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Human Health Countermeasures Element

Evidence Report on:

Risk of Comprised EVA Performance and Crew Health due to Inadequate EVA Suit Systems

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I. PRD Risk Title: Risk of Compromised EVA Performance and Crew Health Due to Inadequate EVA Suit Systems

Description:
Improperly designed EVA systems and procedures 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 EVA system design on crew performance and health to ensure properly designed mobility, pressures, nutrition, life support, and other EVA systems.

II. Executive Summary

Constellation missions to the Moon and Mars will include up to 24 hours of EVA per crewmember per week, involving 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 crewmembers.

The Apollo EVA suits performed very well in the short missions for which they were designed. However, the longer missions, more frequent EVAs, and more varied EVA tasks anticipated during the Constellation program will require EVA suits and systems that are more robust than those used during Apollo. Many of the problems encountered with the Apollo EVA suits, such as 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 Physiology, Systems and Performance (EPSP) Project is working with the Constellation Program to develop and execute an integrated human testing program across multiple environments. This program will provide objective data to enable informed design decisions, thereby ensuring a Constellation EVA system that optimizes crewmembers' 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.

III. Introduction

Fewer than 20 lunar Extravehicular Activities (EVAs) were performed during the entire Apollo program. Current architectures under consideration by NASA's Constellation Architecture Team - Lunar could involve as many as 30,000 hours of lunar exploration EVA time. As Figure 1 demonstrates, 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.

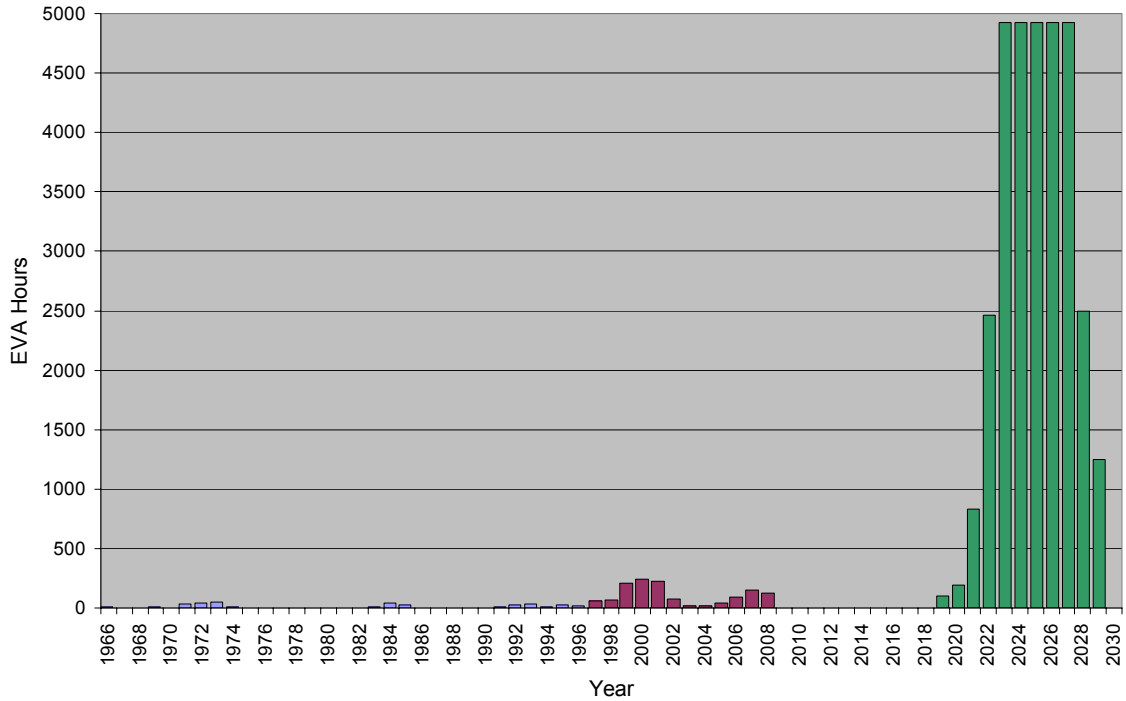

Figure 8-1. EVA Estimates for Current Lunar Architecture

Providing the capability for humans to work productively and safely during EVA involves many important, medically related considerations. Maintaining sufficient total pressure and oxygen partial pressure is vital not only to health, but to survival. Prebreathe protocols must adequately reduce the amount of inert gas in astronauts' blood and tissues to prevent decompression sickness while minimizing the impact on crew efficiency. The suit must be ventilated to remove expired carbon dioxide, 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 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. Nourishment and water must be available for ingestion and accommodations provided for liquid and solid waste collection.

There is considerable evidence that inadequate design of any aspect of the 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., NASA Categories of Evidence III and IV). More recent evidence has been gathered in a rigorous, controlled manner in which subjects serve as their own controls from shirt-sleeve to suited conditions and across repeated measures trials where a single parameter is varied (e.g., NASA Category II evidence). 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: EVA Prebreathe Protocol
- Risk to Work Efficiency: EVA Suit Design Parameters

IV. Evidence

A. Risks to Crew Performance: EVA Suit Design Parameters

Spaceflight Evidence. Throughout the history of spaceflight, astronauts and cosmonauts have performed nearly 300 EVAs. However, only 14 of those EVAs have been conducted on the lunar surface in 1/6 gravity. Accordingly, the current understanding of suited human performance in partial gravity environments is limited. A recent face-to-face summit with the Apollo astronauts provided valuable insight and yielded recommendations for the next generation lunar EVA suit. Fourteen of 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 EMU/EVA Suit Operations, the 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 [1].

The following excerpt 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 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, the mobility recommendation 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*'" [1].

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*" [1]. Additionally, the crew sustained significant fingernail and hand trauma as described in Section C below.

Ground-based Evidence. Physiologists and physicians are using various analog environments to study the effects of suit weight, mass, center of gravity (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 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, subjective ratings of perceived exertion (RPE) [2], and operator compensation using a relative subjective scale modeled after the Cooper-Harper rating scale [3], described in Appendix A.

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

Results from tests conducted on the Pogo have begun to characterize the metabolic cost, biomechanics, and subjective factors associated with ambulation and task performance in the Mark III Advanced Space Suit Technology Demonstrator (MKIII), a prototype EVA suit 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, suit kinematic constraints and stability. Figure 2 shows the current understanding of how these factors contribute to the increased metabolic cost of suited ambulation in the MKIII suit [4].

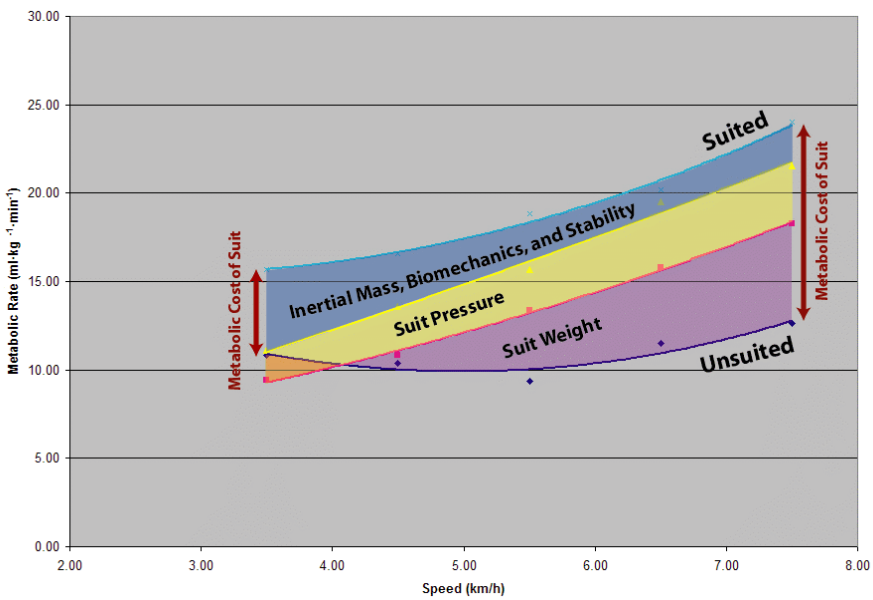

Figure 8-2. Suit design parameters that contribute to the metabolic cost of the suit

The parameter with the largest impact on metabolic rate has been suit weight. Variations in suit pressure made little difference, but varying suit weight led to significant differences in metabolic rate across speeds. Figure 3 shows how varying suit weight affects metabolic rate as a function of level ground ambulation speed [4].

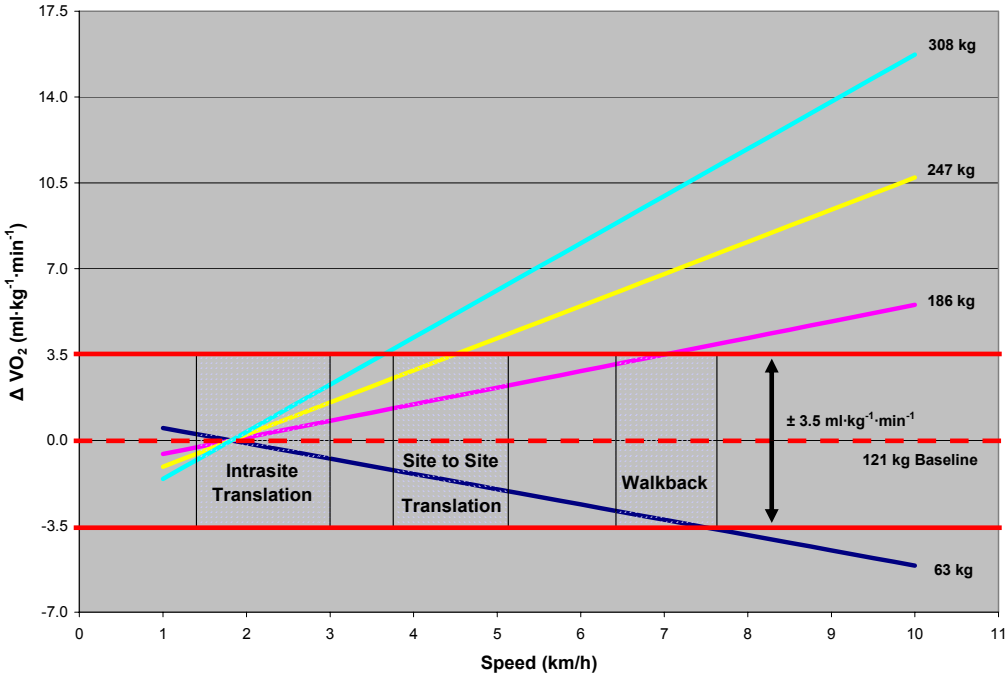

Figure 8-3. Effect of suit weight on metabolic rate across speed of ambulation

This is just one example of how lunar operational concepts will play a large role in determining requirements. If a crewmember is only expected to walk slowly, then suit weight may not be a critical design parameter, but if a 10 km walkback contingency must be prepared for, then suit weight will be absolutely critical.

Based on the Pogo test results, a predictive equation for metabolic rate has been proposed including factors such as subject anthropometrics, locomotion speed, suit pressure and suit weight. As more data is collected, this algorithm will be expanded into an EVA consumables calculator where inputs on the subject, suit, type and duration of tasks can predict a metabolic profile and expected consumables usage. This algorithm is an example of a design tool that can help develop suits that increase efficiency in crew health and performance based on different operational concepts.

Beyond ambulation, the effect of varying suit weight and suit pressure has been examined across a variety of exploration type tasks, such as shoveling and picking up rocks. Figure 4 describes the metabolic rate and modified Cooper-Harper [2] ratings for six subjects averaged over three different tasks (shoveling, picking up and moving rocks and a construction task busy board) as a function of 1g equivalent suit weight. Both the objective and subjective ratings show the same trends, which surprisingly indicated that a heavier suit weight was associated with better performance. The Cooper-Harper scale, as modified for EVA testing and evaluation, quantifies suit operator compensation required for optimal task performance, defined as being equivalent to 1-g shirt-sleeved (unsuited) performance. Ratings of 1-3 indicate acceptable performance, 4-6 indicate that modifications are recommended for optimal performance, 7-9 indicate that modifications are required, and a rating of 10 indicates that the task cannot be performed under

the current conditions. (See Appendix A for further explanation of the modified Cooper-Harper scale.)

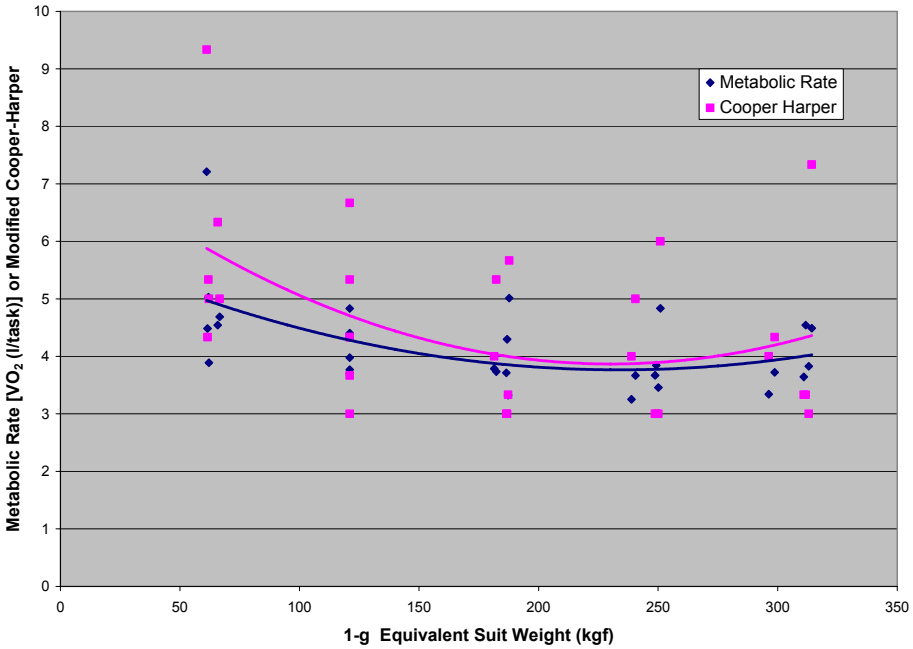

Figure 8-4. Effect of suit weight on metabolic rate and subjective Cooper Harper ratings during exploration tasks

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. One key biomechanical finding relates to ground reaction force (GRF). GRF was higher in suited conditions than unsuited conditions and also increased as suit weight increased. However, GRF's were still lower than what a crewmember 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 [4,5]

Realizing that not all ambulation on the moon will be on a level treadmill, studies have begun 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 [6].

Beyond the above stated parameters, the Apollo Program demonstrated that suit center of gravity (CG) was an important variable affecting 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 6 different CG locations. A reconfigurable back pack with 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 modified Cooper-Harper rating scale to evaluate the CG locations. As shown in Figure 5, subjects preferred the perfect, low, and forward CG over high, aft, or NASA baseline (both high and aft, similar to the Apollo suit CG), which suggests that a conventional back pack PLSS may not be optimal and that alternative configurations should be considered [7].

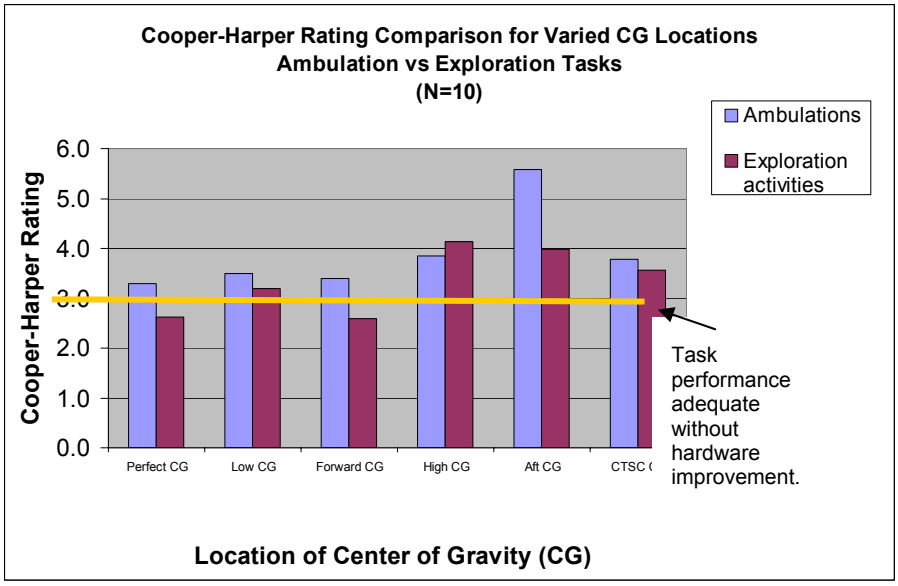

Figure 8-5. Cooper-Harper ratings for suit center of gravity

B. Risks to Crew Performance, Health, and Safety: EVA Biomedical Monitoring and Consumables Management

Overview. The physiologic cost of performing work in a pressure garment is significantly greater than if the same work was performed 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 over-heating or exhaustion, and EVA planners must be able to make real-time adjustments to crew activity in order to conserve consumables required for life support [8,9].

Spaceflight Evidence. Energy expenditure (metabolic rate) was not measured during the Gemini EVAs. However it was clear in several cases that the astronauts worked at levels above the heat removal capability of the gas cooled life support system [8,10]. During Ed White's first US EVA, he found that opening and closing the hatch was much more difficult than planned and he perspired enough to fog the helmet visor. Although the duration of the EVA was short, it took several hours for him to return to thermal equilibrium.

Thermal homeostasis of the crewmember is crucial for safe and effective EVA performance. Heat storage above 480 Btu leads to performance decrements, such as loss of tracking skills and

increased errors in judgment, and tissue damage begins at 800 Btu heat storage [11]. The observations from Gemini led to the development of a liquid cooling system to accommodate high heat production in the suit from high EVA workloads. The liquid cooling garment (LCG) consists of a system of plastic cooling tubes that run along the inside of an undergarment worn inside the suit. The temperature of the coolant (water) running through the tubes regulates the amount of heat removed from the skin's surface. The Apollo LCG had three temperature settings: minimum (21°C), intermediate (15°C) and maximum (7°C) [6]. Figure 6 shows the relationship between heat storage and metabolic rate as a function of LCG inlet temperature [11].

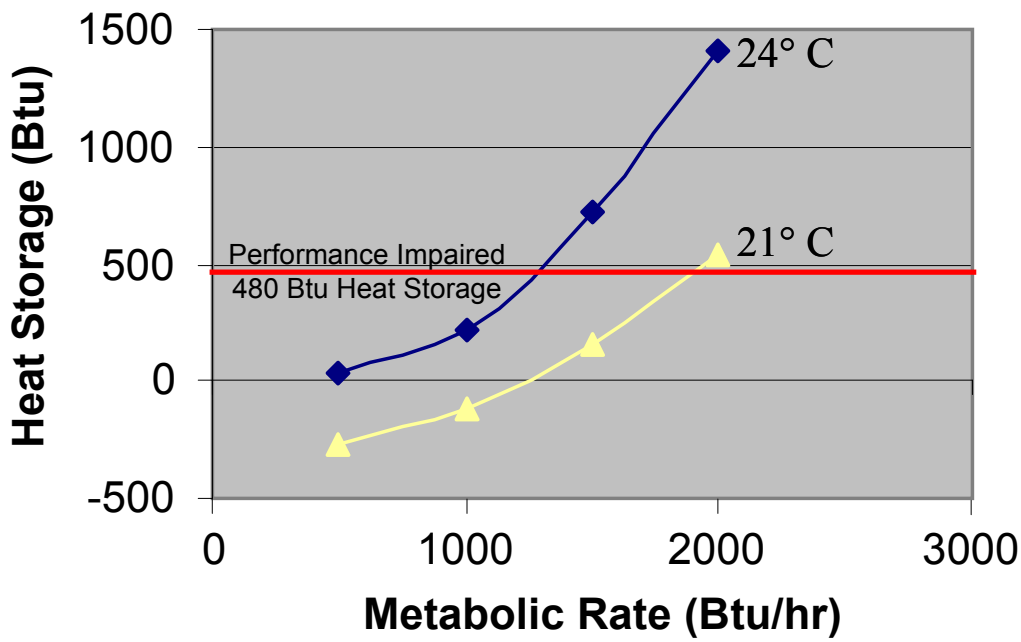

Figure 8-7. Heat storage based on metabolic rate and LCG inlet water temperature

Astronaut energy expenditure during Apollo lunar surface EVA ranged from 780 to 1200 Btu/hr, as determined by three independent methods [9]. The lowest metabolic rates occurred while the astronauts drove and rode in the lunar roving vehicle, while the highest metabolic rates were observed during egress/ingress through the tight-fitting hatch of the lunar module, offloading and set-up of equipment, drilling, and stowage of lunar samples. It is estimated that 60 to 80 percent of the heat 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 experienced during Apollo 15 and 17 [8].

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 where the PLSS consumables were nearly depleted. During Apollo 14, 15 and 17 there were 6 cases where the usable oxygen remaining at the end of the EVA was less than 10%. During Apollo 14, 16 and 17, there were 5 cases in which the power remaining was less than 12% (one of these was <4%), and four cases where the usable feed water was less than 11%. Two crewmembers, on Apollo 15

and 16, completed their EVAs with only 4% and 2%, respectively, of their CO2 removal capability (LiOH) remaining.[12].

Each of the Apollo missions was limited to two or three EVAs, however future missions are expected to consist of three EVAs per week for up to six 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 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-ounce drink bag, however this amount is considered insufficient for crews performing surface EVA. In the Apollo Medical Operations Project report, there were several citations regarding the need for more water. "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." [1]

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*." [1] Similar issues have been reported with the current EVA suit used for microgravity EVA in the Shuttle and ISS Programs. Furthermore, the time needed to prepare the nutrition and hydration systems prior to conducting an EVA needs to be decreased. Filling and degassing the drink bag used in the current US suit is time-consuming and contributes to the poor work efficiency index (WEI) of Shuttle and ISS EVAs.

Additionally, development of an improved in-suit urine collection device was recommended by the Apollo astronauts. In some cases during lunar surface EVA, urine was not fully contained and resulted in skin irritation [1]. Improved in-suit waste management systems will become critical in the event that the crew is required to be suited for up to 152 hours during a contingency return to Earth if the vehicle is 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 (BME) in Mission Control monitor astronaut physical parameters during EVA to assess workload and performance. Real-time medical monitoring can provide emergency medical assistance in response to off-nominal situations. However, bioinstrumentation systems used in the Apollo and Shuttle Programs have been problematic. In the Apollo Medical Operations Project report, there are approximately 75 citations from the flight surgeon logs, BME logs, and medical mission debriefs relating to issues with bioinstrumentation. These ranged from complaints of skin irritation due to the electrode paste to signal drop-outs to sensor failure [1]. Both Apollo and Shuttle/ISS EVA crew members have expressed frustration with the cumbersome and time-consuming process of donning/doffing the biomedical sensor systems. Improvements to the biosensor systems for future missions are warranted.

Ground-based Evidence. At the request of the Constellation EVA Systems Project Office (formerly the Advanced EVA Office), a study was conducted to determine if it is possible for a suited crewmember to walk back to a terrestrial habitat in the event of a failed rover. As a starting point based on the Apollo Program and anticipated lunar surface operational concepts, it

was assumed that 10 km would be the maximum EVA excursion distance from the lander or habitat. Results from the EVA Walkback Test (EWT) provided key insight into how human performance may be impaired by inadequate consumables and or inadequate cooling.

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 crewmembers could only complete half of the distance or that the total duration would exceed 3 hours. However, all 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, with a range of 45% to 61%. Results are summarized in Table 1. Ratings of perceived exertion (RPE) (11.8 ± 1.57 (SD)) equated to a feeling between “light” (11) and “somewhat hard” (13) on the 6-20 point Borg RPE scale, which is used to gauge how much effort a person feels they must exert to perform a task. Similarly, subjects averaged 3.5 ± 1.44 (SD) on the 10-point modified Cooper-Harper scale, indicating “fair” to “moderate” operator compensation required to perform the task [5].

Table 8-1 - Summary data for the lunar 10 km Walkback portion of the test

10k Walkback Summary Data (averaged across entire 10 km unless noted)		
	MEAN	SD
Avg Walkback Velocity (mph)	3.9	0.5
Time to Complete 10k (min)	95.8	13.0
Avg %VO_2pk	50.8%	6.1%
Avg Absolute VO_2 (l/min)	2.0	0.3
Avg Met rate (BTU/hr)	2374.0	303.9
Max. 15-min-avg Met rate (BTU/hr)	*2617.2*	*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
O_2 Used (lb)	.635 lbs.	N/A
Planning / PLSS Sizing Data	**Walkback**	**Apollo**
O_2 Usage	0.4 lbs/hr	0.15lbs/hr
BTU average	2374 BTU/hr	932.8 BTU/hr
Cooling Water	3.1 lbs/hr	0.98lbs/hr
Energy Expenditure	599 kcal/hr	233 kcal/hr

*assumes thermally neutral case and sublimator cooling

Subjects' heat production rates ranged from 1918 to 2667 BTU/hour, averaging 2374 BTU/hour, a rate that would exceed the heat removal rates of the Apollo or Shuttle EVA suits. Core temperature measurements indicated an average rise of 1 °C from normal (37 °C) across the entire test, although one subject's core temperature (39.8 °C) peaked near a level of concern. Subjects unanimously reported cooling to be inadequate at the higher workloads [5].

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, expressed as oxygen consumption per kilogram per kilometer, and can be thought of as the 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 [5].

Unfortunately, at speeds above 3 mph (Figure 7) the heat production, shown on the right axis and the purple tracing, begins to exceed the 2000 BTU/hr cooling limit of both Apollo and Shuttle EVA suits, resulting in increased core body heat storage. Without improvements in cooling for future suits, crewmembers on lunar EVA would not be able to exploit the increased efficiency (shown on red tracing as decreasing transport cost) available at faster ambulation speeds. This would result in increased consumable requirements to cover the same distance [5].

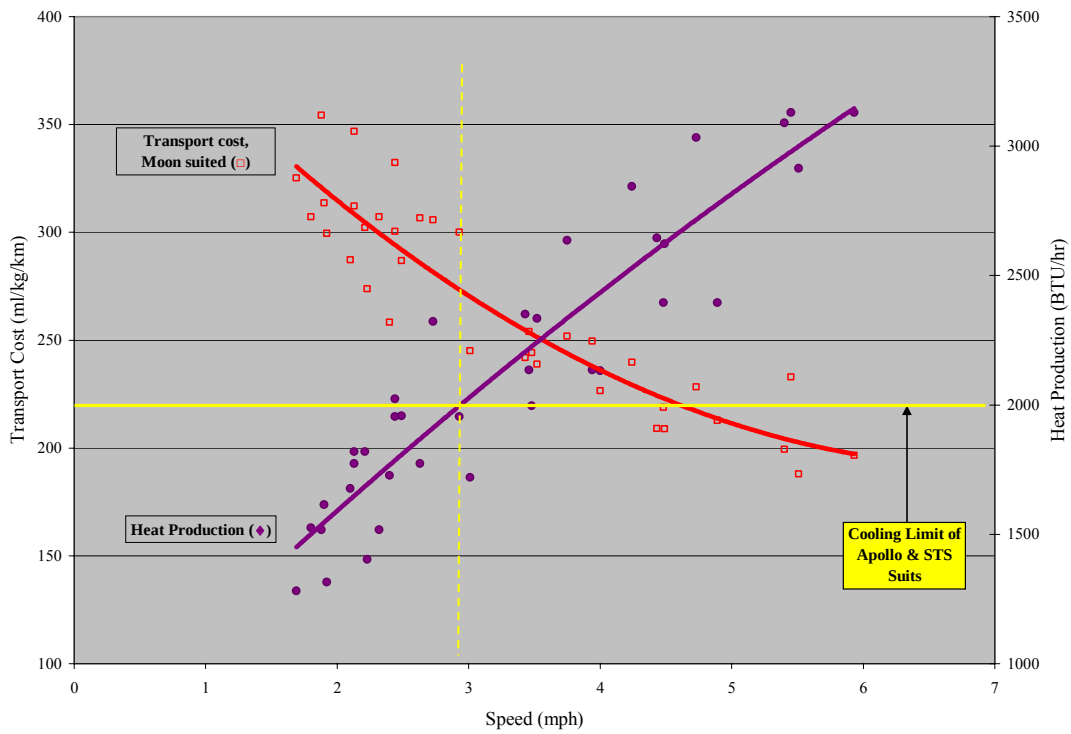

Figure 8-7. Relationship between transport cost and heat production for lunar suited ambulation

Consumables are an important consideration for EVA excursions, and the 10 km Walkback provided some insight into hydration and nutritional requirements for a task of similar duration or intensity. All subjects were provided 32 oz of water in an in-suit drink bag. Crewmembers consumed 50% to 100% of the water provided, and one crewmember would have preferred to have another 20% available. In addition, the 10 km walkback required an average of 944 kcal. All crewmembers felt that a nutritional item, either food such as a bar or energy gel, or flavored electrolyte drink might improve performance and/or endurance [5].

Because the EVA Walkback Test 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 walkback. Results of the Pogo test have indicated that inclined

ambulation does increase metabolic rate, but at a rate much less than what is experienced in the 1-g environment. To classify the effect of lunar terrain and navigation of human performance, subjects completed a series of 10 km traverses at the Haughton Mars Project (HMP) site. The Haughton-Mars Project (HMP) is an international interdisciplinary field research project centered on the 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 10 km from the finish point and were instructed to return at a rapid but sustainable pace using a GPS receiver for navigation and tracking speed and grade. Three separate starting points, each 10 km from the finish point, were defined and subjects completed each route once. Straight line distance between starting and ending points was 9.91 ± 0.22 km (mean ± SD) and actual distance traveled was 10.61 ± 0.61 km. Completion time averaged 126.5 ± 28.7 min, which was longer that the EWT average of 95.8 ± 13.0 min [13].

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 if this increase would be as high in lunar gravity [13].

C. Risks to Crew Health: EVA Suit Design Parameters

Spaceflight Evidence. A comprehensive analysis of all musculoskeletal injuries and minor trauma sustained in flight throughout the US space program was recently completed [14]. This study identified 219 in-flight injuries, 50 of which occurred due to the EVA suit. Use of the EVA suit and performance of EVA were the second and third leading causes of in-flight injuries. The incidence rate of EVA injuries was 0.05 per hour for 1087.8 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 [15]. 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 stated 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 2-3 weeks post-landing [14].

Nine of the injuries were sustained by Apollo astronauts performing lunar surface EVAs. One Apollo astronaut suffered a wrist laceration from the suit wrist ring while working with drilling equipment, while another sustained wrist soreness due to the suit sleeve rubbing repeatedly. One crew member injured his shoulder during lunar EVA as a result of the tight mission timeline to complete multiple surface activities, and unbeknownst to his flight surgeon, 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 commented that his hands were "very sore after each EVA". Another stated that following 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; he is certain further EVA would have been very difficult if not impossible [1,14]. Accordingly, it is no surprise that the Apollo astronauts were adamant that the glove flexibility, dexterity and fit be improved [1].

Ground-based Evidence. In order to adequately prepare for mission EVAs, astronauts undergo extensive ground-based training at the Neutral Buoyancy Laboratory (NBL). The NBL provides controlled neutral buoyancy operations to simulate the zero-g or weightless condition. Articles are configured to be neutrally buoyant with a combination of weights and flotation devices so they seem to "hover" under water, enabling large, neutrally buoyant items to be easily manipulated much like in orbit. The significant increase in EVA NBL training to support construction and maintenance of the International Space Station led to an apparent increase in the incidence of symptoms and injuries experienced by crew members operating in the EVA suit.

A study conducted from July 2002 to January 2004 identified the frequency and incidence rates of symptoms by general body location and characterized mechanisms of injury and effective countermeasures [16]. During this study, 770 suited test sessions using 86 astronaut-subjects were evaluated in the NBL. Symptoms were reported in 352, or 45.7%, of the sessions. Of these symptoms, 47% involved hands, 21% shoulders, 11% feet, 6% each arms, legs and neck, and 3% involved the trunk. Hand symptoms were primarily fingernail de-lamination thought to be secondary to excess moisture in EVA gloves and axial loading of the fingertips (Figure 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 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." [16]

Figure 8-8. Fingernail and shoulder trauma sustained during EVA training [19]

The shoulder injury tiger team was created in December 2002 to evaluate the possible relationship between shoulder injuries and EVA training at the NBL [17]. 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, and resolved 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 EVA suit's "Planar" Hard Upper Torso (HUT), performing 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 [17,18]. 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 hard upper torso of the suit. This further limits scapulothoracic motion of the shoulder [15]. Key elements in the risk mitigation of shoulder injuries 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 [17].

During the 10 km EVA Walkback Test, 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 scale. The knee area and feet/toes were the most frequent sites of discomfort during and after the test (Figure 9). Fatigue and/or muscular tightness were reported most commonly in the quadriceps, thighs, gluteal muscles and lower back [5].

Figure 8-9. Knee and foot trauma sustained during 10 km walkback test

D. Risks to Crew Health: EVA Prebreathe Protocol

Overview. Decompression sickness (DCS) represents a risk to the successful performance of EVAs and 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 where 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 O_2 prebreathe to reduce the amount of inert gas (usually N_2) in the blood and tissues before a crewmember is subjected to decompression in the spacesuit. Many factors influence the required duration of the prebreathe protocol. During Apollo, the environment inside the Lunar Module was 34.5 kPa (5.0 psia) and 100% O_2. The absence of inert gas in the environment meant that prebreathe 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% O_2; 70.3 kPa (10.2 psia) and 26.5% O_2; and/or 55.2 kPa (8.0 psia) and 32% O_2 with balance N_2. In any of these environments, the partial pressure of N_2 will require some amount of O_2 prebreathe prior to performing an EVA at 29.6 kPa (4.3 psia) to reduce the amount of inert gas dissolved in the crewmembers' blood and tissues.

The risk of DCS during EVAs performed during Constellation Program missions will be quantified and mitigated using the same combination of mathematical decompression stress modeling, statistical analysis of relevant ground-based and spaceflight data, expert judgment, and rigorous validation of prebreathe protocols using prospective ground-based hypobaric EVA simulation studies. Through this process prebreathe protocols will be developed that reduce 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. NASA's DCS Risk Definition and Contingency Plan (1998) criteria specify acceptable limits as a total incidence of DCS ≤ 15% at a 95% confidence limit, with < 20% grade IV venous gas emboli (VGE) and 95%

confidence level, and no Type II (serious) instances of DCS. The 1/6 G 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.

Prebreathe protocols are typically developed by experts using models of decompression stress and by considering relevant data from past experiences in ground-based studies and spaceflight. Before being implemented in spaceflight, prebreathe 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 upon acceptable limits. Analysis of the ground-based data using Bayesian statistical methods ensures that a prebreathe protocol is approved for use in spaceflight 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.

Spaceflight Evidence. Two different spacesuits are currently used to perform EVAs from ISS: the Russian Orlan and the US Extravehicular Mobility Unit (EMU). Differences in operating pressures between the US 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 US spacesuit system operates at 29.6kPa (4.3 psia) of oxygen, with traces of carbon dioxide and water vapor.

The Russian EVA preparation protocol includes a 30-minute oxygen prebreathe in the spacesuit at a pressure of 73 kPa (10.6 psia) to partially washout N_2 from crewmembers' blood and tissues [20]. Literature from the Russian program shows that of approximately 114 EVAs in the Russian suit, including 18 EVAs from the ISS, crewmembers have shown no signs of DCS [21,22,23].

Three different prebreathe protocols may be used before EVA in the EMU: exercise prebreathe, four hour in-suit prebreathe, and camp-out prebreathe. The protocols vary in effectiveness and, hence, in risk of DCS. Selection of a particular method depends on the particulars of the EVA, including DCS risk, the timeline, and the operational risk. However, no symptoms of DCS have been reported by astronauts performing EVAs in the EMU spacesuits following any of the three prebreathe protocols [24,25].

Ground-based Evidence. Based on ground-based studies of the US prebreathe protocols, exercise prebreathe 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 ≤ 15% at a 95% confidence limit, with < 20% grade IV venous gas emboli and 95% confidence level, and no Type II (serious) instances of DCS.

The four hour in-suit prebreathe protocol resulted from many years of experience with four hour in-suit prebreathe testing. This was mostly gained from ground testing of suited subjects and crewmembers in preparation for altitude chamber runs. Over 300 such exposures have been completed with <1.5% instances of DCS observed, with no Type II. This method has not been subjected to the same level of controlled laboratory evaluation as the exercise prebreathe method.

When simulating US prebreathe protocols in ground-based studies using volunteers in regular clothing, the rate at which DCS symptoms developed was 17% to 26%. Given this data, and the lack of any observed DCS symptoms during spaceflight 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 the cosmonaut from making abrupt movements during 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 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 pathogenic gas bubble formation intensity and the rate at which they develop in the body as a causative agent of DCS [26,27,28].

Computer-based Simulation Information. A physics-based Tissue Bubble Dynamics Model (TBDM – Eqn. 1) will be used in the development of prebreathe protocols. The TBDM provides a time-varying index of theoretical physiological decompression stress based on variations in pressure and gas composition [29].

Equation 1

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

r = Bubble Radius (cm)
t = Time (sec)
a = Gas Solubility ((mL gas)/(mL tissue))
D = Diffusion Coefficient (cm^2/sec)
h(r,t) = Bubble Film Thickness (cm)
P_a = Initial Ambient Pressure (dyne/cm^2)
v = Ascent/Descent Rate (dyne/$cm^2 \cdot cm^3$)
γ = Surface Tension (dyne/cm)
M = Tissue Modulus of Deformability (dyne/$cm^2 \cdot cm^3$)
P_{Total} = Total Inert Gas Tissue Tension (dyne/cm^2)
$P_{metabolic}$ = Total Metabolic Gas Tissue Tension

The TBDM's index of decompression stress (Bubble Growth Index) can be quantitatively related to % DCS risk using a logistic regression model. Previous analysis has shown the TBDM to provide good prediction of DCS risk [29]. 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 included prebreathe 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-prebreathe data. BGI provided significant prediction of DCS and VGE data ($p < 0.01$). Hosmer-Lemeshow Goodness-of-Fit statistic: p=.35 for DCS, p=.55 for VGE, indicating a good fit of the data [30] (Note: For Hosmer-Lemeshow statistic, $p > .05$ rejects the hypothesis that there is a significant difference between the model predictions and the observed data). A 360 min half-time compartment was assumed.

Conclusion. The combination of spaceflight and ground-based experience points to the high degree of safety in both approaches to mitigating the risk of DCS. The US approach to DCS risk management enables greater crew mobility than 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 prebreathe protocols will need to be streamlined to optimize both crew mobility and work efficiency.

E. Risk to Work Efficiency: EVA Suit Design Parameters

Total work efficiency index (WEI) is defined as:

$$\frac{\textit{EVA Time}}{\textit{(Total suit and airlock prep + prebreathe + airlock depress, repress + post EVA)}}.$$

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 studies will perform evaluations of WEI based on current knowledge and concepts of operations, and will provide data to make recommendations to improve WEI. Studies will include: 1) evaluation of suit components that may improve WEI, such as integrated biosensor systems that are quick don/doff and drink bags that require less preparation time; 2) development of improved prebreathe protocols; 3) studies in lunar analogs that will evaluate the efficiency of different operations concepts and will measure the trends in WEI over time; 4) evaluation of suit prototypes and development of operational concepts to meet WEI requirements.

V. Computer-based Simulation Information

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

VI. Risk in Context of Exploration Mission Operational Scenarios

EVA is a critical factor for the success in the construction, maintenance, scientific, and exploration aspects of every lunar architecture being considered by the Constellation Lunar Architecture Team (CxAT-Lunar). Current plans 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 Section IV, the risks 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, Solar Particle Event (SPE) protection, and on-site treatment or medication of 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/exploration return would be reduced. The possibility of performing single-person EVAs with a second crewmember inside 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 crewmembers.

VII. Conclusion

The Constellation Program will be more dependent on EVA excursions away from a pressurized habitat or vehicle than any program in NASA's history. EVA will be required to conduct planned scientific expeditions, assemble structures, perform nominal maintenance, and to intervene and solve problems outside of the vehicle that cannot be solved 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 performing EVA activities on the lunar surface. Since that time, and using lessons learned from microgravity EVAs aboard the Space Shuttle and Space Station, new prototype suits have been in development for future space exploration activities. However, to date there has been limited quantification of physiological and biomechanical variables associated with suited activities in unit and partial gravity. The integrated human testing program that is underway will help to better characterize the impacts to crew health and performance of the various parameters involved in EVA suit design.

Collaborative work is also underway to enable the development of suit technologies that enhance crew comfort and efficiency, provide for optimal nutrition, hydration, and waste management, while also reducing suit-induced trauma and fatigue. These efforts will provide objective data to enable informed requirements and design of Constellation suit systems that provide sufficient protection and life support for nominal 0-G and surface activities, as well as survival for contingency operations.

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X. Acronyms

BME	Biomedical Engineer
CG	Center of Gravity
DCS	Decompression Sickness
D-RATS	Desert Research and Technology Studies
EMU	Extravehicular Mobility Unit
EPSP	EVA Physiology, Systems & Performance
EVA	Extravehicular Activity
EWT	EVA Walkback Test
GPS	Global Positioning Satellite
GRF	Ground Reaction Force
HHC	Human Health Countermeasures
HMP	Haughton Mars Project

HRP	Human Research Program
HUT	Hard Upper Torso
ISS	International Space Station
LCG	Liquid Cooling Garment
MCP	Metacarpophalangeal
NBL	Neutral Buoyancy Laboratory
NEEMO	NASA Extreme Environment Mission Operations
PLSS	Portable Life Support System
RPE	Rating of Perceived Exertion
SD	Standard Deviation
US	United States
WEI	Work Efficiency Index

APPENDIX A: MODIFIED COOPER-HARPER RATING SCALE

The Cooper-Harper scale has been in wide use since the late 1960s to permit quantification of pilot perceptions of aircraft handling characteristics. Most of EPSP's subjects are astronauts, many of them pilots who are familiar with 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. However 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 across rocky terrain, core sampling, shoveling, and potentially rescuing an incapacitated crewmember. 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 has 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, 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. A rating of '2' on the modified scale (below) during a suited experimental trial is perceived by the subject to be equivalent to his/her unsuited performance of the specific 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 in a suit with 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. With the modifications shown below, this tool is useful for comparing multiple subjects' ratings of operator compensation required to perform a variety of simulated surface exploration tasks across a wide range of suit concepts, configurations, and gravity levels.

MODIFIED COOPER-HARPER RATING SCALE