5.4 Extravehicular Activities

Author
Michael L. Gernhardt
Joseph P. Dervay
James M. Waligora
Daniel T. Fitzpatrick
Johnny Conkin

Introduction

The space shuttle was designed to provide crew and cargo transit from Earth to low-Earth orbit and back for conducting a wide variety of scientific experiments; deploying and capturing of satellites and scientific spacecraft; and providing a means by which to transfer crew and equipment to and from future space stations. Space shuttle extravehicular activities (EVAs) were initially anticipated to be used only for contingencies and, thus, were focused on addressing a variety of malfunctions associated with the deployment of radiators and antennas and the closing and latching of the payload bay doors.

Evolution of the Extravehicular Activity Suits

The shuttle spacesuit system, formally called the extravehicular mobility unit (EMU), was derived from the advanced Apollo suit configuration. In the Apollo Program, most EVAs took place on the lunar surface, where suit durability, integrated liquid cooling garments, and low suit operating pressures (25.8 kilopascals [kPa] or 3.75 pounds per square inch absolute [psia]) were required to facilitate relatively lengthy EVAs that included ambulation and significant physical workloads. Metabolic rates during those EVAs averaged 1000 BTU/hour, with peaks of up to 2200 BTU/hour.[8] The Apollo spacesuit, which had more than 15 components, included a biomedical belt for capturing and transmitting biomedical data, urine and fecal containment systems, a liquid cooling garment, a communications cap, a modular portable life support system, a boot system, thermal overgloves, and a bubble helmet with eye protection. The Apollo astronauts left a 34.4-kPa (5-psia) 100% oxygen environment in the lunar lander to perform as many as 3 EVAs per mission on the lunar surface. The shuttle EMU incorporated many of the same components as the Apollo suit system, but, like the shuttle vehicle, the suit was designed to be reusable.

The shuttle EMU incorporated a hard upper torso design with a range of arm and leg sizing elements that allowed the suits to be resized for a variety of crew members of different body sizes; the Apollo suits, by comparison, were custom fitted. The hard upper torso design also eliminated the need for external life support hoses, which could reduce mobility, present snag hazards, and reduce overall reliability. The shuttle EMU also was designed to incorporate modular gloves and boots, and the boots were designed to be compatible with foot restraints to support working in microgravity.

The Apollo suits were designed to operate at the lowest reasonable pressure to minimize differences in pressure across the suit and to permit optimal crew member mobility and dexterity for performing EVA tasks. They also provided protection against decompression sickness (DCS) and hypoxia under nominal and off-nominal conditions by using lower-pressure secondary oxygen system regulators. The current U.S. spacesuit system, the shuttle/International Space Station (ISS) EMU, has a nominal operating pressure of 30 kPa (4.3 psia). The atmosphere in both the shuttle and the ISS resembles that on Earth, at a pressure of 100 kPa (14.5 psia) and a composition of 79% nitrogen and 21% oxygen. This atmosphere represents a major departure from the low-pressure, high-oxygen-concentration environments aboard previous spacecraft. This combination of cabin atmosphere and suit pressures required the development of special protocols to protect against DCS, which can result when a crew member shifts rapidly from the relatively high-pressure cabin to a low-pressure suit without sufficient time for denitrogenation (the elimination of nitrogen in lungs and tissues via breathing pure oxygen). DCS can result from gas phase separation and bubble growth in various tissues. Depending on the location and degree of gas phase separation, DCS symptoms can range from minor joint discomfort to serious cardiopulmonary or central neurological symptoms that can result in physical disability or loss of life.

In addition to the risk of DCS, several other environmental and physiological stresses must be addressed or controlled for crew members to safely undertake EVAs. These include, but are not limited to: thermal extremes that range from -120°C to +120°C, depending on whether the crew member is working during the day or at night; the need to provide sources of energy (as much as 200 kcal/hour) to keep up with the metabolic energy expenditure on spacewalks, which can last 8 hours or longer; the need to provide hydration (as much

as 1 liter/hour) and appropriate waste management systems; and the need to provide protection from the radiation, micrometeoroid, and orbital debris environments. The operating pressure of the suits, as noted above, is 29.6 kPa (4.3 psi), or approximately the same inflation pressure as a basketball; this also produces biomechanical constraints in mobility and dexterity that can result in significant suit-induced trauma to the shoulders, wrists, and fingernails as well as trauma from point contact loads as the crew member moves within the stiff, pressurized suit.

Preventing the Development of Decompression Sickness

Protecting against DCS has critical operational implications because of the time needed for oxygen breathing to facilitate nitrogen elimination before an EVA can be safely performed, and because of the medical and operational consequences of a DCS episode should one occur.

The shuttle decompression protocols were developed based on findings from several hundred decompression trials that had been performed over a 10-year period. Two protocols were accepted for shuttle flight operations based on an "R" value of 1.65. (The R value is the ratio between the nitrogen tension in a 360-minute half-time tissue compartment and the spacesuit pressure.) These protocols consisted of either a 4-hour oxygen "prebreathe" performed while wearing a suit pressurized to 101.2 kPa (14.7 psia), or a staged decompression protocol. In the staged decompression protocol, the crew members "prebreathe" oxygen for 1 hour before the cabin is depressurized to 70.2 kPa (10.2 psia) with 26.5% oxygen. The entire crew remains at 70.2 kPa (10.2 psia) for a minimum of 12 hours, and then the EVA crew members complete another 75 minutes of oxygen prebreathe in the suit before performing the EVA. The final in-suit prebreathe times are a function of the time spent at 70.2 kPa (10.2 psia) and can be as short as 40 minutes, if 36 hours or more have been spent at the reduced 70.2-kPa (10.2-psia) cabin pressure. Shirtsleeve, ground-based altitude chamber testing of these protocols resulted in a DCS incidence rate of 23.7%,[414,15] with most of the symptoms being minor joint pain. DCS has never been reported during more than 140 space EVAs in which these protocols were used, and the DCS rate has been less than 1.5% during more than 300 ground-based vacuum chamber tests, which were conducted while the subjects wore EMU garments.

Work Rates and Risk of Decompression Sickness

Physical activity during EVA is a significant contributor to the risk of DCS.[4] A pilot study was conducted in 1990 to address the implications of high work rates during EVA. The EMU environmental control system was designed to handle metabolic rates as high as 1600 BTU/hour, but the previous DCS trials had been conducted at work rates of approximately 800 BTU/hour that accurately simulated *average* EVA work rates. The pilot study had a crossover design between normal simulated EVA activity and an activity profile that included 1 hour of 1600 BTU/hour. Work performed during the second hour consisted of nominal activities. The high-intensity exercise protocol was a zero-prebreathe protocol with a final suit pressure of 44.8 kPa (6.5 psi); it resulted in the same R value as the space shuttle protocols without engendering the need for the time-intensive oxygen prebreathe. The hypothesis was that high-intensity exercise would increase symptoms and bubbles; however, the only remarkable finding of that crossover study was that the last 2 high-intensity exercise runs done on consecutive days resulted in Type II symptoms, causing the tests to be terminated. Subsequent analyses suggest that a zero-prebreathe protocol starting at a pressure of 1 atmosphere (atm) may make subjects particularly susceptible to Type II DCS because the nitrogen elimination half-time of the brain and spinal cord is 5 to 7 minutes; hence, an oxygen prebreathe would quickly desaturate the neurological tissues and eliminate the autochthonous bubble formation that produces central nervous system symptoms of DCS. The zero-prebreathe protocols, in contrast, would begin with supersaturation in the brain and spinal cord, even with R values equivalent to those of protocols that incorporated some degree of oxygen prebreathe.

Crews and flight planners preferred to use the 70.2 kPa (10.2 psia) staged decompression protocol for operational timeline reasons; consequently, all but 4 EVAs from the space shuttle used this protocol. Also, for operational reasons, the time spent at 70.2 kPa (10.2 psia) was typically far in excess of the tested 12-hour exposure. Figure 5.4-1 shows the distribution of the duration at 70.2 kPa (10.2 psia) during the space shuttle missions that involved EVAs; it is apparent from this figure that the average time spent at this pressure was over 40 hours.

Equilibration of tissue nitrogen tensions at a given ambient pressure is generally considered to require 36 hours; therefore, longer in-flight times spent at 70.2 kPa (10.2 psia) would be expected to mitigate the decompression stress. Figure 5.4-2 illustrates predicted bubble growth for 12- to 36-hour exposures at 70.2 kPa (10.2 psia);[7] these theoretical calculations suggest that decompression stresses are very low after spending 24 hours at 70.2 kPa (10.2 psia).

In addition to the increased exposure time at 70.2 kPa (10.2 psia), the suit itself provides some protection against decompression because suited crew members have additional operational oxygen prebreathe time and higher metabolic rates during prebreathe than do the resting test subjects in the laboratory trials. During space flight, a series of configuration and leak checks is performed after the crew member dons the suit, followed by an 8- to 12-minute purge cycle before the pre-

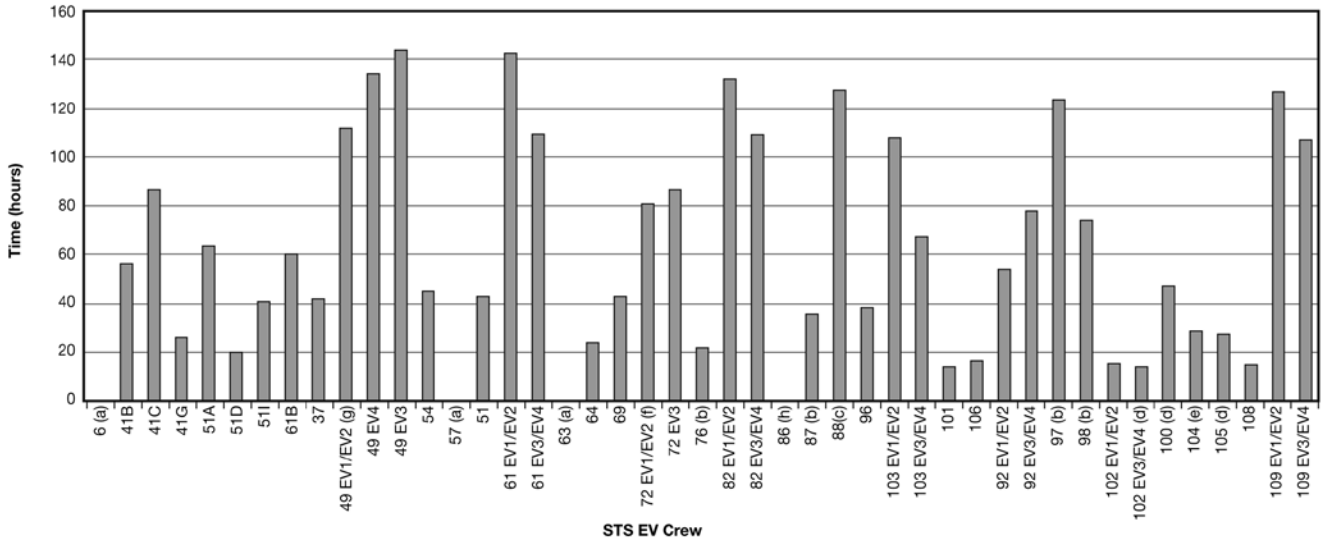

Figure 5.4-1 ***The duration of exposure at 70.2 kPa (10.2 psia) of individual crew members before performing EVA in a 29.6-kPa (4.3-psia) suit. Note: The EVA crew is notated by the STS flight number or International Space Station increment number, followed by the crew member's designation (eg, EV no.) for those instances in which more than 1 crew member is possible on that particular flight or mission. (EVA = extravehicular activity; EV = extravehicular; STS = Space Transportation System). (Reprinted from Katuntsev VP, Osipov YuYu, Gernhardt ML.*** **Space Biology and Medicine,** ***Vol V, p. 205, © 2004. With permission of the American Institute of Aeronautics and Astronautics.)***

breathe clock is started. Then, during depressurization to vacuum, the suit pressure is set by positive pressure relief valves that keep the suit at 34.4 kPa (5 psia) over the ambient pressure; this results in more oxygen prebreathe time before the tissues become supersaturated. The combined effect of these operations is that the suited crew member spends an additional 20 to 30 minutes of prebreathing at elevated oxygen concentration levels. The metabolic rates of crew members "resting in the suit" have also been measured at 6.8 $mL \cdot kg^{-1} \cdot min^{-1}$; by comparison, the typical resting metabolic rate is approximately 3.8 mL/kg-min. Recent research has shown that even small increases in metabolic rate can decrease the incidence of DCS, presumably through increased nitrogen washout.[2,5,9] The combination of all suit-related operational effects reduces decompression stress on crew members relative to shirtsleeve laboratory subjects and offers an explanation as to why the incidence of DCS in suited, ground-based vacuum chamber tests and space flight EVAs is much lower than the initial laboratory trials used to develop these decompression protocols.

International Space Station Assembly and the Prebreathe Reduction Program

As space shuttle crews began EVAs in support of assembling the ISS, a series of new challenges arose. The standard shuttle-based 70.2-kPa (10.2-psia) staged decompression procedure became limiting because it required that the hatch between the space shuttle and the ISS remain closed, as the large volume and limited logistics support of the ISS precluded its cabin pressure from being reduced to 70.2 kPa (10.2 psia). This was a major constraint because the crew members with the most current Space Station Remote Manipulator System (SSRMS) training to support the EVA construction were space shuttle crew members who would need to remain in the space shuttle if the hatches were closed. Further, because the hatches between the 2 vehicles were closed, time-intensive logistics transfers between the shuttle and the ISS could not be done while EVAs were being performed. The required 4-hour in-suit prebreathe times were not compatible with the EVA timelines and the crew scheduling constraints necessary

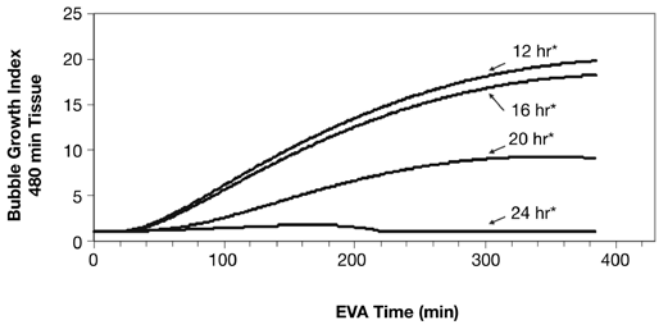

Figure 5.4-2 ***Theoretical bubble growth during a 6-hour EVA after spending 12, 16, 20, or 24 hours at an atmosphere of 70.2 kPa (10.2 psia) with 26.5% oxygen. (EVA = extravehicular activity). (Reprinted from Katuntsev VP, Osipov YuYu, Gernhardt ML.*** **Space Biology and Medicine,** ***Vol V, p. 205, © 2004. With permission of the American Institute of Aeronautics and Astronautics.)***

to assemble and maintain the ISS. To circumvent these constraints, a baseline "overnight campout" protocol in which crew members were to stay in the ISS airlock, pressurized to 70.2 kPa (10.2 psia), was planned for future ISS EVA operations. However, that protocol also had significant limitations, including high oxygen use and exposure to 70.2 kPa (10.2 psia) during sleeping periods, when crew members' metabolic rates were low, in addition to lack of comfort and isolation of the crew members in the airlock. It thus became clear that a new prebreathe protocol would be needed to support shuttle crew EVAs during the early ISS assembly phase. The Prebreathe Reduction Program (PRP) was initiated in 1997. This program had 4 objectives: (1) to prospectively define acceptable DCS risk levels based on a combination of mission success parameters and medical operational considerations; (2) to develop, test, and validate a 2-hour prebreathe protocol from saturation at 101.2 kPa (14.7 psia) in time to support the first EVA from the ISS on assembly flight 7A; (3) to develop further time reductions in prebreathe protocols, if safely possible; and (4) to develop predictive models that would allow DCS risk to be estimated across a range of operational circumstances, including different saturation pressures, prebreathe times, exercise levels, and breaks in the prebreathe period.

Risk Estimation

To develop prospective criteria for acceptable DCS risk, the impact on missions of different DCS symptoms needed to be assessed against well-defined mission success criteria. A well-defined DCS disposition policy was then developed to support the necessary statistical analyses. To summarize, the DCS disposition policy stated that if a crew member had 1 Type I (pain only) DCS incident that resolved completely during repressurization to cabin pressure, that crew member would be allowed to perform another EVA within 72 hours. If a crew member had 2 incidents of Type I DCS on the same mission, he or she would not be permitted to perform EVAs until after return to Earth and clearance by the NASA Aerospace Medical Board. Also, if a crew member had a single incident of Type II DCS (central neurological or cardiopulmonary DCS), that crew member would not be permitted to perform EVA until cleared by the NASA Aerospace Medical Board. This policy was considered conservative and generally consistent with the policies developed by the U.S. Air Force. This DCS disposition policy was applied to Monte Carlo simulation results of the entire assembly and to the maintenance model of the ISS (484 EVAs) to define the highest DCS risk consistent with a 95% probability that 2 of 3 crew members would always be available to perform EVA throughout the life of the ISS. That analysis revealed the highest acceptable risk of DCS to be 21%.

These mission-success-based DCS risk estimates were further reduced to account for other medical operational considerations such as limitations in on-orbit treatment capabilities, a 30- to 45-minute delay from the appearance of symptoms until the crew member could be re-pressurized in the airlock, and the possibility that the presence of sub-symptomatic venous gas emboli (VGE) could increase the risk of Type II DCS in crew members with patent foramen ovale. For these reasons, the incidence of DCS and Grade IV VGE (on the Spencer scale) were set to be below a threshold at which Type II DCS had never been reported in a large database of altitude-decompression studies by NASA, the U.S. Air Force, and others.

The requirement of having a 95% probability that 2 of 3 crew members would be available for EVA throughout the ISS Program, in combination with these additional medical/operational considerations, led to the following accept/reject limits for trials of the reduced prebreathe protocols:

Accept: DCS $\leq$ 15% and Grade IV VGE $\leq$ 20%, at 95% confidence interval
Reject: DCS > 15% or Grade IV VGE > 20%, at 70% confidence interval
Reject: Any case of Type II DCS

These criteria were more conservative than any previous prebreathe ground trial, including the operational space shuttle and Russian Orlan protocols and a 6-hour resting prebreathe protocol.

Countermeasures to Reduce Prebreathe Time

A decade of research suggested 2 countermeasures that were operationally feasible and had the potential to reduce prebreathe time: exercise during oxygen prebreathe and (for Earth-based subjects) microgravity simulation.

The exercise countermeasure involved exercising during the oxygen prebreathe period according to a protocol developed at the U.S. Air Force School of Aerospace Medicine: 10-minute dual-cycle ergometry exercise at 75% VO_2 peak, with 88% of the workload in the lower body and 12% of the workload in the upper body. In ground-based tests of 40 subjects, just 10 minutes of exercise during a 1-hour prebreathe cut the incidence of DCS by 50% relative to a control group who rested during the 1-hour prebreathe; the incidence of DCS was approximately equivalent to that after a 4-hour resting prebreathe (Figure 5.4-3).[16]

The other countermeasure, microgravity simulation, required the test subjects to refrain from walking for 4 hours before and during the simulated EVA. Tests performed at the NASA Johnson Space Center, tests constituting the Argo series,[3,11,12] and tests at Duke University[13] suggested that non-ambulating subjects had lower decompression stress than ambulating subjects. Figure 5.4-4 shows the results of a crossover study performed at Duke University[13] in which a group of subjects remained semi recumbent for 4 hours before and during simulated EVA at 29.6 kPa (4.3 psia) and the control group was ambulatory. This protocol included a 3.5-hour oxygen pre-

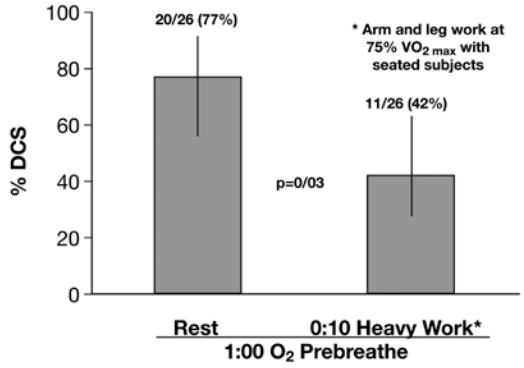

Figure 5.4-3 ***Results of 10 minutes of 75% VO_2 peak exercise in a 1-hour prebreathe protocol before performing simulated EVA at 29.6 kPa (4.3 psia). (EVA = extravehicular activity; O_2 = oxygen; DCS = decompression sickness). (Reprinted from Katuntsev VP, Osipov YuYu, Gernhardt ML.*** **Space Biology and Medicine*****, Vol V, p. 228, © 2004. With permission of the American Institute of Aeronautics and Astronautics.)***

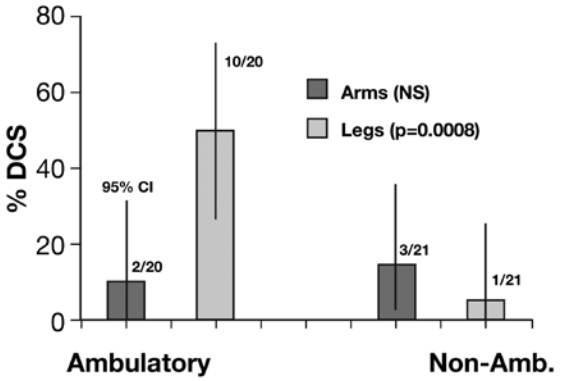

Figure 5.4-4. DCS episodes noted in ambulatory and nonambulatory subjects performing simulated EVAs at 29.6 kPa (4.3 psia) after a 3.5-hour oxygen prebreathe. (DCS = decompression sickness; EVA = extravehicular activity). ***(Reprinted from Katuntsev VP, Osipov YuYu, Gernhardt ML.*** **Space Biology and Medicine*****, Vol V, p. 229, © 2004. With permission of the American Institute of Aeronautics and Astronautics.)***

breathe. Results showed a significantly lower incidence of DCS (Fisher's exact test p = 0.0008) in the legs of the non-ambulatory subjects.

Although this research suggested that prebreathe efficiency could be improved, the observed rates of DCS in these experiments were still higher than the prospectively defined "accept" criteria for validation of the ISS prebreathe protocols. Thus, these 2 countermeasures, exercise prebreathe and microgravity simulation, were integrated to develop an operationally viable prebreathe protocol consistent with ISS assembly and maintenance EVA timelines. A multicenter sequential testing program was initiated and led by the NASA Johnson Space Center with decompression testing occurring at Duke University, the University of Texas Hermann Health Science Center, and the Canadian Defense and Civil Institute for Environmental Medicine.[6]

Four different protocols were tested using various combinations of high-intensity activities (75% VO_2 peak) and "light activities" (VO_2 of 5.8 mL•kg^{-1}•min^{-1}). All of the protocols included 2 hours of oxygen prebreathe time, but each involved exercise at different times and different intensities during that period. An overview of the protocols is shown in Figure 5.4-5.

All 4 protocols incorporated a 2-hour oxygen prebreathe as well as a depress to 70.2 kPa (10.2 psia) and 26.5% oxygen after the initial exercise to avoid the uptake of nitrogen when donning the spacesuit. After the 30-minute simulated suit-donning period, the pressure was increased to 101.2 kPa (14.7 psia), where the subjects completed an additional 40 minutes of "resting prebreathe." The final depressurization from 101.2 kPa (14.7 psia) to the 29.6 kPa (4.3-psia) suit pressure took place over a 30-minute period. The pressure and breathing gas profiles were identical during all 4 protocols tested; only the exercise dose was changed. Results of these tests are illustrated in Figure 5.4-6.

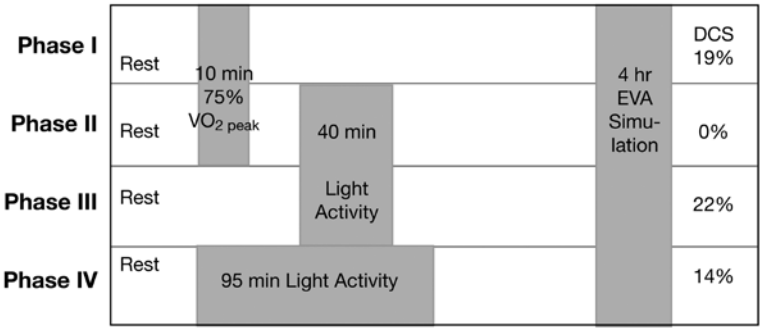

Figure 5.4-5 ***PRP Phase I to IV 2-hour oxygen prebreathe exercise protocols. Exercise varied from the 10 minutes of heavy exercise at 75% VO_2 peak, to 95 minutes of light activity (5.8 mL•kg^{-1}•min^{-1}) that was measured during the normal EVA preparations of configuring and donning the suit. (PRP = Prebreathe Reduction Program; EVA = extravehicular activity). (Reprinted from Katuntsev VP, Osipov YuYu, Gernhardt ML.*** **Space Biology and Medicine*****, Vol V, p. 229, © 2004. With permission of the American Institute of Aeronautics and Astronautics.)***

The initial test of the U.S. Air Force exercise prebreathe protocol ("Phase I") during a 2-hour oxygen prebreathe resulted in a DCS rate of 19%. Two other protocols that incorporated only light exercise resulted in DCS rates of 22% ("Phase III" protocol) and 14% DCS ("Phase IV" protocol). Only the Phase II protocol met the accept conditions for operational use (ie, DCS ≤ 15% and Grade IV VGE ≤ 20% at

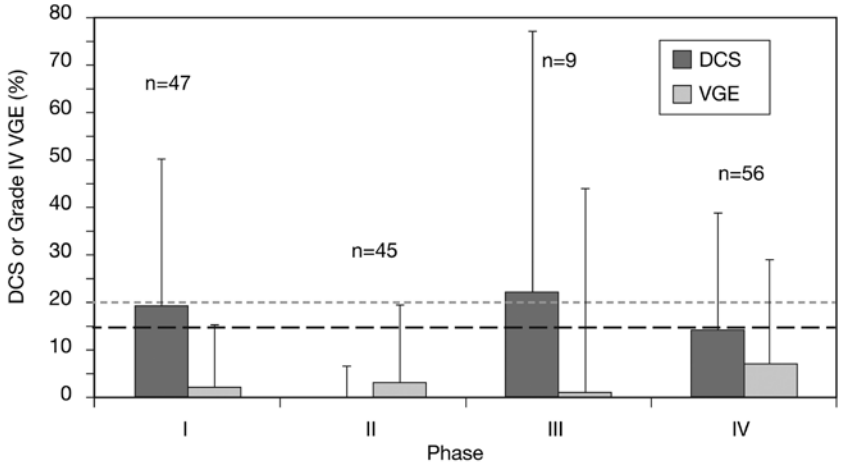

Figure 5.4-6 ***Observed episodes of DCS and Grade IV VGE during testing of each of the 4 Prebreathe Reduction Program protocols ("phases"). Bars indicate the upper bound of the 95% confidence limits. The black dashed line depicts the "accept" level for the number of episodes of DCS (ie, ≤15%); the grey dotted line depicts the "accept" level for the number of episodes of VGE (ie, ≤ 20%). (DCS = decompression sickness; VGE = venous gas emboli). (Reprinted from Katuntsev VP, Osipov YuYu, Gernhardt ML.*** **Space Biology and Medicine*****, Vol V, p. 229, © 2004. With permission of the American Institute of Aeronautics and Astronautics.)***

95% confidence interval). That protocol incorporated a 10-minute 75% VO_2 peak exercise period coupled with 40 minutes of intermittent light exercise at 5.8 $mL \cdot kg^{-1} \cdot min^{-1}$, followed by a 30-minute suit donning period at 70.2 kPa (10.2 psia), and 26.5% oxygen, followed by a 40-minute resting prebreathe period at 101.2 kPa (14.7 psia). Tests of that protocol resulted in no cases of DCS and 6 cases of Grade IV VGE among 45 subjects. Because these results met the prospectively defined accept criteria, this protocol was accepted for flight operations. Neither heavy nor light exercise by itself was sufficient to protect against DCS at acceptable levels. However, the combination of heavy exercise followed by light exercise and then a resting pre-breathe met the accept conditions. Recent research also suggests that depressurization to 70.2 kPa (10.2 psia) followed by re-pressurization to 101.2 kPa (14.7 psia) and additional oxygen prebreathe contributes significantly to reducing decompression stress.[5,6,10]

Detailed flight procedures were then developed together with special exercise and breathing equipment (prebreathe mask, hose, and regulators) that would provide the high ventilation rates necessary to support the 10-minute heavy exercise period for very fit EVA crew members. An in-flight DCS validation program also was developed that included the use of an in-suit Doppler bubble detector. When this detector failed to meet the certification requirements for operating in the 100% oxygen environment of the suit, the decision was made to add a further 20 minutes of oxygen prebreathe time while in the suit. These procedures were finalized and used to perform the first EVA from the ISS, during STS-104, ISS assembly Flight 7A (Figure 5.4-7).

The exercise prebreathe protocol had several operational advantages, including more efficient EVA preparation time-lines and the ability to leave the hatches open between the shuttle and the ISS while the shuttle vehicle was docked to the ISS. When this chapter was written, the exercise pre-breathe protocol had been used on 42 EVAs from the ISS and had played an important role in the success of the early shuttle-based assembly flights. Table 5.4-1 presents data from the early uses of the protocol. The actual prebreathe times for each phase of the protocol are longer than the required times. In practice, crews never spend less time prebreathing 100% oxygen than is required and often spend more, which, in combination with the additional "operational prebreathe time" associated with configuration, communications, leak checks, and oxygen purges, plus the increased metabolic rates associated with these suited activities (Table 5.4-2), adds another degree of conservatism relative to ground-based laboratory trials.

Figure 5.4-7 ***The first in-flight use of the exercise prebreathe protocol (left) and the first EVA from the U.S. airlock "Quest" during STS-104, ISS assembly flight 7A (right). (EVA = extravehicular activity; ISS = International Space Station). (Reprinted from Katuntsev VP, Osipov YuYu, Gernhardt ML.*** **Space Biology and Medicine***, Vol V, p. 230, © 2004. With permission of the American Institute of Aeronautics and Astronautics.)*

Medical Management of Potential Decompression Sickness Incidents

As part of defining acceptable levels of risk of DCS for the ISS era, the methods by which DCS is treated were revisited by a multidisciplinary team established at the NASA Johnson Space Center to formulate a DCS Contingency Plan. This team included representatives from Medical Operations, the Astronaut Office, flight controllers, the EVA support team, and Mission Operations Directorate as well as representatives from the U.S. Navy and the U.S. Air Force. The DCS treatment literature and DCS databases were extensively reviewed. One of the key findings from this effort was the recognition of the need for an operational classification system for various degrees of DCS symptoms, together with the responses necessary for efficient re-pressurization of affected crew members in the airlock while simultaneously maintaining the

Table 5.4-1 ***Early uses of the exercise prebreathe protocol, showing actual prebreathe times for each phase of the protocol vs. the nominal required times. Actual time always exceeds the required time for a variety of operational reasons. (Reprinted from Katuntsev VP, Osipov YuYu, Gernhardt ML.*** **Space Biology and Medicine***, Vol V, p. 230, © 2004. With permission of the American Institute of Aeronautics and Astronautics.)*

Nominal time	80 minutes	20 minutes	30 minutes	60 minutes	30 minutes
Actuals	***80-124 (88)***	***20-45 (30)***	***42-104 (61)***	***60-64 (60.3)***	***35-70 (39)***
Mission	**Mask Prebreathe**	**70.2-kPa (10.2-psia) Depressurization**	**Time @ 70.2 kPa (10.2 psia)**	**In-suit Prebreathe**	**Depressurization**
STS-104-1	97	45*	59	60	70*********
110-1	95	30	45	60	40
110-2	80	26	63	60	43
110-3	80	23	46	60	40
110-4	124	74	32	60	41
111-1	82	24	81	60	41
111-2	87	34	70	60	39
111-3	80	25	61	87	33
112-1	102	29	87	60	43
112-2	80	25	62	60	42
112-3	80	24	53	61	38
113-1	94	25	60	60	35
113-2	81	21	49	60	37
113-3	80	25	104	60	42
Exp-4-1	85	20	42	60	59
Exp-6	87	29	63	64	57

Table 5.4-2 ***Average and maximum metabolic rates and EVA durations associated with representative ISS assembly tasks. (Reprinted from Katuntsev VP, Osipov YuYu, Gernhardt ML.*** **Space Biology and Medicine*****, Vol V, p. 231, © 2004. With permission of the American Institute of Aeronautics and Astronautics.)***

Mission	EVA	Metabolic Rate (kcal/hour)				EVA Duration
		Maximum	Average			
STS-104	1	788.01	230.4	±	105.2	5:59
	2	492.51	193.4	±	80.0	6:29
	3	492.51	229.0	±	79.4	4:02
STS-110	1	472.81	224.8	±	69.7	7:48
	2	866.81	198.7	±	74.2	7:30
	3	433.41	198.6	±	67.5	6:27
	4	394.01	199.3	±	59.9	6:37
STS-111	1	394.01	191.5	±	61.7	7:14
	2	374.31	191.9	±	66.9	5:00
	3	510.42	195.7	±	67.4	7:17
STS-112	1	610.71	254.9	±	86.0	7:01
	2	476.83	233.8	±	73.3	6:04
	3	394.01	215.7	±	66.7	6:36
STS-113	1	965.32	228.2	±	89.1	6:45
	2	453.11	213.6	±	73.2	6:10
	3	N/A	N/A			7:00
Exp-4	1	413.71	203.2	±	68.0	5:49

space shuttle in a safe configuration for reentry. The operational DCS classification system was integrated with the EVA malfunction checklist, which EVA crew members wear on their forearms. This EVA "cuff classification" system represents an "operational" classification of DCS symptoms. A crew member experiencing symptoms during an EVA verbally reports to Mission Control a "cuff class" number based on symptoms and level of interference with performance. A preestablished response plan is then followed that may include termination or abort of an EVA with appropriate "safing" activities of the shuttle/ISS EVA worksite, as required. By establishing predetermined operational responses, this standard system for communicating symptoms to the Mission Control team is designed to maximize the health and safety of crew members. The cuff classification system also serves as the basis for formulating simulated DCS scenarios for the Mission Control flight team and EVA crew members to rehearse during pre-mission training.

Algorithms or decision trees were then developed for the treatment of DCS based on the general concepts of diving treatment tables. The principal tenets of treatment include oxygen and pressure over time, with fluids and medications used as adjuncts. In the previous version of space DCS treatment, crew members were returned to cabin pressure as soon as possible, after which the suit was depressurized to cabin pressure. After this the crew member breathed cabin air for approximately 30 minutes. A "bends treatment apparatus" was installed on the suit providing the capability to increase the suit pressure to up to 57.2 kPa (8.3 psi) above cabin pressure. Database analysis suggested that the return to cabin pressure from the 29.6 kPa (4.3-psia) hypobaric environment of the spacesuit would be sufficient to treat most Type I (pain-only) symptoms (96%). For this reason, the decision was made to initially leave the crew member pressurized in the suit at 29.6 kPa (4.3 psi) over cabin pressure while breathing 100% oxygen. Another tenet of treatment involves treating not just symptoms but also gas bubbles, and for this reason as many as 2 more hours of breathing oxygen was recommended after symptom resolution. A significant percentage of Type II (serious) symptoms also are anticipated to improve with return to ambient pressure. However, procedures and hardware were developed to be able to install the bends treatment unit while the suit was pressurized and while the crew member was breathing oxygen, which provided the capability to increase suit pressure if more serious symptoms did not respond to compression to 29.6 kPa (4.3 psi) above cabin pressure. Unless an affected crew member is severely compromised, he or she would remain in the suit during the initial phases of treatment, with the spacesuit serving as the treatment vessel. Many technical aspects must be considered when addressing the challenges of treating a suited crew member, including communications, EMU and vehicle configuration, suit consumables, and airlock re-pressurization procedures. Treatment outlines were subsequently converted into malfunction procedures that follow the checklist format and decision trees that astronauts are accustomed to using.

As described in detail elsewhere in this book, medical kits were flown on the space shuttle and are being flown on the ISS. Although these kits are necessarily constrained in terms of size and weight, they are designed to address a broad range of medical conditions based on prior space flight experience and anticipated illnesses and injuries. Medical treatment procedures after the suit is doffed (removed)

includes the administration of oral or intravenous hydration and additional oxygen by facemask. The shuttle medical kits contained 3.1 L of normal saline (0.9% NaCl); and 12.1 L of normal saline are available aboard the ISS. At present, no other adjunct medications are currently flown for the specific support of DCS treatment.

A simple DCS neurological examination that can be performed on an EVA crew member by a nonphysician astronaut was developed as a tool to assess signs and symptoms over time. This examination assesses chiefly motor and neurological functions, and can be used to evaluate crew members who are either fully suited or with the suit doffed.

"Flight rules" are preestablished procedures developed for the Flight Control Team in Mission Control to respond to a variety of potential mechanical and operational scenarios throughout all phases of flight. The purpose of flight rules is to avoid miscommunications across disciplines and to maximize effective decisions. Flight rules developed for EVA deal with "oxygen payback" ratios for air breaks in prebreathe periods; they also specify deorbit requirements to designated worldwide Primary Hyperbaric Care sites, and address resolved and unresolved "cuff class" symptoms. Expertise both within and outside NASA has been leveraged to create and implement a system that is now in place to more effectively address potential cases of DCS on orbit.

Extravehicular Activity Frequency and the Work Efficiency Index

The actual EVA is part of a long workday that includes pre-EVA preparation, suit donning, prebreathe, airlock decompression, conducting an EVA that can last more than 8 hours, reentering and securing the airlock, re-compressing the airlock, and doffing the spacesuit. Thus, back-to-back days of EVA would be overly fatiguing. To quantify the time required for each of these functions, an EVA work efficiency index was created and is defined as EVA time/total time for EMU and airlock preparation + prebreathe time + airlock depressurization + airlock re-pressurization + total after-EVA activities. Table 5.4-3 shows work efficiency indices for shuttle and ISS EVA operations. Clearly significant amounts of time are required to prepare all of the individual elements of the suit and airlock: from configuring the biomedical monitoring system to filling and installing the in-suit drink bag to configuring and checking out the suits and airlocks. The work efficiency index ranges from approximately 0.39 to 0.51, meaning that more than twice as much time goes into preparing for an EVA than is spent actually performing the EVA. Significant improvements in this index will be required to support the high frequency of EVAs anticipated in future Exploration Class missions, which includes a requirement for a work efficiency index greater than 3.0.

Approach to Extravehicular Activity Medical Monitoring

Before flight, Flight Surgeons coordinate with members of the Astronaut Conditioning, Strength, and Rehabilitation team to ensure that all EVA crew members have a well-balanced exercise regimen. Emphasis is placed on upper-extremity strength and endurance because EVAs require intensive use of hands and arms.

During flight, all EVAs are preceded and followed by assessments of medical fitness. The primary focus of a pre-EVA medical evaluation is to identify any medical issues that would constrain or potentially harm crew members during EVA. Post-EVA medical evaluations aim to ensure continued crew member health and identify potential suit-related health issues. On the day before an EVA was to take place, the Flight Surgeon held private medical conferences with each shuttle EVA crew member to assess his or her rest, hydration, and nutrition status as well as any physical issues that might have affected his or her EVA performance. For ISS missions, medical clearance and certification are based on medical assessment, which includes a review of recent countermeasures performed to ensure adequate aerobic capacity and strength. This medical evaluation, which is completed 24 hours before a scheduled EVA, consists of a review of physiological systems by the Flight Surgeon, a brief skin and extremity examination by the on-board Crew Medical Officer, and a urinalysis to ensure proper hydration status. On the day of the EVA, the crew member's vital signs (blood pressure, body temperature) are measured and the Flight Surgeon may direct further medical examination based on results from the previous review of systems.

The Surgeon Console position in Mission Control is staffed by both a Flight Surgeon and a biomedical engineer during EVAs to provide medical support as needed. Additional EVA medical and physiological experts are available on call to assist the console surgeon should further consultation be required. Biomedical monitoring is undertaken to provide feedback to the Flight Director. Monitoring includes electrocardiography and heart rate, suit pressure, suit carbon dioxide partial pressure, and estimated metabolic rate. During EVAs, the crew members have access to an in-suit drink bag that contains 0.95 L (32 oz) of water, and they wear a maximum-absorbency garment for urine absorption as needed.

Table 5.4-3 ***Work Efficiency Index (EVA time [based on a 6.5-hour EVA] per the overhead associated with pre- and post-EVA preparations of the suit and airlock systems). (Reprinted from Katuntsev VP, Osipov YuYu, Gernhardt ML.*** **Space Biology and Medicine,** ***Vol V, p. 208, © 2004. With permission of the American Institute of Aeronautics and Astronautics.)***

Prebreathe Protocol	Shuttle Staged Decompression (12 hours @ 70.2 kPa [10.2 psia])	ISS: 4 hours in Suit	ISS CEVIS Exercise (Using ISS O_2)
EVA Overhead Activities	**Time in Minutes**	**Time in Minutes**	**Time in Minutes**
Suit checkout	115	185	185
REBA-powered hardware checkout	25	25	25
SAFER checkout	30	30	30
Airlock configuration	95	90	90
Consumables preparation	60	120	120
EVA preparation – prebreathe related	60	0	80
EVA preparation – EMU related	30	30	30
Suit donning and leak check	60	60	60
SAFER donning	Completed during prebreathe	Completed during prebreathe	Completed during prebreathe
Purge	8	12	12
Prebreathe	75	240	60
Airlock depressurization	15	30	40
Airlock egress	15	15	15
Airlock ingress	15	15	15
Airlock re-pressurization	15	15	15
Suit doffing	25	25	25
SAFER doffing and stow	10	10	10
Post-EVA processing	105	90	90
Total	**758**	**992**	**902**
EVA Work Efficiency Index	**0.51**	**0.39**	**0.43**

*Abbreviations: CEVIS = Cycle Ergometer with Vibration Isolation System; REBA = rechargeable EVA battery assembly; SAFER = simplified aid for EVA rescue.

Typically the maximum duration of EVAs as currently planned is 6.5 hours. However, EVAs can and have been extended to meet mission objectives if suit consumables are available and if the Flight Surgeon concurs that the crew members' physiological parameters are within acceptable limits.

Extravehicular-activity-induced Injuries

The extensive ISS construction tasks performed during EVAs have been associated with crew member injuries, both during Neutral Buoyancy Laboratory training and during actual space flight EVAs. In addition to the EVA tasks themselves, the spacesuit design and sizing, foot restraints, suit humidity control, EVA duration, and repetition factors all influence the likelihood of crew member injury.

As noted at the beginning of this section, the U.S. spacesuit has a hard upper torso design, and sizing is determined using a computer algorithm developed from previous use of such suits. Because the fitting process takes place at 1*g*, an injury-free fit is not necessarily ensured when the suit is used in a neutral buoyancy pool or in a microgravity environment. Another factor contributing to problems with suit fit is the significant increase over time in spinal column dimensions in a microgravity environment. Moreover, the hard upper torso design partially restricts scapulothoracic motion, which can result in shoulder rotator cuff impingement during some arm maneuvers.

The padding and harnesses used, the suit humidity (particularly that over the hands and feet), fitting and sizing, anthropometric factors and the crew member's physical conditioning, the ranges of motion and force required for various tasks, the repetition of those tasks, and recovery times between EVAs all influence the likelihood and prevalence of EVA injuries. Training with heavy tools, prolonged inversion, and overhead arm operations all can increase the probability of injury during training in the Neutral Buoyancy Laboratory at the NASA Johnson Space Center, and tasks are typically performed multiple times during training in preparation for one such event during an actual EVA. Although the combination of the crew member, his or her tools, and the EMU during simulations may collectively be neutrally buoyant, the crew member is not weightless within the suit, and hard-point contact and range-

of-motion limitations can and do result, particularly when the crew member is working in the inverted position.

In a small survey of 22 EVA astronauts at the NASA Johnson Space Center, 14 reported an EVA-related shoulder injury and 10 had experienced a previous shoulder injury. Of those who had experienced pain or injury, 56% experienced shoulder pain or injury during EVA mission training and 18% did so during actual EVA. All 14 subjects experienced right shoulder pain, and 68% were affected in both shoulders. Two of the 14 astronauts required surgical repair after injury. Most of the incidents associated with EVA training were classified as minor and resolved within 48 to 72 hours.

Injuries of the hands and feet associated with EVAs and EVA training also have been reported. One NASA study of 770 suited training test events involved 352 reported symptoms. Of these symptoms, 47% involved hands, 21% involved shoulders, 11% involved feet, 6% involved arms, 6% involved legs, 6% involved the neck, and 3% involved the trunk. Hand symptoms were primarily fingernail delamination (loss), thought to be secondary to excess moisture in the EVA gloves, and axial loading of the fingertips. Also present were abrasions, contusions, and 2 cases of peripheral nerve impingements related to glove fit and hard-point contact compressions. Crew members in microgravity and on the lunar surface have often noted significant hand fatigue related to glove resistance during grasping motions.

Pain and injury to the feet, chiefly of the dorsal surface of the foot and distal toes, were commonly associated with boot-fit problems, compression in foot restraints, or pressure from folds in the foot bladder. Elbows were the most common site of pain or injury in the arms, as were knees in the legs. Neutral-buoyancy EVA training is often intense as a mission launch date approaches; fingernail delamination and shoulder injuries may be related to the frequent and large numbers of training sessions. Mitigations targeting the causal factors are being progressively implemented and incorporated into the designs of the next-generation spacesuits.

Conclusions

As of March 2011, 186 EVAs had been conducted by crew members wearing U.S. spacesuits. All EVAs were successful, and all crew members returned safely and in good health.[1] The successful assembly of the ISS, using EVAs originating from the space shuttle, has been one of the most significant accomplishments in the history of NASA. This success is due in large part to the care and dedication of the physiological research and medical personnel overseeing virtually every aspect of EVA: from the development of procedures and countermeasures to personnel selection and training and finally through providing real-time and post-flight medical support of EVA crews.

References

1. Conkin J. *Preventing Decompression Sickness Over Three Decades of Extravehicular Activity*. Houston, Tex: Lyndon B. Johnson Space Center; 2011. NASA/TP-2011-216147.

2. Conkin J, Gernhardt ML, Powell MR, Pollock N. *A Probability Model of Decompression Sickness at 4.3 psia After Exercise Prebreathe*. Houston, Tex: Lyndon B. Johnson Space Center; 2004. NASA TP-2004-213158.

3. Conkin J, Powell MR. Lower body adynamia as a factor to reduce the risk of hypobaric decompression sickness. *Aviat Space Environ Med*. 2001;72:202-214.

4. Conkin J, Waligora JM, Horrigan DJ Jr, Hadley AT III. *The Effect of Exercise on Venous Gas Emboli and Decompression Sickness in Human Subjects at 4.3 psia*. Houston, Tex: Lyndon B. Johnson Space Center; 1987. NASA TM-58278.

5. Gernhardt ML, Conkin J, Vann RD, Pollock NW, Feiveson AH. DCS risks in ground-based hypobaric trials vs. extravehicular activity. *Undersea Hyperb Med*. 2004;31(3):338.

6. Gernhardt ML, Conkin J, Vann RD , Powell MR. Design of a 2-hour prebreathe protocol for space walks from the International Space Station (abstract 43). Paper presented at: 71st Annual Scientific Meeting of the Aerospace Medical Society. May 14-18, 2000; Houston, Tex.

7. Gernhardt ML. *Development and Evaluation of a Decompression Stress Index Based on Tissue Bubble Dynamics* [dissertation]. Philadelphia, Pa: University of Pennsylvania; 1991.

8. Horrigan DJ, Waligora JW, Bredt JH. Extravehicular activities. In: Nicogossian AE, Huntoon CL, Pool SL, eds. *Space Physiology and Medicine*. 2nd ed.. Philadelphia, Pa: Lea and Febiger; 1989:121-135.

9. Morgenthaler GW, Fester DA, Coolfy CG. An assessment of habitat pressure, oxygen fraction, and EVA suit design for space operations. *Acta Astronautica*. 1994;32(1):39-49.

10. Pollock NW, Natoli MJ, Vann RD, Conkin J, Gernhardt ML. Comparison of V-4 and V-5 exercise/oxygen prebreathe protocols to support extravehicular activity in microgravity (abstract). Paper presented at: Annual Scientific Meeting of the Undersea and Hyperbaric Medical Society. June 14-16, 2007; Maui, Hawaii. Available at: http:www.uhms.org. Accessed September 23, 2011.

11. Powell MR, Waligora JM, Norfleet WT, Kumar KV. *Project ARGO – Gas Phase Formation in Simulated Microgravity*. Houston, Tex: NASA Lyndon B. Johnson Space Center; 1993. NASA TM-104762.

12. Powell MR, Horrigan DJ Jr, Waligora JM, Norfleet WT. Extravehicular activities. In: Nicogossian AE, Huntoon CL, Pool SL, eds. *Space Physiology and Medicine*. 3rd ed. Philadelphia, Pa: Lea & Febiger; 1994:128-140.

13. Vann RD, Gerth WA. Is the risk of DCS in microgravity less than on earth? (abstract 45). Paper presented at: 68th Annual Scientific Meeting of the Aerospace Medical Association. May 11-15, 1997; Chicago Ill,

14. Waligora JM, Horrigan DJ, Conkin J, Hadley AT. *Verification of an Altitude Decompression Sickness Protocol for Shuttle Operations Utilizing a 10.2 psia Pressure Stage*. Houston, Tex: NASA Lyndon B. Johnson Space Center; 1984. NASA TM-58259.

15. Waligora JM, Pepper LJ. Physiological experience during shuttle EVA. Paper presented at: 25th International Conference on Environmental Systems. July 10-13, 1995; San Diego, Calif. SAE Technical Series. No. 951592.

16. Webb JT, Fisher MD, Heaps CL, Pilmanis AA. Prebreathe enhancement with dual-cycle ergometry may increase decompression sickness protection. *Aviat Space Environ Med*. 1996;67:618-624.