing and possibly modeling to characterize and, where possible, mitigate suit donning and doffing-related injury risks.

Status: Planned.

#### *3.7.6.6 Low back Injuries during Functional Tasks*

A targeted effort to quantify low back injury mechanisms will be conducted for exploration tasks. With the proposed lunar EVA missions, lower body mobility will be critical to mission success and injury risk mitigation. Lunar EVA tasks may involve lifting, crouching, and kneeling work postures. Thus, it is important to understand the torso and low-back movement mechanisms inside the suit. Focus on exploration tasks such as lifting at different heights and positions and shoveling will be studied. Additionally, wireless electromyography may be used to quantify musculoskeletal loading.

Status: Planned.

#### *3.7.6.7 Hip/Ankle Injuries during Functional Tasks*

A targeted effort to quantify hip and ankle injury mechanisms will be conducted for exploration tasks. Hip and ankle mobility is needed to maintain balance and is critical for ambulation. Additionally, proper boot fit is important for injury mitigation. Thus, the boot and hip suit designs concepts will be evaluated through HITL testing for EVA-like activities across different body shapes and anthropometry.

Status: Planned.

### 3.7.7 CONOPS AND TRAINING INJURY CONSIDERATIONS AND MITIGATIONS

#### *3.7.7.1 Injury Risk Assessments of (PACES) EVA Tasks and ConOps testing*

The PACES project, described in Section 3.3, aims to develop a catalog of flight-like exploration tasks that best simulate the physical and cognitive exposure an astronaut will experience during missions beyond low Earth orbit. These tasks will be used in multiple studies described in this roadmap and also provide the ability to assess the injury risk of performing them. Understanding injury risk, both in isolation for single tasks and in the context of an overall mission ConOps with repeated EVAs over multiple days, is necessary to determine the cumulative injury risk astronauts face. Risk assessments will include measurement of: functional postures required to complete EVA tasks (e.g., kneeling, crawling, walking, etc.), the frequency and duration of those postures, crew interaction with various payloads/tools (e.g., lifting payloads from a height, working with geology tools, etc.), and crew interaction with vehicles and interfaces (e.g., HLS hatches, ladders, umbilicals, etc.), among others.

The xEMU design provides greater mobility and enables various postures and movements for the astronauts during EVAs, but may lead to unanticipated issues that should be assessed related to injury risk. As mentioned in Section 3.4.1, IMUs donned on each segment of the spacesuit can characterize the postures and activities of the astronauts during EVAs. This would have implications for a variety of stakeholders such as understanding injury risk, suit joint cycles, dust mitigation and suit contact with the surface, or optimizing task completion strategies training for crew.

Status: Ongoing [54].

#### *3.7.7.2 Injury Risk Identification, Sensitivities and Operational Control Agreement Databases for Tasks and Environments*

The HH&P and FOD have the joint obligation of keeping crew safe through all phases of training and flight through collaboration on integrated efforts. It is the responsibility of FOD to develop concepts of operations for accomplishing mission tasks in various environments, procedures for performing these operations, and train crew in proper, safe task execution in these environments. These operations benefit from the insight of HH&P on the risk of injury or sensitivity through physical and cognitive exposure to the environment. Additionally, input from the crew office, through the relationship of the crew office and FOD, are able to provide valuable insight through previous and current mission participation. Crew office contribution may extend beyond a general perspective, as training and mission tasks may be modified to accommodate crew sensitivity and injury.

Therefore, FOD will develop a high-level overview of the concept of operations for executing ISS and lunar operations in the xEMU and map the associated training events. The HH&P can review this map and identify areas of elevated risk injury through results of the suit fit/design parameters, fitness for mission, and environmental control and life support requirement studies with suggestions on how to reduce these risks (adjusting suit fit, body positioning, etc.). The crew office also will provide insight as to the feasibility of implementing these suggestions during real-time operations. The result of this iterative process will be a high-level document that informs crewmembers of the various risks of injury in these environments (both training and mission), and the associated Operational Control Agreement Databases (OCADs) or reporting requirements to prevent/mitigate these risks or to document future injury occurrences. The OCADs are a way to control or mitigate a hazard to crew or hardware through specific operational implementation. Implementation of this hazard control can come in the form of a procedure step, crew training, and/or a Flight Rule.

To continue to refine this high-level map of operations/training/injury risk/mitigation methods, reporting of crew injury or sensitivities (sustained from previous exposure or recent development) is imperative to protect current and future crew. A reporting structure should be developed for the medical team to alert instructors of crew injury or sensitivity to help refine the map, but also to tailor training and mission operation procedures for accommodating crew.

Status: Planned to begin in FY21

#### *3.7.7.3 Work Hardening and Task Allocation*

As EVA tasks and concepts of operations become more defined, models and ergonomic assessments will be performed to assess tasks in terms of position, range of motion (ROM), loads, durations, and frequencies. Many EVA-related tasks can be defined in terms of push, pull, lift, carry, fine motor manipulation, etc. Work hardening can be defined as a program designed to improve astronauts' strength, flexibility, and aerobic condition through exercises and activities that simulate or include the actual EVA functions. Assessments of EVA task-specific demands will be made and communicated with the Astronaut Strength Conditioning and Rehabilitation group such that appropriate fitness training programs can be prescribed before each mission. Functional tests also will be designed to assess crewmember readiness for the EVA tasks assigned within the mission throughout the preflight training period.

Status: Ongoing.

#### *3.7.7.4 EVA Occupational Strength and Manual Materials Handling Capability Evaluation*

To minimize suited ergonomic injuries, general material handling guidelines will be developed that will identify maximum acceptable weights and forces for various suited manual materials handling tasks. These guidelines will provide acceptable weight limits across different population percentiles. Current ergonomic tools do not account for additional physical demands imparted by the suit. In-pilot lifting studies using a suit mock-up, suited subjects have reported a lower weight acceptable limit that they would be willing to lift throughout an 8-hour EVA.

Controlled suited evaluations will be used to define these limits across a broad range of tasks such as lifting, pushing, pulling, carrying and lowering. Additional task parameters such as lifting zone, translation distances, task frequency, grip height, and height of the application of force will be tested and the effects will be quantified. Furthermore, there will be psychophysical measures that are incorporated in defining these limits. The guidelines may be summarized into a set of tables that EVA hardware and task designers can use to assess what proportions of the population should be able to accomplish specific tasks as a regular part of their daily work.

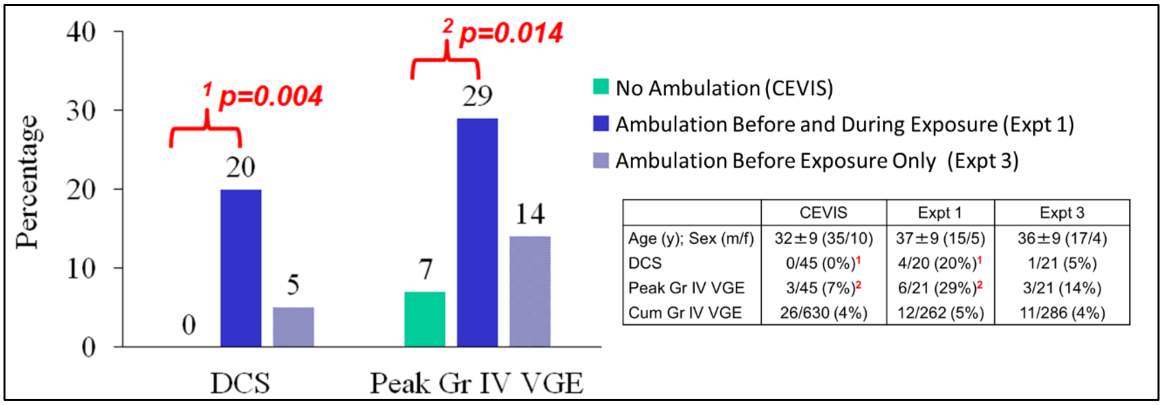
Status: Planned.

## 3.8 EXPLORATION DECOMPRESSION SICKNESS MITIGATION STRATEGY

Tasks in this section are relevant primarily to the Table 1 CHP.EVA.DCS Gap. *Validated and efficient decompression sickness (DCS) risk estimates and mitigation strategies for lunar- and Mars-surface exploration missions.*

Oxygen prebreathe protocols are used to mitigate the risk of DCS before EVAs are performed from the ISS. Existing protocols used aboard the ISS require significant amounts of crew time and consumables (gas) but are consistent with the ISS operations concept of infrequent EVAs, large crews, and relatively simple resupply of consumables from Earth. Existing prebreathe protocols used on the ISS also rely significantly on the existing hardware and facilities related to the Quest airlock. Existing protocols require both mask and in suit $O_2$ prebreathe and require suit donning at an intermediate pressure of 10.2 psia to avoid a break in prebreathe. The airlock must then be repressurized to allow the IV crewmember to leave before final depressurization. Existing protocols assume a single suit pressure of 4.3 psia and infrequent longer duration (>4 hour, typically >6.5 hour) microgravity EVAs. Finally, DCS treatment can only be provided on the ISS with recompression in the airlock and then further treatment requires the bends treatment apparatus, which is installed onto the suit to allow for increased pressure to the crewmember, but at the price of decertifying the EMU for EVA.

Prebreathe protocols that have been validated and used during Space Shuttle and ISS for microgravity EVAs are not acceptable for use during planetary EVA, because the risk of DCS is significantly increased by ambulation. For example, Conkin et al. [55] observed significantly greater DCS incidence (20% vs. 0%) when subjects ambulated before and during the decompression vs. remaining non-ambulatory throughout (Figure 20). Significantly greater Grade IV Venous Gas Emboli (VGE) also was observed among ambulatory subjects; Grade IV VGE represents the highest score assigned to bubbles moving with the blood through the pulmonary artery on the way to the lungs to be filtered (removed) from the venous blood.



| | CEVIS | Expt 1 | Expt 3 |
|---|---|---|---|
| Age (y); Sex (m/f) | 32±9 (35/10) | 37±9 (15/5) | 36±9 (17/4) |
| DCS | 0/45 (0%)[1] | 4/20 (20%)[1] | 1/21 (5%) |
| Peak Gr IV VGE | 3/45 (7%)[2] | 6/21 (29%)[2] | 3/21 (14%) |
| Cum Gr IV VGE | 26/630 (4%) | 12/262 (5%) | 11/286 (4%) |

**Figure 20. Effect of ambulation on DCS and Grade IV VGE [55].**

Although microgravity prebreathe protocols (from the ISS and Space Shuttle) are expected to be applicable to EVAs on Gateway or other microgravity environments, no validated prebreathe protocols exist for planetary EVA. Apollo used a 100% oxygen atmosphere throughout the mission, which made prebreathe unnecessary, as nitrogen ($N_2$) had already been eliminated from the astronauts' bodies. However, all atmospheres being considered by NASA for future exploration missions will include at least 66% $N_2$ due to the flammability risks and costs associated with higher $O_2$ environments, meaning that one or more prebreathe protocols must be developed and validated using ground trials before operational implementation during exploration missions. Development and validation of a suite of exploration prebreathe options is included in this plan.

### 3.8.1 EXPLORATION ATMOSPHERE PREBREATHE VALIDATION AND HYPOXIA CHARACTERIZATION

NASA's design reference missions for human exploration of Mars and the Moon, depend on periods of high frequency EVAs with crew time and consumables availability that will be significantly more constrained than during current ISS operations. Recognizing this challenge, NASA has followed the recommendations of the Exploration Atmospheres Working Group [56], and has directed that NASA exploration missions involving periods of high-frequency EVA be designed to use an atmosphere of 8.2 psia/34% $O_2$/66% $N_2$, often referred to as the "Exploration Atmosphere." The lower partial pressure of $N_2$ compared with the ISS will enable significantly reduced prebreathe durations. However, while the estimated DCS risk is very low, a prebreathe protocol for planetary EVAs still must be developed and validated using ground trials before operational implementation of the Exploration Atmosphere.

The proposed denitrogenation prebreathe protocol is based on the assumption that subjects will be equilibrated with the exploration atmosphere at 8.2 psia/34% $O_2$. Human testing is required to verify with 95% statistical confidence that any new protocol meets the following requirements for acceptance: ≤15% incidence of Type I DCS, ≤20% incidence of Grade IV VGE with no Type II DCS symptoms. A repeated-measures, sequential statistical design is planned, in which at least 2 groups of 6 subjects with physical characteristics similar to those of active-duty astronauts first equilibrate over a 48-hour period to an 8.2 psia atmosphere in a hypobaric chamber containing 34% $O_2$/66% $N_2$, and then each perform a total of 5 EVAs at 4.3 psia, each lasting 6 hours, performed every second day over the next 9 days.

During the simulated EVAs, subjects will simulate EVA work on a planetary surface because DCS risk is affected by the type and intensity of physical work that is being performed during a decompression exposure. For simulated EVAs, each subject will don a mask and breathe 85% $O_2$ (normoxic at 4.3 psia) before each EVA. Using 85% rather than 100% $O_2$ will enable reduced pre-EVA purge durations during exploration missions, saving valuable crew time and consumables, with very minimal anticipated impact on DCS risk [23].

Subjects will follow prescribed repetitive activity against loads in the upper and lower body to simulate ambulatory work in a planetary environment. Doppler ultrasound (2.5 MHz) monitoring for VGE in the pulmonary artery will be performed on 6 subjects by 2 Doppler technicians at 15-minute intervals during the 4.3 psia exposure, then repressurization will return all to 8.2 psia. The cycle will be repeated 4 additional times with a day of hypoxia characterization and rest between each of the simulated EVAs. A statistical power analysis indicates that, given our best estimate of DCS incidence as ≤3.1% for the planetary EVA simulation, then 12 subjects repeated 5 times has 88% probability of meeting the accept condition. The study design includes a liberal reject criterion, to minimize the probability of conducting an expensive trial and neither meeting the criteria for acceptance nor rejection of the protocol. If a protocol is rejected, the prebreathe protocol will be made more conservative by increasing prebreathe time.

Hypoxia characterization quantifies the nature of a breathing atmosphere with an inspired $O_2$ partial pressure ($PiO_2$) of 128 mmHg and includes measures of neurocognitive function, sleep performance, immune stress and oxidative damage, vision, and cardiorespiratory function at rest and mild exercise, as well as assessment of any classic hypoxia symptoms.

Status: Ongoing. The study will be performed in the 20-foot chamber in Building 7 at JSC. Data collection is expected to be completed during FY21.

### 3.8.2 EXPLORATION PREBREATHE FROM ALTERNATE ATMOSPHERES (< 30% $O_2$)

This study will be similar in design to the Exploration Atmosphere Prebreathe Validation study, using the same hypobaric chamber facility and planetary EVA simulation, but with subjects saturated at <30.0% $O_2$, based on increased availability of materials flammability data at 30% $O_2$. The exact atmosphere that will be used has not been determined at the time of writing but is expected to use approximately 28% $O_2$ to ensure that 30% $O_2$ is not exceeded.

Status: Planned for FY21.

### 3.8.3 EXPLORATION PREBREATHE FROM 14.7 PSIA/21% $O_2$ ATMOSPHERE

Exploration missions may require validated prebreathe protocols to enable EVA capabilities from habitats that operate at 14.7 psia, 21% $O_2$. Much like the ISS, these habitats are expected to either be science-focused laboratories where atmosphere is desired to be similar to Earth or they may be vehicles with only contingency or infrequent EVA needs.

Although several validated prebreathe protocols have been used on the ISS, these all assume a specific architecture and capability associated with the ISS and the EMU. Exploration vehicles may not have or even need to have the added cost and complexity of certain needed factors such as mask prebreathe, exercise capability, donning the suit at an intermediate atmosphere of 10.2 psia and 26.5%, or repressurization to 14.7 psia to allow the IVA crewmember to exit the airlock prior to final depressurization.

This study will use the same hypobaric chamber facility and planetary EVA simulation as the other exploration prebreathe validation studies; however, because subjects will be saturated at Earth-normal atmospheric conditions, it will not be necessary to have test subjects living in the hypobaric chamber for multiple days. It is possible that this study will be combined with the Variable Pressure Model Development and Validation task.

Status: Will be conducted only if needed based on lunar vehicle atmospheres.

### 3.8.4 VARIABLE PRESSURE DCS MODEL DEVELOPMENT AND VALIDATION

The prebreathe protocol ground validation studies described earlier in this section are very limited in the extent to which they can be generalized to different combinations of vehicle atmosphere and suit pressure. The variable pressure capability that will be provided by xEMU can potentially reduce necessary prebreathe durations and provide additional DCS risk reduction; however, these anticipated benefits cannot be realized without ground validation testing.

It is known that higher suit operating pressures will decrease DCS risk and enable shorter prebreathe durations at the expense of higher suit leak rates and higher physical workload and fatigue for crewmembers who must perform work against the higher pressure gloves and suit joints. However, brief periods at higher suit pressures may have minimal effect on workload or consumables usage while enabling meaningful reductions in DCS risk and/or prebreathe durations. Gas bubbles form and grow before the onset of DCS symptoms [57], and the use of short periods of recompression to control gas bubble size has previously been proposed as a more effective saturation decompression strategy [58-60]. This advantage of intermittent recompression arises because the benefit of decreasing bubble size outweighs the penalty of inert gas uptake; gas bubbles decrease in size almost instantly whereas the tissue inert gas tensions increase relatively slowly. Experimental data from human [61] and animal [62] decompression trials indicated significantly lower decompression stress among subjects exposed to intermittent recompressions compared with equivalent continuous exposures [59].

As an example, a model-based comparison of two different prebreathe protocols is shown in Figure 21, one of which takes advantage of variable pressure suit capability while the other does not. This example demonstrates the potential for shortening prebreathe durations and/or reducing DCS risk; however, the biophysical model upon which the example is based has not been validated to provide DCS risk estimates for such scenarios.

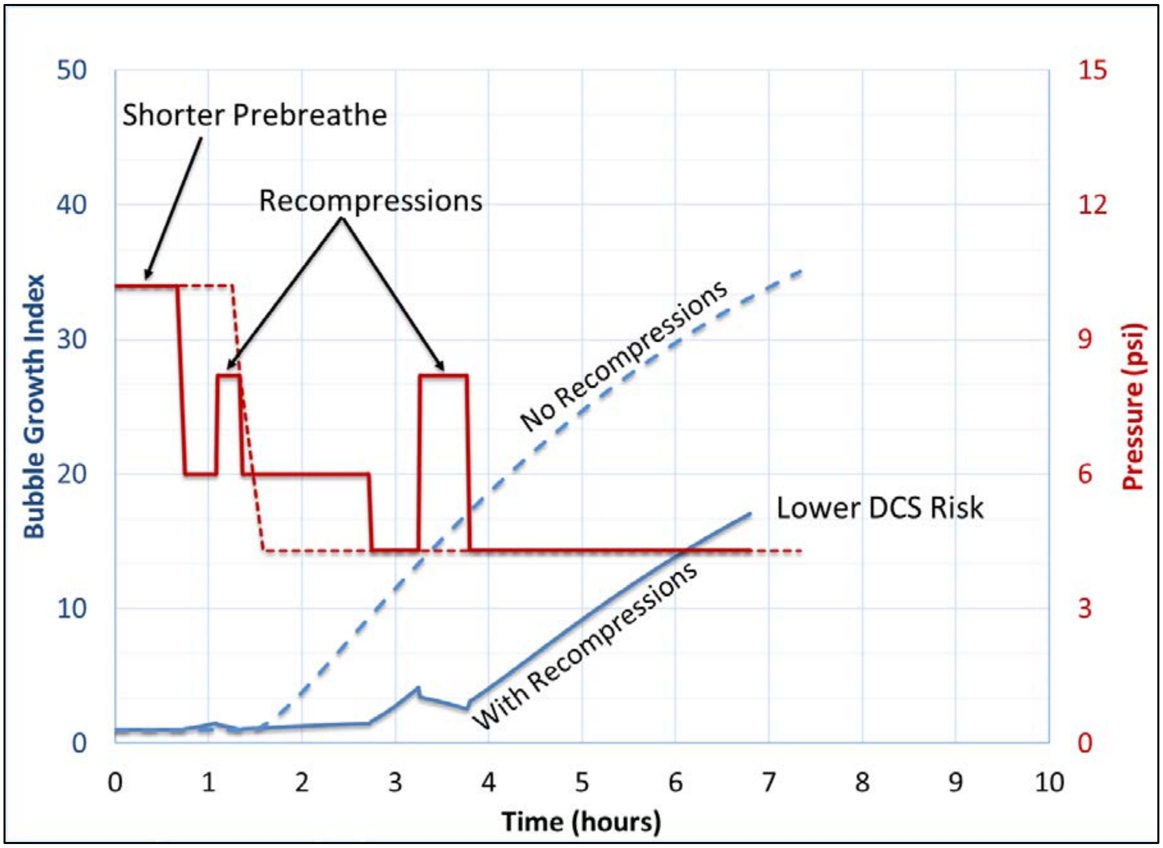


**Figure 21. Model-based comparison of DCS risk (Bubble Growth Index) for two different prebreathe scenarios; one using a staged approach with recompressions (solid lines) and one using a longer prebreathe and no intermediate pressure or recompressions (dashed line).**

The purpose of this task is to develop exploration prebreathe protocols and a validated model of decompression risk that will work for any anticipated combination of cabin atmospheres and suit operating pressures, including variable suit operating pressures, for all future exploration destinations. This study also will include validation of intermittent recompression profiles, which would take advantage of variable pressure space suit capability to further decrease necessary prebreathe durations. In addition to ensuring safe exploration prebreathe protocols, the validated model will function within the HH&P EVA Model and the EMSS informatics to provide real-time and predictive estimates of decompression stress. Any planned EVA operations using intermittent or sustained elevated pressures would need to be evaluated for health and performance impacts prior to operational implementation.

Status: Planned.

# 4 MAINTAINING AND EXECUTING THE PLAN

Given the dynamic nature of NASA organizations, budgets, and priorities, it is understood that this roadmap must be continually reviewed and revised in order to remain useful. 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.

As studies are performed, results will continue to be published via conference papers and presentations, scientific journals, and NASA technical reports. Results will be presented to NASA's HSRB, EVA Configuration Control Board, and/or other EVA forums as appropriate. Updates to xEMU and Exploration EVA ConOps documents will be made during standard review processes. Updates to the status and evidence associated with Gaps will be coordinated via the EVA Office and CHP SCLT.

# 5 ACKNOWLEDGEMENTS

The authors would like to acknowledge and thank Jackie Reeves and Susan Breeden for their thorough and professional technical review and editing of this technical report.

# 6 REFERENCES

1. NASA Strategic Plan 2014. 2014, National Aeronautics and Space Administration, Office of the Administrator: http://science.nasa.gov/media/medialibrary/2014/04/18/FY2014_NASA_StrategicPlan_508c.pdf.
2. Abercromby, A.F., et al. Integrated Extravehicular Activity Human Research Plan: 2016. in 46th International Conference on Environmental Systems. 2016. Vienna, Austria.
3. Abercromby, A.F.J., Integrated Extravehicular Activity Human Research Plan: 2017, NASA, Editor. 2017.
4. Abercromby, A.F.J., Integrated Extravehicular Activity Human Research and Testing Plan: 2019. 2019.
5. 2015 NASA Technology Roadmaps. 2015 [cited 2016 February 15]; Available from: http://www.nasa.gov/offices/oct/home/roadmaps/index.html.
6. NASA, NASA Systems Engineering Handbook, NASA/SP-2016-6105 Rev 2. 2017, NASA: Washington, D.C.
7. Human Research Program EVA Risk: Path to Risk Reduction. 2015 [cited 2016 February 18]; Available from: http://humanresearchroadmap/schedules/?i=84.
8. Conkin, J., et al., Evidence Report: Risk of Decompression Sickness (DCS), N.H.R. Program, Editor. 2016, NASA Johnson Space Center.
9. Norcross, J.R., et al., Risk of Hypobaric Hypoxia from the Exploration Atmosphere, N.H.R. Program, Editor. 2015, NASA Johnson Space Center.
10. Abercromby, A.F.J., M.L. Gernhardt, and H. Litaker, Desert Research and Technology Studies (DRATS) 2009: A 14-Day Evaluation of the Space Exploration Vehicle Prototype in a Lunar Analog Environment, in NASA/TP-2012-217360. 2012.
11. Chappell, S.P., et al., Risk of Injury and Compromised Performance Due to EVA Operations. Human Research Program Evidence Report, 2015.
12. NASA, NASA Space Flight Human-System Standard Volume 2: Human Factors, Habitability, and Environmental Health. 2015.
13. Bekdash, O., et al., Standard Testing Procedure for Quantifying Breathing Gas Carbon Dioxide Partial Pressure for Extravehicular Activity and Launch, Entry, Survival Pressure Suits, in NASA/TM-2020-220525. 2020.
14. English, K.L., et al., High intensity training during spaceflight: results from the NASA Sprint Study. npj *Microgravity*, 2020. 6(1): p. 1-9.
15. Mulavara, A.P., et al., Locomotor function after long-duration space flight: effects and motor learning during recovery. *Experimental Brain Research*, 2010. 202(3): p. 649-659.
16. Sutterfield, S.L., et al., Prediction of Planetary Mission Task Performance for Long-Duration Spaceflight. *Medicine and Science in Sports and Exercise*, 2019. 51(8): p. 1662-1670.
17. Ryder, J.W., et al., A novel approach for establishing fitness standards for occupational task performance. *European Journal of Applied Physiology*, 2019. 119(7): p. 1633-1648.
18. Spiering, B.A., et al., Test battery designed to quickly and safely assess diverse indices of neuromuscular function after unweighting. *The Journal of Strength and Conditioning Research*, 2011. 25(2): p. 545-555.
19. Norcross, J.R., et al., Metabolic Costs and Biomechanics of Level Ambulation in a Planetary Suit, in NASA/TP-2010-216115. 2010, NASA Johnson Space Center: Houston, TX.
20. Norcross, J.R., et al., Metabolic Costs and Biomechanics of Inclined Ambulation and Exploration Tasks in a Planetary Suit, in NASA/TP-2010-216125. 2010, NASA Johnson Space Center: Houston, TX.
21. Waligora, J.M. and D.J. Horrigan, Metabolism and Heat Dissipation during Apollo EVA Periods, in *Biomedical Results of Apollo*, R.S. Johnston, C.A. Berry, and L.F. Dietlein, Editors. 1975.
22. Chappell, S.P., et al., Evidence Report: RISK OF INJURY AND COMPROMISED PERFORMANCE DUE TO EVA OPERATIONS. 2017, NASA Johnson Space Center: NASA.

23. Abercromby, A.F.J., J. Conkin, and M.L. Gernhardt, Modeling a fifteen-minute extravehicular activity prebreathe protocol using NASA's exploration atmosphere (56.5 kPa / 34% O2). *Acta Astronautica*, 2015(0).
24. Pantaleano, M.J. and D.F. Lacey, Satellite Handling Loads on the Shuttle Extravehicular Mobility Unit (EMU) Spacesuit: An Examination of the Loads Imparted to the Suit as a Result of Handling Massive Objects in EVA. 1992, SAE Technical Paper.
25. Coan, D. EVA Lunar Surface Concept of Operations 2020.
26. Grace Wusk, H.G., Andrew Abercromby, Development and evaluation of a virtual reality simulation to study cognitive demand during exploration extravehicular activity, in International Conference on Environment Systems 2020, ICES: Lisbon, Portugal (postponed).
27. Miller, M.J., et al. Scientific Hybrid Reality Environments (SHyRE): Leveraging Terrestrial Fieldwork for Future Planetary Exploration. in American Geophysical Union Fall Meeting. 2018. Washington D.C.
28. Miller, M.J., et al. Scientific Hybrid Reality Environments (SHyRE): Bringing Field Work into the Laboratory. in Planetary Science Informatics and Data Analytics Conference. 2018. St. Louis, MO.
29. Bekdash, O., et al., Standard Testing Procedure for Quantifying Breathing Gas Carbon Dioxide Partial Pressure for Extravehicular Activity and Launch, Entry, Survival Pressure Suits. 2020.
30. Kyoung Jae Kim, O.B., Jason Norcross, Johnny Conkin, Alejandro Garbino, John Fricker, Millennia Young, Andrew Abercromby, Characterization of the Partial Pressure of Inspired Carbon Dioxide Exposure Levels in the Spacesuit. Aerospace Medicine and Human Performance. Aerospace Medicine and Human Performance, 2020.
31. Miller, M.J., K.M. McGuire, and K.M. Feigh. Information flow model of human extravehicular activity operations. in 2015 IEEE Aerospace Conference. 2015.
32. Billman, D., et al., Needs Analysis and Technology Evaluation:Evaluation Case Study of Alternative Software for Controller Planning Work–Part 2. *Journal of Cognitive Engineering and Decision Making*, 2015. 9(2): p. 186-207.
33. Billman, D., et al., Needs Analysis and Technology Alignment Method:A Case Study of Planning Work in an International Space Station Controller Group–Part 1. *Journal of Cognitive Engineering and Decision Making*, 2015. 9(2): p. 169-185.
34. Miller, M.J., Decision Support System Development for Human Extravehicular Activity, in Department of Aerospace Engineering. 2017, Georgia Institute of Technology: Atlanta, GA.
35. Miller, M.J., et al., Design and Development of Support Systems for Future Human Extravehicular Activity, in 55th AIAA Aerospace Sciences Meeting. 2017, American Institute of Aeronautics and Astronautics.
36. Miller, M.J., K.M. McGuire, and K.M. Feigh, Decision Support System Requirements Definition for Human Extravehicular Activity Based on Cognitive Work Analysis. *Journal of Cognitive Engineering and Decision Making,* 2017. 11(2): p. 136-165.
37. Miller, M.J., C.W. Pittman, and K.M. Feigh. Next-Generation Human Extravehicular Spaceflight Operations Support Systems Development. in 68th International Astronautical Congress. 2017. Adelaid, Australia.
38. Kovich, C., Exploration EVA Suit Systems Requirements Document. NASA.
39. Bledsoe, K., Project Technical Requirements Specification for the Exploration Mobility Unit (xEMU) Project). NASA.
40. Kim, K.H., et al., Human Modeling Tools for Spacesuit and Hardware Design and Assessment, in Digital Human Modeling and Posturography, S. Scataglini and G. Paul, Editors. in press, Elsevier Sand T Books: San Diego, CA.
41. Linh Vu, H.K., Sudhakar Rajulu, Posture Transfer Method on Pre-Scanned Full-body Geometry for Space Architecture Design.
42. Davis, K., et al., xEMU Lower Torso Assembly (LTA) Brief Fleet Sizing Study, in International Conference on Environmental Systems

43. Young, K.S. and S. Rajulu, Changes in seated height in microgravity. *Applied Ergonomics*, 2020. 83: p. 102995.

44. Scheuring, R.A., et al., Musculoskeletal injuries and minor trauma in space: incidence and injury mechanisms in US astronauts. *Aviation Space and Environmental Medicine*, 2009. 80(2): p. 117-124.

45. Scheuring, R.A., et al., The Apollo Medical Operations Project: Recommendations to improve crew health and performance for future exploration missions and lunar surface operations. *Acta Astronautica*, 2008. 63(7): p. 980-987.

46. Strauss, S., R.L. Krog, and A.H. Feiveson, Extravehicular mobility unit training and astronaut injuries. *Aviation Space and Environmental Medicine*, 2005. 76(5): p. 469-474.

47. Anderson, A.P., D.J. Newman, and R.E. Welsch, Statistical evaluation of causal factors associated with astronaut shoulder injury in space suits. *Aerospace Medicine and Human Performance*, 2015. 86(7): p. 606-613.

48. Somers, J., et al., Defining NASA risk guidelines for capsule-based spacecraft Occupant injuries resulting from launch, abort, and landing. 2014, NASA/TM-2014.

49. Somers, J.T., et al., Investigation of the THOR anthropomorphic test device for predicting occupant injuries during spacecraft launch aborts and landing. *Frontiers in Bioengineering and Biotechnology*, 2014. 2: p. 4.

50. Fineman, R.A., et al., Objective metrics quantifying fit and performance in spacesuit assemblies. *Aerospace Medicine and Human Performance*, 2018. 89(11): p. 985-995.

51. Anderson, A., et al. In-suit sensor systems for characterizing human-space suit interaction. 2014. 44th International Conference on Environmental Systems.

52. Chappell, S.P., A.F. Abercromby, and M.L. Gernhardt, NEEMO 14: Evaluation of Human Performance for Rover, Cargo Lander, Crew Lander, and Exploration Tasks in Simulated Partial Gravity. NASA Technical Report, 2011. NASA/TP-2011-216152

53. Chappell, S., et al., Access Systems for Partial Gravity Exploration and Rescue: Results from Prototype Testing in an Analog Environment. 2007, SAE Technical Paper.

54. Vu, L.Q., et al., Evaluation of lumbar motion with fabric strain sensors: A pilot study. *International Journal of Industrial Ergonomics*, 2019. 69: p. 194-199.

55. Conkin, J., et al., Venous Gas Emboli and Ambulation at 4.3 psia. *Aerospace Medicine and Human Performance*, 2017. 88(4): p. 370-376.

56. NASA, E.A.W.G., Recommendations for exploration spacecraft internal atmospheres: The final report of the NASA exploration atmospheres working group. NASA Technical Publication NASA/TP-2010-216134, in NASA Technical Publication. 2010.

57. Behnke, A.R., Decompression sickness following exposure to high pressures. Decompression sickness, 1951: p. 53-89.

58. Gernhardt, M.L., Development and evaluation of a decompression stress index based on tissue bubble dynamics. 1991, University of Pennsylvania.

59. Gernhardt, M., A. Abercromby, and J. Conkin, Potential Fifty Percent Reduction in Saturation Diving Decompression Time Using a Combination of Intermittent Recompression and Exercise, in Undersea and Hyperbaric Medical Society Annual Scientific Meeting. 2007: Maui, HI.

60. Abercromby, A.F.J., M. Gernhardt, and J. Conkin. Potential Benefit of Intermittent Recompression in Reducing Decompression Stress During Lunar Extravehicular Activities. in 79th Annual Scientific Meeting of the Aerospace Medical Association. 2008. Boston, MA.

61. Pilmanis, A.A., et al., The effect of repeated altitude exposures on the incidence of decompression sickness. Aviation Space and Environmental Medicine, 2002. 73(6): p. 525-531.

62. Mollerlokken, A., et al., Recompression during decompression and effects on bubble formation in the pig. Aviation Space and Environmental Medicine, 2007. 78(6): p. 557-560.