# Biomedical Support of U.S. Extravehicular Activity

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## Introduction

The world's first extravehicular activity (EVA) was performed by A. A. Leonov on March 18, 1965 during the Russian Voskhod-2 mission. The first US EVA was executed by Gemini IV astronaut Ed White on June 3, 1965, with an umbilical tether that included communications and an oxygen supply. A hand-held maneuvering unit (HHMU) also was used to test maneuverability during the brief EVA; however the somewhat stiff umbilical limited controlled movement. That constraint, plus difficulty returning through the vehicle hatch, highlighted the need for increased thermal control and improved EVA ergonomics. Clearly, requirements for a useful EVA were interrelated with the vehicle design. The early Gemini EVAs generated requirements for suits providing micro-meteor protection, adequate visual field and eye protection from solar visual and infrared radiation, gloves optimized for dexterity while pressurized, and thermal systems capable of protecting the astronaut while rejecting metabolic heat during high workloads.

Subsequent Gemini EVAs built upon this early experience and included development of a portable environmental control and life support systems (ECLSS) and an astronaut maneuvering unit. The ECLSS provided a pressure vessel and controller with functional control over suit pressure, oxygen flow, carbon dioxide removal, humidity, and temperature control. Gemini EVA experience also identified the usefulness of underwater neutral buoyancy and altitude chamber task training, and the importance of developing reliable task timelines. Improved thermal management and carbon dioxide control also were required for high workload tasks.

With the Apollo project, EVA activity was primarily on the lunar surface; and suit durability, integrated liquid cooling garments, and low suit operating pressures (3.75 pounds per square inch absolute [psia] or 25.8 kilopascal [kPa],) were required to facilitate longer EVAs with ambulation and significant physical workloads with average metabolic rates of 1000 BTU/hr and peaks of up to 2200 BTU/hr [6] . Mobility was further augmented with the Lunar Roving Vehicle. The Apollo extravehicular mobility unit (EMU) was made up of over 15 components, ranging from a biomedical belt for capturing and transmitting biomedical data, urine and fecal containment systems, a liquid cooling garment, communications cap, a modular portable life support system (PLSS), a boot system, thermal overgloves, and a bubble helmet with eye protection. Apollo lunar astronauts performed successful EVAs on the lunar surface from a 5 psia (34.4 kPa) 100% oxygen environment in the Lunar Lander. A maximum of three EVAs were performed on any mission.

For Skylab a modified A7LB suit, used for Apollo 15, was selected. The Skylab astronaut life support assembly (ALSA) provided umbilical support through the life support umbilical (LSU) and used open loop oxygen flow, rather than closed-loop as in Apollo missions. Thermal control was provided by liquid water circulated by spacecraft pumps and electrical power also was provided from the spacecraft via the umbilical. The cabin atmosphere of 5 psia (34.4 kPa), 70% oxygen, provided a normoxic atmosphere and because of the very low nitrogen partial pressures, no special protocols were required to protect against decompression sickness (DCS) as was the case with the Apollo spacecraft with a 5 psi, 100% oxygen environment.

## Space Shuttle EVA

The Shuttle was designed to provide crew and cargo transfer from Earth to low earth orbit for deployment and capture of satellites and scientific spacecraft as well as for future space stations. Shuttle EVAs were initially anticipated to be for contingency use associated with various malfunctions of the payload bay doors. The Shuttle EMU was derived from the advanced Apollo configuration and later enhanced. The enhanced EMU is the currently used US EVA integrated space-suit system. The Shuttle EVA space suit was based on a hard upper torso (HUT) that reduced sizing requirements and eliminated the need for

external life support hoses that improved mobility and reduced snag risks. The boot design supported use of more ergonomic foot restraints to lessen metabolic workloads during EVA fixed tasks.

The Shuttle cabin atmosphere was selected to be 14.7 psia (101.2 kPa) with 21% oxygen. This higher pressure and lower oxygen concentration represented a major departure from the previous low pressure high oxygen concentration spacecraft. A suit pressure of 4.3 psia (29.6 kPa) was selected to maintain the increased mobility and dexterity offered from a low-pressure space suit. This combination of cabin atmosphere and suit pressures, required the development of special protocols to protect against DCS. Several hundred decompression trials were performed over a 10-year period and two protocols were accepted for flight operations based on an R-value of 1.65. The R-value is defined as the ratio between the nitrogen tension in a 360-minute half-time compartment and the space-suit pressure. These protocols included a 4-hour oxygen prebreathe performed in the suit at 14.7 psia (101.2 kPa), and a 10.2 psia (70.2 kPa) staged decompression protocol. In the staged decompression protocol, the crewmembers perform 1 hour of oxygen prebreathe before depressing the cabin to 10.2 psia (70.2 kPa) with 26.5% oxygen. The crew remains at 10.2 psia (70.2 kPa) for a minimum of 12 hours and then performs another 75 minutes of oxygen prebreathe in the suit before performing EVA. The final in-suit prebreathe times are a function of the time spent at 10.2 psia (70.2 kPa) and can be as low as 40 minutes, if 36 hours or more had been spent at the reduced 10.2 psia (70.2 kPa) cabin pressure. Shirt-sleeve ground-based altitude chamber testing of these protocols resulted in a DCS incidence rate of 23.7% [10], with the majority of those symptoms being minor joint pain. There have been no reports of DCS in over 140 EVAs using these protocols in space flight, and less than 1.5% DCS reported in over 300 ground-based suited-vacuum chamber tests.

For operational timeline reasons the crews and flight planners preferred using the 10.2 psia (70.2 kPa) staged decompression protocol and all but four EVAs from the Shuttle used this protocol. Additionally for operational reasons, the time spent at 10.2 psia (70.2 kPa) was typically far in excess of the tested 12-hour exposure. Figure 1 shows the distribution of the duration at 10.2 psia (70.2 kPa) by Shuttle mission, with the average time being over 40 hours.

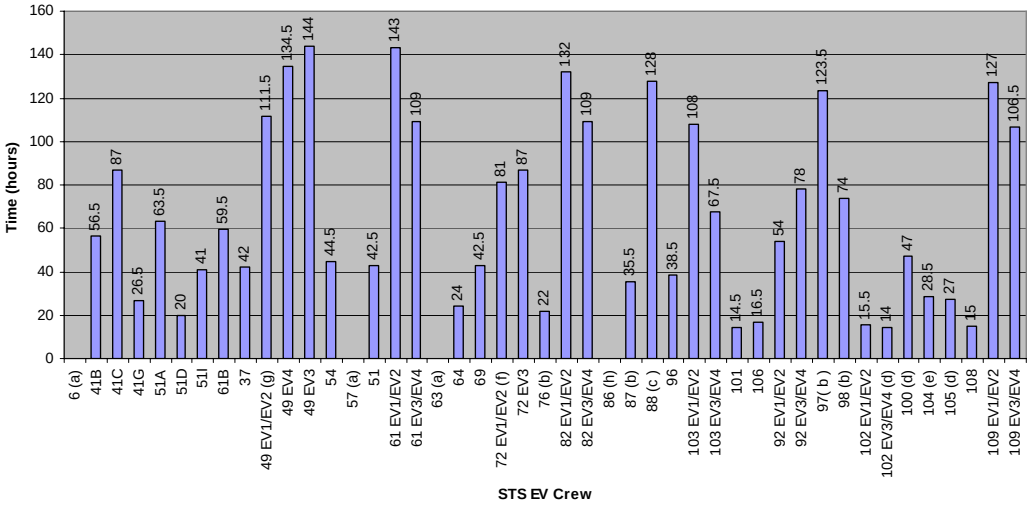


**Figure 1**. The duration of exposure at 10.2 psi before performing EVA in a 4.3 psia suit

Equilibration of tissue nitrogen tensions at a given ambient pressure is generally considered to require 36 hours, and so the increased in-flight times spent at 10.2 psia (70.2 kPa) would be expected to have a mitigating affect on the decompression stress. Figure 2 shows the predictions of theoretical bubble growth for 12 to 36-hour exposures at 10.2 psia (70.2 kPa) [5], suggesting very low decompression stresses after spending 24 hours at 10.2 psia (70.2 kPa).

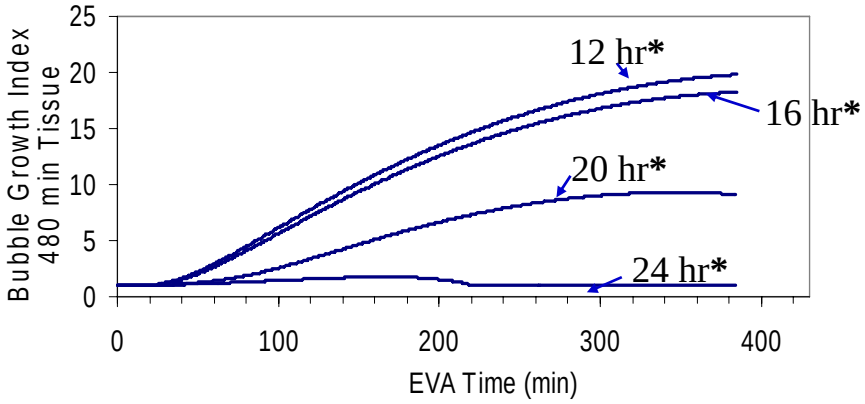


**Figure 2**. Theoretical bubble growth during a 6-hour EVA after spending 12, 16, 20, and 24 hours at 10.2 psia (70.2 kPa) with 26.5% oxygen.

In addition to the increased exposure time at 10.2 psia (70.2 kPa), the suit itself provides some increased decompression protection in the form of additional operational oxygen prebreathe time and higher metabolic rates during prebreathe compared with the resting test subjects of the laboratory trials. Once the suit is donned a series of configuration and leak checks are performed, which are followed by an 8-12 minute purge cycle before the prebreathe clock is started. Then, during depressurization to vacuum, the suit pressure is set by the positive pressure relief valves keeping the suit 5 psia (34.4 kPa) over the ambient pressure; this results in more oxygen prebreathe time before the tissues becoming supersaturated creating decompression stresses. The combined effect of the suit operational overhead is to result in between 20 to 30 minutes additional prebreathe at elevated oxygen concentration levels. Also, the metabolic rates of crewmembers “resting in the suit” have been measured at 6.8 mL/kg-min compared to typical resting metabolic rates of approximately 3.8 mL/kg-min. Recent research has shown that even small increases in metabolic rate can decrease DCS incidence, presumably through increased nitrogen washout [1, 3, 7]. The combination of all suit-related operational effects reduce decompression stress compared to shirt-sleeve laboratory subjects and offer one explanation as to why the incidence of DCS in suited ground-based vacuum chamber tests and spaceflight EVAs are much lower than the initial laboratory trials used to develop these decompression protocols.

**International Space Station (ISS) EVA**

The International Space Station (ISS) ushered in a new era of EVA where EVA would become a routine and enabling capability required for the assembly and maintenance of the ISS. In the previous spaceflight programs EVA was limited to special case or contingency operations. Over 484 EVAs were planned throughout the planned 15-year life of ISS. The early assembly EVAs would have to be conducted from the Shuttle as the US airlock would not be installed on the ISS until the seventh major ISS assembly flight. A significant challenge for performing EVAs from the ISS was the fact that the large volume and limited logistics support would not enable the ISS cabin pressure to be reduced to 10.2 psia (70.2 kPa). This meant that the Shuttle experience base with the successful staged decompression protocol would not be directly applicable to the ISS. Additionally the 4-hour in-suit prebreathe times were not compatible with the EVA timelines and crew scheduling constraints necessary to successfully execute the assembly and maintenance of ISS. A baseline overnight campout protocol at 10.2 psia (70.2 kPa) in the ISS airlock was developed based the Shuttle protocol testing program. However there were limitations with this protocol including high oxygen use, and limited duration exposure at 10.2 psia (70.2 kPa) during sleeping periods with low metabolic rates. Additionally the issues of crew comfort and isolation in the airlock were considered significant limitations of the baseline ISS campout protocol.

**Prebreathe Reduction Program**

Because of the limitations of the baseline ISS campout protocol, the prebreathe reduction program (PRP) was initiated 1997. The objectives of the PRP were to:

1. Prospectively define acceptable levels of DCS based on a combination of mission success parameters and medical operational considerations.
2. Develop, test, and validate a 2-hour prebreathe protocol from saturation at 14.7 psia (101.2 kPa) in time to support the first EVA from the ISS on assembly flight 7A.
3. Develop further time reductions in prebreathe protocols if safely possible.
4. Develop predictive models that would allow estimation of DCS risk across a range of operational circumstances, including different saturation pressures, prebreathe times, exercise levels and breaks in prebreathe.

To develop prospective criteria for acceptable DCS risk, the mission impacts of different DCS symptoms needed to be assessed against well defined mission success criteria. To perform the necessary statistical analysis a well-defined DCS disposition policy was developed. In summary, the DCS disposition policy stated that if a crewmember had one Type I (pain only) DCS incidence that completely resolved during repress to cabin pressure, they would be allowed to perform another EVA within 72 hours. If a crewmember had two cases of Type I DCS on the same mission they would not be available to perform EVAs until they returned to Earth and were cleared by the NASA aerospace medical board (AMB). Additionally if a crewmember had a single case of Type II DCS (central neurological or cardiopulmonary DCS) they would not be able to perform EVA until cleared by the AMB. This DCS disposition policy was conservative but generally consistent with the effective policies developed by the US Air Force. This DCS disposition policy was applied to a Monte Carlo simulation of the entire assembly and maintenance model of the ISS (484 EVAs) to define the highest DCS risk consistent with a 95% probability that 2 of 3 crewmembers would always be available to perform EVA throughout the life of the ISS. That analysis drove out the highest acceptable risk of 21% DCS.

The mission success based DCS risk estimates were further reduced to account for other medical operational considerations that included: on-orbit treatment limitations, a delay of 30 to 45 minutes from occurrence of symptoms until the crewmember could be repressurized in the airlock, and considerations that high degrees of subsymptomatic venous gas emboli (VGE), could possibly increase the risk of Type II DCS in crewmembers with patent foramen ovale (PFO). For these reasons the DCS and Grade IV (Spencer Scale) VGE incidence were subjected to a constraint that they be below a threshold at where there had never been a report of Type II DCS in a large database of NASA, US Air Force, and other published altitude decompression studies.

The mission driver of 95% probability that 2 of 3 crewmembers be available for EVA throughout ISS program, combined with additional medical/operational considerations resulted in the following accept/reject limits for trials of the reduced prebreathe protocols.

- Accept: DCS $\leq$ 15% and Grade IV VGE $\leq$ 20%, @ 95% c.l
- Reject: DCS > 15% or Grade IV VGE > 20%, @ 70% c.l
- Reject: Any case of Type II DCS

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

**Prebreathe Reduction Program Trials**

A decade of enabling research suggested two countermeasures that were operational feasible and had the potential to reduce prebreathe time. These countermeasures included exercise during oxygen prebreathe and microgravity simulation.

Subjects, who exercised during oxygen prebreathe, used a protocol developed at the US Air Force's School of Aerospace Medicine (10-minute dual-cycle ergometry exercise at 75%$V0_2$peak, with 88% of the work load in the lower body and 12% in the upper body). With just 10 minutes of exercise in a 1-hour prebreathe; the DCS incidence in 40 subjects was approximately 50% of that observed in a control group that rested during the 1-hour prebreathe and was equivalent to a 4-hour resting prebreathe [11].

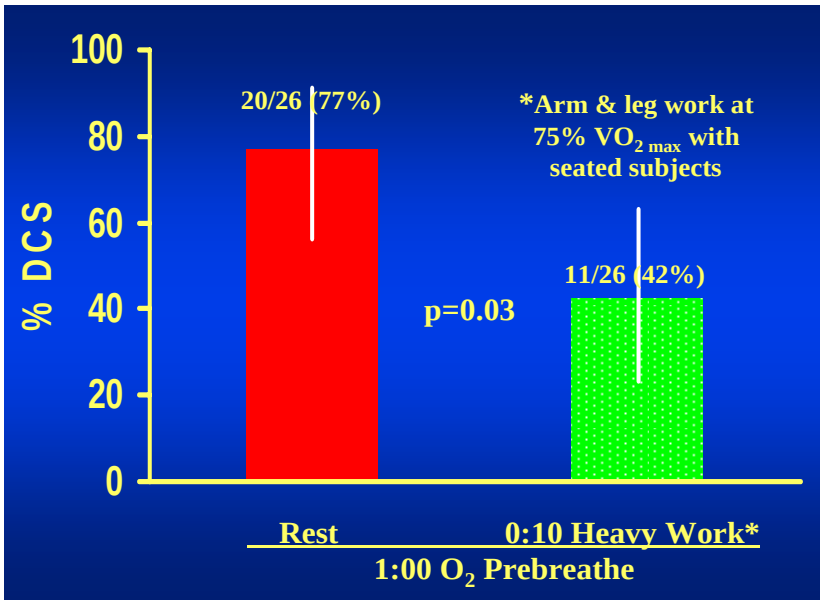


**Figure 3**. Results of 10 minutes of 75% V0$_2$peak exercise in a 1-hour prebreathe protocol before performing simulated EVA at 4.3 psia (29.6 kPa).

The other countermeasure was microgravity simulation where the test subjects did not walk for 4 hours before and while performing EVA. A number of tests performed at NASA JSC, the Argo series [2, 8], and at Duke University suggested that non-ambulating subjects had lower decompression stress than ambulating subjects. Figure 4 shows the results of a crossover study performed at Duke University [9] where one group of subjects remained semi-recumbent for 4 hours before and during simulated EVA at 4.3 psia (29.6 kPa), while the control group was ambulatory. This protocol used a 3.5-hour oxygen prebreathe.

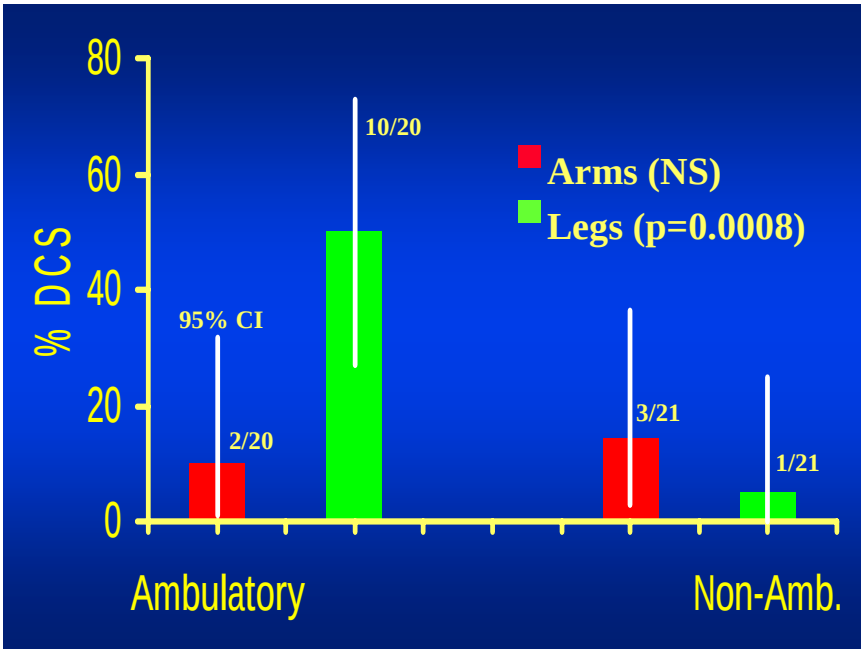


**Figure 4**. DCS observations in ambulatory and non-ambulatory subjects performing simulate EVA at 4.3 psia (29.6 kPa) following 3.5 hours of oxygen prebreathe.

The results of this study showed a statistically significant lower incidence of DCS (Fisher exact test, p = 0.0008) in the legs of the non-ambulatory subjects.

Although this enabling research suggested that improvements in prebreathe efficiency may be possible, the observations of DCS in each of these experiments were higher than the prospectively defined accept criteria for validation of the ISS prebreathe protocols. The two countermeasures of exercise prebreathe and microgravity simulation were integrated to develop an operational viable prebreathe protocol consistent with ISS assembly and maintenance EVA time lines. A multi-center sequential testing program was initiated and led by NASA JSC with decompression testing occurring at Duke University, University of Texas Hermann Health Science Center, and the Canadian Defense and Civil Institute for Environmental Medicine (DCIEM) [4].

Four different protocols were tested using different combinations of high intensity (75% $V0_2$peak) and low intensity exercise (5.8 mL/kg-min). All of the protocols had 2 hours of oxygen prebreathe time, but differing exercise doses. An overview of the protocols is shown below in Figure 5.

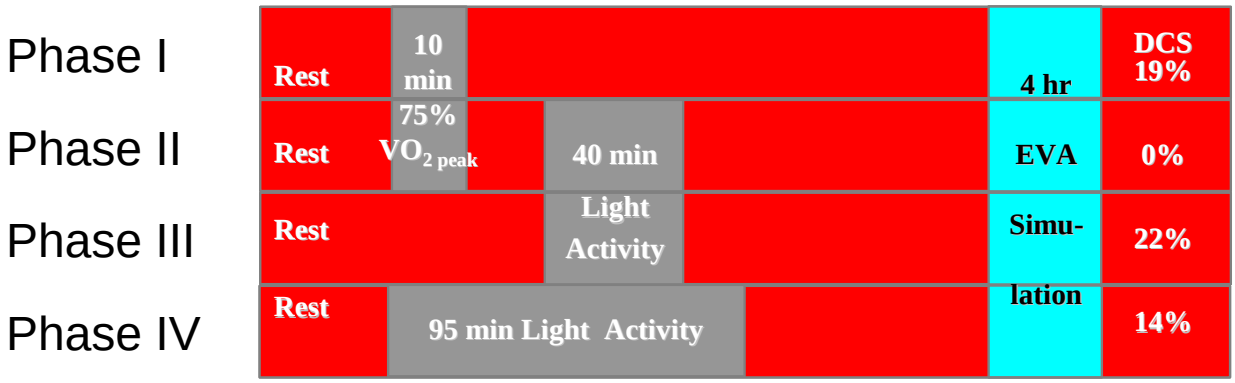


**Figure 5**. PRP Phase I-IV 2-hour oxygen prebreathe exercise protocols. Exercise varied from the 10 minutes of heavy exercise at 75% $V0_2$peak, to 95 minutes of light activity (5.8 mL/kg-min) that was measured during the normal EVA preparations of configuring and donning the suit.

All of these protocols incorporated a depressurization to 10.2 psi, after the initial exercise prebreathe. The subjects remained on 100% oxygen until reaching an environment of 10.2 psi and 26.5% oxygen. This allowed the suits to be donned at reduced nitrogen partial pressures and avoided problems with break in prebreathe and the resulting uptake of nitrogen. After a 30-minute simulated suit donning period, the laboratory subjects were then repressed to 14.7 psi and completed an additional 40 minutes of resting prebreathe. The final depress from 14.7 psi to the 4.3 psi suit pressure occurred over a 30-minute protocol. The pressure and breathing gas profiles were identical on all four protocols tested. Only the exercise dose was changed.

The results of the protocol testing are shown below in Figure 6.

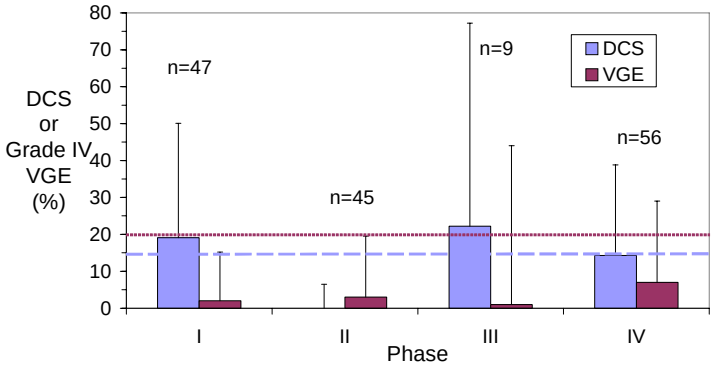


**Figure 6**. DCS and Grade IV VGE observations (shown with 95% upper confidence limit bars dashed lines indicating accept levels for DCS and VGE incidences)

The initial test of the US Air Force exercise prebreathe protocol in a 2-hour oxygen prebreathe resulted in 19% DCS. The two protocols that incorporated only the light exercise resulted in 22% and 14% DCS for Phases III and IV respectively. Only the Phase II protocol met the Accept conditions for operational use. The Phase II protocol incorporated the 10-minute 75% $V0_{2peak}$ exercise period coupled with 40 minutes of intermittent light exercise at 5.8 ml/kg-min, followed by a 30-minute suit donning period at 10.2 psia and 26.5% oxygen, followed by 40 minute resting prebreathe period at 14.7 psi. The Phase II trial resulted in no cases of DCS and 6 cases of Grade IV VGE in 45 subjects. These results met the prospectively defined Accept criteria and the Phase II 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 resting prebreathe met the Accept conditions. Recent research also suggests that the 10.2 psi depress followed by a repress to 14.7 psi and additional oxygen prebreathe plays a significant role in reducing decompression stress [3,4,].

Detailed flight procedures were developed along 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 in very fit EVA astronauts. An inflight DCS validation program was developed that incorporated the use of an in-suit Doppler bubble detector (ISD). When the ISD failed to meet the certification requirements for operating in the 100% oxygen environment of the suit, the decision was made to add an additional 20 minutes of oxygen prebreathe 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 7**. First use of the exercise prebreathe protocol and first EVA from the US airlock “Quest” during STS-104, ISS assembly flight 7A

The exercise prebreathe protocol provided a number of operational advantage, including more efficient EVA preparation timelines and the capability of leaving the hatches between the Shuttle and the ISS open during the duration of the docked phase of the mission. Before implementation of the exercise protocols, hatches had to be closed so that the Shuttle EVA crews could perform the 10.2 psi staged decompression protocol. This resulted in inefficiencies because the Shuttle crewmembers most recently trained on the mission-specific ISS robot arm operations had to remain in the Shuttle and there less time available for logistics transfers between the Shuttle and the ISS.

The exercise prebreathe protocol has now been used on 42 EVAs from the ISS and played an important role in the success of those assembly flights. Table 3 below presents data from the early uses of the protocol. For a variety of operationally driven reasons, the actual prebreathe times for each phase of the protocol are longer than the required times. In operational use, crews will never do less than the required prebreathe and frequently do more for a variety of operational reasons. This combined with the additional “ operational prebreathe” associated with configuration, communications, and leak checks and oxygen purges, and the increased metabolic rates associated with the suit, builds in a degree of conservatism compared to the laboratory trials.

**Table 2**. Early uses of the exercise prebreathe protocol, showing actual prebreathe times for each phase of the protocol versus the nominal required times. Actual time always exceed the required time for a variety of operational reasons.

| **Nominal time** | **80 min** | **20 min** | **30 min** | **60 min** | **30 min** |
|---|---|---|---|---|---|
| ***Actuals*** | ***80-124 (88)*** | ***20-45 (30)*** | ***42-104 (61)*** | ***60-64 (60.3)*** | ***35-70 (39)*** |
| **MISSION** | **MASK P.B** | **10.2 DEPRESS** | **TIME @ 10.2 PSI** | **IN-SUIT PB** | **DEPRESS** |
| 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 3.** Average and maximum metabolic rates and EVA durations, associated with representative ISS assembly tasks.

| **Mission** | **EVA** | **Metabolic Rate (Kcal/hr)** | | | | **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 |

| Mission | EVA | Metabolic Rate (Kcal/hr) | | | | EVA Duration |
|---|---|---|---|---|---|---|
| | | Maximum | Average | | | |
| 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 | NA | NA | | | 7:00 |
| EXP-4 | 1 | 413.71 | 203.2 | ± | 68.0 | 5:49 |

**Development of the ISS Campout PB Protocol**

In 1995, the baseline ISS campout prebreathe protocol was developed that required a 60-minute initial prebreathe before mask doffing at 10.2 psia (70.2 kPa), a 10-hour overnight stay in the airlock at 10.2 psia (70.2 kPa), a minimum of 60 minutes of oxygen via mask during a hygiene break at 14.7 psia (101.2 kPa), and an additional 2.25 hours at 10.2 psi (70.2 kPa), including suit donning, followed by 30 minutes of final in-suit prebreathe. The protocol was approved by similarity to the Shuttle 10.2 psia (70.2 kPa) protocol.

In 1999, the campout protocol was further refined to account for slower airlock depress time than anticipated. The result was an increase of 20 minutes in the total oxygen time on the mask and a decrease in the time at 10.2 psia (70.2 kPa) by 1 hour and 20 minutes.

In the post-Challenger period crew-scheduling constraints became tighter with the result of reducing the amount of time available to perform the long and complex ISS assembly EVAs. These tighter scheduling constraints caused the baseline campout protocol to be revisited. There are rules for protecting time for the crew post-sleep period, which do not allow any mission-related activities to be planned. With the campout protocol, the crewmembers wake up in the airlock at 10.2 psi, don oxygen masks, repressurize to 14.7 psi, egress the airlock and perform a 70-minute hygiene break breathing 100% oxygen. The crews then return to the airlock and depressurize to 10.2 psi, at which point they doff the oxygen masks, eat breakfast and then begin the suit donning procedures. The fact that an additional 70 minutes of oxygen prebreathe is conducted during the post-sleep hygiene break, results in a 60 minute time savings over the exercise prebreathe protocol, where none of the prebreathe activities can be planned for the post-sleep period. The 1-hour time savings made the campout protocol operationally more desirable than initially envisioned. The 1999 version of campout was then modified include 50 minutes of in-suit prebreathe time. These changes were necessary for the model predictions of the campout protocol to meet the same DCS accept conditions used for acceptance of the exercise prebreathe protocol.

Whereas there were no specific ground-based tests of the campout prebreathe protocol, this protocol was very similar to the Phase IV of the exercise prebreathe study. The Phase IV protocol included a 2-hour prebreathe with 95 minutes of light exercise, and a 30-minute suit donning period at 10.2 psia (70.2 kPa) and 26.5% oxygen. This ground-based test of Phase IV is nearly identical to the day-of-EVA campout prebreathe procedure, which has the same amount of oxygen prebreathe, and the same or slightly higher metabolic activity during oxygen prebreathe. For this reason, Phase IV could be considered ground-based data similar to that of campout prebreathe. The Phase IV ground trials resulted in 14% DCS in 57 subjects. Whereas the results did not quite meet the DCS accept criteria for ISS EVAs, they were lower than the ground tests of the Shuttle 10.2 psia (70.2 kPa) staged protocol. Additionally, the campout prebreathe protocol has an extra hour of oxygen prebreathe, and 8 hours and 40 minutes overnight campout at 10.2 psia (70.2 kPa). The combination of the Phase IV study and model predictions resulted in the campout protocol being approved for flight.

While similar, the campout prebreathe for ISS differs from the 10.2 psia (70.2 kPa) staged prebreathe used on the Shuttle in the following ways:

1. Campout prebreathe has shorter time at 10.2 psia (70.2 kPa), ie, 8 hours for sleep compared to the 12-hour minimum required for the Shuttle (13.5 hours is the shortest duration experienced at 10.2 psia (70.2 kPa) with Shuttle, with 40.0 hours being the average).
2. The mask time for campout prebreathe has been increased from 1 hour to 2 hours and 10 minutes to compensate for the decreased time at 10.2 psia (70.2 kPa).
3. On ISS, 60% of the time at 10.2 psia (70.2 kPa) is spent sleeping (compared to 30% in Shuttle), with an anticipated subsequent decrease in metabolic rate, the effects of which are not known.
4. There is a brief repressurization to 14.7 psia (101.2 kPa) on the morning of the EVA for a hygiene break (70 minutes) and then a depressurization back to 10.2 psia (70.2 kPa) to don the suit. An important point is that the 10.2 psia (70.2 kPa) staged prebreathe protocol is the best available procedure for the Shuttle EVA, and the campout prebreathe was designed to be "analytically more conservative," even though there is no ground-based testing for initial validation.

**Medical Management of Potential DCS Incidents**

As part of defining acceptable DCS risks for the ISS era, the methods of treatment of DCS were revisited. A multidisciplinary team was established at the Johnson Space Center to help formulate the DCS Contingency Plan. The team included representatives from Medical Operations, the Astronaut Office, Flight Controllers, EVA community, and Mission Operations Directorate, as well as representatives from the US Navy and US Air Force. Extensive reviews were completed of the DCS treatment literature and DCS databases. A key product from this effort was the recognition of the need to define an operational classification system for various degrees of DCS symptoms, along with the responses necessary to efficiently get the crewmember repressed in the airlock, while also maintaining the Shuttle in a safe configuration for re-entry. The operational DCS classification system was integrated with the EVA malfunction cuff checklist, worn on the forearm of the EVA crewman. The EVA "Cuff Classification" system is an "operational" classification of DCS symptoms. A crewmember experiencing symptoms during an EVA verbalizes to Mission Control a Cuff Class number based on symptoms and level of interference with performance. A pre-established response plan is then followed which 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 communication of symptoms to the Mission Control team is designed to maximize the health and safety of crewmembers. The Cuff Classification system also serves as the basis of formulating "simulated DCS scenarios" for the Mission Control flight team and EVA crewmembers to rehearse during pre-mission training.

DCS treatment flows were developed employing the general concepts of diving treatment tables. The principal tenets of treatment include oxygen and pressure over time, with fluids and medications as adjunctive. In the earlier version of space DCS treatment, crewmembers where returned to cabin pressure as soon as possible. The suit was then depressurized to cabin pressure and after approximately 30 minutes of air breathing, a bends treatment apparatus (BTA) was installed on the suit, providing the capability to increase the suit pressure to up to 8.3 psi above cabin pressure. Database analysis suggested that the return to cabin pressure from the 4.3 psia (29.6 kPa) hypobaric environment of the EMU would be sufficient to treat the majority of Type I (pain only) symptoms (96%). For this reason the decision was made to initially leave the crewmember pressurized in the suit at 4.3 psi over cabin pressure breathing 100% oxygen. Another key development was to not just treat the symptoms, but to treat the gas bubble and for this reason additional oxygen breathing was performed for up to 2 hours 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 BTA while the suit was pressurized and the crewmember breathing oxygen. This provided the capability to increase suit pressure if more serious symptoms did not respond to compression to 4.3 psi above cabin pressure. Unless an affected crewmember is severely compromised, he or she will remain in the suit during the initial phases of treatment with the EMU serving as the treatment vessel. Many technical aspects were taken into consideration when addressing the treatment challenge of a suited crewmember, including communications, EMU and vehicle configuration, suit consumables, and airlock repressurization procedures. Treatment outlines were subsequently converted into Malfunction Procedures (MAL), which follow the checklist format and decision trees that astronauts are accustomed to using.

Medical kits are flown on both the Space Shuttle and the ISS. Although constrained by available size and weight, they are designed to address a broad range of medical conditions based upon prior spaceflight experience and anticipated illnesses and injuries. Post-suit-doffing medical treatment includes oral or IV hydration, as well as additional oxygen by facemask. The Shuttle medical kits currently contain 3.1 liters of normal saline, with 12.1 liters of normal saline aboard the ISS. At the present time, no other adjunctive medications are currently flown for specific support of DCS treatment.

A simple DCS neurological examination was developed hat can be performed on an EVA crewmember, by a non-physician astronaut, as a tool to assess signs and symptoms over time. The exam was created to assess motor and neurological functions when evaluating a crewmember either fully suited or with the suit doffed.

“Flight rules” are pre-established 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. They seek to avoid miscommunication across disciplines and maximize effective decisions. Flight rules have been developed for EVA that deal with “oxygen payback” ratios for air breaks in prebreathe, specify deorbit requirements to designated worldwide Primary Hyperbaric Care sites, and address resolved and unresolved Cuff Classes. Using expertise from both internal and external to NASA, a “system” in now in place to more effectively address a potential case of DCS on-orbit.

**System and Methods for Monitoring Astronaut Health Status**

The goal of EVA medical support is to facilitate safe working conditions for cosmonauts/astronauts during spacewalks, maintain their health and maintain a high level of mental and physical performance capacity. Many of these roles have been previously discussed in other chapters but not specifically attributed to the medical community.

Volume II (need to add title of Volume II, which I forgot to bring home) Chapter 2 discusses the control of toxins and contaminants in space habitats. One of those habitats is the inside of an EVA space suit. With closed-loop life-support systems  recirculating limited interior gas volumes and operating periods that have exceeded eight hours, such control is critical to crewmember comfort, safety and long-term health. For US space-suit use, every possible element and compound that can possibly be in the habitat is analyzed and safe limits are established by NASA medical personnel. The NASA medical community additionally establishes safety limits for ionizing radiation that can cause loss of life and far reaching health issues.

Volume II (need to add title of Volume II, which I forgot to bring home) Chapter 14 discusses current space suits. To reach these states of technical evolution, many hundreds of developments spanning more than four decades had to be extensively human-tested. To prevent suit-subject injury and potentially harmful long-term effects from use, those developments were either monitored directly by space agency or contractor medical staff or conducted under strict medically established protocols. This also applies to earthly training in preparation to working in EVA.

Medical monitoring also is provided during special training, pre-EVA and EVA. As illustrated in Table 4, monitoring of astronauts during EVA has been conducted from the beginning.

**Table 4.** US EVA Real-time Medical Monitoring Parameters

| Program | Medical Monitoring Parameters |
|---|---|
| Gemini | ECG, impedance pneumogram, and space-suit technical parameters |
| Apollo | ECG, metabolic rates (two methods) space-suit technical parameters |
| Skylab | ECG, respiration by impedance pneumogram, body temperature, cardiotachometer, metabolic rate (two methods), and space-suit technical parameters |
| Shuttle/ISS | ECG, metabolic rates ( one method), space-suit technical parameters |

Other facets of NASA physician and biomedical engineer support include crew training on the physiology and treatment of DCS. Mission control simulations for DCS cases are vital to proper handling and dispostition of event. Medical monitoring also is required for baseline physiological and prebreathe protocols. Flight rule development integrated all relevant disciplines involved with EVA. Since EVA crewmembers are international, these multi-dimensional activities require a close dialog among international partners.

### EVA frequency and Work Efficiency Index

The actual EVA itself is part of a long work day that includes pre-EVA preparation, suit donning, prebreathe, airlock decompression, conducting an EVA that can last more than 8 hours, re-entering and securing the airlock, recompressing the airlock and doffing the space suit. Thus, back-to-back days of EVA would be overly fatiguing. An EVA work efficiency index (WEI) for suits and airlocks has been defined as EVA Time / Total EMU/A/L Prep + Prebreathe + A/L Depress + A/L Repress + Total Post EVA). Table 4 below shows the WEI for Shuttle and ISS EVA operations. There is a significant amount of time spent preparing 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 WEI ranges from approximately 0.39 to 0.51, meaning that more than twice as much time goes into preparing for an EVA, than actually performing the EVA. Significant improvements in WEI will be required to support the high frequency EVAs anticipated for the Constellation Lunar Architecture, which includes a requirement for a WEI > 3.0.

**Table 5**. Work Efficiency Index (EVA time (based on a 6.5 hour EVA)/ the overhead associated with pre and post-EVA preparations of the suit and airlock systems.

| PREBREATHE PROTOCOL | Shuttle 10.2 Staged Decompression (12 hrs at 10.2) | ISS: 4 hour In Suit | ISS CEVIS Exercise (Using ISS O2) |
|---|---|---|---|
| **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 config | 95 | 90 | 90 |
| Consumables Prep | 60 | 120 | 120 |
| EVA prep - prebreathe related | 60 | 0 | 80 |
| EVA prep - EMU related | 30 | 30 | 30 |
| Suit donning & 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 depress | 15 | 30 | 40 |
| Airlock egress | 15 | 15 | 15 |
| Airlock ingress | 15 | 15 | 15 |
| Airlock repress | 15 | 15 | 15 |
| Suit doffing | 25 | 25 | 25 |
| SAFER doffing & stow | 10 | 10 | 10 |
| Post EVA processing | 105 | 90 | 90 |
| **TOTAL** | **758** | **992** | **902** |
| **EVA WORK EFFICIENCY INDEX** | **0.51** | **0.39** | **0.43** |

### Conclusions

As of May 2006, over 750 hours of EVA have been conducted in US space suits and over 1,250 hours in US and Russian space suits. All the EVAs were successful with the crewmembers returning safely and in good health. EVAs are one of the most challenging parts of space flight, and this record of success is a tribute to the entire world wide EVA community.

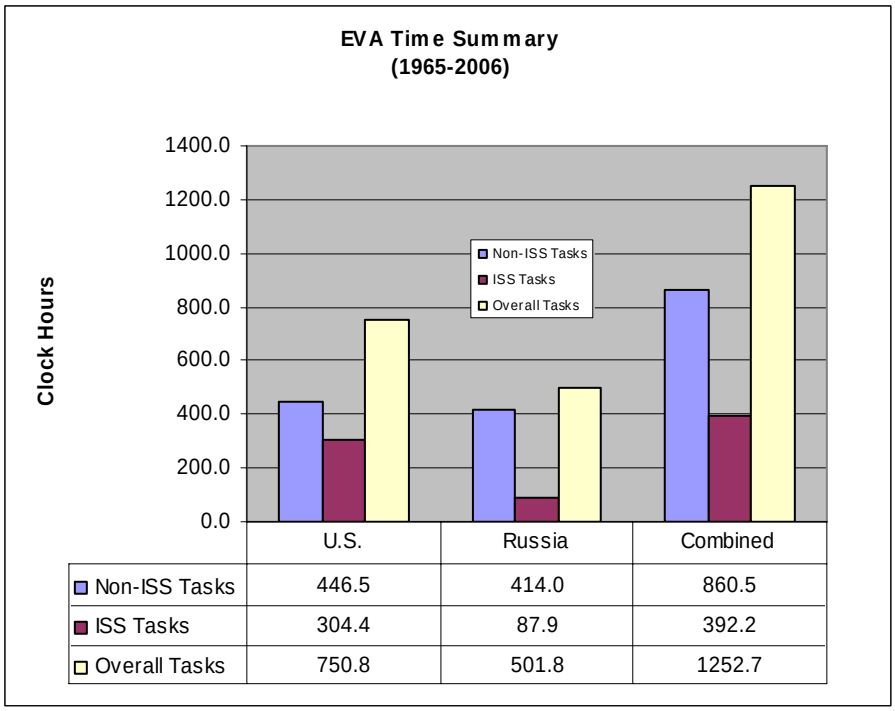


**Figure 8**. Cumulative EVA hours in US and Russian suits from 1965-2006.

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**Acronyms Used**

| | |
|---|---|
| ALSA | astronaut life support assembly |
| AMB | aerospace medical board |
| DCIEM | Defence and Civil Institute of Environmental Medicine |
| DCS | decompression sickness |
| DRDC | Defence Research Development Canada - Toronto |
| ECG | electrocardiogram |
| ECLSS | environmental control and life support system |
| EMU | extravehicular mobility unit |
| EVA | extravehicular activity |
| HHMU | hand-held maneuvering unit |
| HUT | hard upper torso |
| ISD | in-suit Doppler |
| ISS | international space station |
| JSC | Johnson Space Center |
| LSU | life support umbilical |
| NASA | National Aeronautical and Space Administration |
| PFO | patent foramen ovale |
| PLSS | portable life support system |
| PRP | prebreathe reduction program |
| REBA | |
| SAFER | |
| VGE | venous gas emboli |