Evidence Report:

RISK OF INJURY AND COMPROMISED PERFORMANCE DUE TO EVA OPERATIONS

Human Research Program

Human Health and Countermeasures Element

Approved for Public Release: April 15, 2015

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Houston, Texas

CURRENT CONTRIBUTING AUTHORS:

Steven P. Chappell, Ph.D.	**Wyle Science, Technology, & Engineering**
Jason R. Norcross, M.S.	**Wyle Science, Technology, & Engineering**
Andrew F.J. Abercromby, Ph.D.	**NASA Johnson Space Center**
Michael L. Gernhardt, Ph.D.	**NASA Johnson Space Center**

PREVIOUS CONTRIBUTING AUTHORS:

Johnny Conkin, Ph.D.	**Universities Space Research Association**
Nancy House, B.S.	**Stinger Ghaffarian Technologies, Inc.**
Jennifer Jadwick, B.S.	**Wyle Science, Technology, & Engineering**
Jeffrey A. Jones, M.D., M.S.	**Baylor College of Medicine**
Lesley R. Lee, M.S.	**Wyle Science, Technology, & Engineering**
Richard A. Scheuring, D.O., M.S.	**NASA Johnson Space Center**
Jennifer A. Tuxhorn, Ph.D.	**Wyle Science, Technology, & Engineering**

TABLE OF CONTENTS

I. PRD RISK TITLE: RISK OF INJURY AND COMPROMISED PERFORMANCE DUE TO EVA OPERATIONS ... 1
II. EXECUTIVE SUMMARY ... 1
III. INTRODUCTION ... 2
III.1. Injury ... 2
III.2. Compromised Performance ... 3
III.2.1. Integrated Suit Tests ... 4
III.2.2. Analog Tests & Training ... 4
III.2.3. Characterization of EVA Research Environments ... 7
IV. CONTRIBUTING FACTORS ... 9
IV.1. Suit Habitability ... 10
IV.1.1. EVA Suit Design ... 10
IV.1.2. EVA Suit Fit ... 19
IV.1.3. EVA Glove Function ... 21
IV.1.4. Waste Management ... 22
IV.1.5. Nutrition and Hydration ... 22
IV.2. In-Suit Physical Environment ... 24
IV.2.1. Hypoxia ... 24
IV.2.2. Hypercapnia ... 25
IV.2.3. Internal Suit Pressure ... 26
IV.2.4. Hyper/Hypothermia ... 27
IV.2.5. Humidity ... 30
IV.2.6. Excessive Radiation Exposure ... 31
IV.2.7. Decompression Sickness ... 31
IV.2.8. Ebullism ... 32
IV.2.9. Embolism ... 33
IV.3. EVA Factors ... 33
IV.3.1. Work Efficiency Index ... 33
IV.3.2. EVA Task and Timeline Design ... 34
IV.3.3. EVA Resources ... 35
IV.3.4. EVA Environment ... 36
IV.3.5. Quality of EVA Procedures ... 38
IV.3.6. EVA Training ... 38
IV.3.7. EVA Crew Collaboration ... 38
IV.4. Physical State ... 39
IV.4.1. Crewmember Physical Preparation ... 39
IV.4.2. Pre-existing Injury or Illness ... 40
IV.4.3. Fatigue ... 40
IV.5. Mental State ... 41
IV.5.1. Situational Awareness ... 41
IV.5.2. Cognitive State ... 41
IV.5.3. Psychological State ... 42
V. COMPUTER-BASED MODELING AND SIMULATION ... 42
V.1. Life Sciences Implications of EVA ... 42

V.1.1. EVA Timeline Analysis and Computational Modeling ... 43
VI. RISK IN CONTEXT OF EXPLORATION MISSION OPERATIONAL SCENARIOS 44
VII. GAPS ... 46
VIII. CONCLUSION ... 49
IX. REFERENCES ... 49
X. TEAM ... 56
XI. LIST OF ACRONYMS ... 57
XII. APPENDIX A: EVA GAPS AND MASTER LOGIC DIAGRAM CONTRIBUTING FACTORS MAPPING ... 59

I. PRD RISK TITLE: RISK OF INJURY AND COMPROMISED PERFORMANCE DUE TO EVA OPERATIONS

Description: Given the high-performance physiological and functional demands of operating in a self-contained EVA or training suit in various gravity fields and system environments, there is a possibility that crew injury and compromised physiological and functional performance may occur.

II. EXECUTIVE SUMMARY

Future missions to the moon, asteroids, and Mars will most likely include as many as 24 hours of extravehicular activity (EVA) per crewmember per week, which will involve the performance of exploration, science, construction, and maintenance tasks. The effectiveness and success of these missions depends on EVA systems and operations concepts being designed that maximize human performance and efficiency while minimizing health and safety risks for crewmembers.

Over 375 EVAs and counting have been performed in microgravity using the Extravehicular Mobility Unit (EMU). Use of the EMU during EVA led to the successful assembly of the International Space Station as well as other payload experiments and satellite launches and repairs. All of this was completed with no crewmember performing more than 4 EVAs on a single shuttle mission and no back-to-back EVAs for any crewmember. However, these successful missions resulted in injury rates for EVA crewmembers that may be greater than what is acceptable for a long-duration exploration mission.

In a partial-gravity environment, the Apollo astronauts completed necessary tasks in the EVA suits used during short-duration lunar missions, but with noted mobility problems. However, the longer-duration missions, more frequent EVAs, and more varied EVA tasks that are anticipated during the future exploration missions will require EVA suits and systems that are more oriented to human health and performance than those used during the Apollo Program. Many of the problems that were encountered with the Apollo EVA suits (e.g., limited mobility and dexterity, high and aft center of gravity, and other features requiring significant crew compensation) will need to be corrected or mitigated to optimize EVA objectives.

It is critical to understand the effects of EVA system design variables such as suit pressure, weight/mass, center-of-gravity location, joint ranges of motion, and biomedical monitoring on the ability of astronauts to perform safe, efficient, and effective EVAs. To achieve this understanding, the EVA researchers will need to develop and execute an integrated human testing program across multiple environments. The research will provide objective data that will inform design decisions and crewmember standards, thereby ensuring EVA systems that optimize crewmember health, safety, efficiency, and performance.

This report describes the risks to crew health, safety, performance, and efficiency that EVA operations can bring, and provides the evidence base to substantiate the importance of the risks.

III. INTRODUCTION

Providing the capability for humans to work productively and safely while performing EVAs involves many important contributing factors. Maintaining sufficient total pressure and oxygen partial pressure is vital not only to human health, but also to survival. Prebreathe protocols must adequately reduce the amount of inert gas in astronauts' blood and tissues to prevent decompression sickness (DCS) while minimizing the impact on crew efficiency. The EVA suit must be ventilated to remove expired carbon dioxide (CO_2), both perspired and respired water vapor, and metabolically generated heat. Since ventilation flow alone may not be sufficient to control core body temperature and prevent unwanted heat storage, cooling water is typically circulated through small tubes that are located in garments worn close to the skin. Heat influx also must be controlled, and the EVA crewmember must be protected from harmful solar and other radiation. In scenarios with EVA of long duration, nourishment and water must be available for ingestion, and accommodations must be provided for liquid and solid waste collection.

Considerable evidence shows that the inadequate design of any aspect of an EVA suit system can have serious consequences. A large body of evidence in this area consists of astronaut first-hand experience and non-experimental observations (i.e., Category III and Category IV evidence). Evidence has also been gathered in a rigorous, controlled manner in which subjects served as their own controls from shirt-sleeved to suited conditions and across repeated-measures trials in which a single variable is changed (i.e., Category II). This report identifies and describes the various risks, contributing factors, and associated evidence for injury and compromised performance due to EVA operations.

III.1. Injury

Gas-pressurized spacesuits have been shown to cause injuries and increase metabolic expenditure (Carr 2005; Hochstein 2008; Jones et al. 2008; Longnecker et al. 2004; Maida et al. 1996; Opperman et al. 2010; Scheuring et al. 2009; Viegas et al. 2004; Williams and Johnson 2003). During the first spacewalk performed, Alexei Leonov was nearly unable to reenter his spacecraft due to his immobile suit and inability to see through his fogged visor. Apollo astronauts sustained hand, joint, and skin irritation injuries (Scheuring et al. 2008).

Currently, the U.S. spacesuit, the extravehicular mobility unit (EMU), causes a variety of musculoskeletal injuries. The EMU is pressurized with gas to 4.3 psi (29.6 kPa), forcing the astronaut to expend energy to deform the suit and limiting his or her mobility (Jaramillo et al. 2008; Maida et al. 1996; Newman et al. 2000; Norcross et al. 2010c; Norcross et al. 2010d; Schmidt et al. 2001). EVA injuries can be divided into two groups: contact injuries and strain injuries.

Contact injuries refer to contusions, abrasions, and hard impacts with the spacesuit. Strain injuries are due to overuse, repeated movements, and development of high muscle forces. For example, these injuries can occur when astronauts are manipulating heavy tools or working at the limit of their work envelope, forcing the shoulder joint against the spacesuit, among other causes (Straus 2004).

Hand and finger injuries are the most common injuries during both training and flight. Injuries include onycholysis, or fingernail delamination, blisters, contusions, and abrasions (Jones 2004; Opperman et al. 2010; Scheuring et al. 2009; Straus 2004; Viegas et al. 2004). Resolving hand injury is one of the most difficult challenges spacesuit designers face. Shoulder injuries typically occur during training and are some of the most severe injuries astronauts face. These injuries are extensively covered by Williams and Johnson (Williams and Johnson 2003) and continue to be actively researched (Laughlin et al. 2014; Murray et al. 2014). The primary injuries that occur at the limb joints (wrist, arms, knees, and ankles) are abrasions and contusions as a result of rubbing and impact against the soft suit components to move the garment.

Although most reported injuries have been minor and did not affect mission success, injury incidence during EVA is much higher than the incidence of injury that occurs elsewhere on orbit (Opperman et al. 2010; Scheuring et al. 2009; Viegas et al. 2004). EVA-associated injuries have been further exacerbated with the increased number of EVAs and training sessions for the construction of the International Space Station (ISS) in the neutral buoyancy lab (NBL) training pool (Gernhardt and Abercromby 2009). Astronauts and tools are made neutrally buoyant to simulate the weightlessness of microgravity, making possible realistic mission preparation with mockups of the ISS, robotic arms, and other pieces of space hardware. Many hours of training are required for each EVA, and the injuries seen on orbit are magnified as more time is spent inside the suit. Also, gravity shifting the astronaut inside the suit causes new injuries not seen in space flight. Because some training causes the weight of the body to rest on the shoulders, shoulder injuries are one of the largest problems, even leading to surgical intervention (Opperman et al. 2009; Straus 2004; Strauss et al. 2005; Williams and Johnson 2003).

III.2. Compromised Performance

Anyone who has ever spent time inside a pressurized spacesuit understands that their ability to perform tasks is compromised. EVA crewmembers must first be fit into a spacesuit and then make sizing adjustments as they learn to move within the constraints of the suit and complete tasks. Even the simplest of tasks require greater metabolic effort and time to complete than at 1*g* in shirtsleeves. A spacesuit is a closed system, so when crewmembers try to push themselves to complete tasks quickly, they run the risk of overexertion, overheating, fatigue, and frustration. Currently, human performance constraints are dealt with operationally through extensive EVA training in the Neutral Buoyancy Laboratory before flight EVA, but this experience is limited to the EMU, microgravity, metabolic data collection, and operational training paradigms. Detailed discussion of the factors that contribute to compromised performance will be covered in section IV, Contributing Factors.

To advance the state of human performance data during EVA, the EVA Physiology, Systems, & Performance (EPSP) Project utilized lunar analogs (such as parabolic flight aircraft, NASA Extreme Environment Mission Operations, NBL, remote field test sites, and JSC's Partial Gravity Simulator [POGO] in the Space Vehicle Mock-up Facility) to characterize human performance and suit-human interactions during partial-gravity EVA. The project worked with the Constellation EVA Systems Project Office (ESPO) to develop and execute an integrated human testing program across multiple analogs. Along with the EPSP/ESPO tests that provided objective human performance data, the Exploration Analogs and Mission Development (EAMD) team worked to evaluate EVA operational concepts that were based on the latest lunar surface scenarios. The results from these efforts were integrated to enable informed design decisions, thereby ensuring a surface EVA system that optimizes crewmember health, safety, efficiency, and performance.

III.2.1. Integrated Suit Tests

EPSP and ESPO initiated a series of tests collectively referred to as the Integrated Suit Tests in January 2006 with the EVA Walkback Test (EWT). Following the EWT were Integrated Suit Test 1 (IST-1), Integrated Suit Test 2 (IST-2), Integrated Suit Test 3 (IST-3), and the Integrated Parabolic Flight Test. EWT, IST-1, IST-2, and IST-3 were performed on POGO, a simulator in the Space Vehicle Mockup Facility that utilizes a pneumatic system to offload the weight of suited and unsuited subjects to produce partial gravity. The Integrated Parabolic Flight Test utilized the C-9 parabolic flight aircraft provided by the Reduced Gravity Office.

In the EWT, the feasibility of a suited 10-km ambulation was tested to represent a case in which a rover (without a second rover available to help) breaks down on the lunar surface and a crew is forced to walk back to their habitat or ascent vehicle. The EWT was also performed to determine physiological and biomechanical suit parameters (Norcross et al. 2009). The IST-1 objective was to identify the effects of weight, inertial mass, pressure, and suit kinematics on the metabolic cost of ambulation in a spacesuit, specifically in the MKIII spacesuit technology demonstrator, which has a number of features that are expected in future spacesuit designs (Norcross et al. 2010c). Identifying these effects enabled work toward another objective, to develop predictive models of metabolic rate, subjective ratings, and suit kinematics based on measurable suit, task, and subject parameters. Similar to the objective of IST-1, an objective of IST-2 was to establish the metabolic cost associated with changes in weight, inertial mass, pressure, and suit kinematics when performing exploration tasks such as shoveling, rock pickup, kneel-and-recover, and light construction tasks. The additional data furthered development of the predictive algorithms initiated by IST-1 (Norcross et al. 2010d). Unlike the EWT, IST-1, and IST-2, each of which had unsuited and suited components, IST-3 contained only an unsuited component because of POGO lift capacity limitations. For IST-3, the direction of research shifted toward exploring the effects of changes in center of gravity on human performance including metabolic rate, biomechanics, and subjective measures (Norcross et al. 2010b). The Integrated Parabolic Flight Test used the superior partial-gravity environment of the C-9 aircraft to determine the separate effects of changes in suited weight and mass as well as suited center of gravity (Chappell et al. 2010a).

The data gathered from the Integrated Suit Tests have assisted in determining how typical EVA work correlates with exercise. When the metabolic rates, biomechanics, and subjective measures during EVA-like activities (such as walking and shoveling) are quantified, exercise protocols for long-duration missions can be developed that work to supplement the exercise achieved during EVA.

III.2.2. Analog Tests & Training

III.2.2.1. Neutral Buoyancy Laboratory

As part of the astronaut mission training sequence, a crewmember will spend about 7 to 10 hours training for every hour of an EVA, depending on the difficulty of the EVA. Training takes place at the Sonny Carter Training Facility's Neutral Buoyancy Lab (NBL). Training is performed in the 61.6-m-long (202 ft.), 31.1-m-long (102 ft.), 12.2-m-deep (40 ft.) pool, which contains mockups of the International Space Station. The suited astronauts are made neutrally buoyant with the strategic placement of weights to simulate the weightlessness encountered in space.

During the EVA simulation, measurements of the gas flow rate through the spacesuit, both supply and return, are obtained through a digital connection to a flow meter and computer located on the Environmental Control System (ECS) panel. The concentration of expired CO_2 is captured from gas samples taken at the end of the return umbilical that vents out the expired gas mixture. The two samples are fed into a laptop computer running a LabView program specifically designed for this purpose. A series of calculations use the supply flow rate and CO_2 measurements to determine the volume of oxygen consumed (VO_2) and the volume of carbon dioxide (VCO_2) produced. A linear combination of the VO_2 and VCO_2 in the Weir equation is used to determine the metabolic rate (met rate) once every second for the duration of the simulation (Klein et al. 2008).

The test conductor supplies a timeline of the simulation, which is used to break the data into individual tasks. The duration of each task, along with the minimum, maximum, and average metabolic rate and the change in tank pressure, are all calculated and recorded in a task analysis chart. During the training sequence, the EVA trainers and suit engineers use the data to verify the workload of the tasks and consumable consumption, to assist in planning the EVA task sequence to reduce crewmember fatigue and ensure that adequate consumables are available. Flight surgeons and biomedical engineers review the data before an EVA and use the data when monitoring an EVA. If the metabolic rates during the EVA are higher than what was recorded at the NBL, flight surgeons can query crewmembers and determine whether they are having problems with the current task. During an EVA, metabolic rates are calculated from the pressure decrements in the bottle that supplies oxygen to the astronauts in their spacesuits. The data are downlinked to Earth every 2 minutes. These data can then be compared in real time to the NBL data by the flight surgeon and biomedical engineer (Klein et al. 2008).

The end of the shuttle program did not mean the end of EVAs. Training for scheduled EVAs and contingency EVAs continues at the NBL. With far fewer scheduled EVAs, all ISS increment crewmembers now prepare for them using a set of standard EVA skills training profiles covering the most likely contingency and emergency repairs. NBL metabolic rates provide useful information for flight planning and EVA monitoring. Quantifying similarities and differences between training and flight improves knowledge for safe and efficient EVAs.

In addition to training, the NBL has also been used to do EVA research. As the Advanced EVA Space Suit portable life support system (PLSS) was entering its early design phase in 2006, an investigation was launched to determine the most appropriate location for the center of gravity of the PLSS in relation to a crewmember. The Crew and Thermal Systems Division (CTSD) at NASA JSC developed a rig that had the total mass of the new PLSS and could be worn by a SCUBA diver. It had adjustable weights within that could alter the location of the rig's center of gravity. The PLSS rig was also used at NASA Extreme Environment Mission Operations (NEEMO) missions 9-14, off the coast of Key Largo, FL (see next section). Valuable data were collected and combined with the data taken at NEEMO missions to ensure that suit and PLSS designs were acceptable for human performance (Jadwick et al. 2008b).

More recent testing in the NBL for advanced EVA at asteroids has been performed suited, in the current NASA EMU as well as the modified advanced crew escape suit (MACES), to test microgravity asteroid exploration and capsule-based EVA techniques. This testing has also collected human performance data and used timeline and task techniques similar to those described for Shuttle and ISS EVA training. The data collected will be used to ensure that human health and performance is considered in suit, tool, task, and timeline designs.

III.2.2.2. NASA Extreme Environment Mission Operations

Aquarius is the only operational undersea research habitat in the world. It is operated by the Florida International University (FIU). *Aquarius* was built in the mid-1980s, and was previously located in Saint Croix (U.S. Virgin Islands) before it was moved to the reef line 12 miles off Key Largo, Florida, in 1990. In these two locations, *Aquarius* has supported dozens of missions to study the undersea realm for several hundred marine research scientists from around the world.

Aquarius is similar in size to the U.S. Laboratory module on the International Space Station, or ISS (~15 m long × 4.5 m in diameter). It is firmly secured to a sand patch surrounded by large spur-and-groove coral reefs on 3 sides. It sits in water 18 m (60 ft.) deep, but the entrance level is actually closer to 15 m (50 ft), which corresponds to an internal pressure of ~ 2.5 atmospheres. At this depth, aquanauts living and working in the habitat become exposed to excessive levels of nitrogen within the first few hours and must commit to staying in the habitat and undergoing a decompression schedule before returning to the surface. This type of diving is called "saturation" diving, referring to the complete saturation of the body tissues by the breathing gas mixture. A diver in this condition will quickly experience decompression sickness if he or she returns to the surface without going through the requisite decompression schedule, and would most likely experience injury and possibly death if not treated. The danger is real and the environment is truly extreme, which is one of the key reasons it makes such a good analog to living in space. Aquanauts participating in these missions must utilize their training, skills, knowledge, and teamwork to ensure their safety and mission success.

The combination of isolation in a confined and extreme environment along with the ability to simulate weightlessness or reduced gravity during EVA excursions makes *Aquarius* an excellent analog for spaceflight, second only to the ISS itself as judged by a comprehensive assessment of all Earth-based spaceflight analogs (Keeton et al. 2011). NASA's NEEMO project began in 2001 with the primary goal of astronaut training. Over time, the project evolved to include many science and engineering studies during the missions. NEEMO missions have included evaluations of the effects of communications time delay on mission operations, evaluation of telemedicine techniques, and research involving behavioral health, team cohesion, fatigue, and other physiological and psychological adaptations that occur during NEEMO missions. Other objectives have taken advantage of buoyancy while crewmembers are diving on SCUBA or umbilical-supplied diving helmets outside the *Aquarius* habitat; by attaching the appropriate amount of weight or flotation to EVA crewmembers, the effects of different gravity environments and spacesuits of different weights can be simulated. In some cases, custom-built backpacks have been used to simulate the backpacks on EVA suits, except that they are reconfigurable so that the center of gravity (CG) can be moved to simulate the CG of different spacesuit designs (Chappell et al. 2011). Crewmembers have then performed predefined tasks in the simulated partial-gravity environment to provide valuable data on, for example, the design of tasks, EVA interfaces, and hardware, and the effect of spacesuit weight and CG on EVA performance; all of which will help ensure human health and performance during EVA.

III.2.2.3. Land-based Field Testing

Land-based field testing has proven to be a valuable and complementary aspect of EVA research that provides high-fidelity hardware along with true geologic science and actual terrain features, lending realism to the tasks and timelines that humans may need to perform while on EVA. While land-based field testing does not provide the reduced-gravity environment of gravity offload devices or underwater simulations, combined with research from those environments it provides a complete picture of all aspects of exploration destination EVAs.

NASA has utilized a variety of land-based field testing sites and projects while performing EVA systems research. Those sites have included Antarctic, high-arctic (Norcross et al. 2008), desert, and other field locations that simulate particular exploration destinations. NASA's Desert Research and Technology Studies (Desert RATS) tests took place from 1997 to 2011. Initially, these field tests were focused on advanced spacesuit and EVA systems evaluation. Spacesuit configurations, mobility aids, robotic assistant interaction, field test support equipment, and EVA science were the primary objectives for evaluation. The test objectives shifted over time to EVA mobility performance characterization, to evaluation of EVA exploration components, and finally toward performance of integrated mission scenarios. Human interaction with rovers, habitats, robotic assistant elements, and exploration operations control centers formed the central aspects of the later field test objectives (Ross et al. 2013).

In 2012, RATS shifted to be based at NASA Johnson Space Center. Although the studies did not take place in the field, high fidelity hardware and simulations were still used to provide a realistic research environment for EVA (Abercromby et al. 2013b).

III.2.3. Characterization of EVA Research Environments

Simulating partial gravity on Earth is difficult. While many methods exist, all have significant limitations (Chappell and Klaus 2013). The overarching goal of the integrated suit test (IST) series was to evaluate human performance while wearing spacesuits in reduced gravity. To effectively complete this goal, partial-gravity analog environments would ideally need to allow unrestrained freedom of movement in all 6 degrees of freedom (DOF) while accurately simulating partial-gravity kinetics. After the IST series was completed, analysis was performed to understand and highlight the strengths and limitations of the current partial-gravity analog environments and provide recommendations for improved simulators (Norcross et al. 2010a). Two different partial-gravity simulations were primarily used in the IST studies to characterize suited human performance: (1) the Johnson Space Center (JSC) Space Vehicle Mockup Facility's (SVMF's) partial-gravity simulator (POGO) and (2) JSC Reduced Gravity Office's (RGO's) C-9 parabolic flight aircraft. Post-series analysis began with a general characterization of each environment, followed by direct comparisons to evaluate human performance metrics collected in both partial-gravity environments from subjects doing similar tasks. Indirect comparisons were also performed that looked at how human performance during partial-gravity simulation differs from expectations based on physics, models, or results from other studies. Finally, the analysis closed with considerations regarding the usability of each partial-gravity analog environment and suggestions for improved simulations.

The ability to accurately and effectively characterize suited human performance is wholly contingent on understanding the accuracy, limitations, and usability of partial-gravity analog environments. Although parabolic flight may simulate partial-gravity kinetics better than any other environment, the high cost, volumetric constraints, limited parabola duration, and limited data-collection capabilities prevent the use of the C-9 or another parabolic aircraft as the primary partial-gravity analog environment for studying suited human performance (Norcross et al. 2010a).

Although POGO improves on many of the major limitations of parabolic flight, it also introduces several new sources of error including increased inertia, limited DOF, and non-optimized offload kinetics. The ideal partial-gravity analog environment would combine the partial-gravity kinetics of parabolic flight with a large test area, advanced data collection capabilities, unlimited time, treadmill integration, and mock-up inclusion available with ground-based analogs such as POGO. Many of the major limitations of POGO were found to be able to be improved after needed changes were implemented, in that system or a follow-on system (Norcross et al. 2010a).

If the needed changes were to be incorporated into a new overhead suspension system, the system would provide an optimal primary test bed on which to characterize suited human performance. The Active Response Gravity Offload System (ARGOS) is being designed to simulate reduced-gravity environments, and as an improved replacement for POGO. ARGOS uses an in-line load cell to continuously offload a portion of a human or robotic payload's weight during all dynamic motions, which can include walking, running, and jumping under lunar or martian gravities, as well as a wide range of microgravity activities. Using a cable angle sensor, ARGOS actively tracks and follows the payload's motion in all horizontal, translational directions to maintain an accurate vertical offload force. The facility is capable of supporting surface operation studies, suit and vehicle requirements development, suit and vehicle design evaluation, robotic development, mass handling studies, and crew training with both suited and shirt-sleeved subjects (Dungan and Lewis 2013).

Currently under continuous development and improvement, ARGOS is intended to support testing, development, and training for future missions to the Moon, Mars, asteroids, or any other celestial destination. It is also intended to support both intravehicular activity (IVA) and EVA training for NASA's ongoing activities on the International Space Station. The current steel structure, which measures 12.5 m long x 7.3 m wide x 7.6 m tall (41 x 24 x 25 ft.), accommodates movement in all three directions of motion (one vertical and two horizontal). This facility, when completed and usable for human testing, could mitigate all of the limitations of the previously used POGO system and enable the start of a new generation of essential EVA research (Dungan and Lewis 2013).

However, even with all of the improvements in gravity offload systems such as ARGOS, limitations still exist that cannot be removed, including how the lifting path remains only through the CG, and anything outside of that lifting path, particularly the limbs and any accessories, will still operate within 1*g* kinetics. For this reason, parabolic flight and underwater buoyancy should be used for testing that requires that all materials, including the subject, suit, tools, and mock-ups, be at the same partial gravity. Parabolic flight also remains an ideal option for limited verification of ground-based data, assuming the tasks are performed in the same way in both partial-gravity analog environments (Norcross et al. 2010a).

IV. CONTRIBUTING FACTORS

Many factors contribute to the risk of injury and compromised performance due to EVA operations. Extensive review within the EVA research community and NASA Human Systems Risk Board has delineated 24 separate contributing factors grouped within the categories of suit habitability, in-suit physical environment, EVA factors, crewmember physical state, and crewmember psychological state. The groupings as well as their potential contribution to injury and/or compromised performance are shown in Figure 1.

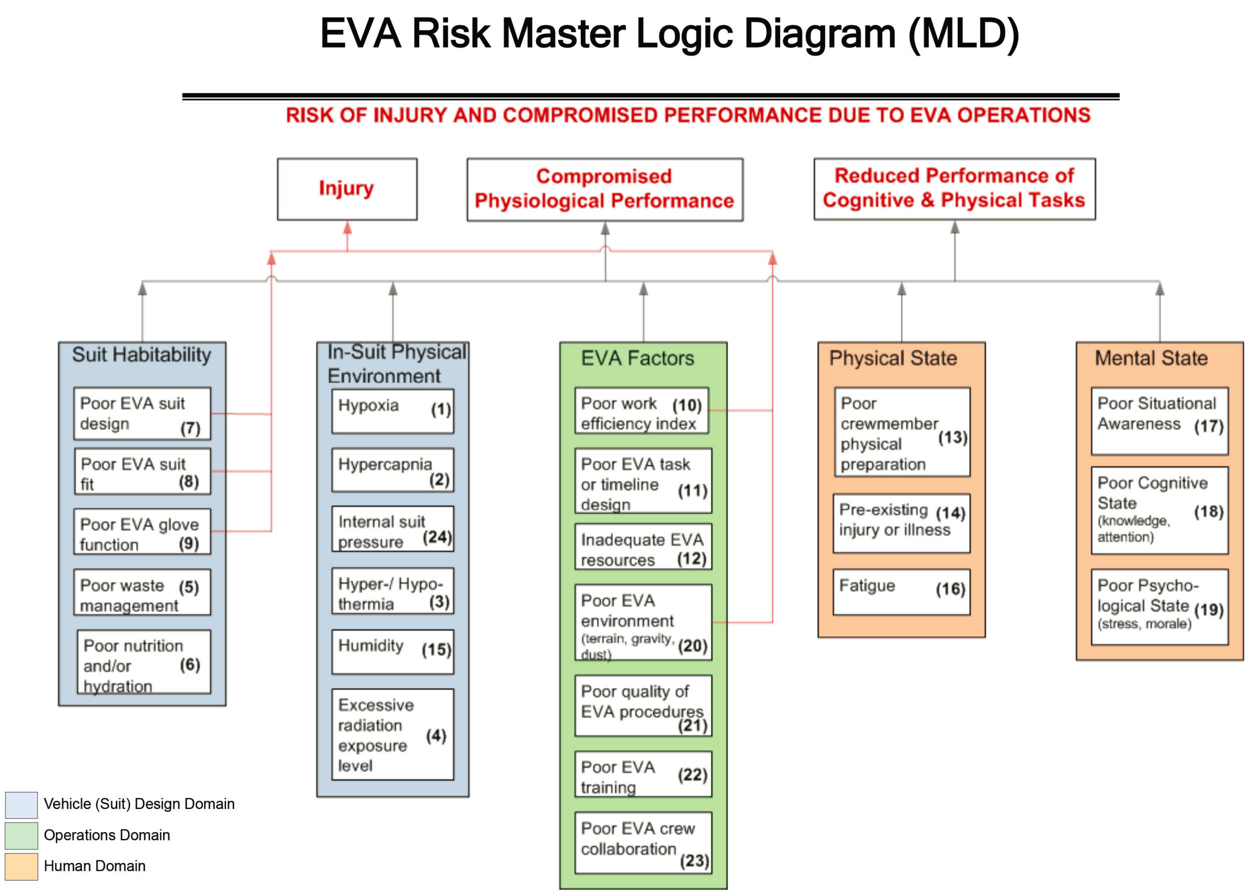


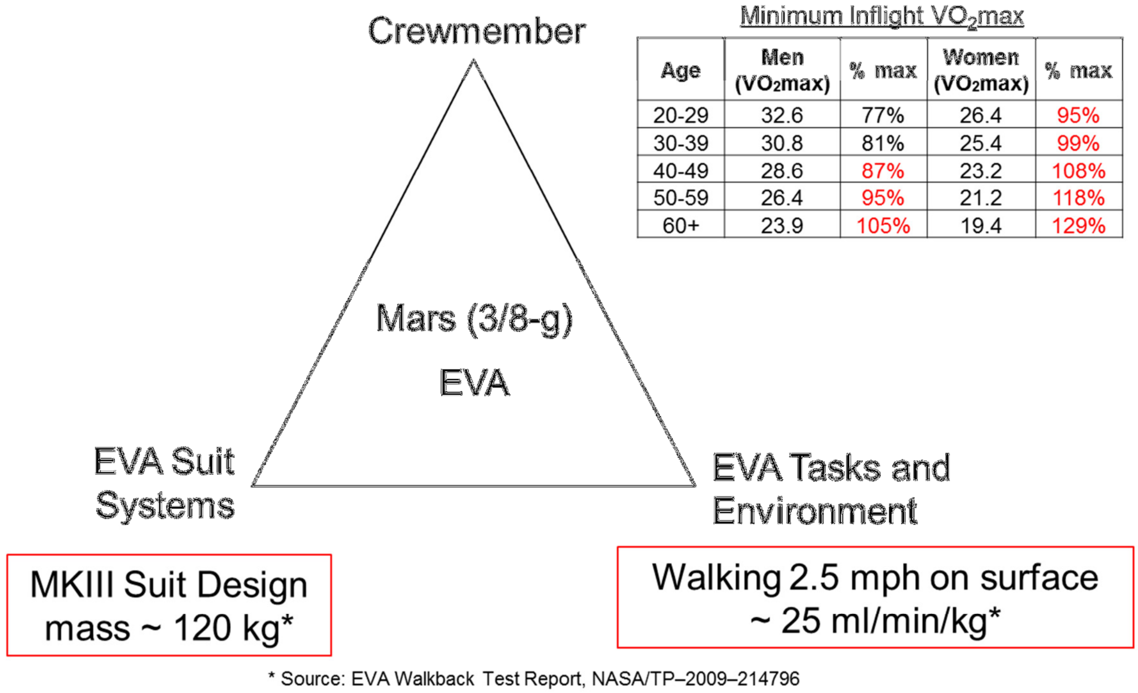
Figure 1 - EVA risk Master Logic Diagram (MLD).

While this figure is helpful, it does not describe which of the contributing factors are adequately controlled, which factors require additional research, or which research and development group is tasked with mitigating the risk. Although certain groups (e.g., Engineering Directorate, EVA Management Office, Mission Operations Directorate, Crew Health and Safety, Human Research Program) within NASA may be responsible for different factors, it is critical to keep all of these factors in mind because of the numerous possible interactions. The following sections address each of the categories and their contributing factors individually, providing an overview of the evidence for each.

IV.1. Suit Habitability

IV.1.1. EVA Suit Design

While spacesuit designs have many design and technology variables, a few general factors may be summarized that are believed to affect human suited health and performance, namely mass, pressure, center of gravity, joint characteristics, and how well the suit can be made to fit the subject. Current suit designs for partial gravity have high mass and may be out of alignment with the allowable fitness level requirements for destinations such as Mars, which is shown in Figure 2. Suit pressure, in some suit designs, has been shown to have an impact on the mobility and task performance of crewmembers (Norcross et al. 2010c). Other factors such as poor centers of gravity have been shown to induce instability while suited crewmembers perform some tasks (Chappell et al. 2010a; Chappell et al. 2011). Shoulder and other injuries have been induced by forced motions due to spacesuit joint characteristics and fit (Strauss et al. 2005; Williams and Johnson 2003).



Minimum Inflight VO_2max

Age	Men (VO_2max)	% max	Women (VO_2max)	% max
20-29	32.6	77%	26.4	95%
30-39	30.8	81%	25.4	99%
40-49	28.6	87%	23.2	108%
50-59	26.4	95%	21.2	118%
60+	23.9	105%	19.4	129%

Figure 2 - EVA crewmember, suit, tasks, and environment interactions. This example shows that the simple act of walking at 2.5 mph on the Mars surface in the MKIII prototype EVA suit would require VO_2 values that are near or even greater than the fitness for duty requirement currently allowed in NASA-STD-3001 Volume 1.

Throughout the history of space flight, astronauts and cosmonauts have performed more than 400 EVAs. However, only 28 of those EVAs have been conducted in partial gravity (i.e., lunar gravity). Accordingly, the current understanding of suited human performance in partial-gravity environments is limited. A face-to-face summit with some of the Apollo astronauts provided valuable insight and yielded recommendations for the next-generation partial-gravity

EVA suit. Fourteen of the 22 surviving (at the time of the summit) Apollo astronauts participated in the Apollo Medical Operations Project to identify Apollo operational issues that had an impact on crew health and performance. In the category of EVA suit operations, recommendations centered on improving the functionality of the suit as well as improving human factors and safety features. The astronauts recommended increasing ambulatory and functional capability through increased suit flexibility, decreased suit mass, lower center of gravity, and reduced internal pressure (Scheuring et al. 2007).

The following excerpt from Scheuring et al. (2007) describes the astronauts' view on the need for increased suit mobility: "EVA suit mobility was more of an issue in terms of surface locomotion and energy expenditure. The crews often felt they were fighting the resistance in the suit. This was fatiguing, especially in the thighs." The astronauts pointed out that the lunar surface is more similar to an ocean than a desert. The undulating surface posed a number of challenges, including ambulating against a suit that did not allow mobility at the hip. Normal human locomotion includes flexion at the hip, knee and ankle, but the Apollo A7LB (lunar surface EVA suit) had limited ability to allow astronauts to bend the suit at the hip and rotate within the suit. This likely contributed to the loping and hopping style of gait, which relied more on knee and ankle range of motion. The crewmember had to bend forward from the knee joint, which demanded considerably more workload on the quadriceps muscles. Therefore, recommendations on mobility centered on adding hip mobility and improving knee flexibility. One comment summarized this point well: "Bending the knee was difficult in the suit. We need a better [more flexible] knee joint" (as quoted in Scheuring et al. 2007).

The Apollo astronauts also strongly recommended improving glove flexibility, dexterity, and fit. According to the crews, the most fatiguing part of surface EVA tasks was repetitive gripping. One crewmember stated that "efficiency was no more than 10% of the use of the hand" (Scheuring et al. 2007).

A comprehensive analysis was completed of all musculoskeletal injuries and minor trauma sustained in flight throughout the U.S. space program (Scheuring et al. 2009). This study identified 219 in-flight injuries, of which 50 resulted from wearing the EVA suit, making this the second leading cause of in-flight injuries. The incidence rate of EVA injuries was 0.05 per hour for 1,087.8 hours of EVA activity. This equates to an incidence rate of 1.21 injuries per day, or 0.26 injuries per EVA. The following excerpts from this study illustrate the types of EVA-induced injury:

> "Hand injuries were most common among EVA crewmembers, often due to the increased force needed to move pressurized, stiff gloves or repetitive motion for task completion. Many astronauts described the gloves causing small blisters and pain across their metacarpophalangeal (MCP) joints. This could be due to dorsal displacement of the MCP joints against the glove in order to flex the fingers (Viegas et al. 2004). While not mission impacting injuries, they can potentially distract an astronaut from important EVA tasks. Astronauts frequently develop onycholysis (separation of nail from nail bed) after Neutral Buoyancy Laboratory training sessions, and it is possible some of these injuries represent exacerbations of underlying ground-based injuries."

However, the authors later state that preflight conditions were not strong predisposing factors for these injuries.

> "Foot injuries also caused problems for EVA astronauts. One astronaut described an episode of 'excruciating, searing, knife-like pain' during an EVA. The astronaut attributed the pain to excess suit pressure bladder material inside the boot, but despite attempts at correcting the problem, the pain persisted with the development of a blister…Though the EVA was completed successfully, the astronaut described the pain from this injury as 'on the forefront of my mind'." "Another astronaut had similar symptoms after his second EVA with resultant numbness and pain on the dorsum of his feet."

Pressure-associated erythema developed on the dorsal surfaces of each foot, and symptoms persisted throughout the mission and 2 to 3 weeks post landing (Scheuring et al. 2009).

Nine of the 219 in-flight injuries were sustained by Apollo astronauts who were performing lunar surface EVAs. One Apollo astronaut suffered a wrist laceration from the suit wrist ring while working with drilling equipment, and another crewmember sustained wrist soreness due to the suit sleeve rubbing repeatedly. One crewmember injured his shoulder during a lunar EVA while attempting to complete multiple surface activities on a tight mission timeline. Unbeknown to his flight surgeon, this crewmember later took large doses of aspirin to relieve the pain. Many Apollo astronauts noted problems with their hands. One astronaut remarked, "EVA 1 was clearly the hardest … particularly in the hands. Our fingers were very sore." Another Apollo astronaut remarked that his hands were "very sore after each EVA," while another astronaut stated that after the third lunar EVA, his metacarpophalangeal and proximal interphalangeal joints (knuckles) were so swollen and abraded from a poor-fitting glove and/or lack of inner liner or comfort glove that he is certain that a further EVA would have been very difficult if not impossible. Accordingly, it is no surprise that the Apollo astronauts were adamant that the glove flexibility, dexterity, and fit be improved (Scheuring et al. 2007).

In a study by Strauss of injuries related to EVA training in the EMU at the NBL, 13 of the study's 86 participants were followed for shoulder-related injuries, and two required surgical interventions (Strauss et al. 2005). There are two primary causes for EVA-related shoulder injury: restriction of normal shoulder movement by the hard upper torso (HUT), a rigid part of the EMU and supporting body weight against the HUT. Depending on the lateral position of the scye bearings, scapulothoracic motion can be restricted, preventing normal shoulder abduction and adduction. To compensate, astronauts rely more heavily on the rotator cuff muscles, which normally stabilize the joint, causing overuse of the rotator cuff, leading to injury (Williams and Johnson 2003). Additionally, as astronauts shift within the suit during training, their bodies press up against the HUT, resting their weight on their shoulders. This is particularly true when the astronaut is in an inverted position, either fully head down, face forward, or face upward. Resting weight on the shoulder impinges on the rotator cuff muscles, causing tears and pinched nerves, in addition to causing uncomfortable pressure contacts (Straus 2004; Williams and Johnson 2003). Inverted NBL training is still performed, but are limited in duration.

Injury data have been compiled from the Lifetime Surveillance of Astronaut Health and an initial characterization of the data has been completed. Data analysis to compare astronaut anthropometry and suit components to injury is ongoing. Rigorous criteria for categorizing astronauts as injured or uninjured are being created and will be reviewed in conjunction with NASA subject matter experts.

Limb joint injuries occur when the convolute suit joint is not aligned well with the body joint, so the propensity for injury is increased (Benson and Rajulu 2009; Straus 2004). Hip and trunk injuries on orbit are fairly limited. They are primarily caused by impact and rubbing with the HUT, waist bearings, and soft elements resulting in abrasions and contusions. In training, additional injuries are seen in both the face-up and the face-down supine position, since the weight of the astronaut is supported by the HUT and the ventilation tubes of the Liquid Cooling and Ventilation Garment (LCVG). This pressure can lead to skin indentation and reddening (Scheuring et al. 2009; Strauss et al. 2005).

Many EVA tasks are performed in footholds as the primary restraint. Although the EMU is designed with limited lower-body mobility, astronauts must produce a counter torque by flexing leg and ankle muscles to maintain proper orientation while they work. Poorly fitting boots and boot inserts allow the astronaut to rotate backward, causing the foot and toes to impact and rub against the boot(Straus 2004). Additional discomfort is caused by bootie and pressure layer wrinkles, which cause blisters, contusions, abrasions, and loss of feeling. In one instance, this almost led to early termination of the EVA (Scheuring et al. 2009). In training and during experiments to evaluate planetary locomotion and exploration procedures, the shifting body also causes the tops of the foot and distal toes to impact the boot (Norcross et al. 2009; Straus 2004).

Data have been collected in the MKIII spacesuit technology demonstrator, mostly in simulated lunar gravity and using the POGO weight offload system (Norcross et al. 2010c; Norcross et al. 2010d; Norcross et al. 2009). Similar data using similar study design have not been collected using suit prototypes other than the MKIII, so it is not currently known whether the effects of suit design parameters are limited to the features of that prototype. Additionally, the limitations of the POGO system used during previous testing are believed to have had negative effects on the results. The ARGOS system offers substantial advancements that improve the accuracy of the data collected (Norcross et al. 2010a).

Physiologists and physicians have used various analog environments to study the effects of suit weight, mass, center of gravity (CG), pressure, biomechanics, and mobility on human performance. Test activities have been designed to characterize performance during ambulation and exploration-type tasks such as ambulation on both level and inclined surfaces, ambulation while carrying a load, rock collecting, shoveling, and kneeling. Other studies examine recovering from a fall and simple exploration and construction tasks using hand tools and power tools. Data collected include metabolic rates, time-series motion capture, ground reaction forces, subjective ratings of perceived exertion (RPEs) (Borg 1982), and operator compensation using a relative subjective scale.

Results from tests conducted on the POGO system have begun to characterize the metabolic cost, biomechanics, and subjective factors that are associated with ambulation and task performance in a suit in partial gravity. These tests have characterized the baseline metabolic cost of suited ambulation in lunar gravity across a wide variety of speeds, and have considered factors such as suit weight, inertial mass, suit pressure, and suit kinematic constraints and stability. Figure 33 illustrates a model describing the current understanding of how these factors contribute to the increased metabolic cost of suited ambulation in the MKIII suit (Norcross et al. 2010c). The parameter that had the largest impact on metabolic rate was suit weight, which is a function of the suit mass and the gravity field it is being operated in. Pressurizing the spacesuit increased metabolic effort, but variations in suit pressure made little difference. Factors such as inertial mass and stability in reduced gravity were placed in a leftover category that was not systematically evaluated. Future studies that can properly increase the mass of the EVA suit and compare different mass options in different gravity fields may provide this clarity.

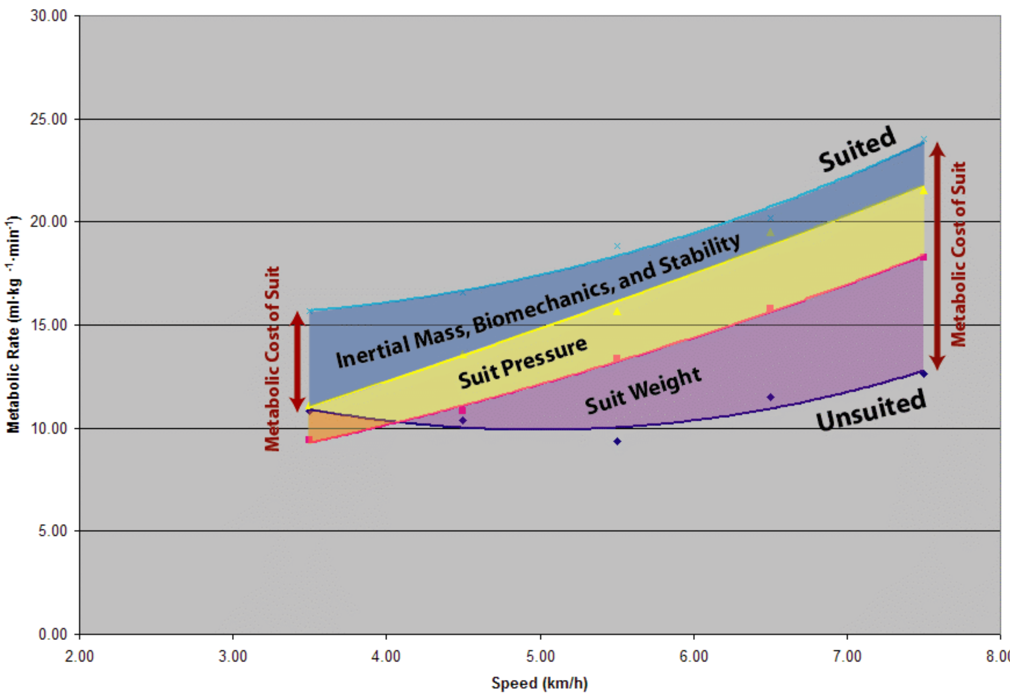


Figure 3 - Proposed model for suit design parameters that contribute to the metabolic cost of ambulation in lunar gravity while wearing the MKIII suit.

On the basis of the POGO test results, a predictive equation for metabolic rate has been proposed that includes factors such as subject anthropometrics, locomotion speed, suit pressure, and suit weight (Figure 4). As more data are collected, this algorithm will be expanded into an EVA consumables calculator in which inputs related to the subject, suit, and type and duration of tasks can predict a metabolic profile and the expected consumables usage. This algorithm is an example of a design tool that can aid development of spacesuits that increase efficiency in crew health and performance based on different operational concepts.

The following is just one example of how operational concepts will play a large role in determining requirements. If a crewmember is only expected to walk slowly, the suit weight may not be a critical design parameter; but if a long, e.g., 10-km/6.2-mile, walkback contingency must be prepared for, the suit weight will be absolutely critical to mission success as well as crew performance and risk of injury.

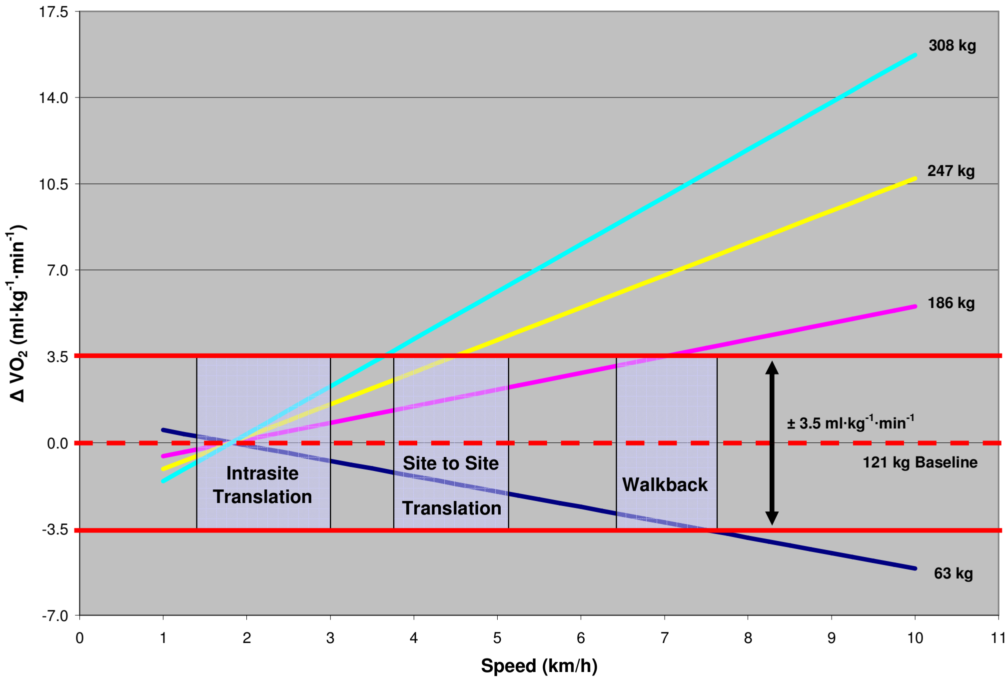


Figure 4 - Model of the effect of suit weight (63, 121, 186, 247, or 308 kg) on metabolic rate across speed of ambulation based on the MKIII data from the POGO.

In addition to ambulation, the effect of varying suit weight and pressure has been initially examined across a variety of exploration-type tasks, such as shoveling and picking up rocks. Figure 5 describes the metabolic cost and the Gravity Compensation and Performance Scale (GCPS) ratings for six subjects for the rock transfer task as a function of gravity or total system weight. The objective (metabolic cost) and the subjective (GCPS) ratings show the same trends, which surprisingly indicate that an increased system weight was associated with better performance. Other tasks (shoveling and a construction task busy board) demonstrated the same trend. However, this testing was performed at a single suit mass (due to limitations of the POGO system) with varied weight offload to simulate different suit weights. Since testing was not performed with mass variation, there is still much to be learned by varying suit mass in a given simulated gravity field. The GCPS quantifies the suit operator compensation that is required for optimal task performance, which is defined as being equivalent to 1*g* shirt-sleeved (i.e., unsuited) performance. Ratings of 1 to 3 indicate acceptable performance, 4 to 6 indicate that modifications are recommended for optimal performance, and 7 to 9 indicate that modifications are required; a rating of 10 indicates that the task cannot be performed under the current conditions. (See Appendix A for further explanation of the GCPS subjective assessment tool.)

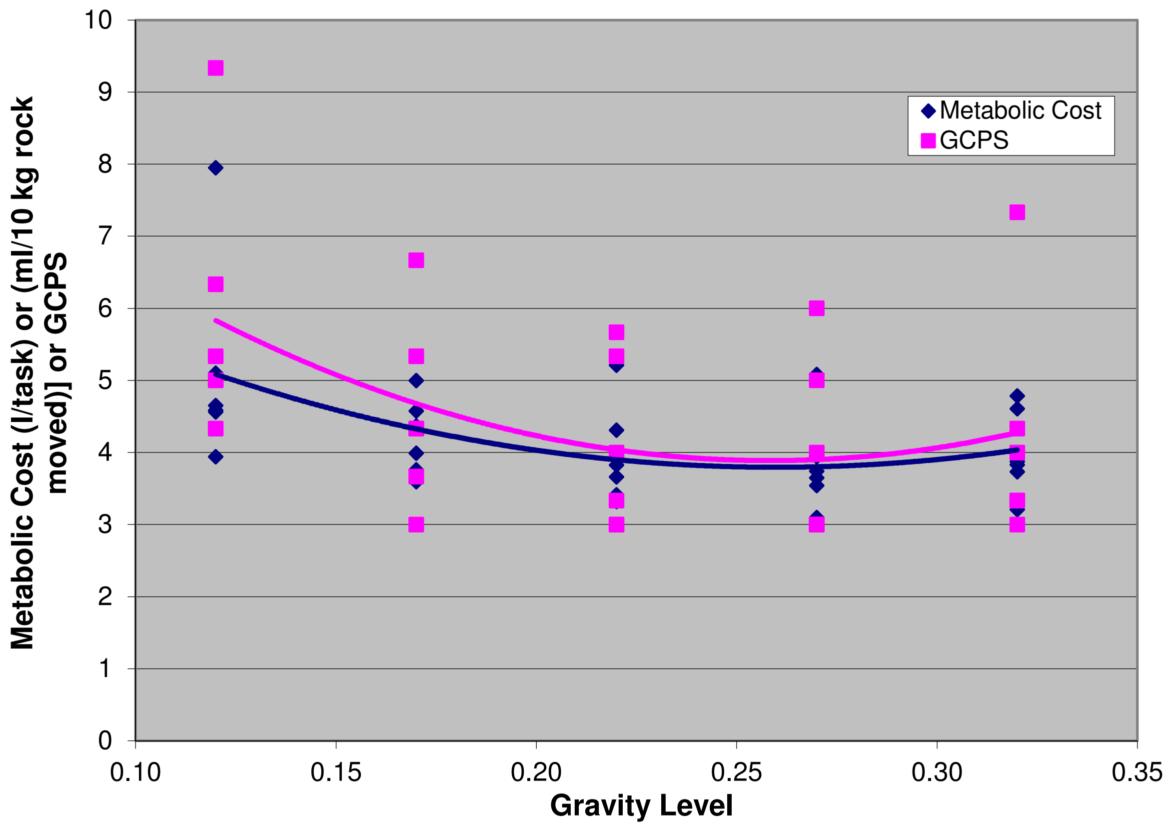


Figure 5 - Effect of suit weight on metabolic rate and subjective GCPS ratings during exploration tasks.

Biomechanical impacts of the suit are more difficult to differentiate; however, they may be critical to understanding skeletal muscle and bone loss in fractional gravity and for developing countermeasures against such losses. A key biomechanical finding relates to ground reaction force (GRF), which was higher during ambulation in suited conditions than in unsuited conditions and also increased as gravity increased. However, the GRFs were still lower than those that a crewmember would normally experience on Earth. This suggests that EVA performance on a reduced-gravity planetary surface may not provide sufficient loading to protect against bone loss, thus indicating the continued need for exercise countermeasures (Norcross et al. 2010c; Norcross et al. 2009).

Recognizing that not all ambulation on a planetary surface will be similar to that on a level treadmill, initial studies were completed to characterize the effects of incline and terrain on metabolic rate. Inclined walking trials inferred that the metabolic cost of the suit that is due to factors other than suit weight went to almost zero, suggesting spacesuit factors may exist that are not well understood (Norcross et al. 2010d), or more likely a problem associated with accurately simulating inclined ambulation using the POGO.

Beyond the above-stated variables, the Apollo Program demonstrated that suited center of gravity (CG) may be an important variable that affects human performance. Studies have evaluated CG in the underwater environments of NEEMO missions and the NBL. These studies assessed crew performance of representative planetary exploration tasks using a single EVA suit weight and mass with different CG locations. A reconfigurable backpack that has repositionable weight modules was used to simulate perfect, low, forward, high, aft, and NASA baseline CG locations under the assumption of a 27-kg (60-lb.) suit, a 61.2-kg (135-lb.) Portable Life Support System (PLSS), and a reference 1.8-m, 81.6-kg (6-ft, 180-lb) subject. Subjects used the GCPS rating tool to evaluate the CG locations. As shown in Figure 66, subjects preferred (with lower GCPS score) the perfect, low, and forward CGs over the high, aft, or NASA baseline (CTSD) CGs (both high and aft, similar to the Apollo suit CG). These findings suggest that a conventional backpack PLSS may not be optimal and that alternative configurations should be considered (Jadwick et al. 2008a).

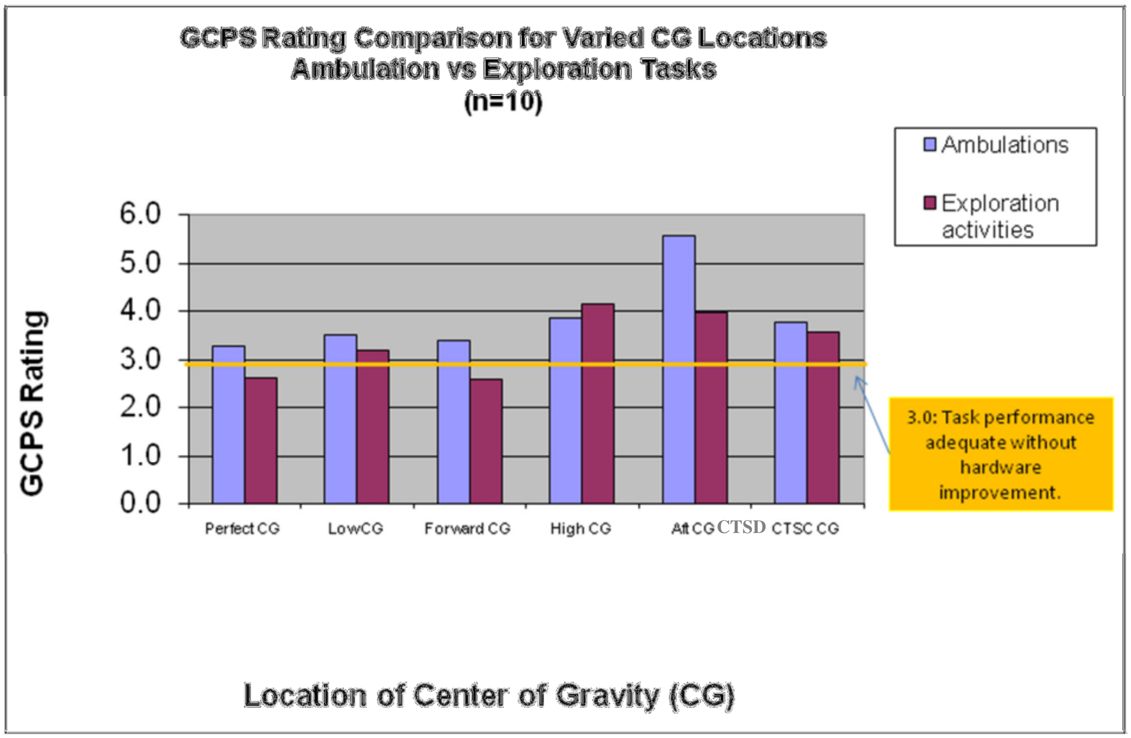


Figure 6 - GCPS ratings for suit center of gravity (Jadwick et al. 2008a).

To adequately prepare for mission EVAs, astronauts undergo extensive ground-based training at the NBL, which provides controlled neutral buoyancy operations to simulate the microgravity or weightless condition. Articles are configured to be neutrally buoyant by using a combination of weights and flotation devices so these articles seem to “hover” under water, thus enabling large, neutrally buoyant items to be easily manipulated much as they would be on orbit. The significant increase in EVA NBL training to support the construction and maintenance of the ISS led to an apparent increase in the incidence of symptoms and injuries experienced by crewmembers operating in the EVA suit.

A study that was conducted from July 2002 to January 2004 identified the frequency and incidence rates of symptoms by general body location and characterized the mechanisms of injury and effective countermeasures (Straus 2004). In this study, 86 astronaut subjects were evaluated in the NBL during 770 suited test sessions. Symptoms were reported by the test subjects in 352, or 45.7%, of the sessions. Of these symptoms, 47% involved hands; 21% involved shoulders; 11% involved feet; 6% each involved arms, legs, and neck; and 3% involved the trunk. Hand symptoms were primarily fingernail delamination, which was thought to be secondary to excess moisture in the EVA gloves and axial loading of the fingertips (Figure 77). There were also abrasions, contusions, and two cases of peripheral nerve impingements related to glove fit and hard point contact compressions. Shoulder symptoms were proposed to be due to hard contact with suit components and strain mechanisms (Figure 77). Elbows were the most common area of pain or injury in the arms, as were knees in the legs. While most of the symptoms and injuries sustained during EVA training were "mild, self-limited, and controlled by available countermeasures," some "represented the potential for significant injury with short- and long-term consequences regarding astronaut health and interference with mission objectives" (Straus 2004).

Figure 7 - Fingernail and shoulder trauma sustained during EVA training (Jones et al. 2006).

A shoulder-injury tiger team was created in December 2002 at the NASA Johnson Space Center to evaluate the possible relationship between shoulder injuries and EVA training at the NBL (Williams and Johnson 2003). This team surveyed 22 astronauts who had participated in EVA training. In this group, 14 astronauts (64%) had experienced some degree of shoulder pain that they attributed to EVA training. A majority of these cases were classified as minor, resolving within 48 to 72 hours. However, 2 of the 14 subjects required surgical repair after injury. It was determined that the major risk factors leading to injury were limited range of motion in the shoulder joint due to use of the "Planar" hard upper torso (HUT) of the EVA suit, performance of tasks in inverted body positions during NBL training, performance of overhead tasks, repetitive motions, use of heavy tools, and frequent training sessions. Additional minor risk factors included suboptimal suit fit and lack of appropriate padding or load alleviation (Williams and Johnson 2003). While the astronaut-tool-EMU simulation package may be neutrally buoyant as a whole, the astronaut is not weightless within the suit. In the inverted (head-down) position, gravity causes the astronaut to "fall into" the head of the spacesuit, pressing the shoulders into the HUT of the suit. This further limits scapulothoracic motion of the shoulder (Viegas et al. 2004). Key elements in the risk mitigation of shoulder injuries that are associated with EVA training include redesign of the extravehicular mobility unit (EMU) shoulder joint or development of the next-generation suit for ISS EVA, reduction of high-risk NBL activities, optimization of suit fit, and continued emphasis on physical conditioning (Williams and Johnson 2003).

During the 10-km EWT, subject discomfort levels were recorded, and a medical monitor examined the subjects for signs of suit-induced trauma at the completion of the test. In terms of discomfort, the mean rating was 1.5 ± 1.1 (SD), which is "very low" to "low" on the 10-point discomfort scale. The knee area and the feet or toes were the most frequent sites of discomfort during and after the test (Figure 8). Fatigue and/or muscular tightness were reported most commonly in the quadriceps, thighs, gluteal muscles, and lower back (Norcross et al. 2009).

Figure 8 - Knee and foot trauma sustained during 10-km EWT (Norcross et al. 2009).

IV.1.2. EVA Suit Fit

To what extent the compromised performance and injury risk due to spacesuits is attributable purely to suit design is a complex question, because one must also factor in suit fit. An EVA suit tailored for a 95th percentile male is almost guaranteed to be a problem for a 5th percentile female. Therefore, EVA suit fit must be characterized and controlled to understand how suit design affects physiological performance and injury risk.

Suit sizes and subject anthropometric accommodation capability will most likely be rather limited in any suit development program. Allowable crew anthropometry during the planned Constellation Program ranged from 1st percentile females to 99th percentile males (NASA 2010). Custom tailoring a spacesuit to each individual astronaut's physical properties may be cost prohibitive, but if suit fit is not appropriate, NASA runs the risk of losing that crewmember's ability to perform EVA with acceptable performance and low risk of injury.

The risk exists that all necessary EVA tasks in exploration environments may not be able to be performed by the current range of crewmembers in the currently planned suit design. The potential impacts could be that EVA responsibilities would have to be limited to only certain crewmembers so that crew health and performance will not be compromised. If that were not possible, some mission objectives could be lost or reduced. Other potential effects of inadequate suit fit may be inability of the crewmember to complete EVA tasks within the time allotted; mission and EVA timeline deviations; inability of the crew to complete exploration tasks; EVA crew physical and mental workload above acceptable levels; acute or chronic injury resulting from inadequate suit fit.

Relatively little is known about how a subject moves inside a spacesuit to make the suit perform necessary movements. However, it is known that inadequate suit fit can contribute to injury and the ability to adequately perform necessary tasks. The hypothesized causes of some injuries are suit fit, shifting within the suit, improper use of protective garments within the suit, and repetitive motion working against an inadequately fitted suit (Benson and Rajulu 2009; Straus 2004; Williams and Johnson 2003). While suit fit seems to be a critical element in preventing astronaut injury, there is not a universal solution that provides for appropriate spacesuit fit and comfort. Achieving the best fit is highly individualized, and discomfort "hot spots" may exist in an area for one crewmember but not for another. It has been shown that even between EVA training sessions minor adjustments sometimes need to be made to a suit to achieve the best fit (Moore and Gast 2010). Additionally, a person's body dimensions, especially height, change as they move into microgravity (NASA 2011). Finally, movement and mobility while working in the suit may be unnatural because of each spacesuit's natural programming (Cowley et al. 2012). Astronauts eventually learn to change their biomechanical movement strategies, rather than attempting to move as they do unsuited (Moore and Gast 2010). How a person moves relative to a spacesuit while performing tasks and how this relates to suit fit has not been adequately characterized. Initial attempts to quantify body joint kinematics within a suit and the resulting suit movement found a 25-degree larger knee angle for the subject's body than the movement of the suit when using the Contingency Hypobaric Astronaut Protective Suit (CHAPS) (Kobrick et al. 2012) for lower-body motions.

No formal methods exist for objectively defining suit fit. Anthropometric measurements of the crewmember are made and an initial suit fit is determined by a proprietary algorithm (NASA). After an initial suit fit check, the fit can be adjusted based on subjective feedback between the crewmember and a suit engineer. Experience in both the microgravity training and flight environments provides the crewmembers and suit engineers with some knowledge about how suit fit may differ between the environments. Suit fit is considered such an important factor that an on-orbit fit check now occurs about a week before a planned EVA. This allows the crewmember to adjust his or her EVA suit if necessary because of any changes during flight.

One difficulty in assessing suit fit for partial gravity is that the crewmember remains in the 1*g* environment. During partial gravity overhead suspension, the suit is lifted and the crewmember falls into the suit. During 1*g* operations, the full weight of the suit is supported by the crewmember via shoulder straps and a waist harness. Neither of these conditions is consistent with exactly how a crewmember and EVA suit will interact in actual partial-gravity conditions, and different gravity conditions may require slightly different suit fits because of the different interactions.

Another issue associated with suit fit has come up with testing the modified advanced crew escape suit (MACES) as an EVA suit rather than purely a launch, entry and abort (LEA) suit. To achieve a fit that optimizes for EVA, the crewmember is placed in a suit notably smaller than his/her normal IVA fit. Subjective feedback has indicated that using an IVA-sized suit for EVA would likely not be acceptable and using an EVA-sized suit for IVA operations would also not be acceptable. Further development will be needed, but this begins to describe some of the difficulties associated with suit sizing.

IV.1.3. EVA Glove Function

From the Space Shuttle Program, ISS, and NBL training have come documented cases of hand injuries and hand fatigue while using current gloves, EVA systems, and tools (Viegas et al. 2004) (Strauss et al. 2005). Minor to moderate glove-induced trauma from EVA and during NBL EVA training have been the most frequently reported injuries. These reported injury rates are specific to the microgravity EVA environment, where the crewmembers perform the majority of tasks with their hands. These rates are likely not going to be the same in the planetary environment, where the crewmember will translate by foot and will not have to work at station keeping because gravity will secure the body and provide more Earth-like kinematics.

Custom tailoring spacesuit gloves to each individual astronaut's physical properties is very expensive, but if an astronaut cannot perform tasks properly in the spacesuit glove available, NASA runs the risk of losing that crewmember's ability to perform EVA effectively. Many factors beyond glove design (such as duration of EVA, suit pressure, tool and task design) may contribute to hand injury, and taking a system view may provide for an overall more effective and efficient way to lower the risk of poor crew health and performance due to hand issues.

Opperman et al. (Opperman et al. 2010) looked at a database of 232 crewmembers' injury records and anthropometry. No significant effect of finger-to-hand size was found on the probability of injury, but circumference and width of the metacarpophalangeal (MCP) joint were found to be significantly associated with injuries. A multivariate logistic regression showed that hand circumference had the dominant effect on the likelihood of onycholysis. Male crewmembers with a hand circumference > 22.86 cm (9 inches) have a 19.6% probability of finger injury, but those with hand circumferences ≤ 22.86 cm (9 inches) have only a 5.6% chance of injury. Findings were similar for female crewmembers. This increased probability may be due to constriction at large MCP joints by the current NASA Phase VI glove. Constriction may lead to occlusion of vascular flow to the fingers that may increase the chances of onycholysis. Injury rates are lower for gloves such as the superseded series 4000 and the Russian Orlan that provide more volume for the MCP joint.

Jones et al. (Jones et al. 2008) researched the current Extravehicular Mobility Unit (EMU) configured with a ventilation tube that extended down a single arm of crewmembers (E) and compared arm E with the unventilated arm (C). Skin surface moisture was measured on both hands immediately after glove removal, and a questionnaire was administered to determine subjective measures. Astronauts (n=6) were examined before and after an NBL training session. When the ventilation tube was used, there were consistent trends in the reduction of relative hydration ratios at the dorsum of the hand (C=3.34, E=2.11) and the first ring finger joint (C=2.46, E=1.96). Ventilation appeared to be more effective on the left hand than the right, implying an interaction of ventilation with hand anthropometry and glove fit. In 2 out of 6 EVA crewmembers, symptom score was lower on the hand that had the long ventilation tube relative to the control hand.

IV.1.4. Waste Management

Waste (i.e. urine, feces) management is an important factor in EVA suit design as well as in EVA execution. Required EVA duration plays an important part in understanding the waste management needs for EVA. The longer the EVA, the more likely it is that crewmembers will need to urinate or defecate during the EVA. This need is currently managed through the use of maximum absorbency garments (MAGs) worn by crewmembers to contain waste products during an EVA as necessary. In addition, crewmembers have been known to adopt a low-residue diet and lower intake of water before EVAs, so as not to have to use the MAG. While these methods may be effective at reducing the chance of needing to urinate/defecate during an EVA, they may not be commensurate with long-term health and performance, as they may have a negative impact on crewmember hydration and nutrition.

Potential methods for mitigating this contributing factor include shorter durations for EVAs to preclude the need for substantial waste management. However, the risks associated with implementing EVAs of shorter duration are that overall work efficiency will decrease to achieve the same amount of EVA time if the “unproductive” crew time (overhead) associated with O_2 prebreathe and suit ingress and egress is not decreased. An alternative method would be to reduce the number of EVA hours required through the use of pressurized roving vehicles and/or robotic assistants to enable some of the work that has been traditionally done only by EVA to be done as IVA.

The potential ramifications of not appropriately managing waste during EVA include the possibility of the need to shorten a planned long-duration EVA and possible loss of mission objectives. Also, acute or chronic injury or illness may occur due to regular use of existing waste management methods on extended-duration missions with high numbers of required EVAs.

The development of an improved in-suit urine collection device was recommended by the Apollo astronauts. In some cases during lunar surface EVAs, astronaut urine was not fully contained and resulted in skin irritation (Scheuring et al. 2007). Improved in-suit waste management systems will become critical in the event that a crew is required to be suited for as many as 144 hours during a contingency return to Earth should the vehicle be unable to maintain pressure. Exposure to urine and fecal waste products for that length of time may lead to skin breakdown, cellulitis, and sepsis.

IV.1.5. Nutrition and Hydration

Proper hydration and nutrition is just as important, if not more important, during EVA as it is during the remainder of a space mission. The duration and metabolic demands of an EVA directly inform nutrition and hydration needs. Longer durations of EVAs and/or more physically demanding EVAs have increased requirements for nutrition and hydration. Hydration needs in the EMU are currently managed through the availability of an in-suit drink bag (IDB) that is mounted to the inside of the hard upper torso (HUT) of the suit. The IDB can hold 1.9 liters (32 ounces) of water and has a small tube, a straw, which is positioned next to the astronaut's mouth. Nutrition needs were partially accounted for in the EMU by inclusion of a modified commercial dried fruit bar that the astronaut could eat if he or she got hungry during an EVA. Making the bars was labor intensive, and they were typically eaten before EVA (or not eaten at all) and were discontinued years ago.

Potential methods for mitigating this contributing factor include making the duration of EVAs short enough to preclude the need for substantial nutrition and hydration supplementation during the EVA. However, the risks associated with implementing EVAs of shorter duration are that overall work efficiency will decrease to achieve the same amount of EVA time if the overhead associated with suit ingress and egress is not decreased. An alternative method of mitigation would be to reduce the number of EVA hours required through the use of pressurized roving vehicles and/or robotic assistants to enable some of the work that has been traditionally done only by EVA to be done as IVA.

EVA suit design, task design, tool design, mission objectives, and exploration environment are all key factors in understanding the hydration and nutrition needs during EVA. The required mass and volume of food and water for EVA over a mission is directly associated with EVA hours required. The caloric and hydration requirements per hour of EVA are directly associated with the physical demands of the EVA work that is required. The physical demands of the EVA work are directly associated with the methods and equipment available to perform the tasks, and the weight and mobility of the suit in which they must be performed.

The potential ramifications of not providing appropriate nutrition and hydration during EVA include the possibility of the need to shorten a planned long-duration EVA and possible loss of mission objectives. Also, health and performance issues may occur due to inadequate hydration or nutrition, within an EVA or over the length of a mission.

The longer and more work-intensive EVAs that are likely to be planned for future exploration missions will need to account for astronaut nutrition and hydration. Specifically, dehydration is an issue that can lead to poor crew performance. The Apollo suit contained a 443 mL (15-oz) drink bag; however, this amount of fluid is considered insufficient for crews that are performing surface EVA. Scheuring et al. (Scheuring et al. 2007) provide several citations from Apollo-era astronauts who walked on the moon regarding the need for more water. The authors wrote, “The astronauts strongly agreed the amount of liquid beverage contained in the suit needed to be increased for future crewmembers, including separate capabilities for plain water and non-caffeinated high-energy drink.”

The delivery systems for nutrition and hydration needed to be improved as well. One Apollo astronaut commented, “The fruit bar mounted inside the suit was sometimes problematic because you couldn’t always get to it, but it’s nice to have something solid to eat” (Scheuring et al. 2007). Similar issues have been reported with the current EVA suit, used for microgravity EVA in the Space Shuttle and International Space Station (ISS) Programs. Furthermore, the time required to prepare the nutrition and hydration systems before conducting an EVA could be decreased. Filling and degassing the drink bag used in the current U.S. suit is time-consuming and contributes to a poor work efficiency index (WEI) of Shuttle and ISS EVAs.

The 10-km lunar walkback test also provided important insight into hydration and nutritional requirements for a worst-case task duration and intensity (Norcross et al. 2009). All subjects were provided with 32 oz. of water in an in-suit drink bag, standard for use of the MKIII suit. Crewmembers consumed 50% to 100% of the water that was provided, and one crewmember would have preferred to have an additional 20% of that volume available. In addition, the 10-km walkback required an average of 944 kcal. All of the crewmembers felt that a nutritional item, either food (e.g. energy bar or gel) or a flavored electrolyte drink might improve their performance and/or endurance. These observations were in accordance with the Apollo recommendations cited above.

Additional background and evidence can be found in the NASA HRP Evidence Report "Nutritional Biochemistry of Space Flight" (Smith et al. 2008) and "Evidence Report: Risk of Performance Decrement and Crew Illness Due to an Inadequate Food System" (Perchonok et al. 2012).

IV.2. In-Suit Physical Environment

IV.2.1. Hypoxia

Hypoxia refers to low environmental oxygen conditions. Normally, 20.9% of the gas in the Earth's atmosphere is oxygen. The partial pressure of oxygen in the standard atmosphere is 20.9% of the total barometric pressure. Atmospheric hypoxia occurs naturally at high altitudes. Total atmospheric pressure decreases as altitude increases, causing a lower partial pressure of oxygen, which is defined as hypobaric hypoxia. Oxygen remains at 20.9% of the total gas mixture, differing from hypoxic hypoxia, in which the percentage of oxygen in the air is decreased. Other potential causes of hypoxia include medical causes such as pulmonary or respiratory disease or obstruction.

Unlike Earth's atmosphere, habitable volumes in space are completely engineered environments, allowing endless possibilities for atmospheric constituents. The ISS is set at a typical sea-level atmosphere of 14.7 psia and 21% O_2. To ensure maximum mobility, EVA suits are kept at a low operating pressure, which is akin to increasing altitude in the Earth environment. To combat hypoxia and decompression sickness (DCS), the suit environment is kept as close to 100% O_2 as possible with some N_2 remaining even after a 10-min purge with 100% O_2. This purge is required to remove the ambient ISS gas (21% O_2, 79% N_2) present in the suit during the suit-donning process. In the engineered environment, hypoxia is best discussed as a partial pressure rather than an altitude. Normoxia is an inspired partial pressure of O_2 (P_IO_2) of 150 mmHg calculated with the following equation:

$$P_IO_2 = P_B\text{-}47 \times (F_IO_2)$$

Where P_B is defined as the total pressure in mmHg, 47 mmHg as the constant water vapor tension (P_{H_2O}) in the human lung, and F_IO_2 as the fraction of inspired O_2 in the ambient air.

At higher pressures, the P_{H_2O} in the lung may be a small portion, but as the total pressure of the environment is significantly reduced, as in EVA, this constant P_{H_2O} becomes a more significant factor. A lower suit pressure may improve mobility but increases the risk of both DCS and hypoxia. For further discussion of DCS, please see the NASA HRP Evidence Report "Risk of Decompression Sickness" (Conkin et al. 2013).

During the lunar missions, the Apollo A7L and A7LB suits were operated at 3.7 psia and 100% O_2, which results in a P_IO_2 of 144 mmHg, which would be at the low end of the range of values considered physiologically normoxic. This level would be equivalent to just under 1000 ft. of altitude. The EMU operates at 4.3 psia and 100% O_2, resulting in a P_IO_2 of 175 mmHg. Assuming the suit can maintain adequate pressure and the life support system continues to deliver 100% O_2, hypoxia is a controlled factor for EVA risk.

Methods for mitigating hypoxia include design of the EVA suit so that it monitors and maintains appropriate breathing atmosphere pressures and oxygen concentrations under all expected EVA durations and human physiological demands. In addition, considerations should be made for contingency situations such as leaks or malfunctions that could compromise the breathing atmosphere within the suit. Current guidelines allow an EVA to continue as long as P_IO_2 is maintained above 127 mmHg (about 4000 ft. equivalent altitude), but this is for contingency only and the nominal approach is to ensure a normoxic environment.

The ramifications of not mitigating the risk of hypoxia during EVA include both health and performance impacts. Health impacts include headache, decreased reaction time, impaired judgment, visual impairment, drowsiness, lightheadedness, and lack of coordination (Guyton and Hall 2000). Performance impacts include reduced oxygen delivery as well as reduced muscle strength and power (Houston 2005).

IV.2.2. Hypercapnia

Hypercapnia is a condition of abnormally high carbon dioxide (CO_2) levels in the blood. Carbon dioxide is present in low concentrations (0.03%) in the standard atmosphere, is a gaseous product of the body's metabolism, and is normally expelled through the lungs during exhalation (Guyton and Hall 2000). Tolerance to CO_2 concentration in inspired air varies as the concentration increases. Concentration levels between 1% and 5% may be able to be tolerated with mild to moderate effects (from mild respiratory stimulation to moderate respiratory stimulation with exaggerated respiratory response to exercise; increased heart rate and blood pressure, reduced hearing, dizziness, confusion, headache) for up to several hours at higher concentrations. Carbon dioxide levels above 5% elicit more prominent respiratory stimulation, exaggerated respiratory response to exercise, mental confusion, and dyspnea. Levels above 8% induce dimmed eyesight, sweating, tremors, unconsciousness, and eventual death (Lambertsen 1971) (Glatte Jr et al. 1967).

Methods by which hypercapnia may occur during EVA are by inadequate air flow within the suit causing "dead spaces" (or local concentrations) of CO_2 that are re-inhaled, or a failure in the suit life support system's ability to scrub excess CO_2 from the breathing air. Diving research has shown that hypercapnia can occur as a diver exhales into a vessel that does not allow all of the CO_2 to escape the environment, such as a full-face diving mask or diving helmet (Lamphier 1956).

EVA suits are expected to meet requirements for adequate CO_2 elimination (or "washout") to prevent significant re-inhalation. Spacesuit portable life support systems (PLSS) are also expected to meet requirements for adequate CO_2 removal. Sensors used on the inlet and outlet for suit gas flow should serve to monitor and control levels of CO_2. If the CO_2 level reaches a given criterion, then suit flow can be increased and/or activity level (thus affecting metabolic rate) of the crewmember can be reduced. If CO_2 levels cannot be improved and continue to rise over a critical threshold, the EVA can be terminated.

Metabolic rates higher than expected and/or faults in the CO_2 removal or ventilation capability of the PLSS would trigger elevated in-suit CO_2.

Carbon dioxide washout studies have been conducted by the suit contractor and the NASA Johnson Space Center Crew and Thermal Systems Division (Chullen and Conger 2013; Chullen et al. 2013; Korona et al. 2014; Mitchell and Norcross 2012). These tests have been performed for several reasons, including evaluating ventilation configuration, characterizing the CO_2 washout within certain spacesuits, and ensuring safe ground-based testing. Much of this work can be characterized as pilot studies that are aiding development of a standard method of assessing CO_2 washout performance in a spacesuit for ground-based testing and eventually a CO_2 washout requirement verification for a flight EVA suit. Throughout this series of CO_2 washout tests, subjects have exercised at metabolic rates up to 3000 Btu/h for several minutes without one subject complaining of CO_2-related symptoms, but they have reported increased thermal stress and overall fatigue. Once CO_2 washout performance is characterized on the ground and verified for flight, CO_2 in the suit will still need to be measured on both the inlet and outlet side during EVAs to ensure adequate CO_2 removal, as an index of CO_2 washout and to measure metabolic rate.

IV.2.3. Internal Suit Pressure

One of the primary functions of an EVA suit is to monitor and maintain a desired internal pressure. A chosen internal pressure in a given spacesuit must be adequate to assist in maintenance of required partial pressures of breathing air while keeping the mobility and workload required to do tasks within the suit at a reasonable level; it is a tradeoff of aspects of spacesuit operations that must be balanced (Abramov et al. 1994). The internal suit pressure to be used during EVA must also be tightly coordinated with the internal habitat or vehicle pressures that are used, to keep the time required to transition from one environment to another to a minimum. Negative pressure differences in moving from habitat or vehicle to a spacesuit can cause decompression sickness, and thus prebreathing of higher concentrations of oxygen are required to reduce the risk of decompression sickness (Clément 2011). A detailed review of how NASA has mitigated DCS primarily through operational prebreathe protocols is discussed in the DCS risk evidence report (Conkin et al. 2013), but both DCS risk and prebreathe time can be reduced by the choice of optimal pressures and gas concentrations in both environments (Abercromby et al. 2013a; Norcross et al. 2013a).

The current working assumption in the EVA community is that a lower suit pressure is better from a human performance and fatigue perspective. The main concern for operating the suit at a higher pressure is hand fatigue. Whole-body tasks such as ambulation did not show much difference in metabolic and subjective measures using the MKIII (Norcross et al. 2010c; Norcross et al. 2010d). Although higher suit pressures would significantly reduce prebreathe time, they are also associated with higher leak rates and greater suit mass to ensure structural integrity.

IV.2.4. Hyper/Hypothermia

The physiologic cost of performing work in a pressure garment is significantly greater than that of performing the same work without a suit. High workloads result in energy expenditure and the production of heat, which, in turn, increase the usage rate of suit consumables. Flight surgeons must ensure that an astronaut is not working at levels that may lead to overheating or exhaustion, and EVA planners and/or crewmember may need to make real-time adjustments to crew activity to conserve consumables that are required for life support (Waligora et al. 1975).

Energy expenditure (metabolic rate) was not measured during the Project Gemini EVAs. It was nonetheless clear that, in several cases, the astronauts worked at levels that were above the heat removal capability of the gas-cooled life support system (Kelley et al. 1968; Waligora and Horrigan 1975) During the first U.S. EVA, astronaut Ed White found that opening and closing the hatch was much more difficult than planned and that he perspired enough to fog the helmet visor. Although the duration of the EVA was short, it took several hours for White to return to thermal equilibrium (Paul 2012).

Thermal homeostasis of the crewmember is crucial for safe and effective EVA performance. Heat storage above 480 Btu/h leads to performance decrements, such as a loss of tracking skills and an increased number of errors in judgment, and tissue damage begins at 800 Btu heat storage (Jones et al. 2006). The observations from the Gemini experience led to the development of a liquid cooling system that could accommodate high heat production in the suit from high EVA workloads. This liquid cooling garment (LCG) consists of a system of plastic cooling tubes that run along the inside of an undergarment that is worn inside the suit. The temperature of the coolant (water) running through the tubes regulates the amount of heat that is removed from the surface of the skin. The Apollo LCG had three temperature settings: minimum (69.8 °F/21 °C), intermediate (59 °F/15 °C), and maximum (44.6 °F/7 °C) (Waligora et al. 1975).

Astronaut energy expenditure rates during Apollo lunar surface EVAs ranged from 780 to 1,200 Btu/h, as determined by three independent methods (Waligora et al. 1975). The lowest metabolic rates occurred while the astronauts drove and rode in the lunar rover vehicle, while the highest metabolic rates were observed during egress and ingress through the tight-fitting hatch of the lunar module, offloading and setup of equipment, drilling, and stowage of lunar samples. It is estimated that 60% to 80% of the heat that was generated with these workloads was dissipated through the LCG. The minimum and intermediate LCG settings were most commonly used; however, the maximum setting was frequently used during the high-workload periods that were experienced during Apollo 15 and Apollo 17 EVAs (Waligora and Horrigan 1975). In a simulation (Figure 9) using a validated thermoregulatory model (Pisacane et al. 2007), the relationship between heat storage and metabolic rate was examined as a function of LCG inlet temperature (tracings, showing 21 °C (69.8 °F) and 24 °C (75.2 °F)) (Thomas et al. 2011). These data suggest that at metabolic rates above ~1200 Btu/h, LCG inlet temperatures exceeding 21 °C may induce crewmember heat storage rates above the 480 Btu/h that leads to performance impairment. Although Apollo metabolic rates rarely exceeded 1200 Btu/h and the LCG inlet temperature minimal setting was 21 °C, these data are instructive for the design of future EVA suits, which may be used in situations in which crew metabolic rates exceed levels seen during Apollo.

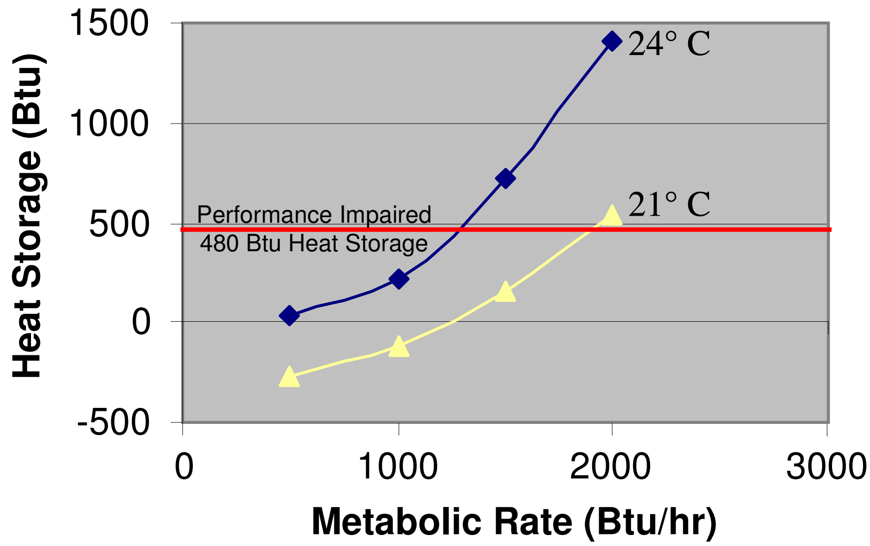


Figure 9 - Heat storage based on metabolic rate and LCG inlet water temperature (Pisacane et al. 2007).

During NASA's Constellation Program, a study was conducted to determine whether it is possible for a suited crewmember to walk back to a terrestrial habitat in the event of rover failure (Norcross et al. 2009). As a starting point that was based on the Apollo Program and anticipated lunar surface operational concepts, it was assumed that 10 km (6.2 miles) would be the maximum EVA excursion distance from the lander or habitat. Results from this EVA Walkback Test (EWT) using the POGO partial gravity offload system provide key insight into how human performance may be impaired by inadequate consumables and/or inadequate cooling.

For the EWT, six suited subjects were instructed to attempt to translate 10 km (6.2 miles) on a level treadmill at a rapid, but sustainable, pace using a self-selected gait strategy and speed. Before this test was done, the investigators expected that crewmembers could complete only half of that distance or that the total duration would exceed 3 hours. However, all of the crewmembers finished the test, and the mean time to complete 10 km was only 96 minutes. The metabolic work level for the entire test averaged 51% of VO_2pk (peak oxygen consumption), with a range of 45% to 61%. Physiological and consumables usage data are summarized in Table 1. Subjective ratings of perceived exertion (RPEs, 11.8 ± 1.57 (SD)) equated to a feeling between "light" (RPE=11) and "somewhat hard" (RPE=13) on the 6- to 20-point Borg RPE scale, which is used to gauge how much effort a person feels that he or she must exert to perform a task. Similarly, subjects averaged 3.5 ± 1.44 (SD) on the 10-point Gravity Compensation and Performance Scale (GCPS), indicating "fair" to "moderate" operator compensation was required to perform the task (Norcross et al. 2009).

Subjects' heat production rates ranged from 1,918 to 2,667 Btu/h, and averaged 2,374 Btu/h, a rate that would have exceeded the heat removal rates of the Apollo EVA suit or the current EMU. Core temperature measurements indicated an average rise (Δ) of 1 °C from normal (98.6

°F/37 °C) across the entire test, although one subject's core temperature (103.6 °F/39.8 °C) peaked near a level of concern. Subjects unanimously reported cooling to be inadequate at the higher workloads (Norcross et al. 2009).

This limited cooling capacity will impede the improved efficiency that was observed at higher speeds. Efficiency of locomotion can be determined by the transport cost, which is expressed as oxygen consumption per kilogram per kilometer, and can be thought of as a human's "gas mileage." In suited conditions in lunar gravity, there was a clear trend of decreasing transport cost as speed increased. So while a crewmember might expend more energy on a per minute basis by traveling at faster speeds, the metabolic cost per kilometer would actually be less (Norcross et al. 2009; Waligora and Horrigan 1975).

Table 1 - Summary data for the lunar 10-km walkback test (Norcross et al. 2009).

10-km Walkback Summary Data (averaged across entire 10 km unless noted)		
	MEAN	**SD**
Avg. Walkback Velocity (mph)	3.9	0.5
Time to Complete 10 km (min)	95.8	13.0
Avg. %VO_2pk	50.8%	0.3%
Avg. Absolute VO_2 (1/min)	2.0	0.3
Avg. Metabolic Rate (Btu/h)	2,374.0	303.9
Max. 15-min-avg Metabolic Rate (Btu/h)	2,617.2	314.6
Total Energy Expenditure (kcal)	944.2	70.5
Water Used for Drinking (oz.)	~24–32	N/A
*Water used for cooling (lb.)	4.91	N/A
Oxygen Used (lb)	0.635	N/A
Planning/PLSS Sizing Data	**Walkback**	**Apollo**
Oxygen Usage (lb/h)	0.4	0.15
Btu Average (Btu/h)	2,374	932.8
Cooling Water (lb/h)	3.1	0.98
Energy Expenditure (kcal/h)	599	233

*Assumes thermally neutral case and sublimator cooling

Unfortunately, at speeds above 3 mph (Figure 10) the heat production, which is shown on the right axis and the red GCPS tracing, begins to exceed the 2,000 Btu/h cooling limit of both the Apollo and the EMU EVA suits, resulting in increased core body heat storage. Without improvements in cooling for future suits, crewmembers performing lunar EVAs would not be able to exploit the increased efficiency (Figure 10, on the blue tracing as decreasing oxygen transport cost) available at faster ambulation speeds. This would result in increased requirements for consumables to cover the same distance (Norcross et al. 2009).

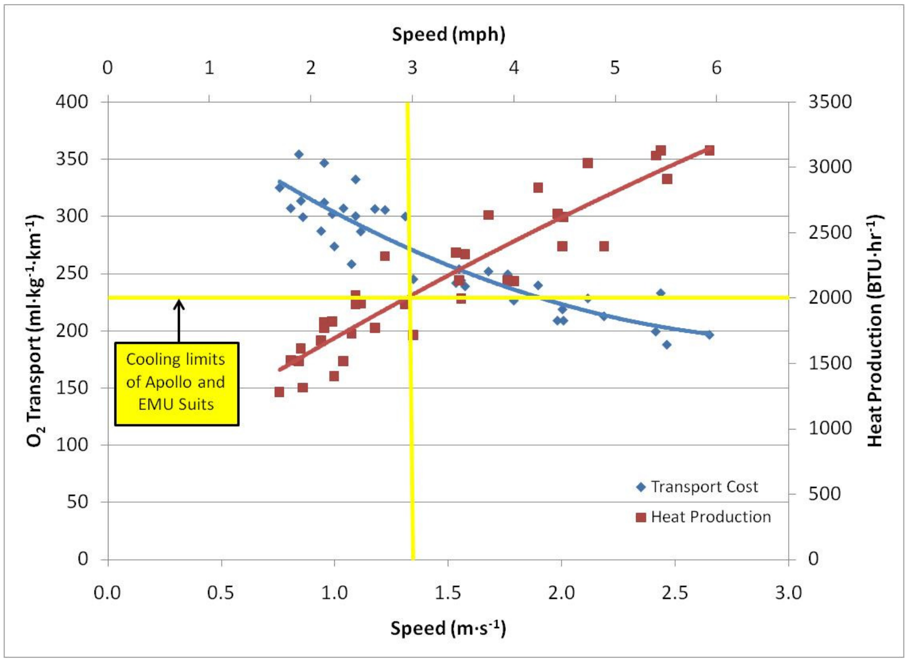


Figure 10 - Relationship between transport cost and heat production for lunar suited ambulation (Norcross et al. 2009).

IV.2.5. Humidity

Humans perspire and exhale molecular water. In a closed environment such as a spacesuit, this quickly causes extremely humid conditions that not only cause discomfort, but can also adversely affect the function of systems in the spacesuit. Thus, a spacesuit system must remove humidity. But removal of the humidity in the ventilation system can cause yet further difficulties. An atmosphere that is too dry can adversely affect the eyes and nasal passages of the suit user. Over 8-hour periods and repeated usage, this can affect the mission and the well-being of the astronaut. An excessively dry atmosphere can also result in hazards from electrostatic discharge. Should a static electricity discharge occur within a spacesuit, it could involve tens of thousands of volts, but only microamps of current. This could shock, but not harm, the crewmember. However, as this could damage sensitive electronic components, suit systems must remove excess humidity while maintaining at least minimum levels of humidity for both comfort and safety (Thomas and McMann 2011).

Problems have been reported with excess moisture in spacesuits causing face plate fogging (Paul 2012). In addition, excess humidity may be a factor in fingernail delamination during EVA (Jones et al. 2008). Excess moisture in a spacesuit may be associated with increased heat loads of EVA crewmembers, as a high level of humidity does not allow sweating to be effective at cooling the body, which may lead to excessive sweating and eventual dehydration. Addressing this contributing factor may result in less risk to crew health and performance by reducing the hand injuries from EVA and better managing the carried heat load.

IV.2.6. Excessive Radiation Exposure

An astronaut performing EVA is exposed to radiation whether on a planetary surface or in deep space. Being close to a planetary body can provide some shielding, but in deep space the EVA suit becomes the only method of protection (Committee on the Evaluation of Radiation Shielding for Space Exploration 2008). Considering an entire mission, not just the EVA portions, the current space radiation permissible exposure limits (PEL) limit mission duration to 3–10 months depending on age and sex of the crewmember and stage of the solar cycle (Steinberg et al. 2013). During EVA, the protection that a spacesuit provides is minimal and thus the duration of exposure becomes a factor in managing radiation risks. As an example, EVA helmets have been shown to produce only a 13% to 27% reduction in head radiation dose relative to a non-helmeted head; similar minimal protection has been shown for the torso and extremities (Benton et al. 2006). Monitoring of solar activity in real time and providing predictions and alerts for high-radiation events is thus important in determining proper scheduling of EVAs so that habitats and/or rovers can provide greater protection from radiation during these events (Johnson et al. 2005). Rovers and/or habitats can be designed with water or other materials in the walls and ceilings to provide good radiation protection to crewmembers inside. In addition, the capability to have rapid egress and ingress to habitat or rover can significantly reduce the chances of excessive radiation exposure since faster access to shielded areas can be gained (Abercromby et al. 2012c).

Additional background and evidence can be found in the NASA HRP Evidence Report “Risk of Acute Radiation Syndromes Due to Solar Particle Events” (Wu et al. 2013) and other radiation-related evidence reports.

IV.2.7. Decompression Sickness

When a diver returns from a hyperbaric environment, or an aviator or astronaut travels to a hypobaric environment, the amount of inert gas in excess of what can be held in solution at the new lower pressure has the potential to come out of solution to form gas spaces that can displace or otherwise damage tissues. Unlike other spaceflight-related human risks, decompression sickness (DCS) is a known problem that has been mitigated since the first EVA. Various DCS mitigation strategies have been used effectively, including a lower pressure, high oxygen environment (Gemini, Apollo, Skylab) requiring a single 4-h pre-launch oxygen prebreathe (PB); a resting 4-h in-suit PB; an intermediate pressure, mildly hypoxic environment requiring a single 40- to 75-min in-suit PB; and several exercise-enhanced protocols combining a mask and in-suit PB. To date, DCS has been effectively mitigated through rigorous adherence to PB protocols validated specifically for the EVA environment and primarily for the microgravity (μG) environment. Although these protocols are effective, they can be complex and require significant preflight training, in-flight crew time, and consumables usage.

Historically, PB protocols have been developed with the goal of preventing DCS and have been designed to meet operational needs. This operationally driven research has left gaps in knowledge about several DCS risk factors including bubble formation in space, nitrogen elimination in space, break in PB, micronucleus generation, and tissue saturation across different pressure and gas environments.

The acceptable risk for DCS has been defined in the NASA Human Spaceflight Standards; therefore, the next step will be to develop and validate procedures, protocols, and countermeasures to meet this standard effectively and efficiently for the range of nominal and off-nominal atmospheres and decompression profiles that crewmembers may experience during future exploration missions. Utilization of the exploration atmosphere (8.2 psia / 34% O_2), suit ports, and variable-pressure suits, and the inability to rapidly deorbit for medical treatment, mean that existing DCS risk mitigation protocols and data sets are not applicable to future exploration missions.

To improve efficiency of meeting the acceptable DCS risk from a sea-level atmosphere, data are needed on the potential differences between bubble formation and N_2 elimination in μG as compared to Earth 1*g*. To improve safety and efficiency in any atmosphere, data are needed to describe the consequences of a break in PB. Finally, the opportunity exists to mitigate DCS primarily through engineering controls by the use of the 8.2 psia / 34% O_2 exploration atmosphere, suitport, and variable-pressure EVA suit. While it seems promising, this strategy still requires validation to ensure it mitigates DCS risk to acceptable levels and to determine if any significant negative physiological effects are associated with the exploration atmosphere's mild hypoxia of about 4000 ft. equivalent altitude (Conkin et al. 2013).

IV.2.8. Ebullism

An astronaut performing EVA is exposed to the risk of rapid decompression due to a suit system failure. One of the effects of rapid decompression is ebullism. Ebullism is a condition where ambient pressure is ≤ the vapor pressure of water, 47 mmHg at a body core temperature of 37° C, and where liquid water undergoes a phase transition to vapor. This condition is conceptualized as low-temperature boiling of water.

The transition from liquid water to water vapor partial pressure at 47 mmHg (37° C) in aviation medicine is termed Armstrong's line, or the Armstrong limit (Murray et al. 2013). It represents a potentially fatal depressurization, equivalent to exposure above an altitude of 19,200 m (63,000 ft.). Loss of aircraft cabin pressurization above 19,200 m without a protective pressure suit or depressurization of a spacesuit to near-vacuum conditions in space or in an altitude chamber results in ebullism. This is a rare event in humans, with two brief descriptions provided by Stepanek (Stepanek 2002). Except for extremely rapid repressurization, less than about one minute from the event, it is unlikely that ebullism is survivable because of limited treatment resources at the time of the event and the time by which resuscitation must be established. As an immediate response, the mass of liquid water contained in lung tissues would vaporize and fill the alveolar space, displacing all other gases as all gases simultaneously exit the lung to establish pressure equilibrium at the new low ambient pressure. Since the lung cannot contain the expanding volume, gases leave the lung while the corresponding partial pressures, particularly O_2, decrease precipitously. Unless a minimum ambient pressure can be established immediately to initiate treatment, then anoxia and death ensue before evolved gas bubbles have the time to damage tissues.

Mitigating factors for ebullism in relation to EVA include the design of the EVA suit systems to resist puncture or rupture under expected operational conditions, as was done with the Integrated

Thermal Micrometeoroid Garment during the Apollo lunar surface missions (Thomas and McMann 2011).

IV.2.9. Embolism

Decompression sickness is associated with gas embolism (the presence of gas bubbles in the vascular system), both venous gas emboli (VGE) and arterial gas emboli (AGE). Although VGE can typically be adequately filtered by the lung, circulating VGE is not a desired condition, especially with the presence of a patent foramen ovale (PFO), which is a hole in the wall separating the right and left atria of the heart. A PFO is a remnant of life in the womb, where oxygenated blood from the placental circulation is shunted away from the pulmonary circulation of the fetus. This connection closes in most newborns, but about 25% of the adult population has some small patency (hole) that allows oxygenated and deoxygenated blood to mix. If denitrogenation is not effective, either because of inadequate vehicle design (either in gas constituency or atmospheric pressure, or a combination of the two) or inadequate operational PB protocols, then the resulting presence of VGE during an EVA could cross through a patent PFO under particular conditions and become arterialized. Many factors in the aerospace environment compromise healthy lung function. These factors, when combined with a high number of VGE entering the pulmonary circulation, can put astronauts at high risk of arterializing VGE that are normally filtered by a healthy lung. AGE put the astronaut at risk of vascular blockages and resulting ischemic damage to brain or other organs (Conkin et al. 2013).

IV.3. EVA Factors

IV.3.1. Work Efficiency Index

Current EVA suits and systems have a significant amount of overhead ("unproductive" crew time) compared to productive time on EVA. The work efficiency index (WEI) is a method of quantifying productivity and comparing different EVA methods and systems. WEI for EVA is calculated as follows:

$$Total\ EVA\ WEI = \frac{Total\ EVA\ Time}{Total\ EVA\ Overhead\ Time}$$

EVAs during the Apollo missions had an average WEI of about 2 with EVA durations of about 7 hours (Walz and Gernhardt 2008). As new spacesuits, namely the current EMU, were designed and became operational, they worked in conjunction with the Space Shuttle and the International Space Station (ISS) to provide an EVA capability in low Earth orbit. Due to a number of factors, including standard atmospheric pressure (760 mmHg / 14.7 psia) as the baseline condition on both the Space Shuttle and the ISS, as opposed to the design operating pressure of the EMU (222 mmHg / 4.3 psia), the EVA WEI went down to about 0.4. The differences in operating pressure between the vehicles and suit require a long oxygen prebreathe to minimize the risk of decompression sickness; this along with other factors causes EVA preparation to take as long as 5-6 hours (Norcross et al. 2013b). In comparison, commercial saturation diving achieves a WEI of between 3 and 10 through the use of synergistically designed habitats, vehicles, and diving suits that together enable much lower overhead per hour of productive time (Cooke et al. 2007). Taking a comprehensive look at operational and engineering design for future EVA systems (i.e., suits, habitats, and vehicles), EVA WEIs of up to 9 should be achievable (Cooke et al. 2007). The first step toward this new operational and design approach has been taken with the decision to use an 8.2 psia / 34% oxygen exploration atmosphere baseline, which will create the potential for significant decreases in required prebreathe time and thus overhead time (Norcross et al. 2013a). Improvements in EVA system design such as improved biomedical sensors, shorter suit checkout and servicing times, efficient egress and ingress times from vehicles and habitats, and decreased suit don and doff times could also produce major improvements in EVA WEI.

IV.3.2. EVA Task and Timeline Design

EVA task and timeline design is important to human health and performance. EVA task design refers to the particular equipment and methods used to perform necessary mission EVA tasks. EVA timeline design refers to the detailed analysis and testing that is required to understand the necessary duration and sequencing of tasks and subtasks within a particular EVA or set of EVAs in order to achieve overall objectives. If EVA tasks or timelines are not developed with human health and performance as a factor in their design, there is a risk that injury or reduced performance may occur along with possible loss of mission objectives.

Currently, very little is defined in the standards that govern NASA human spaceflight, regarding operations that would provide requirements for the design of effective, efficient, and safe EVA tasks and timelines (NASA 2007; NASA 2011). However, spaceflight analog research performed by the Exploration Analogs and Mission Development (EAMD) team has introduced a model for early human testing of prototype systems so that human health and performance can be factored into concepts of operations and system design as early as possible. Before the NASA Extreme Environment Mission Operations (NEEMO) 14 mission in 2010, the EAMD team performed extensive task and time analysis of important lunar surface EVAs, which then informed the NEEMO 14 research study design to validate and collect metrics on different tasks and timelines (Chappell et al. 2011). Similar processes were used before and during NASA's Research and Technology Studies (RATS) missions from 2008 to 2012 (Abercromby et al. 2010; Abercromby et al. 2013b; Abercromby et al. 2012b; Abercromby et al. 2012c), for analogs of both planetary surface and near-Earth asteroid missions. NEEMO 15 and 16 also gave researchers the opportunity to look at near-Earth asteroid mission task analysis and timeline validation (Chappell et al. 2013a; Chappell et al. 2013b). Finally, it is possible to make projections of the human health and performance impacts of operations by using the results of task and timeline testing to inform the need for countermeasures to combat muscle and bone loss. The authors of the report "Life Science Implications of Lunar Surface Operations" used objective data from analog and integrated suit testing to model a day in the life of an EVA crewmember on potential lunar missions (Chappell et al. 2010b); similar modeling could be enabled by future research that is geared toward other destination environments.

The NASA analog and integrated testing program has proven to be a cost-effective and essential method to ensure that end-user health and performance are central to future human task and timeline design (Reagan et al. 2012).

Additional background and evidence can be found in the NASA HRP "Evidence Report: Risk of Inadequate Critical Task Design" (Sandor et al. 2013).

IV.3.3. EVA Resources

The EVA resources contributing factor refers to the necessity of monitoring and managing resources such as EVA systems, plans vs. actuals, and consumables, to help ensure the health and performance of crewmembers. For instance, the physiologic cost of performing work in a pressure garment is significantly greater than that of performing the same work without such a garment. High workloads result in energy expenditure and the production of heat, which, in turn, increase the usage rate of spacesuit consumables. Accordingly, monitoring of crew physiologic parameters and consumables is critical. Flight surgeons must ensure that an astronaut is not working at levels that may lead to overheating or exhaustion, and EVA planners must be able to make real-time adjustments to crew activity to conserve consumables that are required for life support (Waligora et al. 1975; Waligora and Horrigan 1975).

It is important to note that although the metabolic rates experienced during the Apollo EVAs were lower than had been predicted before the missions, there were several cases in which the PLSS consumables were nearly depleted, according to the *Summary of Apollo G Mission Lunar Surface EMU Post Flight Thermal Analysis Results, Table E1* (Mission Operations Directorate (MOD), unpublished internal report). During Apollo 14, Apollo 15, and Apollo 17, there were six cases in which less than 10% of the usable oxygen remained at the end of the EVAs. During Apollo 14, Apollo 16, and Apollo 17, there were seven cases in which 12% or less power remained (in one case, power was at < 4%), and four cases in which 11% or less usable feed water remained. Two crewmembers, on Apollo 15 and Apollo 16, completed their EVAs with only 4% and 2% remaining, respectively, of their CO_2 removal capability (lithium hydroxide).

Although each of the Apollo missions was limited to two or three EVAs, future missions may consist of multiple EVAs per week for up to 6 months. The increased number and frequency of exploration EVAs, coupled with labor-intensive construction and exploration tasks, will require a better understanding of energy requirements, heat dissipation technologies, and consumables management.

Flight surgeons and biomedical engineers (BMEs) in the Mission Control Center monitor astronaut physical parameters during EVAs to assess workload and performance. Real-time medical monitoring can provide emergency medical assistance in response to off-nominal situations. However, bioinstrumentation systems that were used in the Apollo Program and the Space Shuttle Program have been problematic. Scheuring et al. (2007) provide about 75 citations from the flight surgeon logs, BME logs, and medical mission debriefings that relate to issues associated with bioinstrumentation. These range from complaints of skin irritation due to the electrode paste to signal dropouts and sensor failure (Scheuring et al., 2007). Both Apollo and Shuttle/ISS EVA crewmembers have expressed frustration with the cumbersome and time-consuming process of donning and doffing their biomedical sensor systems. Improvements to the biomedical sensor systems for future missions are therefore warranted.

Additional and more detailed background and evidence can be found in the NASA HRP "Evidence Report: Risk of Inadequate Human-Computer Interaction" (Holden et al. 2013).

IV.3.4. EVA Environment

IV.3.4.1. Background/significance specific to the contributing factor

The EVA environment in which crewmembers must perform depends on the destinations chosen for human exploration. Those destinations present inherent, unchangeable factors that must be dealt with, such as sloped and/or extreme terrain, zero or partial gravity, and dust. The EVA systems may not be designed to mitigate the effects on human health and performance of these factors without appropriate research to address them.

Slope

The effect of slope on the mechanics and metabolic cost of locomotion has been extensively studied (Minetti et al. 2002). However, the combined effect of partial gravity and sloped terrain has a more limited research base. The human health and performance effects of factors such as sloped terrain on an EVA crewmember were studied during integrated suit testing. Sloped terrains of 10-30% grade were shown to have a substantial impact on metabolic load required to ambulate in a spacesuit (Norcross et al. 2010d). Another study evaluated boot design for gradients up to 32 degrees (Hodgson et al. 2000).

Specific studies targeting the effects of slope have shown that internal work has no role in determining the optimal gradient (Minetti et al. 1994). The different efficiencies of the muscles have been hypothesized to explain the metabolic optimum gradient for running of about -10%. Additionally, gradients as low as +15% are about 2.5 times higher in metabolic cost than the optimum low cost of slight downhill running (Minetti et al. 1994). In other studies, electromyography has shown that uphill running activates more of the lower-extremity muscles than does horizontal running through an altered pattern of muscle activation (Sloniger et al. 1997). It has been hypothesized that uphill movement allows less storage of elastic energy and thus is less efficient. Also hypothesized is that differences in posture change the orientation of the ground reaction force vector and thus the mechanical advantage of muscles and tendons when ascending hills (Chang and Kram 1999).

Models have been proposed by military scientists for load carriage on sloped terrain. Results from these models have proposed that the total work for uphill walking can be calculated from the baseline value for walking (with and without load) by adding a term for positive external work against gravity (Santee et al. 2001). For downhill load carriage, the force applied through the body is modified not by muscle inefficiency, but by a combination of energy absorption into the joints and within the muscles. Any reduction in the energy cost of downhill walking due to the negative work of gravity is offset or reduced by eccentric work within the muscles, some additional energy absorption by the muscles and joints, and voluntary braking action to slow or control descent. The minimum value for VO_2 was found to be at a downhill grade of -8% for both walking and running (Santee et al. 2001).

Little attention has been paid to study of the cost of locomotion at high-angle slopes. A single study has shown that the optimum gradient for mountain paths is close to 0.2-0.3, both uphill and downhill (Minetti et al. 2002). It shows that the running speeds adopted in downhill competition are far lower than metabolically feasible speeds, mainly because of safety reasons. Athletes back off on speed to minimize joint and tissue injury. Also, at high angles, the body center of mass accelerates down the hill rather than being subject to a controlled constant braking. This may result in a lack of the fine motor control needed to maintain body trajectory on rough and slippery terrain (Minetti et al. 2002). These effects are likely to be amplified in reduced-gravity environments, but no research performed in this area could be found in the literature.

Surface Properties

Some studies have been performed to examine the effects of surface properties on locomotion and associated metabolic cost. For instance, it has been determined that walking on sand requires 1.6-2.5 times more mechanical work than does walking on a hard surface at the same speed (Legeune et al. 1998). In contrast, running on sand requires only 1.15 times more mechanical work than does running on a hard surface at the same speed. Major differences in the energy expended depend on the surface properties. Walking on sand requires 2.1-2.7 times more energy expenditure whereas running on sand requires 1.6 times more energy expenditure than do walking and running on a hard surface at the same speed, respectively. It has been stated that the increase in energy expenditure is due primarily to two effects: the mechanical work done on the sand, and a decrease in the efficiency of positive work done by the muscles and tendons (Legeune et al. 1998). These effects are likely to be amplified in a reduced-gravity environment such as the moon and Mars, as implied by the aforementioned stability concerns. Also, the environment on the surface of the moon and Mars consists of sand, loose soil, and scree field in many regions of scientific interest (Eckhart 1999).

Surface properties were considered a significant factor when comparing a speed- and grade-matched shirtsleeve 10-km walkback on Devon Island against a treadmill control. Although the average 1-min speed and grade were matched more than 98% of the time on the treadmill, the treadmill testing did not fully simulate the demands of traversing extreme terrain and underestimated the demand by about 56% (Norcross et al. 2008). This research clearly showed the necessity of both lab-based and field-based testing to be able to understand the effects of terrain and slope on EVA operations. Future EVA simulations need to consider the combined effects of performing EVA tasks both in reduced gravity and on loose substrates.

Reduced Gravity

Most of what is known about EVA performance and injury rates is from the combination of the flight microgravity environment and the NBL microgravity simulation. These data are also limited to the EMU. Although these data are critical for current and future microgravity EVA, their extensibility to partial-gravity EVA is difficult to see.

The effects of reduced gravity on EVA crewmember health and performance have been studied via various methods (e.g., underwater (Trout and Bruchey 1969), on parabolic flight aircraft (Moran 1969), using weigh offload systems (Robertson and Wortz 1968; Sanborn et al. 1967; Wortz 1969; Wortz and Prescott 1966)) since the days before the Apollo moon landings. Limited data were collected during Integrated Suit Test 1 and 2 that included level and inclined ambulation as well as a set of core exploration tasks. However, the POGO system used during that test was not able to provide enough weight offload to properly simulate both the weight and mass of suits in different gravitational environments. Therefore, metabolic, biomechanical, and other data need to be validated with true weight/mass matching on a more capable system such as ARGOS. Additionally, data were collected using only the MKIII suit, and the effects of other suits on health and performance are not understood.

IV.3.5. Quality of EVA Procedures

Procedural guidance for EVA can be a factor contributing to risk when written direction, checklists, or procedures are inadequate. Because procedures drive virtually every spaceflight task, the probability of poor procedural guidance causing an incident is high. For long-duration missions, there will be a longer delay between training and task performance, increasing the level of reliance on procedures. In addition, ground personnel may not be available to interpret or rework poorly written procedures during time-critical events (Love and Reagan 2013; Sandor et al. 2013).

The cost of adequate procedure design is minimal compared to the cost of lost mission objectives or a severe incident due to poorly written procedures. If procedures are inadequate, crewmembers will ask for help from another crewmember or from ground support; this may lead to delays in task completion and the need for complex and costly schedule changes. Alternatively, crewmembers may proceed without help (taking their best guess), increasing the potential for improperly executed tasks leading to errors and missed mission objectives.

Additional and more detailed background and evidence can be found in the NASA HRP "Evidence Report: Risk of Inadequate Critical Task Design" (Sandor et al. 2013).

IV.3.6. EVA Training

EVA training issues can become a contributing factor when necessary training programs are inadequate or unavailable. There is a high likelihood of minor time losses and inefficiencies and a small, but non-zero, likelihood of serious damage to space systems due to errors resulting from inadequate training. Generally, the likelihood of issues may increase with increased mission duration and crew autonomy. In some cases, training programs may be inadequate because they do not result in appropriately generalizable skills. Additional risk factors (fatigue, stress, excessive workload) can significantly alter the conditions of task performance relative to those during task training, and this can lead to decrements in performance. In addition, the passage of time and the lack of opportunity to rehearse or refresh acquired knowledge or skills can result in performance declines, reflecting a lack of recollection of what was learned. Training programs that do not account for degradation of learned skills or knowledge (e.g., by including refresher training or by providing just-in-time training rather than advance training on the ground) may result in inferior task performance. A further complication arises as a result of the novel technologies and operational scenarios that may exist for deep-space missions.

Additional and more detailed background and evidence can be found in the NASA HRP "Evidence Report: Risk of Performance Errors Due to Training Deficiencies"(Barshi 2012).

IV.3.7. EVA Crew Collaboration

Coordination and autonomy aspects of EVA will need to be addressed for team coordination to remain intact and effective for long-duration missions, so as to optimize task performance, psychosocial performance, and teamwork. No formal procedure to handle coordination issues currently exists. Within the current hierarchy of the crew, it is assumed that the commander will make any final decisions. Multiple incidents of a lack of coordination between flight crewmembers or between flight and ground crews have occurred. Environmental constraints, including communication delays, and isolated, confined, and extreme environments over a long duration may make any issues related to crew collaboration more impactful over time. Crews may have to make decisions independently of ground control when presented with novel tasks in time-critical situations. Understanding how teams may still effectively coordinate and collaborate to accomplish the tasks and objectives set before them is imperative; completing what is required of them as a team is even more difficult in the context of a long-duration mission; thus it is essential that research identifies the most effective mitigation strategies to address this contributing factor.

Additional and more detailed background and evidence can be found in the NASA HRP Evidence Book "Risk of Performance Errors due to Poor Team Cohesion and Performance, Inadequate Selection/Team Composition, Inadequate Training, and Poor Psychosocial Adaptation" (Schmidt et al. 2009).

IV.4. Physical State

IV.4.1. Crewmember Physical Preparation

Decreases in muscle strength, power, and endurance as well as aerobic capacity in microgravity transit to exploration destinations may have an impact on a crew's ability to perform necessary EVA tasks. Crew health and performance may be at risk due to EVA operations after such deconditioning. Preventive mitigation by selecting astronauts who have higher baseline fitness and/or strength levels may offer benefits. In addition, exercise countermeasures are baselined as mitigation for other risks, but their effectiveness is unknown in relation to future exploration EVA operations.

Functional Task Testing (FTT) is currently performed to assess crewmember physical preparation and recovery (Phillips et al. 2012). The EVA Physiology, Systems, and Performance (EPSP) Project initiated a subject characterization study that was intended to measure physical characteristics of all subjects participating in EVA performance studies, but the study has not yet been completed. Current fitness-for-duty standards are limited and not well defined (NASA 2007). A pre-EVA health check is currently conducted, with ground concurrence, before a crewmember begins an EVA, but the effectiveness of this for long-duration missions will be difficult to assess, with the consequences for error in judgment possibly being severe.

Additional and more detailed background and evidence can be found in the NASA HRP "Evidence Book: Risk of Impaired Performance Due to Reduced Muscle Mass, Strength, and Endurance" (Ryder et al. 2008).

IV.4.1.1. Decreased Muscle Power, Decreased Muscle Strength, Decreased Muscle Endurance

Exercise countermeasures will be a part of any exploration program, and forward research to develop maximally effective countermeasures to protect muscle power, strength, and endurance will help to ensure mission success and crewmember safety. Mission architectures, EVA surfacesuits and systems, and EVA task plans need to be designed around the potential limitations of crewmembers after long-duration transits to or at a partial-gravity exploration destination. Additional research needs to be performed to understand whether current standards are appropriate to help ensure that EVA mission objectives can be achieved while crewmember health and risk of injury are reasonable.

Additional and more detailed background and evidence can be found in the NASA HRP "Evidence Book: Risk of Impaired Performance Due to Reduced Muscle Mass, Strength, and Endurance" (Ryder et al. 2008).

IV.4.2. Pre-existing Injury or Illness

Pre-existing injuries or illness can have significant effects on EVA performance, depending on the severity of the injury or illness. An injury to an upper extremity that causes pain or requires disuse is likely to have an impact on completion of mission objectives (Viegas et al. 2004). In addition, treatment of an injury or illness may delay mission objectives or prevent mission objectives from being completed. Possible mitigations to loss of mission objectives are cross-training of crewmembers on EVA activities so that another crewmember could perform that EVA if necessary. Private medical conferences (NASA 2007) and/or a pre-EVA checklist of physical capabilities can also be mitigating activities. If one of these shows that the astronaut could not complete an EVA, then workarounds must come into play. Finally, limiting the amount of time spent on EVA by enabling some traditionally EVA tasks to be done as IVA should be considered for long-duration exploration (Hörz et al. 2013).

IV.4.3. Fatigue

According to the Apollo lunar crews, the most fatiguing part of surface EVA tasks was repetitive gripping. Regarding the glove, one crewmember stated, "Efficiency was no more than 10% of the use of the hand." It is also interesting to note that the lunar crews stated that they did not experience hand or forearm trauma in training, though muscle fatigue occurred. However, these training sessions typically lasted only 2 to 3 hours whereas the lunar EVAs plus pressurized preparation time were 7 to 9 hours in duration. [Note: Recent experience with ISS-related EVAs suggests that better conditioning can solve most of the forearm fatigue problems; however, lack of dexterity and hand trauma remain critical issues. Additionally, significant improvements in glove design have occurred since the Apollo Program but without complete alleviation of fatigue for longer EVAs (Scheuring et al. 2007).]

The Apollo crews also reported that sloped terrain on the lunar surface caused fatigue. Although the exact angle of the slope was an estimate, the crews remarked that stable footing was limited and leg fatigue would become more pronounced in terrain steeper than about 26°. Lack of suit mobility, primarily at the hips, made getting in and out of steep terrain difficult (Scheuring et al. 2007).

Experience from Apollo also indicated that mental and physical rest plans should be introduced into extended moon stays to allow adequate rest between lunar EVAs. Apollo astronauts stated (Scheuring et al. 2007), "Consider mental and physical fatigue here separately. Although there was not a lot of physical fatigue [during the lunar activity], the mind was being used quite a bit. You can sometimes wear your brain out before your body is fatigued."

IV.5. Mental State

IV.5.1. Situational Awareness

Operations tempo is driven by the scheduling of mission tasks, and can affect performance, workload, and situation awareness (SA) of crewmembers. The same amount of work can be more or less taxing on a crew depending on other factors such as fatigue, deconditioning, stress, anxiety, and medical conditions. Low workload levels have been associated with boredom and decreased attention to task, whereas high workload levels have been associated with increased error rates and the narrowing of attention to the possible detriment of tasks. In addition, when materials such as procedures, directions, checklists, graphic depictions, tables, charts, or other published guidance are misleading or unclear, workload is further affected and an unsafe situation results. The severity of the consequences increases with the duration of the mission (Sandor et al. 2013).

Current spaceflight crews rely on onboard automated systems. As increasing numbers of automated or robotic systems are designed to assist the human, a synergistic relationship must be developed between the human and automation to allow the two to work together to successfully accomplish tasks. On future missions with increased flight duration, greater EVA demands, and increased autonomy, crews will rely even more on these systems to provide information that is appropriate, accurate, and up to date. In addition, increased automation will result in the need for special emphasis on task design and additional training to ensure that the crew can perform the automated tasks in the event of automation failure. Automated tasks must be carefully designed to prevent the crew from losing SA or becoming unaware or complacent about potential hazards. These situations could ultimately result in system errors, degraded crew performance, and compromised crew and vehicle safety (Sandor et al. 2013).

IV.5.2. Cognitive State

Research in the area of theoretical and applied psychology identifies that humans' physical, sensory, perceptual, and cognitive capabilities have constraints that are related to performance inefficiencies, including workload increases and operator error. In the area of cognitive capabilities, for example, the amount of information that can be processed is limited by working memory (Baddeley 1992; Miller 1956). Therefore, information overload can be a problem for accomplishing tasks that load the working memory of the operator. On the other hand, information under-load can lead to decreased vigilance and can lead to loss of SA, that is, crewmembers may be less aware of important aspects of the environment needed for the current task and future actions. For all these reasons, human capabilities and limitations should be taken into consideration in the design of tasks and associated procedures, hardware, and software (Sandor et al. 2013).

Human capabilities and limitations can be affected greatly by the duration of a mission and the degree of subsequent deconditioning of crewmembers. Spaceflight crewmembers' strength and aerobic power of load-bearing muscles can decrease during spaceflight missions. On-orbit exercise regimens have been implemented to counteract these deficits, but to date have been only partially effective. Overall, the long-term effects of living in space and its effects on performance are still generally unknown. What is known is that a person's perception in every modality, reaction time, motor skills, and workload can be affected while the person is in space, and this situation can affect performance (Legner 2004). Thus, it is important to understand how tasks, procedures, and schedules may need to be modified as deconditioning occurs (Sandor et al. 2013).

Additional and more detailed background and evidence can be found in the NASA HRP "Evidence Report: Risk of Inadequate Critical Task Design" (Sandor et al. 2013).

IV.5.3. Psychological State

Stressful conditions are inherent to space missions. Working in space involves danger, isolation, and confinement; therefore, space is understood to be an extreme work environment. Survival in space requires the provision of constant shelter or the wearing of protective gear, and it is also subject to equipment malfunctions. To survive, crewmembers must adapt to a certain level of danger or threat. They must also adapt to certain levels of isolation, as contact with others (i.e., outside of the immediate crew) may be very limited and inconsistent at times, and isolation from family and friends may create social rifts and isolation that persist after landing. Finally, space flight crewmembers must adapt to being confined to a limited living and working space. Ground-based research involving similar conditions (e.g., submarines, offshore oil rigs, polar stations) has found that such conditions are generally detrimental to psychological health and social well-being over prolonged periods (Braun and Sells 1962; Britt and Bliese 2003; Krueger 2001; NASA 1987; Schmidt et al. 2009).

Space missions may require crews and ground controllers to operate more or less autonomously over the course of a mission as the degree of crew isolation oscillates in accordance with the distance that the spacecraft travels from the Earth. Crews are likely to have some periods of great control as well as some periods of very little control over what tasks are done, how the tasks are done, and when they are done. Ground operations are likely to necessitate total control at certain points in the mission, and have no opportunity to exercise any control during other parts of the mission. Shifts in operational autonomy are expected to have an impact on psychosocial adaptation to space flight demands (Kanas and Manzey 2008). It is important to understand how these factors (e.g., isolation, physical space, individual and group autonomy) influence psychosocial adaptation among crewmembers, as these factors ultimately will affect crew performance (Langfred 2000; Schmidt et al. 2009).

Additional and more detailed background and evidence can be found in the NASA HRP Evidence Report "Risk of Performance Errors due to Poor Team Cohesion and Performance, Inadequate Selection/Team Composition, Inadequate Training, and Poor Psychosocial Adaptation" (Schmidt et al. 2009)

V. COMPUTER-BASED MODELING AND SIMULATION

V.1. Life Sciences Implications of EVA

In 2010, an effort was undertaken to document preliminary, predicted, life sciences implications of expected operational concepts for lunar surface EVA (Chappell et al. 2010b). Algorithms developed through simulation and testing in lunar analog environments were used to predict crew metabolic rates and ground reaction forces experienced during lunar EVA. Subsequently, the total metabolic energy consumption, the daily bone load stimulus, total oxygen needed, and other variables were calculated and provided to Human Research Program and Exploration Systems Mission Directorate stakeholders. To provide context to the modeling, the report included an overview of some lunar surface scenarios that were under consideration as part of NASA's Constellation Program. Concise descriptions of the contributing analog testing and development of the algorithms were also provided.

The effort undertaken to model the life sciences implications of lunar EVA can be extended to remain current with evolving exploration destinations, assumptions, and concepts, and to provide additional data and analyses collected during ongoing analog research and integrated testing results.

V.1.1. EVA Timeline Analysis and Computational Modeling

Modeling was performed using timelines from DRATS 2009 (Abercromby et al. 2012a) and a reasonable estimation of a typical EVA on a planetary surface. Data from field tests were combined with physiological and performance data collected during the Integrated Suit Tests to project some of the life sciences implications associated with these lunar surface operations (Chappell et al. 2010b). A model was developed that takes into account such variables as subject mass, suit mass, suit pressure, gravity level, ambulation speed, ambulation distance, ground reaction forces, exploration task type, and time spent performing each exploration task. The model then output information such as metabolic energy consumed, oxygen used, water used, and accumulated load/bone stimulus. The analysis has been used to guide planning for development of other research plans as in Fig. , which shows an overview of the process used to produce the simulation to be undertaken as part of a future validation study of exploration atmospheres.

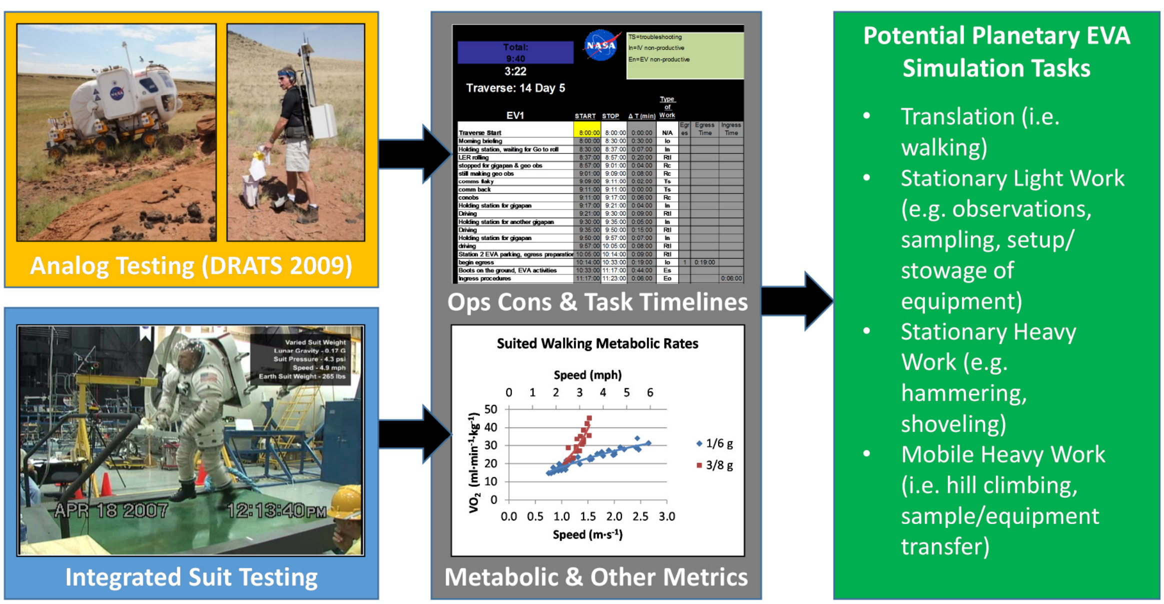


Fig. 11. Process used to produce the proposed planetary EVA simulation for an exploration atmospheres validation study.

The proposed split of EVA times and activity proposed for the exploration atmospheres validation study will be based on that observed in DRATS 2009, during which there were on average 4 EVAs per day, each of 45 minutes duration. The split of activities observed during DRATS 2009 is shown in
Fig. .

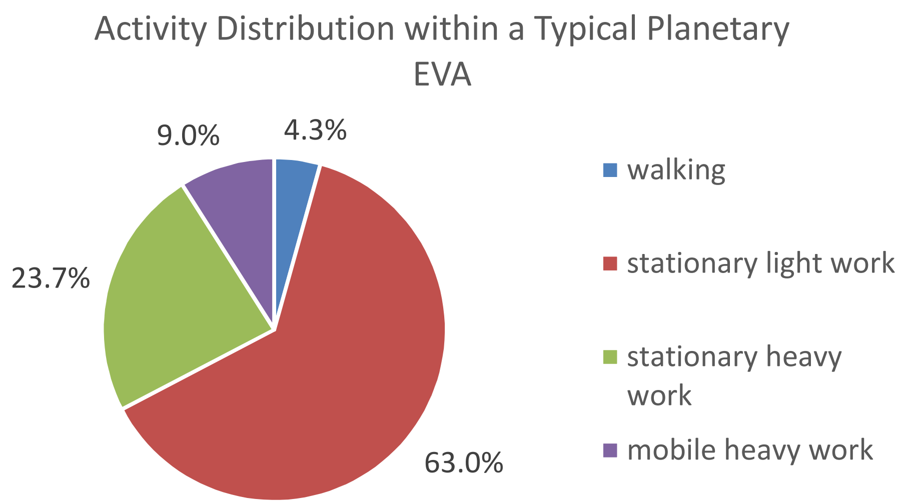


Fig. 12. The activity distribution during a typical planetary EVA is shown and based on the distribution that was observed during DRATS 2009.

To estimate the amount of exercise achieved that is related to EVA tasks, data from the Integrated Suit Tests (Abercromby et al. 2010) and field tests will be used to predict the metabolic rate during exploration activities. For metabolic rates during the different activities (Fig.), measured rates from IST-1 and IST-2 will be used and correlated with tasks according to whether the tasks are mostly stationary or not and whether they required light or heavy work. The specific methods and equipment that can be adapted to work within the altitude chamber will be formulated, developed, tested, and verified in the first part of the study before the start of formal testing with test subjects.

This use of EVA timeline analysis, results from previous testing, and modeling serves as an example of an integrated approach to test planning and execution. The results iteratively inform follow-on testing and provide stakeholder deliverables.

VI. RISK IN CONTEXT OF EXPLORATION MISSION OPERATIONAL SCENARIOS

EVA is a critical factor in the success of the construction, maintenance, scientific, and exploration aspects of every exploration architecture concept being considered by NASA. Some concepts of operation call for each crewmember to perform up to 24 hours of EVA per week for missions lasting up to 6 months. This corresponds to as many as 624 hours of EVA per crewmember in a single mission. As described in this evidence report, the risks associated with any inadequacies that exist in current EVA systems – particularly with respect to suit-induced trauma – will be greatly amplified by such frequent EVAs.

Planetary mission architectures include small pressurized rovers (SPRs) as a core element of the surface mobility system. The implications of SPRs on crew health, safety, productivity, and efficiency are potentially enormous. The availability of a pressurized safe haven within 20 minutes at all times to provide treatment of DCS, protection from solar particle events, and on-site treatment of or medication for an injured crewmember would significantly reduce many of the risks associated with planetary exploration. Furthermore, because crewmembers would be inside the SPRs during most surface translations, the overall number of in-suit EVA hours to achieve the same (or greater) science and/or exploration return would be reduced. The possibility of performing single-person EVAs with a second crewmember inside the SPR would further reduce total EVA hours. As an additional result, the number of cycles on the EVA suits would be decreased, thereby increasing the life of each EVA suit and reducing the risk of hardware failure for crewmembers.

VII. GAPS

In the following table, the current defined gaps associated with this risk are listed along with associated metrics that will help to determine gap closure.

Gap #		HRP EVA Risk Gap	Metric
EVA Crew, Systems, Environments, & Tasks	6	What crew physiological & performance capabilities[1] are required for EVA operations[2] in exploration environments[3]?	A. Minimum aerobic fitness standard on performance during suited operations defined.
			B. Muscle strength and power required for performance during suited operations understood and minimum standards defined
			C. Anthropometry (baseline as well as in-flight changes) effect on human performance during suited operations defined
			D. Losses in physiological function and EVA preparation during transit to exploration destinations understood
			E. Degree that surface EVA activities serve as physiological countermeasures understood
	7	How do EVA suit system design parameters[4] affect crew health and performance in exploration environments?	A. CG location effect on suited performance in exploration environments defined
			B. Joint characteristics (range of motion, location, torque, hard vs soft) and overall mobility effects on performance in exploration environments understood
			C. Suit mass effect on performance in exploration environments understood
			D. Suit pressure effect on performance in exploration environments understood
			E. Suit design parameter changes on human health and performance model completed
			F. Objective measure(s) of suit fit defined
	8	What are the physiological inputs and outputs associated with EVA operations[2] in exploration environments[3]?	A. Metabolic cost required to perform EVA operations[2] in exploration environments[3] defined
			B. Nutrition and hydration needs during suited operations defined
			C. In-suit heat and moisture effects on crew health & performance understood
			D. Excess levels of in-suit CO_2 effects on crew health & performance understood
			E. Reduced-gravity effects on crew physiological and functional performance during EVA tasks defined

Gap #		HRP EVA Risk Gap	Metric
			F. Variation of terrain (e.g., slope angle, surface hardness, surface variation) effects on crew physiological and functional performance during EVA tasks defined
	9	What is the effect on crew performance & health of variations in EVA task design and operations concepts for exploration environments[3]?	A. Task design (i.e., EVA equipment & methods) effects on crew health and performance understood
			B. Objective measures of fatigue related to EVA suited operations defined
			C. EVA duration and frequency (e.g., 8x1 h, 4x2 h, 2x4 h, 1x8 h EVA frequency x duration) effects on crew performance and health understood
	10	Can knowledge and use of real-time physiological and system parameters during EVA operations improve crew health and performance?	A.Physiological and EVA system parameters that must be monitored, displayed, alerted, and/or sent to the ground to enable safe and effective suited operations are defined
			B.Effective methods for provision of real-time knowledge of physiological and EVA system parameters to the EVA crewmember understood
			C. Effective methods for utilization of real-time physiological and EVA system parameters with biofeedback systems to improve EVA crew health, performance and autonomy are understood
Injury	11	How do EVA operations[2] in exploration environments[3] increase the risk of crew injury and how can the risk be mitigated?	A. Mechanisms or tasks that lead to acute, chronic, cumulative, or repetitive suit-induced injury are tracked and understood
			B. Glove design parameters that affect crew performance and safety defined
			C. Technologies or countermeasures developed to reduce the likelihood of suit-induced trauma
			D. Suit-related trauma monitoring, logging, and treatment tracking
			E. Techniques and technologies developed to treat, stabilize, monitor, and transport incapacitated suited crew in exploration environments
Integratio	14	What other EVA-related risks, developments and technologies exist that may affect EVA research?	A. Monitoring of and/or involvement in other HRP risk activities and developments that are ongoing or planned that may affect the EVA risk and/or research portfolio

Gap #		HRP EVA Risk Gap	Metric
			B. Monitoring of and/or involvement in EVA-related hardware developments outside of HRP that are ongoing or planned and may affect the EVA risk and/or research portfolio
			C. Monitoring of and/or involvement in EVA-related mission or architecture development outside of HRP that may affect the EVA risk and/or research portfolio
[1]e.g., anthropometry, aerobic fitness, muscle strength & power			
[2]acceptable functional performance of expected nominal and contingency suited tasks			
[3]i.e., moon, near-Earth asteroid, 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			

VIII. CONCLUSION

Future human space exploration missions will be more dependent on EVA excursions away from a pressurized habitat or vehicle than any program in the history of NASA. EVA will be required to conduct planned scientific expeditions, assemble structures, perform nominal maintenance, and intervene and solve problems outside of the vehicle that cannot be solved either robotically or remotely. The ultimate success of future exploration missions depends on the ability to perform EVA tasks efficiently and safely in these challenging environments.

To date, our direct understanding of human health and performance parameters in partial-gravity environments is limited to observations of, and lessons learned from, Apollo-era astronauts who performed EVAs on the lunar surface. Since the Apollo Program ended, and using lessons learned from microgravity EVAs aboard the Space Shuttle and ISS, new prototype suits have been in development for future space exploration activities. However, to date, quantification of the physiological and biomechanical variables associated with suited activities in micro and partial gravity has been limited. An integrated EVA testing research plan is required to better characterize the impacts on crew health and performance of the variables that are involved in EVA operations.

IX. REFERENCES

Abercromby AF, Gernhardt ML, Conkin J (2013a) Fifteen-minute extravehicular activity prebreathe protocol using NASA's xxploration atmosphere (8.2 psia / 34% O2). Paper presented at the 43rd International Conference on Environmental Systems, Vail, CO, July 2013

Abercromby AF, Gernhardt ML, Litaker HL (2010) Desert Research and Technology Studies (DRATS) 2008 evaluation of Small Pressurized Rover and unpressurized rover prototype vehicles in a lunar analog environment NASA Technical Report TP-2010-216136 NASA Johnson Space Center, Houston, TX, p 131

Abercromby AF, Gernhardt ML, Litaker Jr HL (2012a) Desert Research and Technology Studies (DRATS) 2009: Evaluation of small pressurized rover and unpressurized rover prototype vehicles in a lunar analog environment NASA Technical Report TP-2012-21736. NASA Johnson Space Center, Houston, TX, p 144

Abercromby AFJ, Chappell SP, Litaker HL, Reagan ML, Gernhardt M (2013b) NASA Research and Technology Studies (RATS) 2012: Evaluation of human and robotic systems for exploration of near-Earth asteroids. Paper presented at the 43rd International Conference on Environmental Systems, Vail, CO, July 2013

Abercromby AFJ, Gernhardt ML, Jadwick J (2012b) Evaluation of dual multi-mission space exploration vehicle operations during simulated planetary surface exploration. Acta Astronautica 90(2):203-214

Abercromby AFJ, Gernhardt ML, Litaker H (2012c) Desert Research and Technology Studies (DRATS) 2009: A 14-day evaluation of the space exploration vehicle prototype in a lunar analog environment NASA Technical Report TP-2012-217360. NASA Johnson Space Center, Houston, TX

Abramov I, Stoklitsky A, Barer A, Filipenkov S (1994) Essential aspects of space suit operating pressure. Paper presented at the 24th International Conference on Environmental Systems, Friedrichshafen, Germany, 1994

Baddeley A (1992) Working memory. Science 255(5044):556-559

Barshi I (2012) Evidence Report: Risk of Performance Errors Due to Training Deficiencies. NASA Johnson Space Center, Houston, TX

Benson E, Rajulu SL (2009) Complexity of sizing for space suit applications. Paper presented at the 2nd International Conference on Digital Human Modeling, San Diego, CA, July 2009

Benton ER, Benton EV, Frank AL, Moyers MF (2006) Characterization of the radiation shielding properties of US and Russian EVA suits using passive detectors. Radiation Measurements 41(9–10):1191-1201

Borg GA (1982) Psychophysical bases of perceived exertion. Medicine and science in sports and exercise 14(5):377-381

Braun JR, Sells SB (1962) Military small group performance under isolation and stress, Critical Review, III. Environmental Stress and Behavior Ecology. Arctic Aeromedical Laboratory, Aerospace Medical Division, Air Force Systems Command, Fort Wainwright, AK

Britt TW, Bliese PD (2003) Testing the stress-buffering effects of self-engagement among soldiers on a military operation. Journal of Personality 71(2):245-266

Carr C (2005) Bioenergetics of Walking and Running in Space Suits. Doctoral thesis, Massachusetts Institute of Technology

Chang YH, Kram R (1999) Metabolic cost of generating horizontal forces during human running. Journal of Applied Physiology 86(5):1657-1662

Chappell S, Klaus D (2013) Enhanced simulation of partial gravity for extravehicular activity. Journal of Human Performance in Extreme Environments 10(2) doi:http://dx.doi.org/10.7771/2327-2937.1052

Chappell S, et al. (2010a) Final report of the integrated parabolic flight test: Effects of varying gravity, center of gravity, & mass on the movement biomechanics, & operator compensation of ambulation & exploration tasks NASA Technical Report TP-2011-216152. NASA Johnson Space Center, Houston, TX, p 127

Chappell SP, Abercromby AF, Gernhardt ML (2013a) NEEMO 15: Evaluation of human exploration systems for near-Earth asteroids. Acta Astronautica 89:166-178 doi:10.1016/j.actaastro.2013.03.002

Chappell SP, Abercromby AF, Todd WL, Gernhardt ML (2011) NEEMO 14: Evaluation of human performance for rover, cargo lander, crew lander, and exploration tasks in simulated partial gravity NASA/TP-2011-216152 NASA Johnson Space Center, Houston, TX, p 178

Chappell SP, Abercromby AFJ, Reagan M, Gernhardt M (2013b) NEEMO 16: Evaluation of systems for human exploration of near-Earth asteroids. Paper presented at the AIAA 43rd International Conference on Environmental Systems, Vail, CO, July 2013

Chappell SP, Norcross J, Abercromby A, Gernhardt M (2010b) Life sciences implications of lunar surface operations NASA Technical Report TM-2010-216138. NASA Johnson Space Center, Houston, TX

Chullen C, Conger B (2013) Maintaining adequate CO2 washout for an advanced EMU via a new rapid cycle amine technology. Paper presented at the 43rd International Conference on Environmental Systems, July 2013

Chullen C, Navarro M, Korona A, McMillin S, Norcross J, Swickrath M (2013) Maintaining adequate carbon dioxide washout for an advanced extravehicular mobility unit. Paper presented at the 43rd International Conference on Environmental Systems, Vail, CO, July 2013

Clément G (2011) Fundamentals of Space Medicine, 2 edn. Springer-Verlag, New York, NY

Committee on the Evaluation of Radiation Shielding for Space Exploration NRC (2008) Managing Space Radiation Risk in the New Era of Space Exploration. The National Academies Press, Washington, DC

Conkin J, et al. (2013) Evidence Report: Risk of Decompression Sickness. NASA, Houston, TX

Cooke D, Yoder G, Leshin L, Gernhardt M (2007) Exploration Systems Mission Directorate lunar architecture update. Paper presented at the AIAA Space 2007 Conference, Long Beach, CA, Sept. 2007

Cowley MS, Margerum S, Harvill L, Rajulu SL (2012) Planetary suit hip bearing model for predicting design vs. performance. Paper presented at the 4th International Conference on Applied Humaun Factors and Ergonomics San Francisco, CA, July 2012

Dungan L, Lewis K (2013) Active Response Gravity Offload System (ARGOS). In: NASA Johnsons Space Center. http://www.nasa.gov/centers/johnson/engineering/integrated_environments/active_response_gravity/ Accessed 12/19/2013

Eckhart P, ed. (1999) The Lunar Base Handbook. The McGraw-Hill Companies, Inc., New York, NY

Gernhardt M, Abercromby A (2009) Use of variable pressure suits, intermittent recompression and nitrox breathing mixtures during lunar extravehicular activities. Paper presented at the Undersea and Hyperbaric Medical Society Annual Meeting, Las Vegas, NV, June 2009

Glatte Jr H, Motsay G, Welch B (1967) Carbon dioxide tolerance studies. School of Aerospace Medicine, Brooks Air Force Base, TX

Guyton AC, Hall JE (2000) Textbook of Medical Physiology, 10th edn. W.B. Saunders Company, Philidelphia, PA

Hochstein J (2008) Astronaut Total Injury Database and Finger/Hand Injuries During EVA Training and Tasks. Masters thesis, International Space University

Hodgson E, Etter D, Abramov I, Moiseev N, Stoklitsky A (2000) Effects of enhanced pressure suit angle mobility on locomotion on uneven terrain. Paper presented at the 30th International Conference on Environmental Systems, Toulouse, France, 2000

Holden K, Ezer N, Vos G (2013) Evidence Report: Risk of Inadequate Human-Computer Interaction. NASA Johnson Space Center, Houston, TX

Hörz F, et al. (2013) The traverse planning process for D-RATS 2010. Acta Astronautica 90(2):254-267 doi:http://dx.doi.org/10.1016/j.actaastro.2012.02.008

Houston C (2005) Going Higher: Oxygen, Man, and Mountains, 5th edn. Mountaineers Books, Seattle, WA

Jadwick J, Rullman K, Skytland N, Gernhardt M (2008a) Influence of center of gravity on human performance in partial gravity. Aviation, Space, and Environmental Medicine 79(3):293

Jadwick JM, Rullman K, Skytland NG, Gernhardt ML Influence of center of gravity on human performance. In: Aerospace Medical Association Annual Conference, Boston, MA, 2008b. vol 79. Aviation, Space, and Environmental Medicine, p 293

Jaramillo MA, Angermiller BL, Morency RM, Rajulu SL (2008) Refinement of optimal work envelope for extravehicular activity suit operations NASA Technical Report TP-2008-21478. NASA Johnson Space Center, Houston, TX

Johnson AS, Golightly MJ, Weyland MD, Lin T, Zapp EN (2005) Minimizing space radiation exposure during extra-vehicular activity. Advances in Space Research 36(12):2524-2529 doi:http://dx.doi.org/10.1016/j.asr.2004.05.008

Jones E (2004) The Apollo Lunar Surface Journal. In. http://www.hq.nasa.gov/office/pao/History/alsj/ Accessed February 16 2003

Jones J, et al. Medical issues for extravehicular activity. In: National Space Biomedical Research Institute Retreat, Houston, TX, 2006.

Jones JA, et al. (2008) The use of an extended ventilation tube as a countermeasure for EVA-associated upper extremity medical issues. Acta Astronautica 63(7–10):763-768 doi:http://dx.doi.org/10.1016/j.actaastro.2007.12.067

Kanas N, Manzey D (2008) Space Psychology and Psychiatry. In: Wertz JRE-i-C (ed) Space Technology Library. 2nd edn. Microcosm Press, Springer, Berlin, Germany

Keeton K, Whitmire A, Feiveson AH, Ploutz-Snyder R, Leveton L, Shea C (2011) Analog assessment tool report NASA Technical Report TP–2011-216146. NASA Johnson Space Center, Houston, TX

Kelley G, Coons D, Carpentier W (1968) Medical aspects of Gemini extravehicular activities. Aerospace Medicine 39:611-615

Klein J, Conkin J, Gernhardt M, Srinicasan R (2008) Metabolic expenditures during extravehicular activity: spaceflight versus ground-based simulation. Paper presented at the 79th Annual Scientific Meeting of the Aerospace Medical Association, Boston, MA, May 2008

Kobrick R, Carr C, Meyen F, Domingues AR, Newman D, Jacobs S (2012) Using inertial measurement units for measuring spacesuit mobility and work envelope capability for intravehicular and extravehicular activities. Paper presented at the 63rd International Astronautical Congress, Naples, Italy, Oct. 2012

Korona A, Norcross J, Conger B, Navarro M (2014) Carbon dioxide washout testing using various inlet vent configurations in the Mark-III space-suit. Paper presented at the 44th International Conference on Environmental Systems, Tucson, AZ, July 2014

Krueger GP (2001) Psychological and performance effects of chemical-biological protective clothing and equipment. Military medicine 166(12):41-43

Lambertsen C (1971) Carbon dioxide tolerance and toxicity. Environmental Biomedical Stress Data Center, Institute for Environmental Medicine, University of Pennsylvania Medical Center, Philadelphia, PA

Lamphier EH (1956) Nitrogen-Oxygen Mixture Physiology. Phase 5. Added Respiratory Dead Space (Value in Personnel Selection Tests) (Physiological Effects Under Diving Conditions). Navy Experimental Diving Unit, Washington, D.C.

Langfred CW (2000) The paradox of self-management: Individual and group autonomy in work groups. Journal of Organizational Behavior 21(5):563-585

Laughlin M, Murray J, Foy M, Wear ML (2014) Shoulder injury incidence rates in NASA astronauts. Paper presented at the NASA Human Research Program Investigators' Workshop, Galveston, TX, Jan. 2014

Legeune TM, Willems PA, Heglund NC (1998) Mechanics and energetics of human locomotion on sand. Journal of Experimental Biology 201:2071-2080

Legner K (2004) Humans in Space & Space Biology. United Nations Programme on Space Applications 15:77-135
Longnecker DE, Manning FJ, Worth MH, Jr. (2004) Review of NASA's Longitudinal Study of Astronaut Health. The National Academies Press, Washington, DC
Love SG, Reagan ML (2013) Delayed voice communication. Acta Astronautica 91(0):89-95 doi:http://dx.doi.org/10.1016/j.actaastro.2013.05.003
Maida JC, Demel KJ, Morgan DA, Wilmington RP, Abhilash K (1996) Comparison of extravehicular mobility unit (EMU) suited and unsuited isolated joint strength measurements NASA Technical Paper 3613. NASA Johnson Space Center, Houston, TX
Miller GA (1956) The magical number seven, plus or minus two: some limits on our capacity for processing information. Psychological review 63(2):81
Minetti AE, Ardigo LP, Saibene F (1994) Mechanical determinants of the minimum energy cost of gradient running in humans. Journal of Experimental Biology 195:211-225
Minetti AE, Moia C, Roi G, Susta D, Ferretti G (2002) Energy cost of walking and running at extreme uphill and downhill slopes. Journal of Applied Physiology 93:1039-1046
Mitchell K, Norcross J (2012) CO2 washout testing of the REI and EM-ACES space suits. Paper presented at the 42nd International Conference on Environmental Systems, San Diego, CA, July 2012
Moore SK, Gast MA (2010) 21st Century extravehicular activities: Synergizing past and present training methods for future spacewalking success. Acta Astronautica 67(7–8):739-752 doi:http://dx.doi.org/10.1016/j.actaastro.2010.06.016
Moran MJ (1969) Reduced-gravity human factors research with aircraft. Human Factors 11(5):463-472
Murray DH, et al. (2013) Pathophysiology, prevention, and treatment of ebullism. Aviat Space Environ Med 84(2):89-96
Murray J, Laughlin M, Foy M, Wear ML (2014) Rate of shoulder surgery among NASA astronauts. Paper presented at the NASA Human Research Program Investigators' Workshop, Galveston, TX, Jan. 2012
NASA EMU Sizing: Requirements and Constraints. NASA Johnson Space Center, Houston, TX
NASA (1987) Effects of confinement, social isolation, and diurnal disruption of crew adjustment and performance in long duration space missions NASA Technical Report NASA/JSC-CR-188280. NASA Johnson Space Center, Houston, TX
NASA (2007) NASA Space Flight Human System Standard, Volume 1: Crew Health NASA-STD-3001. vol 1. NASA, Washington, D.C.
NASA (2010) Human Integration Design Handbook NASA/SP-2010-3407. NASA, Washington, D.C.
NASA (2011) NASA Space Flight Human-System Standard, Volume 2: Human Factors, Habitability, and Environmental Health NASA-STD-3001. vol 2. NASA, Washington, D.C.
Newman D, Schmidt P, Rahn D (2000) Modeling the extravehicular mobility unit (EMU) space suit: Physiological implications for extravehicular activity (EVA). Paper presented at the 30th International Conference on Environmental Systems, Toulouse, France, July 2000
Norcross J, et al. (2013a) Effects of the 8 psia / 32% O2 atmosphere on the human in the spaceflight environment NASA Technical Report TM-2013-217377. NASA Johnson Space Center, Houston, TX

Norcross J, et al. (2008) The effects of terrain and navigation on human extravehicular activity walkback performance on the moon. Aviation, Space, and Environmental Medicine 79(3):292

Norcross J, Wessel III J, Klein J, Thompson M (2013b) Operational data on crew exporsure to mild hypobaric hypoxia in microgravity. Paper presented at the 84th Annual Scientific Meeting of the Aerospace Medical Association, Chicago, IL, May 2013

Norcross JR, et al. (2010a) Characterization of partial gravity analog environments for EVA suit testing NASA Technical Report TM-2010-216139. NASA Johnson Space Center, Houston, TX

Norcross JR, et al. (2010b) Effects of changing center of gravity on shirtsleeve human performance in reduced gravity NASA Technical Report TM-2010-216127. NASA Johnson Space Center, Houston, TX

Norcross JR, et al. (2010c) Metabolic costs and biomechanics of ambulation in a planetary suit NASA Technical Report TP-2010-216115. NASA Johnson Space Center, Houston, TX

Norcross JR, et al. (2010d) Metabolic costs and biomechanics of inclined ambulation and exploration tasks in a planetary suit NASA Technical Report TP-2010-216125. NASA Johnson Space Center, Houston, TX

Norcross JR, et al. (2009) Feasibility of performing a suited 10 km ambulation on the moon: Final report of the EVA walkback test (EWT) NASA Technical Report TP–2009–214796. NASA Johnson Space Center, Houston, TX

Opperman RA, et al. (2009) Anthropometric and blood flow characteristics leading to EVA hand injury. Paper presented at the 39th International Conference on Environmental Systems, Savannah, Georgia, July 2009

Opperman RA, Waldie JM, Natapoff A, Newman DJ, Jones JA (2010) Probability of spacesuit-induced fingernail trauma is associated with hand circumference. Aviation, Space, and Environmental Medicine 81(10):907-13

Paul H (2012) Energy expenditure during extravehicular activity through Apollo. Paper presented at the 42nd International Conference on Environmental Systems, San Diego, CA, July 2012

Perchonok M, Douglas G, Cooper M (2012) Evidence Report: Risk of Performance Decrement and Crew Illness Due to an Inadequate Food System. NASA Johnson Space Center, Houston, TX

Phillips T, Arzeno N, Stenger M, Lee S, Bloomberg J, Platts S (2012) Functional task test: Spaceflight-induced cardiovascular changes and recovery during NASA's functional task test. Paper presented at the NASA Human Research Program Investigators' Workshop, Houston, TX, Jan. 2012

Pisacane VL, Kuznetz LH, Logan JS, Clark JB, Wissler EH (2007) Thermoregulatory models of space shuttle and space station activities. Aviation, Space, and Environmental Medicine 78(4 Suppl):A48-55

Reagan ML, Janoiko B, Johnson J, Chappell SP, Abercromby A (2012) NASA's analog missions: Driving exploration through innovative testing. Paper presented at the SPACE 2012 Conference & Exposition, Pasadena, CA, Sept. 2012

Robertson WG, Wortz EC (1968) Effect of lunar gravity on metabolic rates. Aerospace Medicine August:799-805

Ross A, Kosmo J, Janoiko B (2013) Historical synopses of desert RATS 1997–2010 and a preview of desert RATS 2011. Acta Astronautica 90(2):182-202 doi:http://dx.doi.org/10.1016/j.actaastro.2012.02.003

Ryder J, et al. (2008) Evidence Book: Risk of Impaired Performance Due to Reduced Muscle Mass, Strength, and Endurance. NASA Johnson Space Center, Houston, TX

Sanborn WG, Wortz BA, Wortz EC (1967) Metabolic rates during lunar gravity simulation. Aerospace Medicine April:380-382

Sandor AS, Schuh SV, Gore BF (2013) Evidence Report: Risk of Inadequate Critical Task Design. NASA Johnson Space Center, Houston, TX

Santee W, Allison W, Blachard L, Small M (2001) A proposed model for load carriage on sloped terrain. Aviation, Space, and Environmental Medicine 72(6):562-566

Scheuring RA, et al. (2008) The Apollo Medical Operations Project: Recommendations to improve crew health and performance for future exploration missions and lunar surface operations. Acta Astronautica 63(7–10):980-987 doi:http://dx.doi.org/10.1016/j.actaastro.2007.12.065

Scheuring RA, et al. (2007) The Apollo Medical Operations Project: Recommendations to improve crew health and performance for future exploration missions and lunar surface operations NASA Techical Report TM-2007-21475. NASA Johnson Space Center, Houston, TX

Scheuring RA, Mathers CH, Jones JA, Wear ML (2009) Musculoskeletal injuries and minor trauma in space: incidence and injury mechanisms in U.S. astronauts. Aviation, Space, and Environmental Medicine 80(2):117-24

Schmidt L, Keeton K, Slack K, Leveton L, Shea C (2009) Evidence Report: Risk of Performance Errors due to Poor Team Cohesion and Performance, Inadequate Selection/Team Composition, Inadequate Training, and Poor Psychosocial Adaptation. NASA Johnson Space Center, Houston, TX

Schmidt P, Newman D, Hodgson E (2001) Modeling space suit mobility: Applications to design and operations. Paper presented at the 31st International Conference on Environmental Systems, Orlando, Florida, July 2001

Sloniger MA, Cureton KJ, Prior BM, Evans EM (1997) Lower extremity muscle activation during horizontal and uphill running. Journal of Applied Physiology 83(6):2073-2079

Smith S, Zwart S, Kloeris V, Heer M (2008) Nutritional Biochemistry of Space Flight. Nova Science Publishers, New York, NY

Steinberg S, Kundrot C, Charles J (2013) Human health and performance considerations for near earth asteroids (NEA). Acta Astronautica 92(1):119-124 doi:http://dx.doi.org/10.1016/j.actaastro.2012.05.026

Stepanek J (2002) Decompression Sickness Fundamentals of Aerospace Medicine. 3rd edn. Lippincott Williams & Wilkins, Philadelphia, PA, p 95-96

Straus S (2004) Extravehicular mobility unit training suit symptom study report. NASA Johnson Space Center, Houston, TX

Strauss S, Krog RL, Feiveson AH (2005) Extravehicular mobility unit training and astronaut injuries. Aviation, Space, and Environmental Medicine 76(5):469-74

Thomas KS, McMann HJ (2011) U. S. Spacesuits. Springer Science+Business Media, LLC, New York, NY

Thomas M, David N, Grant B, Lawrence K (2011) Dynamic simulation of human thermoregulation and heat transfer for spaceflight applications. Paper presented at the 41st International Conference on Environmental Systems, Portland, OR, July 2011

Trout OF, Bruchey WJ (1969) Water immersion reduced-gravity simulation. Human Factors 11(5):473-488

Viegas SF, Williams D, Jones J, Strauss S, Clark J (2004) Physical demands and injuries to the upper extremity associated with the space program. The Journal of hand surgery 29(3):359-66 doi:10.1016/j.jhsa.2004.01.015

Waligora J, Hawkins W, Humbert G, Nelson L, Vogel S, Kuznetz L (1975) Apollo experience report - assessment of metabolic expenditures NASA Technical Note TN D-7883. NASA, Washington, DC

Waligora J, Horrigan D (1975) Metabolism and heat dissipation during Apollo EVA periods Biomedical Results of Apollo. NASA, Washington, D.C.

Walz C, Gernhardt M (2008) Extravehicular activity - challenges in planetary exploration. Paper presented at the 3rd Space Exploration Conference, Denver, CO, Feb. 2008

Williams DR, Johnson BJ (2003) EMU shoulder injury tiger team report NASA Technical Report TM-2003–212058. NASA Johnson Space Center, Houston, TX

Wortz EC (1969) Work in reduced-gravity environments. Human Factors 11(5):433-440

Wortz EC, Prescott EJ (1966) Effects of subgravity traction simulation on the energy costs of walking. Aerospace Medicine 37(12):1217-1222

Wu H, Huff J, Casey R, Kim M, Cucinotta F (2013) Evidence Report: Risk of Acute Radiation Syndromes Due to Solar Particle Events. NASA Johnson Space Center, Houston, TX

X. TEAM

It is impossible to acknowledge by name all those involved in the testing, analysis, and documentation of work related to the risk of injury and compromised performance due to EVA operations in more than 50 years of EVA and EVA research from the Gemini, Apollo, Skylab, Shuttle, Russian *Mir* space station, and International Space Station programs. However, the core team that is primarily responsible for the EVA risk within the Human Research Program (as of the writing of this report) consists of the following:

- Steven P. Chappell, Ph.D, Wyle Science, Technology & Engineering
- Jason R. Norcross, M.S., Wyle Science, Technology & Engineering
- Andrew F.J. Abercromby, Ph.D., NASA Johnson Space Center
- Michael L. Gernhardt, Ph.D., NASA Johnson Space Center

Primary contributors and authors to previous versions of this evidence report include

- Johnny Conkin, Ph.D. , Universities Space Research Association
- Nancy House, B.S., Stinger Ghaffarian Technologies, Inc.
- Jennifer Jadwick, B.S., formerly Wyle Science, Technology & Engineering
- Jeffrey A. Jones, M.D., M.S., Baylor College of Medicine (formerly NASA Johnson Space Center)
- Lesley R. Lee, M.S., Wyle Science, Technology & Engineering
- Richard A. Scheuring, D.O., M.S., NASA Johnson Space Center
- Jennifer A. Tuxhorn, Ph.D., Wyle Science, Technology & Engineering

As the EVA risk is cross-disciplinary, the HRP EVA team would like to acknowledge the critical efforts and partnerships with the EVA community that are related to this work, such as related HRP risks (referenced in this document, when applicable, in the Contributing Factors section, and as coauthors of numerous publications) as well as other stakeholders at NASA JSC (e.g., Engineering, EVA Management Office, Crew Office, Space Medicine, Anthropometric & Biomechanics Facility, Exercise Lab, etc.) and other NASA centers.

XI. LIST OF ACRONYMS

ARGOS – Active Response Gravity Offload System
BME – biomedical engineer
CG – center of gravity
CHAPS – Contingency Hypobaric Astronaut Protective Suit
COM – center of mass
CTSD – Crew and Thermal Systems Division
DCS – decompression sickness
DOF – degrees of freedom
EMU – Extravehicular Mobility Unit
EAMD – Exploration Analogs and Mission Development
ECS – Environmental Control System
EPSP – EVA Physiology, Systems, and Performance
ESPO – EVA Systems Project Office
EVA – extravehicular activity
EWT – EVA Walkback Test
FIU – Florida International University
FTT- functional task testing
GCPS – gravity compensation and performance scale
GRF – ground reaction force
HRP – Human Research Program
HUT – hard upper torso
IDB – in-suit drink bag
ISS – International Space Station
IST – Integrated Suit Test
JSC – Johnson Space Center
LCG – liquid cooling garment
MACES – Modified Advanced Crew Escape Suit
MAG – maximum absorbency garment
MOD – Mission Operations Directorate
NASA – National Aeronautics and Space Administration
NBL – Neutral Buoyancy Lab
NEA – near-Earth asteroid
NEEMO – NASA Extreme Environment Mission Operations
PB – prebreathe
PLSS – portable life support system
POGO – partial-gravity simulator
RATS – Research and Technology Studies

RGO – Reduced Gravity Office
RPE – rating of perceived exertion
SA – situational awareness
SCUBA – self-contained underwater breathing apparatus
SD – standard deviation
SPE – solar particle event
SPR – small pressurized rover
SVMF – Space Vehicle Mockup Facility
U.S. – United States
VGE – venous gas emboli
WEI – work efficiency index

XII. APPENDIX A: EVA GAPS AND MASTER LOGIC DIAGRAM CONTRIBUTING FACTORS MAPPING

Table 2 - Gap to Contributing Factor Mapping, Gaps 6, 7, 8, 9

Gap #	Gap	Metric	EVA Suit Design	EVA Suit Fit	EVA Glove Function	Waste Management	Nutrition and Hydration	Hypoxia	Hypercapnia	Internal Suit Pressure	Hyper/Hypothermia	Humidity	Excessive Radiation Exposure	Work Efficiency Index	EVA Task & Timeline Design	EVA Resources	EVA Environment (Terrain, Gravity, Dust)	Quality of EVA Procedures	EVA Training	EVA Crew Collaboration	Crewmember Physical Preparation	Pre-Existing Injury or Illness	Fatigue	Situational Awareness	Cognitive State (Knowledge, Attention)	Pschological State (Stress, Morale)
		Contributing Factors	Suit Habitability					In-Suit Physical Environment						EVA Factors							Physical State			Mental State		
6	What crew physiological & performance capabilities[1] are required for EVA operations[2] in exploration environments[3]?	A. Minimum aerobic fitness standard on performance during suited operations standard defined.	x	x											x		x				x					
		B. Muscle strength and power required for performance during suited operations understood and minumum standards defined	x	x	x										x		x				x					
		C. Anthropometry (baseline as well as in-flight changes) affect on human performance during suited operations defined	x	x											x		x									
		D. Losses in physiological function and EVA preparation during transit to exploration destinations understood															x		x		x					
		E. Degree that surface EVA activities serve as a physiological countermeasures understood	x												x		x									
7	How do EVA suit system design parameters[4] affect crew health and performance in exploration environments?	A. CG location affect on suited performance in exploration environments defined	x	x											x		x				x		x			
		B. Joint characteristics (ROM, location, torque, hard vs soft) and overall mobility affects on performance in exploration environments understood	x	x						x					x		x				x		x			
		C. Suit mass affect on performance in exploration environments understood	x	x											x		x				x		x			
		D. Suit pressure affect on performance in exploration environments understood	x	x						x					x		x				x		x			
		E. Suit design parameter changes on human health and performance model completed	x	x						x					x		x				x		x			
		F. Objective measure(s) of suit fit defined	x	x																						
8	What are the physiological inputs and outputs associated with EVA operations[2] in exploration environments[3]?	A. Metabolic cost required to perform EVA operations[2] in exploration environments[3]	x	x				x		x					x		x				x					
		B. Nutrition and hydration needs during suited operations defined	x	x			x								x		x				x					
		C. In-suit heat and moisture effects on crew health & performance understood	x							x	x	x			x		x				x					
		D. Excess levels of in-suit CO_2 effects on crew health & performance understood	x						x	x					x		x									
		E. Reduced gravity effects on crew physiological and functional performance during EVA	x	x	x					x				x	x		x				x		x			
		F. Variation of terrain (e.g. slope angle, surface hardness, surface variation) effects on	x	x						x					x		x				x		x			
9	What is the effect on crew performance & health of variations in EVA task design and operations concepts for exploration environments[3]?	A. Task design (i.e. EVA equipment & methods) effects on crew health and performance understood	x	x	x									x	x	x	x	x	x	x						
		B. Objective measures of fatigue related to EVA suited operations defined	x												x		x						x			
		C. EVA duration and frequency (e.g. 8x1 hr, 4x2hr, 2x4 hr 1x8 hr EVA frequency x duration) effects on crew performance and health understood	x	x	x	x	x							x	x	x	x	x	x	x	x		x	x	x	x

[1]e.g. anthropometry, aerobic fitness, muscle strength & power

[2]acceptable functional performance of expected nominal and contingency suited tasks

[3]i.e. Moon, NEA, Mars, L2 and other deep space microgravity locations

[4](e.g. CG, mass, pressure, mobility, joint characteristics, suit fit; includes suit, PLSS, and other enabling equipment)

Table 3 - Gap to Contributing Factor Mapping, Gaps 10, 11, 14

			Contributing Factors																							
			Suit Habitability					In-Suit Physical Environment						EVA Factors							Physical State			Mental State		
Gap #	Gap	Metric	EVA Suit Design	EVA Suit Fit	EVA Glove Function	Waste Management	Nutrition and Hydration	Hypoxia	Hypercapnia	Internal Suit Pressure	Hyper/Hypothermia	Humidity	Excessive Radiation Exposure	Work Efficiency Index	EVA Task & Timeline Design	EVA Resources	EVA Environment (Terrain, Gravity, Dust)	Quality of EVA Procedures	EVA Training	EVA Crew Collaboration	Crewmember Physical Preparation	Pre-Existing Injury or Illness	Fatigue	Situational Awareness	Cognitive State (Knowledge, Attention)	Pschological State (Stress, Morale)
10	Can knowledge and use of real-time physiological and system parameters during EVA operations improve crew health and performance?	A.Physiological and EVA system parameters that must be monitored, displayed, alerted, and/or sent to the ground to enable safe and effective suited operations are defined	x												x	x	x							x	x	
		B.Effective methods for provision of real-time knowledge of physiological and EVA system parameters to the EVA crew member understood	x												x	x	x							x	x	
		C. Effective methods for real-time physiological and EVA system parameters utilization with biofeedback systems to improve EVA crew health, performance and autonomy are understood	x												x	x	x							x	x	x
11	How do EVA operations[2] in exploration environments[3] increase the risk of crew injury and how can the risk be mitigated?	A. Mechanisms or tasks that lead to acute, chronic, cummulative, or repetitive suit-induced injury are tracked and understood	x	x	x									x	x		x				x	x				
		B. Glove design parameters that impact crew performance and safety defined	x		x					x					x		x				x					
		C. Technologies or countermeasures developed to reduce the likelihood of suit-induced trauma	x	x											x		x		x		x					
		D. Suit-related trauma monitoring, logging, and treatment tracking																	x			x				
		E. Techniques and technologies developed to treat, stabilize, monitor, and transport incapacitated suited crew in exploration environments	x												x	x	x		x	x						
14	What other EVA-related risks, developments and techologies exist that may affect EVA research?	A. Monitoring and/or involvment in other HRP risk activitites and developments that are ongoing or planned that may affect the EVA risk and/or research portfolio																								
		B. Monitoring and/or involvment in EVA-related hardware developments outside of HRP that are ongoing or planned and may affect the EVA risk and/or research portfolio																								
		C. Monitoring and/or involvement in EVA-related mission/architecture development outside of HRP that may affect the EVA risk and/or research portfolio																								

[1] e.g. anthropometry, aerobic fitness, muscle strength & power

[2] acceptable functional performance of expected nominal and contingency suited tasks

[3] i.e. Moon, NEA, Mars, L2 and other deep space microgravity locations

[4] (e.g. CG, mass, pressure, mobility, joint characteristics, suit fit; includes suit, PLSS, and other enabling equipment)