

# Risk of Compromised EVA Performance and Crew Health Due to Inadequate EVA Suit Systems

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Improperly designed EVA suits can result in the inability of the crew to perform as expected, and can cause mechanical and decompression injury. Suit developers must fully understand the impact of the suit design on crew performance and health to ensure properly designed mobility, pressures, nutrition, life support, etc. – *Human Research Program Requirements Document, HRP-47052, Rev. C, dated Jan 2009.*

*Although the Apollo EVA suits performed very well on the short missions for which they were designed, longer missions to the moon and Mars will require more robust suit designs. An integrated human testing program across multiple environments aims to correct or mitigate many of the problems with the Apollo EVA suits, thus maximizing human performance and efficiency while minimizing crew member health and safety risks on future missions.*





## Executive Summary

Constellation Program missions to the moon and Mars will include as many as 24 hours of EVA per crew member per week, which will involve the performance of exploration, science, construction, and maintenance tasks. The effectiveness and success of these missions is dependent on designing EVA systems and protocols that maximize human performance and efficiency while minimizing health and safety risks for crew members.

The Apollo EVA suits performed very well in the short-duration missions for which they were designed. However, the longer-duration missions, more frequent EVAs, and more varied EVA tasks that are anticipated during the CxP will require EVA suits and systems that are more robust 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 (CG), and other features requiring significant crew compensation) will need to be corrected or mitigated to optimize EVA objectives.

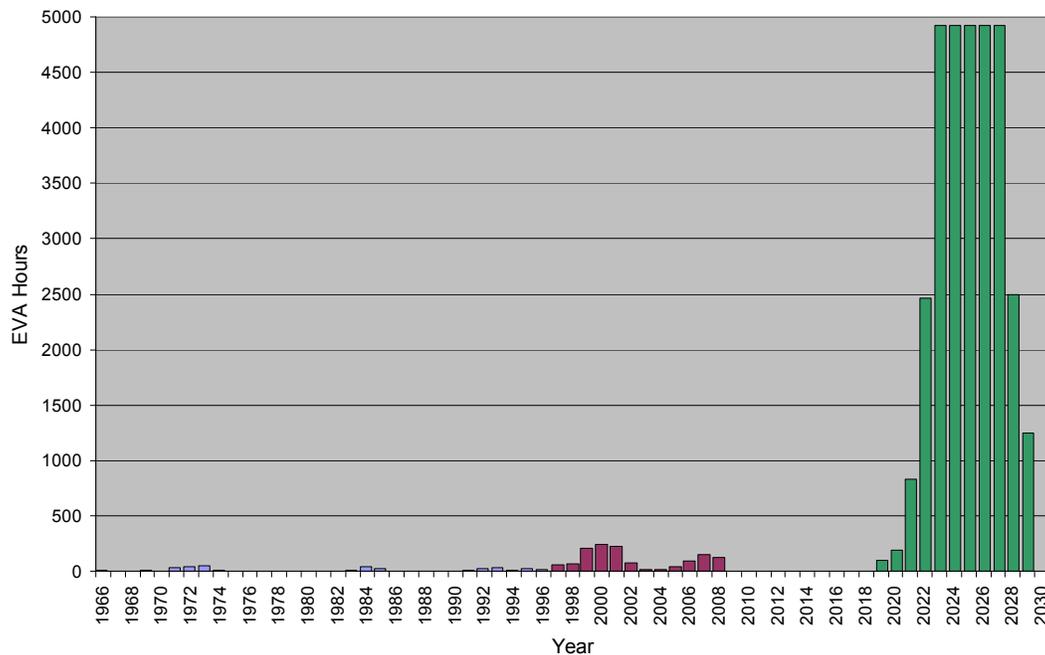
It is critical to understand the effects of EVA system design variables such as suit pressure, weight/mass, CG location, joint ranges of motion, and biomedical monitoring on the ability of astronauts to perform safe, efficient, and effective EVAs. To achieve this understanding, the EVA Physiology, Systems, and Performance (EPSP) Project is working with the CxP to develop and execute an integrated human testing program across multiple environments. This program will provide objective data that will enable informed design decisions, thereby ensuring a Constellation EVA system that optimizes crew member health, safety, efficiency, and performance.

This report describes the risks to crew health, safety, performance, and efficiency that an inadequate EVA suit system design would bring, and provides the evidence base to substantiate the importance of the risks.

## Introduction

Fewer than 20 lunar EVAs were performed during the entire Apollo Program. Current architectures under consideration by the NASA Constellation Architecture Team-Lunar (CxAT-Lunar) could involve as many as 30,000 hours of lunar exploration EVA time. As demonstrated in figure 14-1, these plans represent an enormous increase in EVA hours in an extreme and challenging environment. No previous astronaut or spacesuit has performed more than three lunar EVAs, yet future astronauts and their EVA suits must be capable of performing as many as 76 lunar EVAs during a 6-month mission.

Providing the capability for humans to work productively and safely while performing an EVA involves many important, medically related considerations. Maintaining sufficient total pressure and oxygen partial pressure is vital not only to human health, but also to survival. Pre-breathe protocols must adequately reduce the amount of inert gas in astronauts' blood and tissues to prevent DCS (also known as "the bends") while minimizing the impact on crew efficiency. The EVA suit must be ventilated to remove expired carbon dioxide (CO<sub>2</sub>), 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 crew member must be protected from harmful solar and other radiation. Nourishment and water must be available for ingestion, and accommodations must be provided for liquid and solid waste collection.



**Figure 14-1. EVA estimates for current lunar architecture.**

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 (e.g., Category III and Category IV<sup>23</sup>). More recent evidence has been gathered in a rigorous, controlled manner in which subjects serve as their own controls from shirt-sleeved to suited conditions and across repeated measures trials in which a single parameter is varied (e.g., Category II). This report identifies and describes the various risks and associated evidence as follows:

- Risks to Crew Performance: EVA Suit Design Parameters
- Risks to Crew Performance, Health, and Safety: EVA Biomedical Monitoring and Consumables Management
- Risks to Crew Health: EVA Suit Design Parameters
- Risks to Crew Health: Decompression Sickness
- Risk to Work Efficiency: EVA Suit Design Parameters

<sup>23</sup>To help characterize the kind of evidence that is provided in each of the risk reports in this book, the authors were encouraged to label the evidence that they provided according to the “NASA Categories of Evidence.”

- Category I data are based on at least one randomized controlled trial.
- Category II data are based on at least one controlled study without randomization, including cohort, case-controlled or subject operating as own control.
- Category III data are non-experimental observations or comparative, correlation and case, or case-series studies.
- Category IV data are expert committee reports or opinions of respected authorities that are based on clinical experiences, bench research, or “first principles.”

## Evidence

### Risks to crew performance: extravehicular activity suit design parameters

#### Space Flight Evidence

Throughout the history of space flight, astronauts and cosmonauts have performed nearly 300 EVAs. However, only 14 of those EVAs have been conducted on the lunar surface in one-sixth gravity. Accordingly, the current understanding of suited human performance in partial-gravity environments is limited. A recent face-to-face summit with some of the Apollo astronauts provided valuable insight and yielded recommendations for the next-generation lunar EVA suit. Fourteen of the 22 surviving Apollo astronauts participated in the Apollo Medical Operations Project to identify Apollo operational issues that impacted crew health and performance. In the category of EVA Suit Operations using the shuttle/ISS EMU, 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 CG, 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 and the Apollo A7LB {lunar surface EVA suit} had limited ability to bend the suit at the hip and to rotate within the suit. The crewmember had to bend forward from the knee joint, which demanded considerably more work load 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*'."

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 crew member stated that "*efficiency was no more than 10% of the use of the hand*" (Scheuring et al., 2007). The crew also sustained significant fingernail and hand trauma, as described in "Risks to crew health: EVA suit design parameters" below.

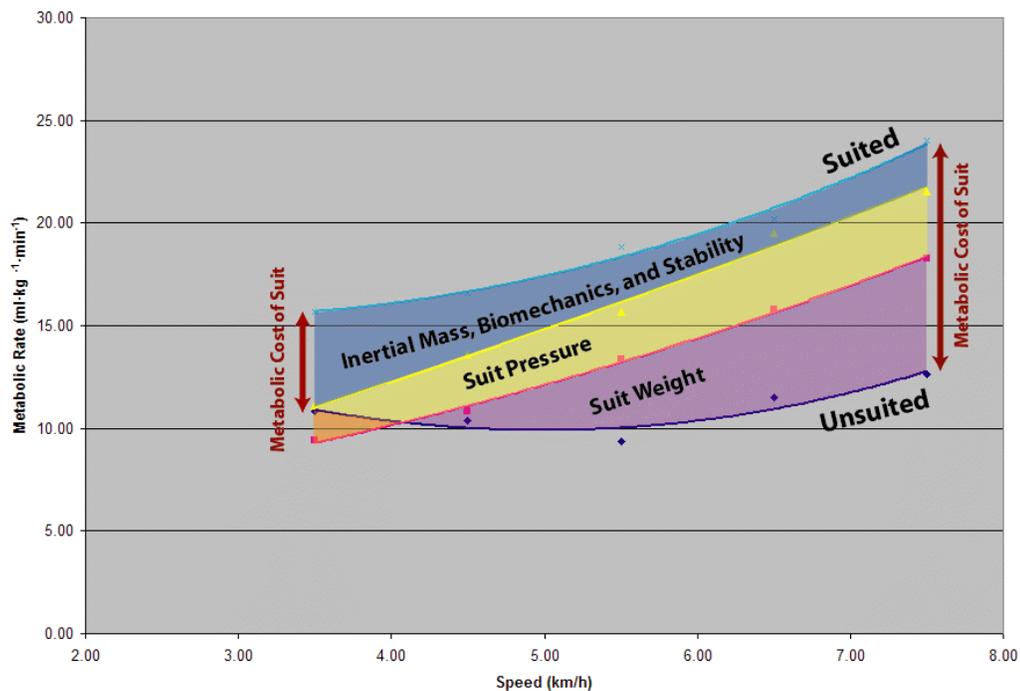
#### Ground-based Evidence

Physiologists and physicians are using various analog environments to study the effects of suit weight, mass, CG, pressure, biomechanics, and mobility on human performance. Test activities are 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, subject anthropometrics, time series motion capture, ground reaction forces (GRFs), subjective ratings of perceived exertion (RPEs) (Borg, 1982), and operator compensation using a relative subjective scale. The operator compensation scale, the gravity compensation and performance scale (GCPS), is modeled after the Cooper-Harper rating scale (Cooper and Harper, 1969) and is described in Appendix A.

The lunar analogs used include the Partial Gravity Simulator (Pogo) and Neutral Buoyancy Laboratory (NBL) at NASA JSC, parabolic flight, Desert Research and Technology Studies (D-RATS), the Haughton Mars Project (HMP), and NEEMO.

Results from early tests conducted on the Pogo have begun to characterize the metabolic cost, biomechanics, and subjective factors that are associated with ambulation and task performance in the Mark III Advanced Spacesuit Technology Demonstrator (MKIII), which is a prototype EVA suit that was designed for multi-axial mobility in planetary environments.

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 14-2 shows the current understanding of how these factors contribute to the increased metabolic cost of suited ambulation in the MKIII suit (Gernhardt et al., in preparation (a)).



**Figure 14-2.** Suit design parameters that contribute to the metabolic cost of the suit.

The parameter that has the largest impact on metabolic rate has been suit weight. Variations in suit pressure make little difference, but varying suit weight has led to significant differences in metabolic rate across speeds. Figure 14-3 shows how varying suit weight affects metabolic rate as a function of level ground ambulation speed (Gernhardt et al., in preparation (a)).

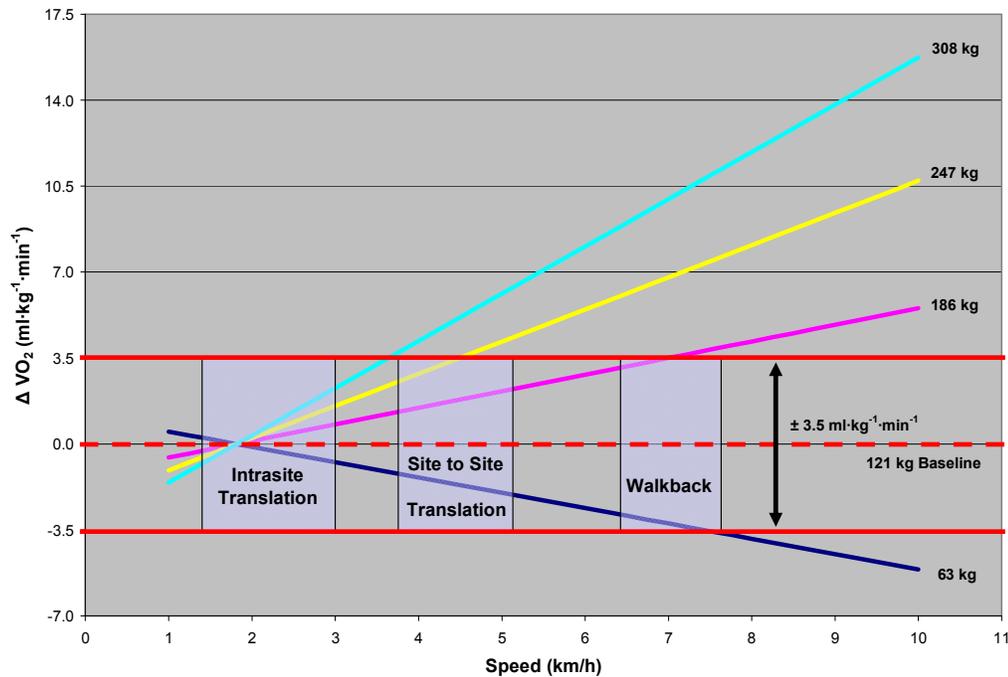


Figure 14-3. Effect of suit weight on metabolic rate across speed of ambulation.

This is just one example of how lunar operational concepts will play a large role in determining requirements. If a crew member 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.

Based on 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. As more data are collected, this algorithm will be expanded into an EVA consumables calculator in which inputs on 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 help to develop suits that increase efficiency in crew health and performance based on different operational concepts.

In addition to ambulation, the effect of varying suit weight and pressure has been examined across a variety of exploration-type tasks, such as shoveling and picking up rocks. Figure 14-4 describes the metabolic rate and GCPS ratings for six subjects averaged over three different tasks (i.e., shoveling, picking up and moving rocks, and a construction task busy board) as a function of 1g-equivalent suit weight. Both the objective and the subjective ratings show the same trends, which surprisingly indicate that a heavier suit weight is associated with better performance. The GCPS quantifies the suit operator compensation that is required for optimal task performance, which is defined as being equivalent to 1g 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.)

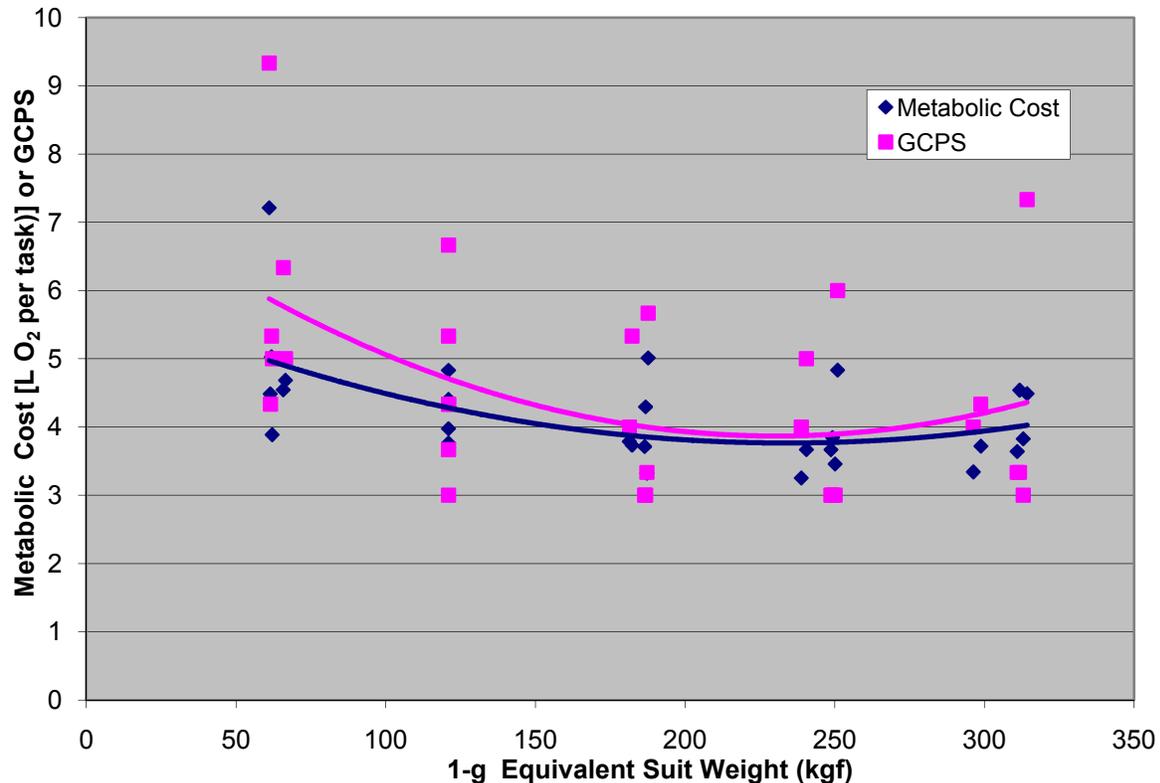


Figure 14-4. Effect of suit weight on metabolic rate and subjective GCPS ratings during exploration tasks.

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 the GRF, which was higher in suited conditions than in unsuited conditions and also increased as suit weight increased. However, the GRFs were still lower than those that a crew member would normally experience on Earth. This suggests that EVA performance on the lunar surface may not provide sufficient loading to protect against bone loss, thus indicating the continued need for exercise countermeasures (Gernhardt et al., in preparation (a); in preparation (b)).

Recognizing that not all ambulation on the moon will be similar to that on a level treadmill, EPSP personnel have initiated studies to characterize the effects of incline and terrain on metabolic rate. Inclined walking trials have shown that the metabolic cost of the suit that is due to factors other than suit weight goes to almost zero, indicating an energy recovery component of the suit that is currently not well understood (Gernhardt et al., in preparation (c)).

Beyond the above stated parameters, the Apollo Program demonstrated that suit CG is an important variable that affects human performance. Recent studies have evaluated CG in the underwater environments at NEEMO and the NBL. These studies assessed crew performance of representative planetary exploration tasks using a single EVA suit weight with six 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 60-lb. suit, a 135-lb. Portable Life Support System (PLSS), and a reference 6-ft, 180-lb subject. Subjects used the GCPS rating tool to evaluate the CG locations. As shown in figure 14-5, subjects preferred (with lower GCPS score) the perfect, low, and forward CGs over the high, aft, or NASA baseline

(Crew and Thermal Systems Division (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., 2008).

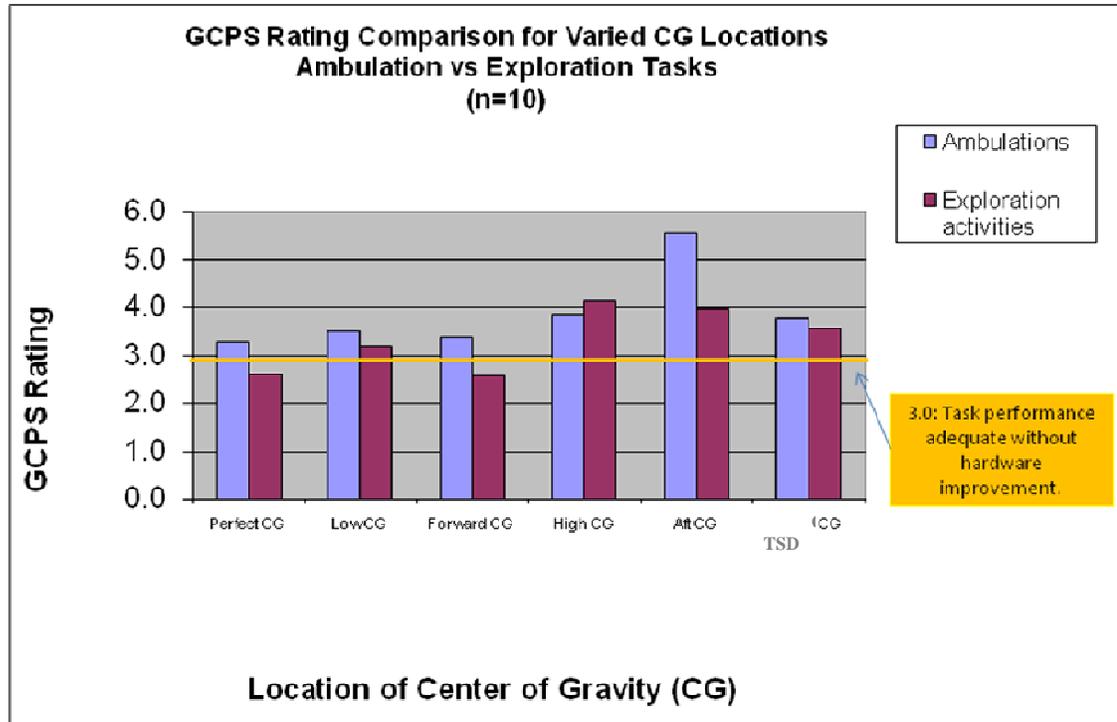


Figure 14-5. GCPS ratings for suit center of gravity.

## ■ Risks to crew performance, health, and safety: extravehicular activity biomedical monitoring and consumables management

### ■ Overview

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. 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 and Horrigan, 1975; Waligora et al., 1975).

### ■ Space Flight Evidence

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 (Waligora and Horrigan, 1975; Kelley et al., 1968). 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.

Thermal homeostasis of the crew member is crucial for safe and effective EVA performance. Heat storage above 480 Btu/hr leads to performance decrements, such as a loss of tracking skills and increased errors in judgment, and tissue damage begins at 800 Btu heat storage (Jones, 2007). 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/hr, 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/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 14-6) using a validated thermoregulatory model (41 Node Metabolic Man; 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)) (Kuznetz, 2004). These data suggest that at metabolic rates above ~1,200 Btu/hr, LCG inlet temperatures exceeding 21°C (69.8°F) may induce crew member heat storage rates above the 480 Btu/hr that lead to performance impairment. Although Apollo metabolic rates rarely exceeded 1,200 Btu/hr and the LCG inlet temperature minimal setting was 21°C (69.8°F), these data are instructive for the design of future lunar EVA suits, which may be used in situations in which crew metabolic rates exceed levels seen during Apollo.

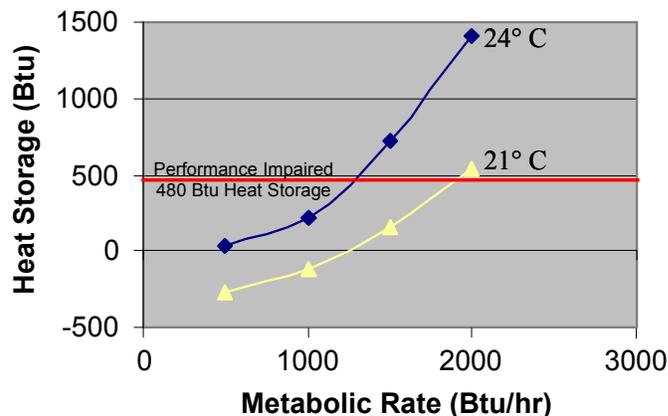


Figure 14-6. Heat storage based on metabolic rate and LCG inlet water temperature.

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* (MOD, unpublished internal report). During Apollo 14, Apollo 15, and Apollo 17, there were six cases in which less than 10% 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 crew members, on Apollo 15 and Apollo 16, completed their EVAs with only 4% and 2% remaining, respectively, of their CO<sub>2</sub> removal capability (lithium hydroxide (LiOH)).

Although each of the Apollo missions was limited to two or three EVAs, future lunar missions are expected to consist of three 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.

### ■ Nutrition, hydration, and waste management

The longer and work-intensive EVAs that are planned for future Exploration missions will also need to account for astronaut nutrition, hydration, and waste management. Specifically, dehydration is an issue that can lead to poor crew performance. The Apollo suit had a 15-oz drink bag; however, this amount of fluid is considered insufficient for crews that are performing surface EVA. Scheuring et al. (2007) provide several citations regarding the need for more water. As the authors write: “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 need 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 ISS Programs. Furthermore, the time that is required to prepare the nutrition and hydration systems prior to conducting an EVA must be decreased. Filling and degassing the drink bag that is used in the current U.S. suit is time-consuming and contributes to the poor work efficiency index (WEI) of shuttle and ISS EVAs.

Additionally, 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 a crew is required to be suited for as many as 152 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.

### ■ Biomedical monitoring

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 are being used in the Space Shuttle Program have been problematic. Scheuring et al. (2007) provide approximately 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 crew members have expressed frustration with the cumbersome and time-consuming process of donning/doffing their biomedical sensor systems. Improvements to the biomedical sensor systems for future missions are therefore warranted.

### ■ Ground-based Evidence

At the request of the Constellation EVA Systems Project Office (formerly known as the Advanced EVA Office) management, a study was conducted to determine whether it is possible for a suited crew member to walk back to a terrestrial habitat in the event of a failed rover. As a starting point that is 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 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 on a level treadmill at a rapid, but sustainable, pace using a self-selected gait strategy and speed. Prior to this test, the investigators expected that crew members could only complete half of that distance or that the total duration would exceed 3 hours. However, all of the crew members 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  $\text{VO}_{2\text{pk}}$  [volume of oxygen consumption, peak], with a range of 45% to 61%. Physiological and consumables usage data are summarized in Table 14-1. RPEs ( $11.8 \pm 1.57$  (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  $3.5 \pm 1.44$  (SD) on the 10-point GCPS, indicating “fair” to “moderate” operator compensation was required to perform the task (Gernhardt et al., in preparation (b)).

**Table 14-1. Summary Data for the Lunar 10-km Walkback Portion of the Test**

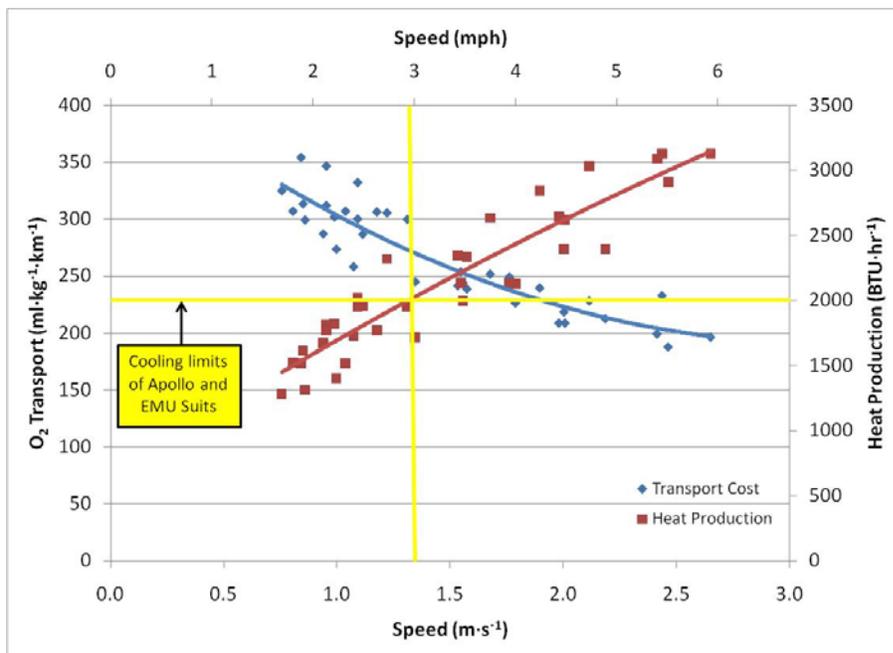
10k Walkback Summary Data (averaged across enter 10 km unless noted)		
	Mean	SD
Avg Walkback Velocity (mph)	3.9	0.5
Time to Complete 10 km (min)	95.8	13.0
Avg % $\text{VO}_{2\text{pk}}$	50.8%	0.3%
Avg Absolute $\text{VO}_2$ (l/min)	2.0	0.3
Avg Metabolic Rate (Btu/hr)	2,374.0	303.9
Max. 15-min-avg Metabolic Rate (Btu/hr)	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/hr)	0.4	0.15
Btu Average (Btu/hr)	2,374	932.8
Cooling Water (lb/hr)	3.1	0.98
Energy Expenditure (kcal/hr)	599	233

\*Assumes thermally neutral case and sublimator cooling

Subjects’ heat production rates ranged from 1,918 to 2,667 Btu/hour, and averaged 2,374 Btu/hour, a rate that would exceed the heat removal rates of the Apollo or space shuttle EVA suits. Core temperature measurements indicated an average rise ( $\Delta$ ) of  $33.8^\circ\text{F}/1^\circ\text{C}$  from normal ( $98.6^\circ\text{F}/37^\circ\text{C}$ ) across the entire test, although one subject’s core temperature ( $103.6^\circ\text{F}/39.8^\circ\text{C}$ ) peaked near a level of concern. Subjects unambiguously reported cooling to be inadequate at the higher workloads (Gernhardt et al., in preparation (b)).

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 crew member might expend more energy on a per-minute basis by traveling at faster speeds, the metabolic cost per kilometer would actually be less (Gernhardt et al., in preparation (b)).

Unfortunately, at speeds above 3 mph (figure 14-7) the heat production, which is shown on the right axis and the red tracing, begins to exceed the 2,000 Btu/hr cooling limit of both the Apollo and the shuttle EVA suits, resulting in increased core body heat storage. Without improvements in cooling for future suits, crew members performing lunar EVAs would not be able to exploit the increased efficiency (figure 14-7, on the blue tracing as decreasing oxygen transport cost) available at faster ambulation speeds. This would result in increased consumable requirements to cover the same distance (Gernhardt et al., in preparation (b)).



**Figure 14-7. Relationship between transport cost and heat production for lunar suited ambulation.**

While life support consumables are an important consideration for EVA excursions, the 10-km Walkback also provided important insight into hydration and nutritional requirements for a task of similar duration or intensity. All subjects were provided with 32 oz of water in an in-suit drink bag, standard for use of the MKIII suit. Crew members consumed 50% to 100% of the water that was provided, and one crew member 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 crew members felt that a nutritional item, either food (e.g., an energy bar or a gel) or a flavored electrolyte drink might improve their performance and/or endurance (Gernhardt et al., in preparation (b)). These observations were in accordance with the Apollo recommendations cited above.

Because the EWT was limited to 10 km on a level treadmill, additional studies were performed to understand how a more realistic simulation would affect the results. Factors such as incline/decline, lunar-like terrain, and real-time navigation will all contribute to the performance of a 10-km traverse. Results of these Pogo tests have indicated that inclined ambulation does increase metabolic rate, but at a rate that is much less than experienced in the 1g environment. To classify the effect of lunar terrain and navigation of human performance, subjects completed a series of 10-km traverses at the HMP site, which is an international interdisciplinary field research project centered on scientific study of the Haughton impact crater and surrounding terrain on Devon Island, Canada. The rocky polar desert setting and geologic features provide a good analog of the lunar surface for EVA translation and navigation studies. At HMP, unsuited subjects began at a location that was 10 km from the finish point and were instructed to return at a rapid, but sustainable, pace using a global positioning satellite (GPS) receiver for navigation and tracking speed and grade. Three separate starting points, each equidistant from the finish point, were defined, and the subjects completed each route once. The straight-line distance between starting and ending points was  $9.91 \pm 0.22$  km/ $6.16 \pm 0.14$  miles (mean  $\pm$  SD), and the actual distance traveled was  $10.61 \pm 0.61$  km/ $6.59 \pm 0.38$  miles. Completion time averaged  $126.5 \pm 28.7$  min, which was longer than the EWT average of  $95.8 \pm 13.0$  min (Norcross et al., 2008).

Comparison between these field tests and speed/grade matched treadmill controls has provided a crude correction factor for terrain, suggesting that metabolic rates in the actual environment were an average of 56% higher than in controlled treadmill conditions. Further studies are needed to understand whether this increase would be as high in lunar gravity (Norcross et al., 2008).

## ■ Risks to crew health: extravehicular activity suit design parameters

### ■ Space Flight Evidence

A comprehensive analysis was recently 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 are illustrative of 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 pre-flight 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 crew member sustained wrist soreness due to the suit sleeve rubbing repeatedly. One crew member injured his shoulder during a lunar EVA while attempting to complete multiple surface activities on a tight mission timeline. Unbeknownst to his flight surgeon, this crew member 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 following the third lunar EVA, his MCP 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).

#### ■ Ground-based Evidence

To adequately prepare for mission EVAs, astronauts undergo extensive ground-based training at the NBL, which provides controlled neutral buoyancy operations to simulate the zero-g 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 in 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 crew members 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 (Strauss, 2004). During 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 14-8). There were also abrasions, contusions, and two cases of peripheral nerve impingements related to glove fit and hard point contact compressions. Shoulder symptoms were due to hard contact with suit components (figure 14-8) and strain mechanisms. 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.” (Strauss, 2004)



**Figure 14-8. Fingernail and shoulder trauma sustained during EVA training (Jones et al., 2006).**

A shoulder injury tiger team was created in December 2002 at NASA JSC 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, two 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, performing tasks in inverted body positions during NBL training, performance of overhead tasks, repetitive motions, the 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; Jones et al., in review 2009). 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 the 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 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  $1.5 \pm 1.1$  (SD), which is “very low” to “low” on the 10-point discomfort scale. The knee area and the feet/toes were the most frequent sites of discomfort during and after the test (figure 14-9). Fatigue and/or muscular tightness were reported most commonly in the quadriceps, thighs, gluteal muscles, and lower back (Gernhardt et al., in preparation (b)).



Figure 14-9. Knee and foot trauma sustained during 10-km EWT.

## ■ Risks to crew health: decompression sickness

### ■ Overview

Decompression sickness represents a risk to the successful performance of EVAs as well as to the health and safety of the astronauts. Type I (pain-only) DCS symptoms can range from awareness in a joint or muscle to pain in which the performance of a task is affected. Symptoms of Type II (serious) DCS can include confusion, memory loss, headache, impaired vision, extreme fatigue, seizures, vomiting, shortness of breath, unconsciousness, paralysis, and, ultimately, death.

The risk of developing DCS is decreased by performing an oxygen pre-breathe to reduce the amount of inert gas (usually nitrogen) in the blood and tissues before a crew member is subjected to decompression in the spacesuit. Many factors influence the required duration of the pre-breathe protocol. During the Apollo missions, the environment inside the lunar module was 34.5 kPa (5.0 psia) and 100% oxygen. The absence of inert gas in the environment meant that pre-breathe was unnecessary to reduce DCS risk. However, concerns over flammability mean that Orion, Altair, and any surface assets during future lunar exploration will likely operate at 101 kPa (14.7 psia) and 20.8% oxygen; 70.3 kPa (10.2 psia) and 26.5% oxygen; and/or 55.2 kPa (8.0 psia) and 32% oxygen with the balance nitrogen. In any of these environments, the partial pressure of nitrogen will require some amount of oxygen pre-breathe prior to a crew member performing an EVA at 29.6 kPa (4.3 psia) to reduce the amount of inert gas that is dissolved in that crew member's blood and tissues.

The risk of DCS during EVAs performed during CxP missions will be quantified and mitigated using the same combination of mathematical decompression stress modeling, statistical analysis of relevant ground-based and space flight data, expert judgment, and rigorous validation of pre-breathe protocols using prospective ground-based hypobaric EVA simulation studies. Through this process, pre-breathe protocols will be developed that will reduce the DCS risk to within acceptable limits while minimizing the impact on crew work efficiency.

Protocols are designed to reduce the risk of DCS to within acceptable limits. The NASA *DCS Risk Definition and Contingency Plan* (1998) criteria specify acceptable limits as a total incidence of DCS  $\leq 15\%$  at a 95% CL, with  $< 20\%$  Grade IV venous gas emboli (VGE) and 95% CL, and no Type II (serious) instances of DCS.

The 1/6g environment, the increased time to return to Earth in the event of serious DCS, and the more frequent EVAs planned for lunar surface missions may necessitate the development of new limits of acceptability for DCS risk for these missions.

Pre-breathe protocols are typically developed by experts using models of decompression stress and by considering relevant data from past experiences in ground-based studies and space flight. Before they are implemented in space flight, pre-breathe protocols are typically tested in ground-based hypobaric chamber EVA simulation studies to verify that the observed incidence of DCS and VGE are indeed within the agreed-to acceptable limits. Analysis of the ground-based data using Bayesian statistical methods ensures that a pre-breathe protocol is approved for use in space flight only when the incidence of DCS and VGE are within acceptable limits *and* the level of confidence in the estimate of true DCS and VGE risk is 95% or greater.

### ■ Space Flight Evidence

Two different spacesuits are currently used to perform EVAs from the ISS: the Russian Orlan and the U.S. EMU. Differences in operating pressures between the U.S. and Russian spacesuits have led to different EVA preparations. The Russian Orlan spacesuit system operates at 40.0 kPa (5.8 psia). By contrast, the U.S. EMU system operates at 29.6 kPa (4.3 psia) of oxygen, with traces of CO<sub>2</sub> and water vapor.

The Russian EVA preparation protocol includes a 30-minute oxygen pre-breathe in the Orlan spacesuit at a pressure of 73 kPa (10.6 psia) to partially wash out nitrogen from crew members' blood and tissues (Barer and Filipenkov, 1994). Literature from the Russian program shows that of approximately 114 EVAs that had been performed in the Russian spacesuit, including 18 EVAs from the ISS, crew members showed no signs of DCS (Malkin, 1994; Davis et al., 1977; Fulton, 1951).

Three different pre-breathe protocols may be used before performing an EVA in the U.S. EMU: an exercise pre-breathe, a 4-hour in-suit pre-breathe, or a campout pre-breathe. The protocols vary in effectiveness and, hence, in risk of DCS. Selection of a particular method depends on the particulars of the EVA, including the DCS risk, the timeline, and the operational risk. However, no symptoms of DCS have been reported to date by astronauts who have performed EVAs in the EMU spacesuits following any of the three pre-breathe protocols (Horrikan et al., 1997; Waligora and Pepper, 1995).

### ■ Ground-based Evidence

According to ground-based studies of the U.S. pre-breathe protocols, exercise pre-breathe is the method that has the lowest predicted risk of DCS. It has been tested extensively under laboratory conditions and meets the NASA *DCS Risk Definition and Contingency Plan* (1998) criteria of a total incidence of DCS  $\leq 15\%$  at a 95% CL, with  $< 20\%$  Grade IV VGE and 95% CL, and no Type II (serious) instances of DCS.

The 4-hour in-suit pre-breathe protocol resulted from many years of experience with 4-hour in-suit pre-breathe testing. This was primarily gained from ground testing of suited subjects and crew members in preparation for altitude chamber runs. More than 300 such exposures have been completed with  $< 1.5\%$  instances of DCS observed, with no Type II DCS. However this method has not been subjected to the same level of controlled laboratory evaluation as the exercise pre-breathe method.

When simulating U.S. pre-breathe protocols in ground-based studies using volunteers wearing regular clothing, the rate at which DCS symptoms developed was 17% to 26%. Given these data and the lack of any observed DCS symptoms during space flight using the same protocols, the conclusion can be drawn that the

risk of DCS occurring in actual weightless EVA conditions is significantly lower compared to ground simulation. Russian physiologists explain this by citing the inhibiting effect of the spacesuit and microgravity on nucleation mechanisms in human tissues. The hard shell of the spacesuit prevents a crew member from making abrupt movements during an EVA, thus decreasing amplitude/speed characteristics, lowering the intensity of cavitations, and lessening the possibility of developing gas bubbles in tissues. Moreover, removing the mass load and decreasing the muscular exertion when performing static or dynamic tasks in microgravity decreases the number of pre-EVA gas bubble formations. The effect of these factors leads to a decrease in the intensity of and the rate at which pathogenic gas bubbles develop in the body as a causative agent of DCS (Conkin et al., 1987; Kumar et al., 1993; Powell et al., 1993).

### ■ Ground-based Simulation Information

A physics-based tissue bubble dynamics model (TBDM) will be used in the development of pre-breathe protocols. The TBDM provides a time-varying index of theoretical physiological decompression stress, referred to as a Bubble Growth Index (BGI), which is based on variations in pressure and gas composition (Gernhardt, 1991). BGI is defined as the radius of a theoretical gas bubble,  $r$ , divided by the initial radius of the bubble. The TBDM models the rate of change of bubble radius ( $dr/dt$ ) according to Equation 1. Thus, the predicted decompression stress (BGI) at time  $t$  can be calculated throughout the entire time course of any decompression profile.

$$\frac{dr}{dt} = \frac{\frac{\alpha D}{h(r,t)} \left[ P_a - vt + \frac{2\gamma}{r} + \frac{4}{3} \pi r^3 M - P_{\text{Total}} - P_{\text{metabolic}} \right] + \frac{rV}{3}}{P_a - vt + \frac{4\gamma}{3r} + \frac{8}{3} \pi r^3 M} \quad (1)$$

where:

$r$  = bubble radius (cm)

$t$  = time (sec)

$\alpha$  = gas solubility ((mL gas)/(mL tissue))

$D$  = diffusion coefficient ( $\text{cm}^2/\text{sec}$ )

$h(r,t)$  = bubble film thickness (cm)

$P_a$  = initial ambient pressure ( $\text{dyne}/\text{cm}^2$ )

$v$  = ascent/descent rate ( $\text{dyne}/\text{cm}^2 \cdot \text{cm}^3$ )

$\gamma$  = surface tension (dyne/cm)

$M$  = tissue modulus of deformability ( $\text{dyne}/\text{cm}^2 \cdot \text{cm}^3$ )

$P_{\text{Total}}$  = total inert gas tissue tension ( $\text{dyne}/\text{cm}^2$ )

$P_{\text{metabolic}}$  = total metabolic gas tissue tension

The TBDM's index of decompression stress, BGI, can be quantitatively related to the percentage of DCS risk using a logistic regression model. Previous analysis has shown the TBDM to provide good prediction of DCS risk (Gernhardt, 1991). For example, a logistic regression was performed using DCS and VGE data from NASA Bends Tests 1–7 ( $n=345$ , 57 DCS cases, 16.5% DCS, 41.4% VGE). Data that were derived from the pre-breathe staged decompressions, all with exercise at altitude, included data points at 70.3, 41.3, and 29.6 kPa (10.2, 6.0, and 4.3 psia), and did not include adynamic or exercise pre-breathe data. BGI provided signifi-

cant prediction of DCS and VGE data ( $p < 0.01$ ). The Hosmer-Lemeshow Goodness-of-Fit statistic:  $p=.35$  for DCS,  $p=.55$  for VGE, indicates a good fit of the data (Abercromby, 2008). (Note: For the Hosmer-Lemeshow statistic,  $p > .05$  rejects the hypothesis that there is a significant difference between the model predictions and the observed data.) A 360-minute half-time compartment was assumed.

### ■ Conclusion

The combination of space flight and ground-based experience points to a high degree of safety in both approaches being used to mitigate the risk of DCS. The U.S. approach to DCS risk management enables greater crew mobility than does the Russian approach due to lower pressure in the EMU spacesuit; however, the simpler and shorter Russian protocol is preferable in terms of work efficiency. Over time, these pre-breathe protocols will need to be streamlined to optimize both crew mobility and work efficiency.

### ■ Risks to work efficiency: extravehicular activity suit design parameters

The total WEI is defined as

$$\frac{EVA\ Time}{(Total\ suit\ and\ airlock\ prep + pre-breathe + airlock\ depress, repress + post\ EVA)}$$

The current NASA EVA total WEI is 0.39 to 0.51. Constellation EVA Systems Project documentation contains requirements stating that EVA WEI shall be 3.0. Many factors contribute to WEI, including vehicle systems, suit systems, and operational procedures. Future EPSP studies will evaluate WEI based on current knowledge and concepts of operations, and will provide data to make recommendations to improve WEI. These studies will include: (1) an evaluation of suit components that may improve WEI (e.g., integrated biosensor systems that are quick don/doff; drink bags that require less preparation time); (2) development of improved pre-breathe protocols; (3) studies in lunar analogs that will evaluate the efficiency of different mission operations concepts and measure the trends in WEI over time; and (4) an evaluation of suit prototypes and the development of operational concepts to meet WEI requirements.

### ■ Computer-based Simulation Information

Computer-based simulation data are discussed above in the Decompression Sickness section.

### ■ Risk in Context of Exploration Mission Operational Scenarios

Extravehicular activity is a critical factor in the success of the construction, maintenance, scientific, and exploration aspects of every lunar architecture concept being considered by the CxAT-Lunar team. Current plans call for each crew member 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 crew member in a single mission. As described in the Evidence section of this chapter, the risks that are associated with any inadequacies that exist in current EVA suit designs – particularly with respect to suit-induced trauma – will be greatly amplified by such frequent EVAs.

Current CxAT-Lunar 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 DCS

treatment, SPE protection, and on-site treatment of or medication for an injured crew member would significantly reduce many of the risks associated with planetary exploration. Furthermore, because crew members would be inside the SPRs during most surface translations, the overall number of in-suit EVA hours to achieve the same (or greater) science/exploration return would be reduced. The possibility of performing single-person EVAs with a second crew member inside the SPR would further reduce total EVA hours during the lunar architecture to the same order of magnitude as during ISS construction. As a result, the number of cycles on the EVA suits would be decreased, thereby increasing the life of each EVA suit and reducing EVA risk for crew members.

## Conclusion

The CxP will be more dependent on EVA excursions away from a pressurized habitat or vehicle than any program in the history of NASA. EVAs 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 is dependent on the ability to perform EVA tasks efficiently and safely in these challenging environments.

With lunar missions planned for up to 30 times more EVA hours than during the Apollo era, exploration missions to the moon and Mars will present many new challenges with regard to crew health, safety, and performance. To date, our 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, 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 there has been limited quantification of the physiological and biomechanical variables associated with suited activities in unit and partial gravity. The integrated human testing program that is under way at NASA will help to better characterize the impacts to crew health and performance of the various parameters that are involved in EVA suit design.

Collaborative work is also under way to enable the development of suit technologies that enhance crew comfort and efficiency; provide for optimal nutrition, hydration, and waste management; and reduce suit-induced trauma and fatigue. These efforts will provide objective data to enable informed requirements and the design of Constellation suit systems that will provide sufficient protection and life support for nominal zero-G and surface activities, as well as survival for contingency operations.

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## Appendix A: Gravity Compensation and Performance Scale<sup>24</sup>

The Cooper-Harper scale, which has been in wide use since the late 1960s, permits quantification of pilot perceptions of aircraft handling characteristics. Most of the participants in EPSP studies are astronauts, many of whom are pilots and familiar with the use of this scale; however, the scale itself assumes a certain level of consistency in both pilot skills and specifications of the desired aircraft performance. In the development of next-generation EVA suits for Exploration missions, NASA requires controlled evaluations of varied suit concepts across an ambitious range of activities. These evaluations must be performed by astronauts or test subjects whose skills are limited to microgravity and/or simulated partial-gravity environments – far from equivalent to the skilled pilot population for whom the Cooper-Harper scale was originally designed.

EVA suit development for lunar and martian surface operations will require a wide range of evaluations encompassing tasks as varied as habitat building, traversing rocky terrain, core sampling, shoveling, and, potentially, rescuing an incapacitated crew member. In addition, suit concepts vary widely in mass, weight, CG, and pressure, and each must be evaluated across this range of tasks. NASA does not currently have rigorous performance measures for such tasks, and the EPSP Project personnel have begun the process of characterizing human-suit system performance under a variety of conditions and suit concepts using available analog facilities. Due to the many limitations of using the Cooper-Harper scale under these circumstances, scientists in the EPSP Project adapted the Cooper-Harper scale to reflect handling/controllability characteristics of task performance in reduced-gravity environments when compared relative to one's own shirt-sleeved performance of the same task in 1g. This modified scale, the GCPS, is shown on the following page. Using this scale, a rating of 2 during a suited experimental trial is perceived by the subject to be equivalent to his/her unsuited performance of the same task in 1g, thereby providing a quantitative rating of desired task performance in the suit.

As an example, a subject who is performing a shoveling task while wearing a suit that has a high-and-aft CG may rate the task performance as a 5 because the selected CG setting requires considerable effort/compensation compared to performing the same task unsuited with nominal CG. This new tool is useful for comparing multiple subjects' ratings of operator compensation that is required to perform a variety of simulated surface exploration tasks across a wide range of suit concepts, configurations, and gravity levels.

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<sup>24</sup>Modified from the Cooper-Harper scale.

### GRAVITY COMPENSATION AND PERFORMANCE SCALE (GCPS)

