



Updates to NASA's Break-in-Prebreathe Flight Rules Due to Type II Decompression Sickness Risk Considerations

Andrew F. J. Abercromby, PhD¹

Alejandro Garbino, MD, PhD, MPH²

Matthew S. Makowski, MD³

Emily E. Matula, PhD⁴

Elias K. Myrmo¹

Robert Sanders, MD¹

¹*NASA Johnson Space Center, Houston, Texas*

²*Geocontrol Systems, Houston, Texas*

³*University of Texas Medical Branch, Galveston, Texas*

⁴*KBR, Houston, Texas*

National Aeronautics and Space
Administration

*Johnson Space Center Houston,
Texas 77058*

October 2024

NASA STI Program Office ... in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Report Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.

- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>
- E-mail your question to help@sti.nasa.gov
- Phone the NASA STI Information Desk at 757-864-9658
- Write to:
NASA STI Information Desk
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199



Updates to NASA's Break-in-Prebreathe Flight Rules Due to Type II Decompression Sickness Risk Considerations

Andrew F. J. Abercromby, PhD¹

Alejandro Garbino, MD, PhD, MPH²

Matthew S. Makowski, MD³

Emily E. Matula, PhD⁴

Elias K. Myrmo¹

Robert Sanders, MD¹

¹NASA Johnson Space Center, Houston, Texas

²Geocontrol Systems, Houston, Texas

³University of Texas Medical Branch, Galveston, Texas

⁴KBR, Houston, Texas

National Aeronautics and Space
Administration

*Johnson Space Center Houston,
Texas 77058*

October 2024

Available from:

NASA STI Program
Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161

This report is also available in electronic form at <http://www.sti.nasa.gov/> and <http://ntrs.nasa.gov/>

CONTENTS

ACRONYMS & DEFINITIONS	vi
EXECUTIVE SUMMARY	viii
1.0 Introduction and Background	10
1.1 Team Formation and Purpose	10
1.2 Decompression Sickness Risk Mitigation	11
1.2.1 Types of Decompression Sickness	11
1.2.2 Decompression Sickness Risk Mitigation for Spaceflight	12
1.3 Ground Vacuum Test Setup & Timeline	14
1.3.1 Chamber Test Objective, Setup, and Timeline	14
1.3.2 Type II Decompression Sickness Case	15
2.0 Post-Mishap Approach	15
3.0 Assessment of Vacuum Chamber DCS Risk Mitigation Protocols	16
3.1 Prebreathe Duration	16
3.2 Late Break-in-Prebreathe	17
3.3 Fit-related Mask Leak	19
3.4 Thermal Effects	20
3.5 Subject Predisposition	20
4.0 Ground Testing Recommendations	21
4.1 Restart Prebreathe Following Break During Ground Testing	21
4.2 Assess Flight Rule Adequacy Regarding Breaks in Prebreathe	22
4.3 Prohibit Mask-to-Suit Transitions During Prebreathe	22
4.4 Improve Test Subject Thermal Neutrality	22
4.5 Quantify Possible Prebreathe Mask Leakage	23
4.6 Continue with Existing Nominal Ground-Based Prebreathe Protocols With Exceptions ...	23
4.7 Re-evaluate Risk Estimates and Protocols for Runs Exceeding 6 Hours	24
5.0 Assessment of Flight Rules Regarding Breaks-in-Prebreathe	24
5.1 In-Suit Light Exercise (ISLE) Prebreathe Protocol	25
5.2 Review of Flight Rule History & Documentation	26
5.3 Consultation with Subject Matter Experts	28
5.4 Review of Relevant Literature	28
5.5 Review of NASA's Operational Experience	30
5.6 Model Analysis	30
5.7 EVA IPT Discussion	32
6.0 Flight Rule Update Recommendations	34
6.1 Recommended Phase 3 Changes	34
6.2 Recommended modifications to the flight rule wording	35
7.0 Management Review, Approval, and Implementation of Recommendations	37

8.0	Report Archiving	38
9.0	Acknowledgements	38
10.0	References	39

TABLES

Table 1 – Expected Number and Type of Suited Vacuum Chamber Runs from 2018-2028.....	Error! Bookmark not defined.
Table 2 – NASA’s DCS Disposition Policy (from JPD 1800.3 DCS Manual)	Error! Bookmark not defined.
Table 3 – Tiger Team Work Plan.....	Error! Bookmark not defined.
Table 4 – Highest Acceptable Type II Risk to Meet Acceptable Cumulative Risk Criteria, Assuming Equal Risk for All Runs	Error! Bookmark not defined.
Table 5 – Estimated Type I and Type II DCS Risk Associated with Current 4-hour Prebreathe	Error! Bookmark not defined.
Table 6 – Prebreathe Durations Meeting Acceptable Risk Criteria.....	Error! Bookmark not defined.
Table 7 – Current and Planned Duty Days for Test Subject and Test Team	Error! Bookmark not defined.
Table 8 – Recommended Prebreathe Durations and Associated Type I and Type II Risk Estimates for Suited Vacuum Chamber Runs	Error! Bookmark not defined.
Table 9 – DCS Symptoms Tracking Log Excerpt with Example Entries...	Error! Bookmark not defined.
Table 10 – Hypobaric Chamber DCS Archive Excerpt.....	Error! Bookmark not defined.
Table 11 – Risk Assessment Codes for Type I and Type II DCS During Suited Ground Vacuum Chamber Testing	Error! Bookmark not defined.
Table 12 – Summary of Tiger Team Recommended Changes	Error! Bookmark not defined.

FIGURES

Figure 1 – Effect of ambulation on DCS and Grade IV VGE.	Error! Bookmark not defined.
Figure 2 – Space Shuttle prebreathe ground trial DCS data. A 4-hour prebreathe results in a 360-minute tissue ratio of 1.65.....	Error! Bookmark not defined.
Figure 3 – Methodology flowchart.	Error! Bookmark not defined.
Figure 4 – Modeling approach.	Error! Bookmark not defined.
Figure 5 – SSATA run duration data for most recent 27 SSATA runs as of June 2018.	Error! Bookmark not defined.
Figure 6 – Example SSATA run pressure profile.	Error! Bookmark not defined.
Figure 7 – Comparison of recommended prebreathe risk levels with observed Type II DCS incidence threshold. Purge (12 min) and Depress (20 min) are reason that “4:00 PB” is shown below threshold; total time = 4:32.....	Error! Bookmark not defined.
Figure 8 – Post-test DCS diagnosis criteria flowchart.	Error! Bookmark not defined.

ACRONYMS & DEFINITIONS

AFRL	Air Force Research Laboratory
ATA	Atmosphere Absolute
BGI	Bubble growth index
BTGI360	Computed bubble growth index in theoretical 360-min half-time tissue compartment
CCB	Configuration Control Board
CEVIS	Cycle Ergometer with Vibration Isolation and Stabilization
CM	cutis marmorata
CMO	crew medical officer
CTSD	Crew and Thermal Systems Division
DCS	decompression sickness
EMU	extravehicular mobility unit
EVA	extravehicular activity
HH&P	Human Health and Performance
HH&P EVA-IPT	Human Health & Performance Extravehicular Activity Integrated Product Team
HHPD	Human Health and Performance Directorate
HSRB	Human Systems Risk Board
ISLE	In-suit Light Exercise
ISS	International Space Station
JSC	Johnson Space Center
LBA	lower body adynamia
mmHg	millimeters of Mercury
O ₂	oxygen
PB	prebreathe
P _I N ₂	computed tissue nitrogen partial pressure
P(DCS)	probability of decompression sickness
PMC	private medical conference
PO ₂	partial pressure oxygen

PRP	Prebreathe Reduction Program
psi	pounds per square inch
psia	pounds per square inch absolute
P(serious DCS)	probability of serious decompression sickness
RAC	risk assessment code
SSATA	Space Station Airlock Test Article
SSPCB	Space Station Program Control Board
STS	Space Transportation System
TBDM	Tissue Bubble Dynamics Model
TR	tissue ratio
TR360	Computed tissue ratio in theoretical 360-min half-time tissue compartment
UPTD	Unit pulmonary toxicity dose
USAF	United States Air Force
VGE	venous gas emboli

EXECUTIVE SUMMARY

Investigation of a central neurological decompression sickness (DCS) case during hypobaric ground testing at Johnson Space Center (JSC) identified a ~3 min break-in-prebreathe (BiP) late in the prebreathe (13 min prior to depressurization) as the leading credible cause for the DCS case. This occurred despite applicable prebreathe payback rules being followed. Applicable NASA rules, for ground and flight, directed 2:1 payback of breaks up to 10 min in duration, regardless of when a break occurs relative to depress. Breaks lasting longer than 10 min require a complete restart of the prebreathe protocol. The adequacy of NASA's BiP rules was evaluated prior to resuming any hypobaric ground testing or International Space Station (ISS) extravehicular activity (EVA).

Of particular interest to the authors was the timing of the BiP in relation to the overall prebreathe timeline. Although there exists no agreed-upon definition, a 'late' BiP means towards the end of the prebreathe period, and in particular, the last hour prior to depressurization.

The following information sources were reviewed prior to formulating recommendations: i) the type II DCS case report and findings from the investigation; ii) documented rationale for existing flight rules, iii) consultations with subject matter experts involved in definition of existing flight rules (several of whom had since left NASA); iv) relevant published literature; v) tissue gas loading model estimates; and vi) NASA's operational experience with late breaks in prebreathe.

NASA's nominal prebreathe protocols are validated via extensive ground testing to ensure DCS risk is reduced to within acceptable limits. Conversely, there exists a paucity of data, zero validated models, and limited documentation regarding BiP risk for NASA prebreathe protocols. Flight rules for Shuttle and later ISS appear based primarily on expert opinion and an assumption of symmetric on-gassing and off-gassing dynamics, which would suggest 2:1 payback a conservative mitigation for a BiP. However, exponential gas kinetics make late breaks higher risk, or requiring greater payback, than earlier breaks. Two BiPs have occurred on ISS using the current ISS prebreathe protocol, each of which was followed by greater than 2:1 payback and followed by at least 59 min of 100% O₂ prebreathe prior to the actual depress. No DCS cases have been reported during EVA operations.

Because of this serious DCS case with a late BiP as the presumptive cause, interim changes were implemented to protect against late breaks during both ground and flight prebreathes. Given the paucity of human tests or BiP models, this approach used a negligible difference in calculated tissue/compartments ppN₂ pre-depressurization compared to validated protocols as a proxy of equivalence. Additional documentation and literature review elicited no further data that could be used to further refine these assumptions. As a result, the interim changes have been extended indefinitely, and a recommendation has been made to support future chamber tests with the objective of additional ground and flight rule updates, as well as the development and validation of a BiP risk model.

(This page intentionally left blank.)

1.0 INTRODUCTION AND BACKGROUND

1.1 TEAM FORMATION AND PURPOSE

Prebreathe protocols for ground-based vacuum chamber testing do not eliminate the risk of Type II (i.e., serious) decompression sickness (DCS) but are estimated to reduce the risk to less than 1 in 1,000 for any given exposure (Abercromby et al, 2019). As such, when a Type II DCS event was diagnosed following a suited vacuum chamber test at NASA Johnson Space Center (JSC), an investigation was initiated to identify and evaluate possible contributing factors. Additionally, the JSC Chief Medical Officer (CMO) requested recommendations regarding the adequacy of DCS risk mitigation protocols for other NASA vacuum chamber ground testing in light of the Type II DCS event.

This report details the recommendations provided to the JSC CMO along with rationale and anticipated impacts. A high-priority assessment of ISS extravehicular activity (EVA) flight rules was included among the initial recommendations, promptly initiated at the direction of the JSC CMO. This report also describes the approach and outcome of that assessment. The broader mishap investigation is not described in detail in this report.

The decision was made to leverage the existing EVA Integrated Product Team (EVA-IPT) rather than form an ad hoc Tiger Team. The primary EVA-IPT participants in the assessment and formulation of recommendations are listed in Table 1.

Table 1. Primary EVA IPT participants involved in formulation of recommendations.

Andrew Abercromby, Ph.D.	Human Physiology, Performance, Protection & Operations (H-3PO)/SK (Team Lead)
Robert Sanders, M.D.,	Space and Occupational Medicine Branch/SD (EVA-IPT Chair)
Joseph Dervay, M.D.,	Space and Occupational Medicine Branch/SD
Alejandro Garbino, M.D., Ph.D., MPH	Human Physiology, Performance, Protection & Operations/SK
Richard Watson	Crew and Thermal Systems Division/EC
Sharmila Watkins, M.D., MPH	Human Health & Performance Directorate/SA
Jason Norcross	Human Physiology, Performance, Protection & Operations/SK
Mallory Jennings	Crew and Thermal Systems Division/EC5
Matthew Makowski, M.D., Ph.D.	Space and Occupational Medicine Branch/SD
Scott Ross	Safety & Mission Assurance/NA
Emily Matula, Ph.D.	Flight Operations Directorate/CX
Elias Myrmo	Flight Operations Directorate/CA
Rebecca Wingfield	Flight Operations Directorate/CA

1.2 DECOMPRESSION SICKNESS RISK MITIGATION

1.2.1 TYPES OF DECOMPRESSION SICKNESS

Astronauts and test subjects are exposed to the risk of DCS during EVAs and/or during ground-based vacuum chamber testing. Individuals are saturated with inert gas (mostly nitrogen) at a pressure equivalent to the inert gas pressure of their environment. Spacesuits operate at reduced pressure, and when the amount of inert gas in an occupant's body exceeds what can be held in solution at the new lower pressure, that gas has the potential to come out of solution to form gas spaces that can displace or otherwise damage tissues.

DCS is often classified as either Type I or Type II; understanding the difference between these classifications is essential to understanding the risk mitigation approach and associated recommendations provided by the Tiger Team. In simple terms, Type I is often referred to as “pain-only” and Type II as “serious.” NASA's Decompression Sickness Manual JPR 1800.3E provides the following more-detailed classifications:

- 1) Mild DCS (Type I): symptoms involving joint pain, peripheral nervous system, or simple skin bends.
- 2) Serious DCS (Type II): symptoms involving the central nervous system, cardiovascular system (circulatory collapse/shock), pulmonary system (chokes).

However, these classifications do not encompass the full spectrum of decompression-sickness related findings.

- Cutis Marmorata (CM) is a skin DCS symptom that results in a mottled rash; often on the truncal areas. Both in NASA and altitude/diving medicine, it has been alternately classified as a type I or type II symptom—even though it in of itself does not cause significant pain nor long-lasting sequelae (“mild”), it is often observed along with significant symptoms, including neurological deficits (“severe”). The JSC Medical Operations Board and the Aerospace Medical Board placed CM in its own category—classified as Type I DCS in the absence of serious symptoms (Conkin, 2002, see JPD 1800.2B, DCS Disposition Policy).
- Arterial gas emboli can result in bubbles on the arterial side flowing to the brain, causing neurological injury, i.e., severe DCS. The most dangerous mechanism to introduce gas bubbles into the arterial circulation is where alveolar gas is forced into the arterial circulation as a result of pulmonary barotrauma. However, when significant venous gas loads are generated, the possibility of arterializing venous bubbles (“right to left shunt”) increases, particularly if there is a preexisting patent foramen ovale (PFO) or other shunt. The significance of right-to-left shunts in altitude DCS is still debated; NASA hosted an expert panel in June 2024 highlighting the paucity of both data and human data on the topic (NASA/SP-2024-0010473).
- “Subtle” Type II symptoms can also be detected on post-exposure detailed neurological examination. These findings show some change from the baseline medical exam but were not reported nor apparent to the patient. Although they concern the neurological system (i.e., “type II”), they are not “severe”—not noticed by the afflicted individuals, with full resolution, and no apparent long-term health effects. These sub-clinical findings are sometimes noted on research exposures and would most likely be missed in the operational setting, potential highlighting a gap in detection, diagnosis, clinical significance, and classification.

Importantly, the 2019 DCS Tiger Team (Abercromby et al. 2019) looked for and found no reports of untreatable Type I altitude DCS symptoms; in all cases, symptoms were fully resolved with no long-term health effects. As such, while symptoms can be painful and there is an ethical responsibility to limit that risk, it was recognized that Type I DCS symptoms do not represent a risk to life or long-term health if treated appropriately.

1.2.2 DECOMPRESSION SICKNESS RISK MITIGATION FOR SPACEFLIGHT

The risk of DCS can be reduced by oxygen prebreathe. Prebreathe gradually eliminates nitrogen from the body, thereby reducing the likelihood that nitrogen bubbles will expand inside the body during decompression, recognized as the cause of DCS symptoms (Conkin, 2001). A detailed historical description of the development and implementation of prebreathe protocols is available (Conkin, 2011) but is not included in this report. Waligora (Waligora, 2000) provides a chronology of the evolution of prebreathe protocols used by NASA from Gemini until the beginning of the Prebreathe Reduction Program (PRP), which are summarized below:

- Mid-Apollo Program: Change from 4-hour to 3-hour pre-launch prebreathe. Rationale not available.
 - Anecdotal (non-medical) self-diagnosis of DCS during Gemini 10, Apollo 11
- 1978: United States Air Force (USAF) study (for NASA) finds 42% DCS with 3-hour prebreathe; concerns raised over safety of 3-hour prebreathe.
- 1982: Ground testing finds 36% DCS with 3.5-hour prebreathe; 21% DCS with 4-hour prebreathe; 23% with 10.2 psi staged protocol. 3.5-hour and staged protocols approved for flight.
- 1983-86: Ground testing finds 10% DCS with 6-hour prebreathe; 0% DCS with 8-hour prebreathe.
- 1986: Post-Challenger center-wide safety review results in change from 3.5- to 4-hour prebreathe.
- 1993-4: Research study finds reduced DCS in simulated microgravity (vs. ambulatory) and with mild exercise during prebreathe.
- 1997+: Initiation of ISS Prebreathe Reduction Program with the objective to decrease prebreathe from 4 hr to 2 hr for ISS EVA; use of simulated microgravity and mild exercise to develop and validate Cycle Ergometer with Vibration Isolation and Stabilization (CEVIS) and In-suit Light Exercise (ISLE) protocols (applicable only to microgravity exposures).
- 2010: ISLE Protocol approved for use. Becomes the de-facto ISS prebreathe protocol.
- 2016: CEVIS is formally archived. It was used for 52 person-exposures, primarily during ISS assembly (2001–2006). However, due to its procedural complexity, crew training requirements, and significant consumable burden (primarily high-pressure O₂), it was archived in favor of ISLE. This effectively made ISLE the primary protocol, with over 150 person-exposures to date.

Additional details are provided in the DCS Tiger Team Report, which also describes the most recent assessment of NASA's DCS risk mitigation protocols for ground-based vacuum chamber testing.

Decompression Sickness Risk Mitigation for Ground Vacuum Chamber Testing

Suited vacuum chamber testing is critical to flight crew training, sustaining engineering, and development engineering. At the current time, the ISS Program relies upon the training of flight crew in the Space Station Airlock Test Article (SSATA) at a rate of approximately seven vacuum runs per year. The ISS Extravehicular Mobility Unit (EMU) also requires testing events in the 11-foot chamber for the revalidation of refurbished EMUs prior to delivery for flight at the beginning of their maintenance interval and for hardware special studies. Both types of events are long duration with relatively high workloads but are infrequently performed. Vacuum and thermal-vacuum chamber testing is also essential for the development and testing of a range of new launch-entry-abort (LEA) and EVA spacesuits currently in development, as well as developing new prebreathe protocols for Exploration-class missions.

In 2018, planning for a new series of chamber tests that would entail high metabolic workloads for 8 hr or longer at 4.3 psia raised concerns about the adequacy of the 4-hour prebreathe. In response, a Chamber Test Tiger Team was stood up, composed of experts from the medical, chamber engineering, and EVA/space suit divisions. The goal of this team was to reassess and provide recommendations to mitigate the DCS risk specifically for chamber testing events, not flight protocols. This differed significantly from previous flight protocols in several ways. A major difference is that the presence of the Earth's gravity—and subjects ambulating in the chamber—significantly increases both metabolic rate and tribonucleation compared to microgravity EVAs (and recumbent chamber tests where subjects do not ambulate), resulting in a significantly higher DCS risk (Conkin et al., 2017). Conversely, subjects of ground chamber tests benefit from the ability to recompress and exit hypobaric chambers within minutes (as opposed to during flight, where a return to an airlock/safe haven could take much longer) and can also deploy to an adjacent hyperbaric chamber, allowing for almost immediate treatment of even severe symptoms. In flight, treatment for DCS is limited to over pressuring the suit inside the airlock (which does not meet ground treatment protocol pressures and has never been validated) while support is from fellow crew who may not necessarily be medically trained or current in said training. Ground testing can provide immediate standard of care and benefits from access to on-site and regional medical resources.

After reviewing existing human test data, models, and procedures, the Tiger Team published their findings in 2019. A variety of pressure exposures and durations were assessed, and model calculations for both Type I and Type II DCS were included as well as guidance for any exposures outside this range. The most common type of exposures are from sea level to a particular final pressure, with varying durations of exposure. Using an equal-risk approach, DCS models were used to provide minimum prebreathe durations necessary for various exposure durations/pressures, and are summarized in JPR1830.6 Table 4-1.

Table 4-1 Acceptable Crew Member Hypobaric Exposure and Prebreathe Times

Lowest Exposure Pressure on Body (psia)	Altitude (feet)	Exposure Time From Leaving Site Pressure to Returning to Site Pressure (minutes)	Prebreathe Time Requirement using $\geq 95\%$ Oxygen (minutes)
7.4	18,000	Unlimited	None
6.5	21,000	Unlimited	90
5.4 ¹	25,000	0-15	35
5.4 ¹	25,000	15-35	45
4.3	30,500	30	60
4.3 ²	30,500	31-120	240
4.3	30,500	>120	270

¹Specific NASA Hypobaric Chamber Flight used in physiologic training.

²This exposure and prebreathe combination does allow for brief period of less than 15 minutes total at 3.5 psia.

The Tiger Team did not address BiPs. Mask-to-suit transitions were ground-ruled out due to the architecture and concept of operations of NASA’s suited testing, but not explicitly precluded. Both played a role in the 2023 Type II DCS case.

1.3 GROUND VACUUM TEST SETUP & TIMELINE

Details and imagery of the specific test, suit, chamber, and test subject event that triggered this report are not included due to the potential for attributability and the necessity to maintain medical privacy. The pertinent information is summarized in the following sub-sections.

1.3.1 CHAMBER TEST OBJECTIVE, SETUP, AND TIMELINE

The primary objective of the test was to evaluate the spacesuit hardware under flight-like environmental conditions. The test was not intended as an evaluation of human physiological responses to the decompression. The intent was to use a known safe prebreathe protocol based on existing NASA policies and protocols for this type of suited hardware evaluation.

Based on the suit operating pressure (≥ 4.3 psi) and the planned duration of the decompression (3-6 hr), the required prebreathe duration per JPR1830.6 was no less than 4.5 hr.

The pre-test Type II DCS risk was estimated at less than 1 in 1,800 based on JPR1830.6, assuming completion of the 4.5 hr of 100% O₂ prebreathe. However, for operational reasons, the test protocol called for the subject to perform the prebreathe on an oxygen mask prior to donning the spacesuit, with a short, planned interruption or “break” in the prebreathe while the subject took off the oxygen mask to don the spacesuit. After closing the spacesuit visor and flowing 100% O₂ into the spacesuit, the subject would then continue the oxygen prebreathe from inside the suit without the mask. To account for the BiP, the test plan called for a “payback” of prebreathe duration equivalent to at least double the duration of the break. For example, a 2 min break would be followed by at least 4 min of additional prebreathe, consistent with the 2:1 payback rule documented in the chamber test team procedures.

An assessment of the protocol was not requested from NASA’s DCS risk estimation experts as it was understood by both the NASA and non-NASA chamber test team to be within the scope allowed by applicable policies, including JPR1830.6.

As executed, the timeline was as follows:

- 4 hr 44 min 100% O₂ Mask Prebreathe
- 2–3 min off-mask during suit donning (two attempts were required to don suit)
- Visor down, 100% O₂ to helmet for 13 min before initial depressurization
- 3 hr 35 min total hypobaric time (2:53 at 5.0 to 4.3 psia)
- During the decompression, the suited subject performed ambulatory and non-ambulatory tasks at low metabolic rates of approximately 500 BTU/hr.

1.3.2 TYPE II DECOMPRESSION SICKNESS CASE

The test subject developed clinically significant symptoms consistent with central neurological (i.e., serious) DCS several hr after completion of the suited test. Due to the very low ($< 1/1000$) probability of a serious (type II) DCS event, this case triggered an investigation. The subject later gave permission to share their medical information and answered questions to support the investigation. No additional details of the test subject's medical case are included in this report.

2.0 POST-MISHAP APPROACH

An investigation into the potential causes of the Type II DCS case was initiated following the mishap, which is summarized below but is not described in detail in this report. The simplified investigation fault tree is shown in Figure 1.

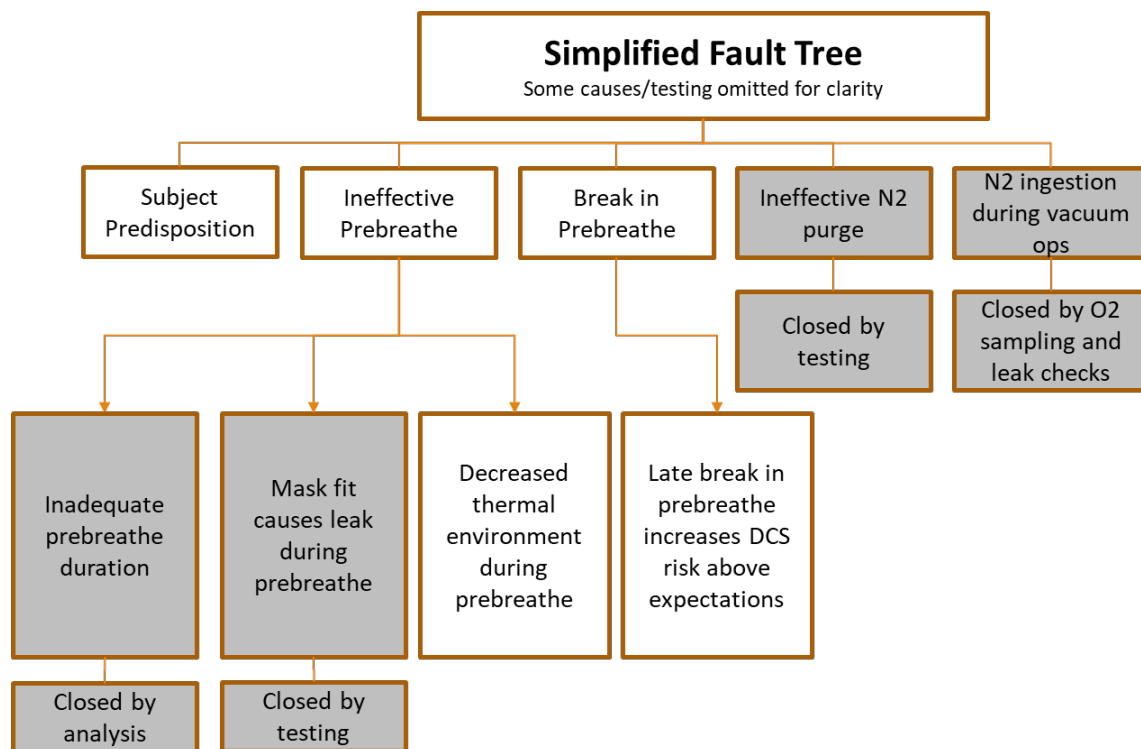


Figure 1 – Simplified investigation fault tree.

Following the Type II DCS event, all related hardware was identified and quarantined, and the test area was isolated. The test team then performed inspections of all hardware, a leak check of the integrated setup, sampling of oxygen at the cylinders and at delivery to the suit, and confirmation of prebreathe mask functionality. All hardware was verified to have performed as expected.

The test protocol involved a transition from a prebreathe using an oxygen mask to a spacesuit being supplied with oxygen. There was an expected period, before ambient nitrogen had been eliminated from the spacesuit, during which the subject would be breathing a mixture of oxygen and nitrogen inside the suit. Post-event testing was performed to quantify the rate at which residual nitrogen was purged from the spacesuit and concluded that $> 90\%$ O_2 was reached within 30 s of closing the spacesuit visor and was not impacted by limb movement. Ineffective nitrogen purge and nitrogen ingestion during vacuum operations were therefore considered to not represent credible causes or factors in the Type II DCS outcome.

In addition to the mishap investigation, the JSC Chief Medical Officer requested recommendations regarding potential implications for other NASA vacuum chamber ground testing. The decision was made to leverage the existing EVA Integrated Product Team (EVA IPT) rather than form an ad hoc Tiger Team (see Section 1.1). The EVA IPT was requested to complete a rapid assessment of the adequacy of existing DCS risk mitigation policies and processes in advance of a planned suited vacuum chamber training event in the SSATA chamber on September 7th, 2023.

On August 18, 2023, the mishap investigation team briefed the EVA IPT on their investigation. A series of follow-on EVA IPT meetings were then convened to discuss and formulate recommendations regarding NASA ground chamber testing. The EVA IPT meetings included representatives from EVA Physiology (SK), Medical Operations (SD), Engineering (EC), EVA Operations (CX), and Test Safety (NS), including the individuals identified in Section 1.1. The EVA IPT assessment focused on the remaining open branches of significance, identified in Figure 1. The assessment of each area is described in Section 3.0.

3.0 ASSESSMENT OF VACUUM CHAMBER DCS RISK MITIGATION PROTOCOLS

3.1 PREBREATHE DURATION

NASA's approach to estimating and managing Type II DCS risk for ground based vacuum chamber exposures is documented in the DCS Tiger Team Report (Abercromby et al, 2019). The model-estimated risk of Type I and Type II DCS for ground based vacuum chamber tests are shown in Table 1. Models estimating the risk of Type II DCS are inherently limited because it is unethical to conduct human testing in which serious DCS is an expected outcome. Data on Type II DCS outcomes is therefore much more limited than Type I DCS data, and much of the Type II data that does exist is based on exposures that are not comparable to decompression scenarios involving multi-hour prebreathe durations and multi-hour decompressions.

The chamber run being assessed had a total of 3hr 35min decompression, of which 2 hr 53 min was at a 4.7 psia test point. The required prebreathe duration was 4 hr 30 min based on the planned decompression profile. For operational reasons the mask prebreathe lasted 4 hr 44 min and following the 3-min break during suit donning an additional 13 min of O_2 breathing were completed prior to depressurization. Based on the suit purge testing, it is estimated that the O_2 fraction exceeded 90% within 30 s of that 13-min period. As such, the completed prebreathe met and exceeded the required 4.5 hr. Additionally, for engineering reasons the suit operating pressure

was greater (ie, lower DCS risk) than the 4.3 psi that is assumed in the risk estimates shown in Table 1.

Table 1 - Model-estimated DCS risk for ground vacuum chamber exposures (from DCS Tiger Team Report). Risk estimates assume a 4.3 psi altitude exposure.

Run Location	Suit	Exposure Duration (hr)	Number of Planned Runs	Prebreathe Time (hr)*	Risk of Type II DCS				Risk of Type I DCS	
					Risk Model			Cuff 1	TBDM All DCS	
					PDCS per Run	Risk per Run (1 in x)	Prob. of 0 Cumulative Incidents	PDCS per Run	PDCS per Run	Risk per Run (1 in x)
SSATA	ISS EMU	55 min	73	4:00	0.043%	2348	96.9%	Below Type II Threshold	5.0%	20
	xEMU	≤ 2	4		0.076%	1316	99.7%		7.9%	13
11 Foot Chamber	OCSS	≤3	10	4:30	0.052%	1938	99.5%		8.8%	11
		≤6	4		0.053%	1882	99.8%		16.1%	6
	ISS EMU	6 - 8	17		0.053%	1881	99.1%		19.5%	5
Chamber B										
Probability of 0 Type II incidents in 108 runs:							95.1%			

* Prebreathe durations assume 12 minute purge and 20 minute depress.

** SSATA Runs assume up to 15 mins at 3.5 psi at end of run.

The model-estimated Type I DCS risk for the as-performed profile was negligibly greater than for the same protocol without the break. It is important to understand that the models will allow for a user to input a profile that includes a break in prebreathe; however, the models themselves are not designed or validated to accurately estimate the risk associated with a break in prebreathe. As such, the sufficiency of the prebreathe duration itself was evaluated without accounting for the BiP. The implications of the BiP were then evaluated as a separate potential cause or contributing factor (see Section 2.2.2).

While the models have significant limitations, the as-performed chamber run extended the prebreathe beyond the required 4.5 hr, it involved a relatively short duration exposure, and used a higher-than-normal suit operating pressure, all of which contribute to a lower level of decompression stress than other accepted NASA profiles and historical data, none of which have resulted in Type II DCS.

Based on the analysis and comparison with relevant empirical data, it was concluded that inadequate prebreathe duration—absent a BiP—cannot be definitively eliminated but does not appear to be a credible cause of the Type II DCS case.

3.2 LATE BREAK-IN-PREBREATHE

The purpose of oxygen prebreathe is to remove nitrogen from the body prior to a decompression. An interruption or “break” in prebreathe can occur for a variety of reasons and results in reuptake of nitrogen into the body during the break. This reuptake of nitrogen is expected to increase the DCS risk associated with a subsequent decompression unless an appropriate “pay back” is completed to compensate for the break. There are currently no validated models to estimate how much DCS risk is increased due to a break, the amount of payback that is required, or how much the timing of a break relative to the decompression affects the risk and required payback.

Because of this inability to quantify the risk due to BiPs, NASA does not typically use protocols with planned breaks. NASA ISLE protocol allows for unplanned breaks in prebreathe of up to 10

min provided that a 2:1 payback is performed, regardless of when a break occurs relative to depressurization. If a break exceeds 10 min in duration, the prebreathe must be restarted. Although this flight rule is formally documented, no documented rationale for the rule was found during the initial assessment, and it was apparent that—unlike nominal prebreathe protocols—BiP flight rules are not based on any significant empirical data. The basis for the existing BiP rules is discussed further in Section 5.0.

The 2:1 payback rule was implemented for the chamber run being assessed, with the time off mask being just over 2 min, followed by 13 min of additional oxygen breathing prior to depressurization. As described in Section 2.0, the post-break prebreathe was performed in the spacesuit and would have initially included ambient nitrogen, but this was characterized post-event and found to be > 90% O₂ within 30 s. As such, the payback for the BiP met and exceeded the required 2:1 payback rule.

As stated, the current BiP flight rules, in effect for over 20 years, prescribe a 2:1 payback, regardless of when in a prebreathe the break occurs. However, common models of gas kinetics assume exponential equilibration dynamics such that the rate of inert gas elimination during prebreathe decreases over time as the off-gassing gradient decreases. As such, the rate of nitrogen reuptake during a break may exceed the rate at which it is eliminated during a subsequent payback period, perhaps significantly. If exponential gas kinetics are assumed, it would result in asymmetric initial on-gassing and off-gassing rates. As a result, the timing of a break in prebreathe would be expected to affect the resulting increase in DCS risk and associated payback requirement. This is discussed further in Section 5.5.

The chamber run being assessed involved a late BiP, only 13 min prior to depressurization following 4 hr 44 min of prebreathe. If the asymmetric washout assumption is used, the rate of nitrogen reuptake during the break would have far exceeded the rate of subsequent nitrogen elimination following the break. It is important to understand that models are not validated for such analyses, rather they are meant to illustrate the theoretical magnitude of the effect of this gas kinetics asymmetry, a model-predicted payback of approximately 130 min would have been required to achieve an equivalent level of denitrogenation as an “unbroken” 4.5-hr prebreathe. This would correspond to a payback ratio of ~43:1, far exceeding the prescribed 2:1.

This simple analysis may overstate the magnitude of the effect because the quantities of theoretical inert gas elimination are very small as the asymptote of gas elimination is approached. NASA’s models of DCS often use the partial pressure of nitrogen in a theoretical 360-min half-time compartment as a primary explanatory variable in estimating Type I DCS risk, and these theoretical compartments are negligibly affected by brief BiPs.

Interestingly, the half-time compartments most affected by late breaks-in-prebreathe and which would require the highest payback ratio are those with 20 to 40-min half-times, not the 360-min compartments. These “faster” compartments are thought of as representing parts of the body that are more efficiently perfused and more able to rapidly on-gas and off-gas, for example the brain and spinal cord. Conversely the “slow” compartments, such as the 360-min compartment, represent the areas such as joints and cartilage—often associated with Type I DCS symptoms—from which nitrogen elimination is thought to be much slower. Perhaps significantly, the faster compartments are also used in some models as primary explanatory variables in predicting Type II DCS.

While acknowledging the theoretical nature of the model analysis, the EVA IPT concluded that there is a possibility that the 2:1 payback rule is inadequate to limit DCS risk following late BiPs.

The EVA IPT found no records of late breaks in prebreathe during ground testing or spaceflight operations, but there have been several instances in which the 2:1 payback rule has been implemented following much earlier BiPs (see Section 5.5).

It was concluded that the plausibility of inadequate payback following the late break-in-prebreathe is a credible cause or factor in the Type II case.

3.3 FIT-RELATED MASK LEAK

During the mishap investigation, the test subject described a subjective loss of mask seal while speaking during prebreathe, with attempts to compensate by limiting speaking and holding the mask to their face when speaking. The mask used for prebreathe was the SOLR[®] Oxygen Mask by Airborne Systems (Figure 2), primarily designed for use by high altitude parachutists, but has been used for prebreathe and supplemental oxygen purposes during NASA's exploration prebreathe protocol development tests.

The NASA chamber tests can last > 6 hr on mask. To allow for hydration during these extended-duration exposures (and because dehydration is considered a risk factor for DCS), the SOLR masks have been fitted with drink ports. This modification was performed pre-delivery by the manufacturer and has lineage tracing to nuclear/biological/chemical protection variants for similar masks. As part of the investigation, the mask drink port was tested for leaks and was found not to result in a measurable leak of ambient air into the mask space.

The SOLR mask uses a demand regulator without constant positive pressure, meaning that a compromise in the seal between the mask and the face could potentially allow for ambient air to infiltrate the mask and be inspired by the wearer. It is possible that a small chronic mask leak and/or intermittent larger leaks, for example while speaking or moving the head, could compromise a prebreathe by allowing on-gassing of ambient nitrogen.



Figure 1. SOLR[®] oxygen mask.

While it is possible that the actual fit of the mask to the subject on the day of the event was compromised, post-event investigation found no evidence of mask hardware or sizing/fit procedural issues. Mask sizing measurements were reperformed, evaluated against guidelines, and matched the assigned specifications; furthermore, Airborne Systems verified performance of the mask used by the subject.

The EVA IPT considered a fit-related mask leakage as a credible cause or factor in the Type II DCS case, but less likely than the impact of the late BiP. The EVA IPT recommended experimental testing of the mask seal performance under a range of fit configurations.

Testing was subsequently performed to measure seal performance (% O₂ delivery) when using the same mask and same test subject as worn in the Type II DCS event under a variety of fit configurations, including intentionally poor fits.

Based on the results of the subsequent mask seal testing, it was concluded that a fit-related mask leakage does not appear to be a credible cause or factor in this Type II DCS case.

3.4 THERMAL EFFECTS

The test subject reported during the mishap investigation that they had felt thermally cool or cold during the mask prebreathe portion of the test. Subjective ratings of thermal state and ambient temperature during the prebreathe were not collected but were not adjusted specifically for this test (i.e., nominal HVAC conditions prevailed; there were no failures or extraordinary situations). A cool or cold thermal state in subjects is not uncommon during suited prebreathes and altitude exposures, with many subjects preferring to maintain a cool temperature out of personal preference. However, reduced body temperature may reduce the rate of denitrogenation and increase DCS risk, although evidence of this is predominantly from cases of diving DCS with more extreme cold thermal conditions (Gerth et al, 2007). Additionally, both excess heat as well as reduced body temperature can affect dexterity and cognitive performance.

The EVA IPT concluded that the cold thermal state of the test subject during prebreathe was a credible contributing factor in the Type II DCS case but considered it less likely than the late break-in-prebreathe as a significant contributing factor.

3.5 SUBJECT PREDISPOSITION

Patent Foramen Ovale (PFO) is a hole between the left and right upper chambers of the heart that is present in 25–30% of the general population. In most instances, the presence of a PFO is inconsequential and will remain undetected. However, during decompressions in which gas emboli (i.e., bubbles) form in the body, the presence of a PFO can allow for the shunting of a portion of those bubbles from the right side to the left side of the heart, rather than passing them from the right ventricle to the lungs where most or all would be eliminated. Bubbles that pass directly to the left side of the heart will instead be passed to the rest of the body where they may grow and/or potentially result in DCS symptoms. While PFOs vary in size and the presence of a PFO does not mean that a person will experience DCS, it has been shown to be a risk factor for serious DCS (Pristipino et al, 2021).

NASA screens for atrial-septal defects—congenital heart defects detectable on ultrasound—but does not use an intravenous bubble contrast study to screen astronauts or test subjects for PFO. Screening for PFO involves imaging the heart while injecting an agitated saline solution, then quantifying the extent to which bubbles can be seen shunting from the right to the left side of the

heart. There was no plan (or possibility) to monitor the subject for left-sided bubbles during the test, and a post-event screening for PFO was declined by the test subject who experienced the Type II event.

The EVA IPT concluded that subject predisposition to DCS cannot be discounted as a credible cause or factor in the Type II DCS case without additional screening. If present, PFO would be a very credible cause or risk factor in the Type II DCS case.

As a result of this gap, the Office of the Chief Health & Medical Officer (OCHMO) stood up an expert panel review of NASA’s PFO guidelines. NASA’s PFO guidelines had been last reviewed in 2001 by the Medical Policy Advisory Group (“Church” Report, 2001). Given the unexpected severity of this chamber test event, and other chamber exposures that elicited left-sided venous gas emboli, a group of NASA and external experts met at JSC in June 2024 (NASA/SP-2024-0010473). The PFO policies and Type II cases were reviewed. Briefly, the panel stated that the role of PFO in predisposing subjects to higher risk of serous DCS is still devoid of significant data sets. However, they cautioned against leveraging diving reports (where an arterialized bubbles goes to a nitrogen-saturated tissue that would maintain/support bubble growth) in altitude exposures (where the arterialized bubble goes to a nitrogen-devoid tissue, i.e., would support bubble collapse). Although no recommendations to change screening policies were made, offering PFO testing to individuals with unexpected type II DCS or observed LVGE was supported. The individual involved in this chamber test declined PFO testing.

4.0 GROUND TESTING RECOMMENDATIONS

The EVA IPT formulated seven recommendations, detailed below, based on the conclusions described in the previous section. The rationale and anticipated impact associated with each recommendation was also documented and briefed to the JSC CMO who concurred and directed their immediate implementation. In addition to JSC CMO, briefings were provided at the directorate level (Human Health and Performance, Flight Operations, Engineering, Safety, ISS, EVA, and Human Mobility directorates) and to the Center Director.

4.1 RESTART PREBREATHE FOLLOWING BREAK DURING GROUND TESTING

ID	Recommendation	Rationale	Anticipated Impact
1	Require full restart of prebreathe in the event of a break-in-prebreathe for all ground-based suited operations (e.g., helmet removal, visor opening, opening the Body Seal Closure, hatch opening in exploration EMU). Note 1: Nominal Metox changeout is not considered a break-in-prebreathe. Boot bladder manipulations and glove removal remain acceptable with purge/payback as per existing test rules.	Break-in-prebreathe a credible cause or contributing factor in Type II DCS case. Existing payback rules and allowance for late breaks in prebreathe may be insufficient to control DCS risk.	Temporary restriction believed unlikely to significantly impact operations. Updated recommendation based on additional review of historical data, literature, and models may enable less restrictive break-in-prebreathe rules. Target completion for updated recommendation: FY24 Q2.

4.2 ASSESS FLIGHT RULE ADEQUACY REGARDING BREAKS IN PREBREATHE

ID	Recommendation	Rationale	Anticipated Impact
2	Complete a high-priority EVA IPT assessment of EVA flight rule adequacy regarding break in prebreathe based on review of historical data, literature, and model analyses.	Break-in-prebreathe a credible cause or contributing factor in Type II DCS case. Successful history of break-in-prebreathe 2:1 “payback” in flight; however, flight rules allow for late breaks-in-prebreathe, thus reconsideration is warranted.	Future recommendations—if any—affecting break-in-prebreathe flight rules may impact ISS and future Exploration EVA operations. Interim recommendation to be provided prior to completion of comprehensive review.

4.3 PROHIBIT MASK-TO-SUIT TRANSITIONS DURING PREBREATHE

ID	Recommendation	Rationale	Anticipated Impact
3	Prohibit ground prebreathe protocols involving mask-to-suit transitions unless approved by the EVA IPT. Note: Mask-to-mask transitions with breath-hold and exhalation purge is acceptable.	Break-in-prebreathe is a potential cause or contributing factor in the Type II DCS case. NASA does not utilize mask-to-suit prebreathe protocols for ground-based testing, but current NASA policies do not preclude the practice.	No anticipated impact to current NASA operations.

4.4 IMPROVE TEST SUBJECT THERMAL NEUTRALITY

ID	Recommendation	Rationale	Anticipated Impact
4	Update work instructions to improve test subject thermal neutrality during prebreathe and vacuum chamber testing.	Test subject’s subjectively cold thermal state during prebreathe identified as credible contributing factor in Type II DCS case. Reduced body temperature can reduce the rate of denitrogenation and increase DCS risk, while also affecting dexterity and cognitive	No anticipated impact.

	Note: Slide to be added to test subject briefings.	performance. Excess heat can also negatively affect both human and hardware performance.	
--	--	--	--

4.5 QUANTIFY POSSIBLE PREBREATHE MASK LEAKAGE

ID	Recommendation	Rationale	Anticipated Impact
5	Utilize alternatives to SOLR oxygen masks where available for mask-based prebreathe pending results of SOLR mask leak testing. *	SOLR masks were used for prebreathe in Type II DCS case and fit-related mask leakage was identified as a potential factor or cause. Masks are not positive pressure and may allow users to inspire an unknown fraction of ambient air.	No anticipated impact to NASA suited ground testing or to flight operations (SOLR not used on-orbit). Alternative masks available for Dual Glove Box tests (October 2023). Potential operational impact to Exploration Prebreathe testing in 20' chamber depending on outcome of SOLR leak testing.

*As described in Section 3.3, the results of the SOLR mask leak testing led to the conclusion that mask leakage was unlikely to be a cause or contributing factor in the Type II DCS case, and the SOLR masks have been cleared for use.

4.6 CONTINUE WITH EXISTING NOMINAL GROUND-BASED PREBREATHE PROTOCOLS WITH EXCEPTIONS

ID	Recommendation	Rationale	Anticipated Impact
6	Continue use of existing prebreathe protocols, when conducted without interruption, for nominal ground-based suited operations up to and including 6-hour EVA simulations. Note: EMU recertification runs (6.5 hr) also permitted.	Inadequate prebreathe duration not believed to be a credible factor in Type II DCS case. Existing models are not applicable to estimate DCS risk associated with the break-in-prebreathe (BiP) during the test. EMU recertification runs permitted based on history of use within acceptable Type I DCS limits. Recommendation #7 describes rationale for excluding runs > 6 hr.	No impact to nominal prebreathe durations for runs ≤ 6 hr or for EMU recertification runs (6.5 hr).

4.7 RE-EVALUATE RISK ESTIMATES AND PROTOCOLS FOR RUNS EXCEEDING 6 HOURS

ID	Recommendation	Rationale	Anticipated Impact
7	Update DCS risk estimates and prebreathe recommendations (if necessary) based on observed DCS incidence since 2018, prior to resuming suited vacuum chamber tests with > 6 hr hypobaric exposure. Note 1: EMU recertification runs (6.5 hrs) also permitted based on history of use within acceptable Type I DCS limits. Note 2: Test subject screening criteria will also be reviewed for higher risk chamber tests.	Observed Type I DCS incidence for runs > 6 hr since 2018 exceeds model estimates; actual risk for these runs may exceed previously accepted levels. Additional analysis required to incorporate relevant data into DCS risk models, update risk analysis, and provide associated recommendations. EMU recertification runs permitted based on history of use within acceptable Type I DCS limits.	Possible impacts to testing cost and operations if additional prebreathe duration is recommended. Updates to informed consent and possibly Hazard Analysis RAC codes. Next scheduled tests with decompressions > 6 hr scheduled NET 2024. Anticipate updated recommendations prior to this time. See DCS Tiger Team Report Section 2.4 for details on impacts of increased prebreathe durations.

5.0 ASSESSMENT OF FLIGHT RULES REGARDING BREAKS-IN-PREBREATHE

In response to Recommendation #2, the EVA IPT was directed to complete the recommended high-priority assessment of EVA flight rule adequacy prior to the next scheduled EVAs, which at the time were planned for October 2023. The approach taken in the assessment of EVA flight rules regarding break-in-prebreathe are described in Section 5.0, and the resulting recommendations are detailed in Section 6.

The assessment described in this report was a preliminary assessment completed rapidly to enable implementation of any recommendations in time for the EVAs the following month; it was recognized that a more thorough review and revised recommendations were expected to follow.

The assessment included several components, described in Sections 5.2 to 5.7, including a review of the history and documentation of the existing break-in-prebreathe flight rules; consultation with subject matter experts involved in formulation of existing flight rules; review of relevant literature; review of NASA's operational experience with breaks-in-prebreathe; model analysis; and EVA IPT discussion.

5.1 IN-SUIT LIGHT EXERCISE (ISLE) PREBREATHE PROTOCOL

The assessment of break-in-prebreathe flight rule adequacy considered only breaks during the In-Suit Light Exercise (ISLE) prebreathe protocol; ISLE is the only nominal protocol currently used on ISS. The ISLE prebreathe protocol was validated through extensive ground testing with supporting data and documentation. As such, there was no concern with the adequacy of the standard ISLE prebreathe protocols and this was not reviewed.

The ISLE prebreathe protocol is summarized in Figure 3. Briefly, subjects don a mask (Phase 1) while conducting the initial preparation. The airlock is then depressurized to 10.2 psi, and O₂ increased to 26.5%. This lowers the partial pressure of nitrogen, allowing the crewmember to conduct Phase 2 without on-gassing nitrogen. Phase 2 is off-mask; the crew dons the EMU, purges it from any remaining nitrogen, and conducts a pressurization check. This pressure increase has the added benefit of “clearing” any bubbles that (per modeling) may have formed with the depress to 10.2 psi. The crewmembers are sealed inside the spacesuit during the 3rd and final phase of the protocol. Each Phase has different payback rules; this analysis and rules update is focused on the ‘late’ breaks and thus focuses explicitly on the break-in-prebreathe flight rules associated with Phase 3 (Table 3). These rules direct a 2:1 payback for breaks of up to 10 min and a full restart or alternate protocol for breaks exceeding 10 min.

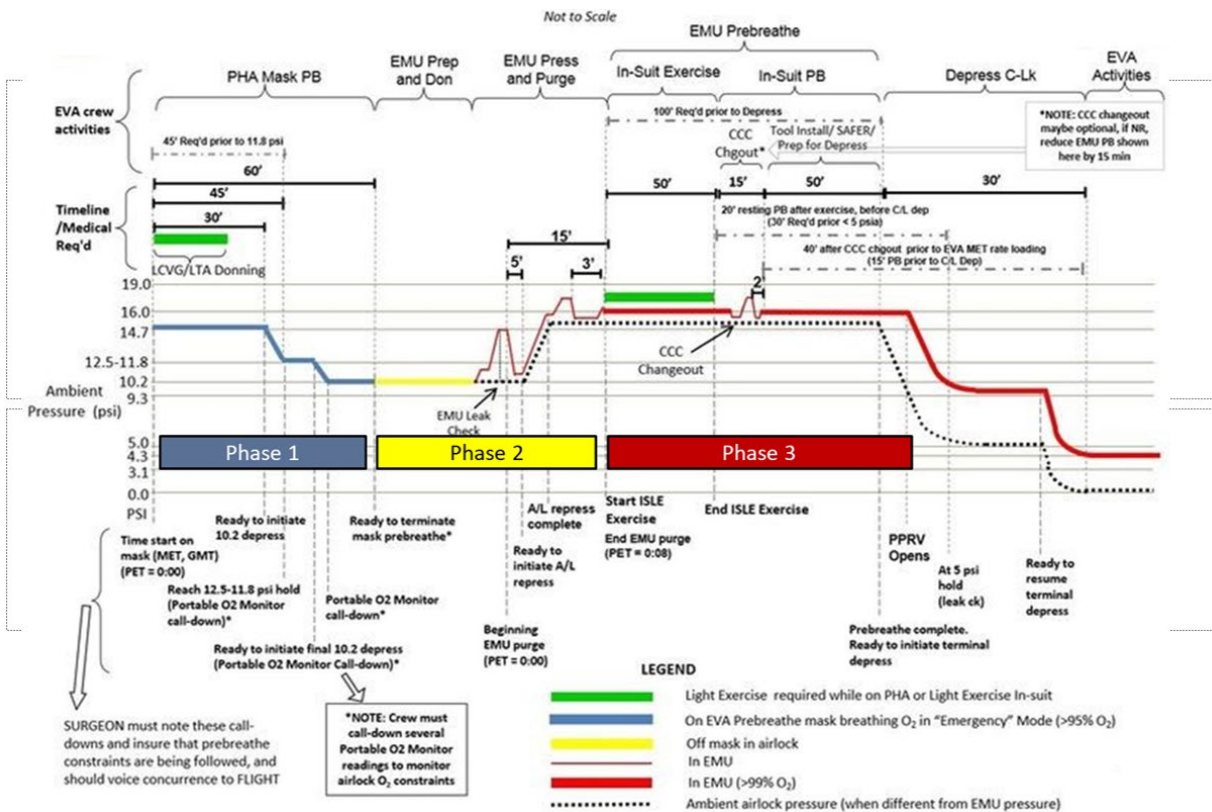


Figure 2. ISLE prebreathe protocol.

Table 2. Break-in-prebreathe flight rules during Phase 3 of ISLE prebreathe protocol.

PHASE THREE				
	PRESSURE BETWEEN CONTROL ZONE AND 14.7 PSI/760 MMHG	≤ 10-MINUTE INTERRUPTION (SINGLE OR CUMULATIVE)	MAKE UP O ₂ TIME IN SUIT. [1] [5] [7] [9]	MAKEUP RATIO: 2:1
	PRESSURE BETWEEN CONTROL ZONE AND 14.7 PSI/760 MMHG	> 10-MINUTE INTERRUPTION (SINGLE OR CUMULATIVE)	REPEAT IN-SUIT LIGHT EXERCISE PREBREATHE PROTOCOL OR CONSIDER ALTERNATE PREBREATHE PROTOCOL. [4] [7] CREW SCHEDULING CONSTRAINTS MAY NECESSITATE SHORTENING OR RESCHEDULING THE EVA.	ON MCC CALL

5.2 REVIEW OF FLIGHT RULE HISTORY & DOCUMENTATION

On contrast with the exhaustive validation and documentation of NASA's nominal prebreathe protocols, the rules for breaks-in-prebreathe are not validated with ground test data and limited documentation could be located to explain the process by which they were established. A review of EVA IPT meeting minutes from 2000 to 2014 and the associated flight rules iterations was conducted to determine the origin of the break in prebreathe (BiP) 2:1 payback rule.

Since 2000, the EVA IPT has evaluated and modified the flight rules defining the prebreathe protocols for exercise (CEVIS), 4-hr in-suit, campout, and ISLE. In 2000, the exercise prebreathe protocol required BiP payback from 1:1 to 4:1 depending on the ambient pressure and timing at which BiP occurred. For example, during airlock depress while on mask oxygen, the payback was 4:1 if ambient pressure was > 12.5 psia but 2:1 if ≤ 12.5 psia. Later in the protocol, the 4:1 payback was required for any BiP during in-suit prebreathe that occurred at ambient pressure anywhere above 10.2 psia but only 2:1 at 10.2 psia. Overall, the exercise protocol prioritized 4:1 over 2:1 payback when ambient pressure was higher and BiP occurred in the latest phase of prebreathe. Furthermore, maximum BiP was set at ≤ 10 min, depending on phase of protocol. Other prebreathe protocols at the time were the campout, with payback ranging from 1:1 to 2:1, and the 4-hr in-suit prebreathe, which was constant at 2:1.

In 2002, the EVA IPT discussed a strategy for foreseeable BiP to decrease payback time by depressing the airlock to 10.2 psia prior to opening the suit to meet the requirement for 2:1 payback rather than using the 4:1 payback. This approach did not suggest BiPs are nominal operations, but it did provide for strategic management of off nominal operations to limit adverse scheduling impact. Importantly, flight rules by this time included rationale that renitrogenation is faster than denitrogenation so that BiP requires additional payback time. This statement supported payback greater than 1:1.

In 2004, there was significant effort to ensure consistency between Shuttle and ISS flight rules. This resulted in reconciling the BiP flight rules between Volumes A (Space Shuttle) and B (ISS). As part of this effort, Dr. Johnny Conkin reviewed and presented the BiP literature explaining that the literature was nonspecific in its guidance and the study designs and small sample sizes were not reliable for making definitive conclusions. This later led to Dr. Conkin proposing a human BiP study. The overall study design included a control group of no-BiP versus BiP of 20 min. The proposed profile aligned with the exercise prebreathe protocol in use at the time and involved 150 min breathing oxygen with the first 10 min on a cycle ergometer at 70% $\dot{V}O_2$ peak. The subjects would decompress over 30 min to 4.3 psia and remain there for 4 hr with light upper limb exercises. BiP would occur at 10 min or 120 min into the prebreathe. No payback was scheduled. Outcomes were to include DCS rate and VGE score. 72 subjects were planned with each undergoing exposure

to control and one of the BiP protocols. Unfortunately, the study was awarded but never completed due in part to delays from employment contract changes and hypobaric chamber equipment upgrading.

BiP was again discussed in 2005 at the EVA IPT meetings, due to an April 2005 ground vacuum chamber run wherein a 4-hour prebreathe was completed then a 30 second BiP occurred due to a Metox (metal oxide CO₂ scrubber cannister) changeout. The test was cancelled due to the payback procedure not clearly defined in the Crew and Thermal Systems Division test protocol. This late BiP sparked discussion on a straight 2:1 payback and/or also requiring a minimum of 30 min of uninterrupted oxygen prior to decompression. The decision was made to maintain the 2:1 protocol since this was already considered to be a conservative approach. 2005 was also when the term “Control Zone” was adopted to describe the 10.2 psia dwell in staged decompression. The campout protocol split the payback requirements between day 1 and day 2. The 60-min mask prebreathe on Day 1 had a straight 2:1 payback, whereas the 70-min mask prebreathe on day 2 had 2:1 payback within the control zone but 4:1 when ambient pressure was above the control zone.

In 2006 the exercise prebreathe and campout protocols had BiP that occurred at pressure greater than the control zone downgraded from 4:1 payback to 2:1 payback. Specific reasons for the changes were not included in available meeting minutes. Possibly these changes were to reconcile shuttle and ISS flight rules.

In 2011, the ISLE protocol was included in the flight rules as an additional available prebreathe option. The ISLE BiP payback was 2:1 with a maximum BiP of 10 min before repeating the 100-min ISLE or the entire protocol, depending on the timing of BiP. In 2011 the exercise protocol still had 1:1 to 4:1 payback, depending on BiP timing and ambient pressure. Campout required 1:1 to 2:1, also dependent on BiP timing and ambient pressure. The 4 hr in-suit payback was always 2:1. In January, 2011, Dr. Conkin gave a BiP presentation during which he stressed the origin of the 10.2 psia control zone staged decompression due to the inevitability of a BiP when transitioning from an oxygen mask to a pressure suit. The control zone eliminated a 14.7 psia BiP and the inevitable nitrogen on gassing at this ambient pressure that would occur during a mask-to-suit transition. Furthermore, Dr. Conkin had collaborated with Brooks Air Force Base and reviewed 207 altitude exposures testing BiP effect on DCS. His conclusions were as follows:

- Air break without payback increased DCS rate and incidence early in altitude exposure with incidence plateauing at ~80% after 4 hr hypobaric exposure
- 2:1 BiP payback at NASA is likely sufficient, especially if BiP ≤ 10 min
- “Prudent” to have minimum of 30 min of uninterrupted oxygen prebreathe prior to decompression
- BiP during heavy exercise should have payback > 2:1

In addition to reviewing meeting minutes, a review of emails exchanged during the timeframe of flight rule reviews provided additional insight.

- Expert 1: “I think that the 2:1 payback is appropriate”
- *Expert 2*: “...we don't break at the end to avoid even the discussion about Type II.”
“I feel 2:1 is conservative enough...”
- *Expert 3*: “...suspect that break in prebreathe is not that important **as long as you do at least another 60 min of prebreathe after the break.** However, that is only

an intuitive opinion and no substitute for getting real data on the subject, which has been part of our integrated plan.”

5.3 CONSULTATION WITH SUBJECT MATTER EXPERTS

Three of the DCS experts involved in the formulation of NASA’s BiP policies have since left the agency but made themselves available for consultation. Consistent with the discussions described in Section 5.2, the experts recalled that the 2:1 payback rule was “not based on any significant empirical data” and confirmed that the approach had been “mostly analytical and expert opinion”. A third expert recalled that operational considerations had motivated the 2:1 rule.

5.4 REVIEW OF RELEVANT LITERATURE

There are only a small number of studies that have investigated BiP. One study from Brooks Air Force Base evaluated timing and duration of BiP. (Cooke, 1979) Subjects were required to prebreathe 95% oxygen at 14.5 psia for 3 hours with BiP duration of 0, 5, or 10 minutes at times of 1, 2, or 3 hours into the prebreathe. (Cooke, 1979) The remainder of the 3 hour prebreathe duration was completed after the BiP plus an additional 1:1 payback time of 0, 5, or 10 minutes. The subjects were subsequently decompressed to 3.8 psia on 92% oxygen for 2 hours. There were 7 cases of DCS in 71 exposures that involved BiP. In contrast, there were no DCS cases in 17 exposures without a BiP. These data suggest that the 1:1 payback was insufficient to prevent DCS. However, statistical significance was not reached with a Fisher’s exact test p-value of 0.21 comparing BiP to no BiP. Furthermore, there were 1 to 2 DCS cases in each of the six variations of BiP protocols in sample sizes of 10 to 15. This suggests the timing of the BiP may not matter as much as the presence or absence of BiP. However, the study was not powered to detect such small differences in DCS rates among the various BiP protocols.

Another study evaluated nitrogen elimination and uptake during prebreathe and BiP by measuring the exhaled nitrogen concentration at the onset and end of BiP. (Hart, 1979) Subjects performed a prebreathe on 95% oxygen up to 3 hours, followed by a BiP of 1 to 10 minutes, then resumed the prebreathe. This study found that a 3 hour prebreathe followed by a 1 minute BiP required an additional 34 minutes of oxygen breathing to return the exhaled nitrogen to the same concentration as it was before the BiP. This result suggests a payback time as high as 1:34. However, later evaluation noted the extreme results may have derived from the slow response of the gas analyzers to large shifts in nitrogen concentration rather than the physiological response to BiP. (Conkin, Aviat Space Environ Med, 2011) Furthermore, exhaled nitrogen concentrations are important from a basic science perspective but less operationally relevant than DCS risk from BiP.

Modeling of nitrogen uptake and elimination also provides some insight into the effect of BiP on tissue nitrogen concentrations. A conference abstract from 2005 compared three BiP models. (Conkin et al, 2005) The single compartment model showed that late BiP increases tissue nitrogen more so than early BiP. In contrast, the three-compartment model showed early BiP causes greater tissue nitrogen. A more complex model with variable tissue half-time showed that early versus late BiP did not matter. The point was made that a human study was required to resolve model discrepancy.

A study from the Air Force Research Lab (AFRL) investigated duration of BiP and a follow up analysis built a predictive model based on these data. (Conkin, Aviat Space Environ Med, 2011; Pilmanis et al, 2010) The intended application of the study was to evaluate breaks in prebreathe

among U2 pilots. Participants underwent a 30 minute 100% oxygen prebreathe, a BiP of variable duration (10, 20, or 60 minutes), followed by an additional 30 minutes of breathing 100% oxygen, then exposure to 4.37 psia for 4 hours. After exposure, all subjects received the initial treatment for DCS, ground level oxygenation (GLO). This potentially masked/resolved some DCS cases that may have otherwise presented later/post flight (the study was focused on in-flight events, so per their IRB required post flight treatment). Control data without BiP were collected from the AFRL DCS database. Participants were monitored for DCS symptoms and VGE on echocardiography. The initial publication of the study showed that at 1 hour into the hypobaric exposure, all three BiP groups (10, 20, 60 minutes) had a higher DCS rate than controls (Pilmanis et al, 2010). At 2 hours, both the 20 and 60 minutes BiP groups still had higher DCS rates than controls. The control group sample size shrank after 2 hours decreasing power to differentiate DCS rates later in the hypobaric exposure. There was no difference in VGE rates between BiP groups versus the control group. The authors postulated that the very high level of decompression stress—up to 84% of test subjects experienced DCS, including 25% Type II DCS—may have resulted in a ceiling effect. It is also suggested that the ongoing denitrogenation during the altitude exposure may further reduce differences in tissue nitrogen between the control and break conditions. Overall, these data show that a BiP increases DCS rate, but the study did not address the effect of timing of BiP nor how to approach prebreathe payback.

The very high decompression stress differs significantly from ISS EVA profiles in which ~5% DCS is expected based on ground validation data (and, following additional prebreathe duration for operational implementation, is modeled closer to ~0.5%) and for which no cases of DCS have been reported during flight. No changes to NASA's break-in-prebreathe rules were proposed following the 2010 study.

The follow up modeling analysis to the AFRL study provided additional insight into BiP nitrogen kinetics.(Conkin, Aviat Space Environ Med, 2011) The model consisted of a single compartment consisting of mixed venous blood, an exponential decay equation to calculate partial pressure of nitrogen, and defined the decompression dose as either the ratio or difference of blood nitrogen partial pressure and the final hypobaric ambient atmospheric pressure. The model was optimized using maximum likelihood on the parameters of time proportionality constant, time exponential constant, decompression dose exponential constant, uptake half-time, and elimination half time. The best fit model used a 60-minute half-time for nitrogen elimination and a 10-minute half-time for uptake. The marked difference in half-times further increases the already asymmetric nitrogen elimination and uptake rates. The exponential decay model described slow nitrogen elimination late in prebreathe followed by rapid nitrogen uptake during the BiP. The shorter uptake half-time further disrupts the balance and indicates nitrogen uptake during BiP is much faster than subsequent elimination. The more operationally relevant finding was the probability of DCS increased with increasing duration of BiP. Additionally, the study described a method to calculate the requisite prebreathe payback time. The limitations of the study include a rudimentary single tissue compartment and the narrow range of test conditions. The prediction methods are not validated for prebreathe protocols outside of 1 hour and BiP occurring outside of 30 minutes into the prebreathe.

Overall, the literature shows that BiP increases DCS rate, a 1:1 payback is likely insufficient, and a model to calculate prebreathe payback time is only valid under specific conditions. Further studies addressing payback requirements from a wider range of prebreathe conditions are needed

to better inform operational response to BiP. As mentioned above the 2004 break in prebreathe study was funded but never started due to logistical delays.

5.5 REVIEW OF NASA’S OPERATIONAL EXPERIENCE

Seven instances of in-flight breaks in prebreathe were identified in reviewing records back to 2003, each of which is summarized in Table 5. Two breaks-in-prebreathe have occurred during preparation for 72 total EVAs (144 crewmembers) since the ISLE protocol was first implemented in 2011, confirming that these are very rare occurrences. In all cases, a minimum of 2:1 payback was followed, and the latest break-in-prebreathe occurred 48 min prior to depressurization to reconnect a communication cable that had become disconnected (STS-124). The column in Table 4 labeled “Time to Depress” indicates the duration of oxygen prebreathe that followed each break-in-prebreathe prior to the start of depressurization.

No DCS cases have been reported during any of NASA’s EVA operations.

Table 3. NASA’s operational experience with breaks in prebreathe during spaceflight since 2003.

EVA #	Date (GMT / calendar)	Flight/ Increment	Prebreathe Protocol	Type of Break	Break Duration (min)	When did break occur / Minutes before Depress	Re-Purge	Purge duration (min) if applicable	Break Payback (min)	Add'l O2	Time to Depress (min) if applicable	Schedule Changes	Description / Details (e.g. cause of break, controlled or uncontrolled break, config, etc)
8	2007/039:10:00	INC-14	Campout	Prebreathe Mask	1.5	Occurred at pressure of 615 mmHg during hold (~40 min into mask PB at start of day)	No	N/A	4		long before depress to EVA	4 added mins, noting other	AR 002203 - PB Mask failure, regulator detached from mask during the Day of EVA morning Hygiene Break's mask prebreathe. Per audio clip in AR, sounds like it occurred during depress back down to 10.2, around the 12 psi hold as part of the hygiene break (was 2.315 Hygiene Break procedure, now 2.302), so ~ step 21.7
STS-124 (11) EVA 1	2008/155:14:23	STS-124 (11)	Campout	Helmet Removed	3 min and 5 seconds	GMT 13:39:38 - nominal Purge (8 min, 2 part) start GMT 15:02:02:55 - start of Break in PB GMT 15:03:51 - helmet back on/connected GMT 15:51 - Depress starts	Yes	12	6 min 10 seconds	Yes	48		EV1 comm cap pigtail became disconnected after EMU Purge. Break in PB performed (prior to published procedure) to reconnect.
STS-128 (17A) EVA 2	2009/246:20:25	STS-128/17A	Campout	Helmet Removed	3.5	GMT 246/20:25 - break start GMT 246/21:41 - Depress start	Yes	12* - not fully valid	7	Yes	76		AR 004218 - Comm Cap strap unsnapped. Performed nominal Break in PB procedure to recover. However, 8 min into 12 min purge GND team noticed UJA O2 Vlv closed - had crew open vlv and continue rest of 12 min purge. The EMU O2 P was as low as 390 psi, so GND had crew repeat 12 min purge again.
STS-129 (ULF-3) EVA 2	2009/325:02:52	STS-129/ULF-3	Campout	Control Zone	7	GMT 02:52 - A/L repress due to false rapid depress GMT 02:55 - Crew on PB Mask GMT 03:01 - false fire alarm shuts off O2, crew has to doff PB Mask GMT 3:07 - O2 re-open, crew back on PB Mask GMT 13:47 - depress started (next day)	No	N/A	N/A		>10 hr different PB protocol	picked up the next day	Downmode to CEVIS Exercise day of EVA after a false rapid depress and false fire alarm broke overnight campout and ground could not get A/L back in good config in time to still do 10.2 psi for overnight and be on track for EVA next day. Had crew doff PB Masks and just perform CEVIS exercise the next day
STS-129 (ULF-3) EVA 3	2009/327:11:37	STS-129/ULF-3	Campout	Helmet Removed	6	GMT 11:15 - start depress to 10.2 GMT 11:37 - open purge vlv to depress GMT 11:43 - start 2nd purge to end break in PB GMT 11:49 - start repress GMT 12:54 - start of depress	Yes	8			71 mins		Contingency Depress back to 10.2 psi to fix DIB bite vlv that came off DIB, stayed under 10 min for Break in PB while at 10.2 to avoid repeating all of 50 min PB.
38	2017/006:10:50	INC-50	ISLE	Other	13 sec - assumed 4 min	Metox Changeout	Yes	12	8	Yes	~59	lost ~20 mins on schedule	AR 007938 - Crew performed METOX changeout with FAN still on, 13 sec METOX removed (suit open to 14.7 atmosphere), started Helmet Purge at 4 min mark. Off-nominal break. Assumed 4 min break and performed 2:1 buy back, and did 12 min purge vs 2 min purge after METOX changeout
73	2021/072:11:21	INC-64	ISLE	Helmet Removed	6	GMT 11:21 - break start GMT 12:42 - depress start	Yes	12	12	Yes	81	lost ~24 mins on schedule	Comm cap issue - opened helmet and swapped to spare comm cap

5.6 MODEL ANALYSIS

Outside of the BiP model based on 1 hour prebreathe prior to decompression to 4.3 psia (Conkin, 2011), existing DCS risk models are not applicable or validated for estimating DCS risk due to break-in-prebreathe but do offer some insight. As described in Section 3.2, the models of gas kinetics used in NASA’s DCS risk estimation models assume asymmetric on-gassing and off-gassing rates. A later break-in-prebreathe is therefore associated with a higher model-predicted level of tissue nitrogen at EVA start as compared with an earlier break, with “faster” (20 min and 40 min) compartments being most affected. However, existing models are not able to provide

quantitative risk estimates of Type I or Type II DCS risk changes due to breaks in prebreathe. The existing BiP model (Conkin, 2011) is not useful to NASA operations due to the short (1 hour) prebreathe used to generate this model.

While recognizing the limitations of the inert gas modeling approach, the EVA IPT compared model estimates of pre-EVA tissue nitrogen levels under a range of break-in-prebreathe scenarios and compared them with the nominal ISLE protocol (Figure 4). In the example shown in Figure 5, the slower compartments (90-min to 360-min) are adequately denitrogenated when the 2:1 payback is implemented, but 20-min and 40-min compartments have greater ppN₂ than in the nominal protocol.

In addition to evaluating breaks at different times during the protocol, scenarios were modeled in which it was assumed that the airlock was returned to the “control zone” (10.2 psi/26.5% O₂) prior to breaks occurring during Phase 3. Because of the lower atmospheric ppN₂ in the control zone, the rate of renitrogenation during a break-in-prebreathe is significantly reduced. Model analysis showed that the calculated tissue ppN₂ in all tissues was equivalent to the nominal protocol if Phase 3 breaks occurred while in the control zone and the full 100-min Phase 3 in-suit prebreathe was repeated.

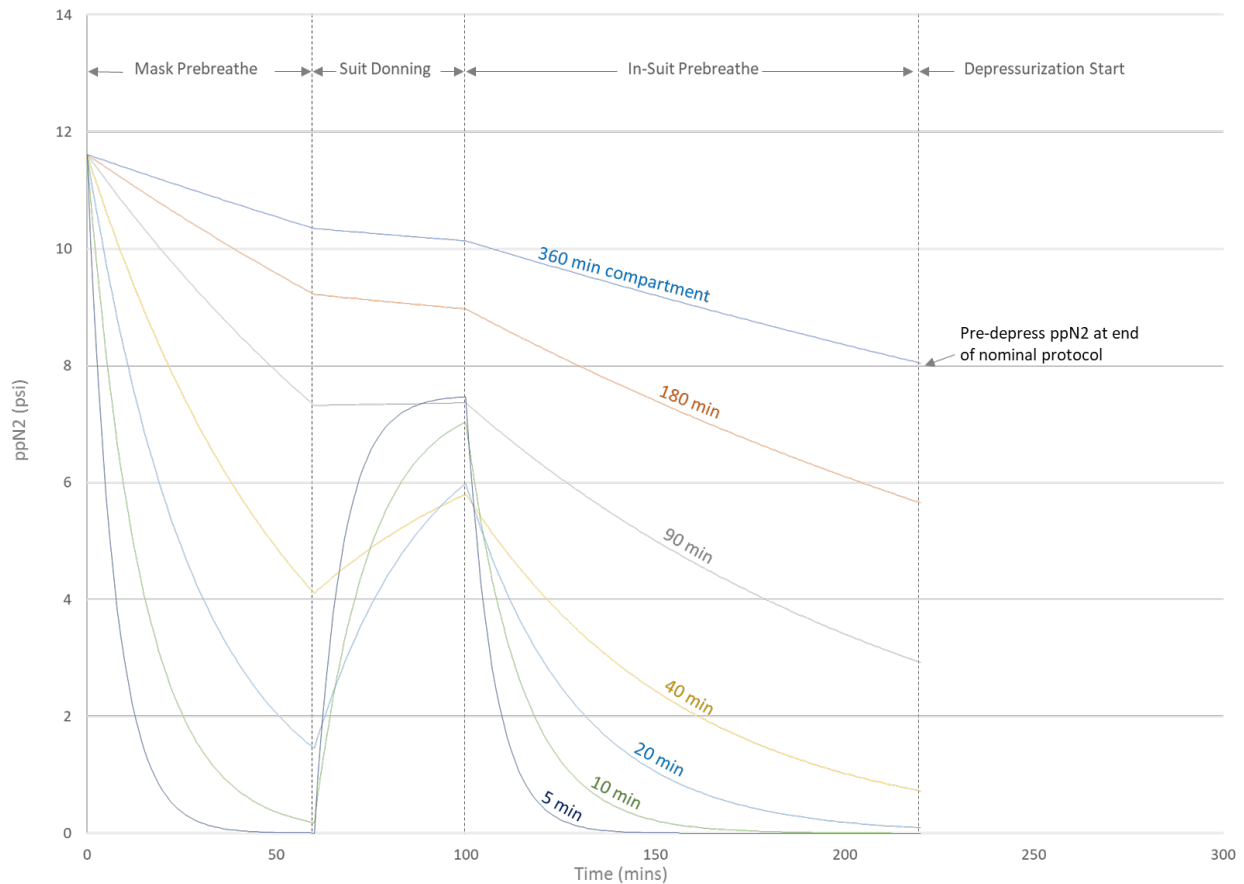


Figure 3. Model output showing calculated tissue nitrogen (ppN₂) for 5-min to 360-min half-time compartments during the nominal ISLE prebreathe protocol.

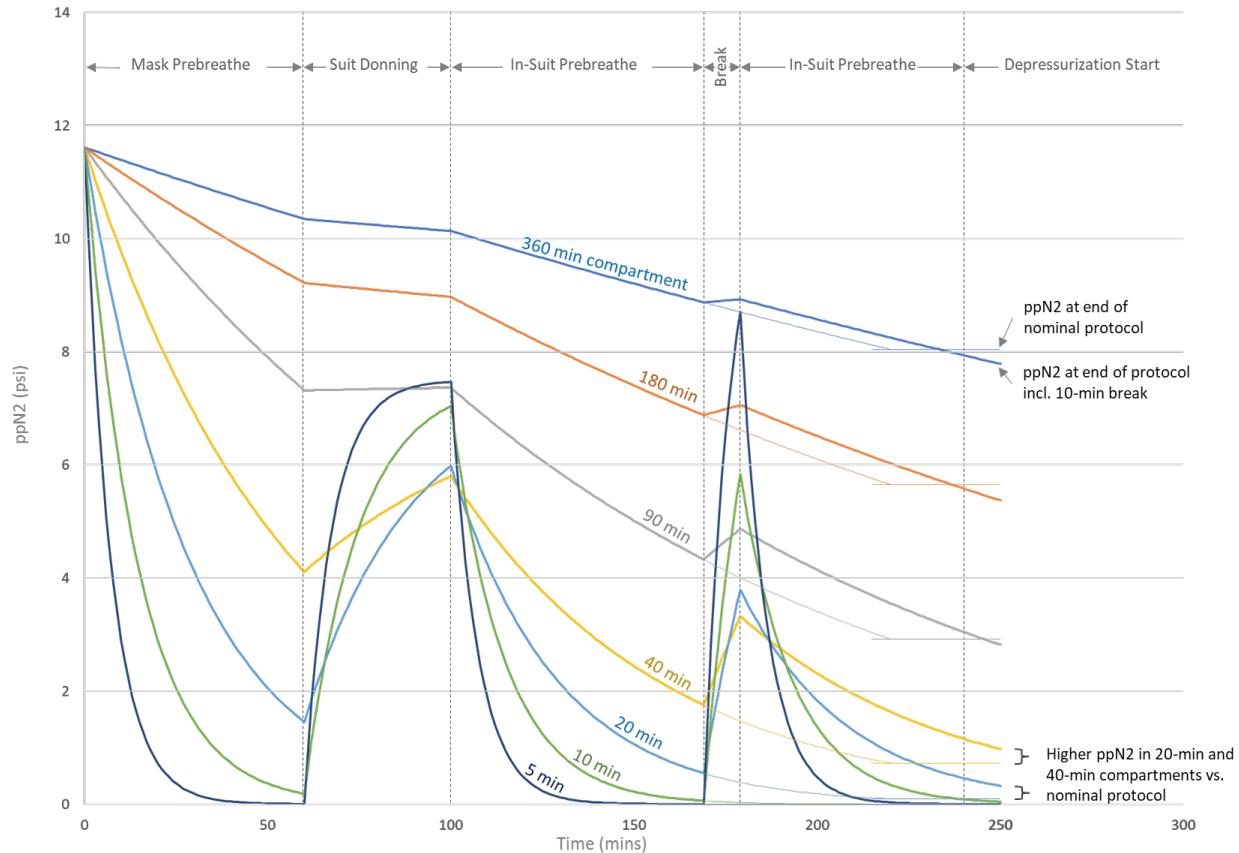


Figure 4. Model output comparing calculated tissue nitrogen (ppN₂) for 5-min to 360-min half-time compartments during the ISLE prebreathe protocol with (bold) and without (thin) a notional 10-min break-in-prebreathe followed by 2:1 payback. Note that calculated ppN₂ at the start of depressurization is greater than for the nominal protocol in the 20-min and 40-min compartments despite the additional 20 min of prebreathe.

5.7 EVA IPT DISCUSSION

Having examined all available pertinent information, the EVA IPT discussed and agreed on the following observations:

- A late break-in-prebreathe was a credible cause or factor in the Type II DCS case
- Documented rationale for existing break-in-prebreathe flight rules could not be retrieved
- Consultation with SMEs as well as review of emails and meeting minutes from the early 2000s reflect a recognized gap in data and knowledge and an apparent lack of consensus on the sufficiency of 2:1 payback
- Simplistic unvalidated model of asymmetric gas kinetics suggests the following:
 - A BiP with 2:1 payback during Phase 3 results in increased tissue N₂ vs. baseline
 - Earlier breaks (pre-Phase 3) with 2:1 payback yield equivalent tissue N₂ vs. baseline
 - Returning to Control Zone (10.2 psi/26.5% O₂) during a break “pauses” prebreathe
- There are very few instances (2 out of 72 EVAs) of BiPs during the ISLE protocol.

- Interim flight rule update recommendations are required immediately to support planned upcoming EVAs and any potential contingency EVAs; however, further recommendations may be submitted following more comprehensive retrieval and review of relevant information.

The EVA IPT provided consensus recommendations for interim flight updates, described in Section 6.0; these were implemented by the Flight Rules Control Board in September 2023 and will be maintained further data (animal/human chamber tests/models) can be leveraged.

6.0 FLIGHT RULE UPDATE RECOMMENDATIONS

Based on the team's consensus observations, described in the previous section, a series of recommendations were formulated, discussed, refined, and agreed upon by the entire team.

The consensus of the EVA IPT was that the flight rule updates were likely conservative but appropriate. It was believed that the updated flight rules had a low likelihood of substantially impacting ISS EVA operations due to the low frequency of EVAs, the historically low occurrence of breaks-in-prebreathe, and the ability to reschedule most EVAs with relatively limited operational impact if required due to a break-in-prebreathe.

The need to expediently update flight rules prior to upcoming EVAs meant that the extent of the EVA IPT's review and discussions were necessarily limited in scope. As such, it was initially recommended that the updated flight rules be considered interim. However, after the conclusion of all the additional testing by the investigation, the in-depth literature review, and the lack of any other applicable models or human testing, the rule changes were deemed definite and no longer subject to change/review until new studies are conducted.

Given the lack of other studies, relevant models, or the impetus for such development by other organizations, it was recommended that NASA take the lead in supporting hypobaric chamber testing that would address this issue. This will require a research effort to understand the fundamental physiology underlying breaks in prebreathe, including the gas kinetics behind on and off-gassing inert gasses, as well as the critical tissue compartments driving type II DCS risk.

No changes recommended to Phase 1 or 2

6.1 RECOMMENDED PHASE 3 CHANGES

- 1) For ANY BiP above the control zone < **10 min**

- *Repeat the full 100-min in-suit PB with exercise*

- 2) For a break > 10 min *EITHER*

- a. Return to control zone prior to the break and go to 3)

OR

- b. Repeat entire ISLE protocol or consider alternate PB protocol

- 3) For any break *within* the control zone: repeat full 100-min in suit PB with exercise cycles

6.2 RECOMMENDED MODIFICATIONS TO THE FLIGHT RULE WORDING

PREBREATHE ACTIVITY PORTION	POINT OF INTERRUPTION	TIME ELEMENT	REQUIRED ACTION	REQUIRED PROFILE
PHASE THREE				
100-MINUTE IN-SUIT PREBREATHE [6]	WITHIN CONTROL ZONE	≤ 10-MINUTE INTERRUPTION (SINGLE OR CUMULATIVE)	MAKE UP O₂ TIME IN SUIT OR PHA. [4] [2] [5] [7] [8] [9]	MAKEUP RATIO: 2:1
	WITHIN CONTROL ZONE	> 10-MINUTE INTERRUPTION (SINGLE OR CUMULATIVE)	REPEAT 50 MINUTES OF RESTING IN-SUIT PREBREATHE AND ANY REMAINING EXERCISE CYCLES. [3] [7] [8] [9]	ON MCC CALL
	PRESSURE BETWEEN CONTROL ZONE AND 14.7 PSI/760 MMHG	≤ 10-MINUTE INTERRUPTION (SINGLE OR CUMULATIVE)	REPEAT FULL 100-MINUTE IN-SUIT PREBREATHE WITH EXERCISE CYCLES [2] [3] [5] [7] [9] MAKE UP O ₂ TIME IN SUIT. [4] [5] [7] [8]	ON MCC CALL MAKEUP RATIO: 2:1
	PRESSURE BETWEEN CONTROL ZONE AND 14.7 PSI/760 MMHG	> 10-MINUTE INTERRUPTION (SINGLE OR CUMULATIVE)	RETURN TO CONTROL ZONE PRIOR TO BREAK AND TAKE REQUIRED ACTION FOR POINT OF INTERRUPTION WITHIN CONTROL ZONE [2] [3] [5] OR REPEAT IN-SUIT LIGHT EXERCISE PREBREATHE PROTOCOL OR CONSIDER ALTERNATE PREBREATHE PROTOCOL. [4] [7] CREW SCHEDULING CONSTRAINTS MAY NECESSITATE SHORTENING OR RESCHEDULING THE EVA.	ON MCC CALL
	WITHIN CONTROL ZONE	ANY AMOUNT OF TIME	REPEAT FULL 100-MINUTE IN-SUIT PREBREATHE WITH EXERCISE CYCLES [2] [3] [5] [7] [9]	N/A
	EXERCISE ONLY	1 EXERCISE CYCLE MISSED	NO MOD REQUIRED [409] [4410]	N/A
	EXERCISE ONLY	> 1 EXERCISE CYCLE MISSED	PERFORM REMAINING EXERCISE TO COMPLETE 10 EXERCISE CYCLES [409] [4410]	PAUSE

©[081811-00392A]

PREBREATHE ACTIVITY PORTION	POINT OF INTERRUPTION	TIME ELEMENT	REQUIRED ACTION	REQUIRED PROFILE
PHASE THREE				
	PRESSURE BETWEEN CONTROL ZONE AND 14.7 PSI/760 MMHG	≤ 10-MINUTE INTERRUPTION (SINGLE OR CUMULATIVE)	REPEAT FULL 100-MINUTE IN-SUIT PREBREATHE WITH EXERCISE CYCLES [2] [3] [5] [7] [9]	ON MCC CALL
	PRESSURE BETWEEN CONTROL ZONE AND 14.7 PSI/760 MMHG	> 10-MINUTE INTERRUPTION (SINGLE OR CUMULATIVE)	RETURN TO CONTROL ZONE PRIOR TO BREAK AND TAKE REQUIRED ACTION FOR POINT OF INTERRUPTION WITHIN CONTROL ZONE [2] [3] [5] OR REPEAT IN-SUIT LIGHT EXERCISE PREBREATHE PROTOCOL OR CONSIDER ALTERNATE PREBREATHE PROTOCOL. [4] [7] CREW SCHEDULING CONSTRAINTS MAY NECESSITATE SHORTENING OR RESCHEDULING THE EVA.	ON MCC CALL
	WITHIN CONTROL ZONE	ANY AMOUNT OF TIME	REPEAT FULL 100-MINUTE IN-SUIT PREBREATHE WITH EXERCISE CYCLES [2] [3] [5] [7] [9]	N/A
	EXERCISE ONLY	1 EXERCISE CYCLE MISSED	NO MOD REQUIRED [9] [10]	N/A
	EXERCISE ONLY	> 1 EXERCISE CYCLE MISSED	PERFORM REMAINING EXERCISE TO COMPLETE 10 EXERCISE CYCLES [9] [10]	PAUSE

@[081811-00392A]

NOTES: @[081811-00392A]

- [1] $O_2 \text{ MAKEUP TIME} = (\text{MAKEUP RATIO}) \times (\text{INTERRUPTION DURATION})$
- ORIGINAL TIME REMAINING + [O₂ MAKEUP TIME] SHOULD NOT EXCEED THE PREBREATHE TIME REQUIREMENT FOR THE PARTICULAR PHASE WHERE THE BREAK OCCURRED.
- EXAMPLE FOR PHASE ~~THREE-ONE (IN-SUIT MASK)~~: ORIGINAL TIME REMAINING + (2X INTERRUPTION DURATION) SHOULD NOT EXCEED ~~6400~~ MINUTES. IF THIS TIME EXCEEDS ~~400-60~~ MINUTES, THE CREW SHOULD ONLY PAY BACK THE ORIGINAL O₂ PREBREATHE TIME REQUIREMENT OF ~~400-60~~ MINUTES.
- [2] INTERRUPTION DURATION DEFINED AS TIME BREATHING CABIN ATMOSPHERE + TIME BREATHING SUIT ATMOSPHERE PRIOR TO REINITIATING OF SUBSEQUENT SUIT PURGE. TOTAL TIME NOT TO EXCEED ORIGINAL O₂ PREBREATHE (CONTACT FCR SURGEON FOR ANY REQUIRED TIME INCREASE).
-
- [3] IN THE EVENT THAT AN INTERRUPTION OF THE PREBREATHE IS REQUIRED, AND IT IS ANTICIPATED THAT THE INTERRUPTION MAY LAST LONGER THAN 10 MINUTES, TO AVOID REPEATING THE ENTIRE IN-SUIT LIGHT EXERCISE PROTOCOL, THE AIRLOCK CAN BE DEPRESSURED BACK DOWN TO THE CONTROL ZONE. IF THE INTERRUPTION FOR >10 MINUTES OCCURS WHILE AT THE CONTROL ZONE, THERE WILL BE NO NEED TO REPEAT THE ENTIRE PROTOCOL. INSTEAD, THE CREW WILL SIMPLY BE REQUIRED TO REPEAT THE ~~5100-~~ MINUTES ~~OF RESTING~~ IN-SUIT PREBREATHE ~~WITH AND ANY REMAINING~~ EXERCISE CYCLES ONCE THE CAUSE OF THE INTERRUPTION HAS BEEN RESOLVED AND THE SUIT PURGE TIME IS COMPLETE.
- [4] PERFORMING THE 4-HR IN-SUIT PREBREATHE REQUIRES 4.5-5 HRS FROM TIME THE PROTOCOL STARTS UNTIL THE EV HATCH IS OPEN. A FULL DURATION EVA AND THE MINIMUM POST-EVA REQUIRE ANOTHER 8 HRS. THIS RESULTS IN POST-EVA TASKS COMPLETE AT A CREW AWAKE TIME OF 17-18 HRS, NOT INCLUDING THE EMU WORKAROUND TO RESOLVE THE PROBLEM THAT CAUSED THE PREBREATHE INTERRUPTION. DEPENDING ON THE EVA, IT MAY BE MORE PRUDENT TO REDUCE THE EVA DURATION 1-2 HRS TO PREVENT AN EXCESSIVE CREW DAY LENGTH.
- [5] MOST SUIT-RELATED BREAKS WOULD TAKE LONGER THAN 10 MINUTES TO RESOLVE. HOWEVER, THERE MAY BE A MINOR ISSUE THAT CAN BE RESOLVED QUICKLY (I.E., MIC BOOM POSITION). THE CONSEQUENCE OF NOT MEETING THE 10-MINUTE TIME LIMIT IS A REPEAT OF ~~50 MINUTES OF RESTING IN SUIT PREBREATHE OR THE ENTIRE PROTOCOL. DEPENDING ON THE PRESSURE AT WHICH THE BREAK OCCURRED IF THE BREAK OCCURS AT A PRESSURE BETWEEN THE CONTROL ZONE AND 14.7 PSI/760 MMHG.~~ THIS WILL MOST LIKELY RESULT IN A SHORTENED OR RESCHEDULED EVA. IN ALMOST ALL CASES, A RETURN TO THE CONTROL ZONE IS THE MOST PRUDENT COURSE OF ACTION.
- [6] METOX CHANGEOUT IS NOT CONSIDERED TO BE A BREAK IN PREBREATHE, BUT A PAUSE. PRIOR TO A METOX CHANGEOUT, THE SUIT FAN IS POWERED OFF, THE HELMET PURGE VALVE IS OPEN, AND POSITIVE SUIT PRESSURE IS MAINTAINED WITH THE O₂ ACTUATOR IN IV SO NO CABIN AIR IS INTRODUCED INTO THE SUIT. THE SMALL AMOUNT OF ATMOSPHERIC NITROGEN FOUND WITHIN A NEW METOX CONTAINER WILL BE DILUTED AND PURGED WITH A 2-MINUTE SUIT PURGE ONCE THE CHANGEOUT IS COMPLETE. FOLLOWING METOX CHANGEOUT, THE PREBREATHE CLOCK WILL PAUSE WHEN THE SUIT FAN IS POWERED ON AND WILL RESUME ONCE THE SUIT PURGE IS COMPLETE. @[032723-02579]
- [7] EMU PURGE OPTIONS TO BE CONSIDERED FOLLOWING A BREAK IN PREBREATHE ARE LISTED BELOW:
- IF PERFORMING PURGE AT 12.5-14.7 PSI/646-760 MMHG: PURGE SUIT FOR MINIMUM OF 12 MINUTES.
- IF PERFORMING PURGE IN CONTROL ZONE: PURGE SUIT FOR 5 MINUTES IN CONTROL ZONE, PAUSE PURGE AND REPRESS A/L TO 12.5-14.7 PSI/646-760 MMHG. CONTINUE PURGE FOR 3 ADDITIONAL MINUTES.
- [8] TIME SPENT ON A PHA IN NORMAL MODE CAN BE TREATED AS A PAUSE.
- [9] ~~FOR ISLE ONLY, O₂ PREBREATHE MAKEUP TIME INCURRED DURING LIGHT IN-SUIT EXERCISE CAN BE COMPLETED PRIOR TO COMPLETING THE BALANCE OF LIGHT IN-SUIT EXERCISE REMAINING OR COMPLETED AT THE CONCLUSION OF LIGHT IN-SUIT EXERCISE.~~
- [940] MINIMUM ACCEPTABLE TOTAL EXERCISE IS 9 CYCLES (45 MINUTES); THEREFORE, A BREAK OF LESS THAN OR EQUAL TO 1 EXERCISE CYCLE (5 MINUTES) MISSED IS ACCEPTABLE.
- [4410] TIME SPENT NOT EXERCISING COUNTS TOWARDS THE 50 MINUTES OF RESTING PREBREATHE. @[081811-00392A] ----
- [112] THIS SCENARIO IS NOT CONSIDERED A BREAK IN PREBREATHE. DURING PHASE 2 OF THE ISLE PREBREATHE, THE AIRLOCK IS CONSIDERED TO BE A CLOSED SYSTEM WHICH HAS THE PPN2 LEVELS FIXED ONCE THE CREW HAS POWERED OFF THE DEPRESS PUMP IN THE CONTROL ZONE. PPO2 CHANGES DURING THIS TIME ARE NOT A FACTOR IN DENITROGENATION; THUS, DO NOT AFFECT PREBREATHE AND ARE ONLY CONSTRAINED BY PHYSIOLOGICAL AND FLAMMABILITY LIMITS. @[100614-01054]

7.0 MANAGEMENT REVIEW, APPROVAL, AND IMPLEMENTATION OF RECOMMENDATIONS

The EVA IPT's recommendations were briefed to the JSC Chief Medical Officer who accepted all recommendations and directed implementation. Additional briefings were made to JSC Center Leadership, Flight Operations Directorate, and ISS Program Management, all of whom agreed with the recommendations. The flight rule updates were formalized via the established ISS Program integration panels and control boards. Although intended as interim updates, the flight

rule updates were formalized such that they would remain applicable for all future EVAs unless and until they are updated again.

8.0 REPORT ARCHIVING

At time of writing, this report is expected to be archived and available for reference via the NASA Technical Report Server (<https://ntrs.nasa.gov/>).

9.0 ACKNOWLEDGEMENTS

The team is grateful to the affected subject for their open participation in the follow-on investigation, and their willingness to help ensure that lessons learned from this test will reduce risk for future suited subjects and crewmembers. The team also acknowledge and thank Melisa Radford for her invaluable support in the technical editing of this report.

10.0 REFERENCES

- Abercromby AFJ, Conkin J, Gernhardt ML. Modeling a 15-min extravehicular activity prebreathe protocol using NASA's exploration atmosphere (56.5 kPa / 34% O₂). *Acta Astronautica* 2015; 109:76-87.
- Abercromby AFJ, Anchondo, C; et al. Suited Ground Vacuum Chamber Testing Decompression Sickness Tiger Team Report. NASA Technical Publication NASA/TP-2019-220343, Johnson Space Center, July 2019
- Bendrick GA, Ainscough MJ, Pilmanis AA, Bisson RU. Prevalence of decompression sickness among U-2 pilots. *Aviat Space Environ Med.* 1996;67:199-206.
- Conkin J. Decompression sickness after air break in prebreathe described with a survival model. *Aviat Space Environ Med.* 2011;82:589-598.
- Conkin J. Preventing decompression sickness over three decades of extravehicular activity. NASA Technical Publication NASA/TP-2011-216147, Johnson Space Center, June 2011.
- Conkin J. Evidence-based approach to the analysis of serious decompression sickness with application to EVA astronauts. NASA Technical Publication 2001-210196, January 2001.
- Conkin J, Abercromby AFJ, Dervay JP, Feiveson AH, Gernhardt ML, Norcross JR, Ploutz-Snyder R, Wessel JH, III. Hypobaric decompression sickness treatment model. *Aerosp Med Hum Perform* 2015; 86:508-17.
- Conkin J, Abercromby AFJ, Dervay JP, Feiveson AH, Gernhardt ML, Norcross J, Ploutz-Snyder R, Wessel JH, III. Probabilistic assessment of treatment success for hypobaric decompression sickness. Houston, TX: NASA Johnson Space Center; November 2014. NASA Technical Publication NASA/TP-2014-218561.
- Conkin J, Gernhardt ML, Powell MR. The decompression sickness and venous gas emboli consequences of air breaks during 100% oxygen prebreathe. 2005 Annual Bioastronautics Investigators Workshop National Space Biomedical Research Institute Meeting Houston, Texas.
- Conkin J, Pilmanis AA, Webb JT. Case descriptions and observations about cutis marmorata from hypobaric decompressions. NASA Technical Publication 2002-210779, Houston: Johnson Space Center, April 2002.
- Conkin J, MR Powell, PP Foster, JM Waligora. Information about venous gas emboli improves prediction of hypobaric decompression sickness. *Aviat Space Environ Med* 1998; 69:8-16.
- Conkin J, Pollock NW, Natoli MJ, Martina SD, Wessel JH, III, Gernhardt ML. Venous gas emboli and ambulation at 4.3 psia. *Aerosp Med Hum Perform* 2017; 88:370-76.

- 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.
- Conkin J, Sung H-G, Feiveson AH. A latent class model to assess error rates in diagnosis of altitude decompression sickness. *Aviat Space Environ Med* 2006; 77:816-824.
- Cooke JP. Denitrogenation interruptions with air. *Aviat Space Environ Med* 1976;47:1205-1209.
- Francisco, D, et al: Assessment of Patent Foramen Ovale (PFO) as Related to Decompression Sickness (DCS) in the Spaceflight Environment and During Ground Testing. Washington, DC: U.S. Government Printing Office, NASA/SP-2024-0010473, 2024
- Gernhardt M.L. Development and Evaluation of a Decompression Stress Index Based on Tissue Bubble Dynamics. Ph.D dissertation, University of Pennsylvania, UMI #9211935, 1991.
- Gernhardt ML, Dervay JP, Waligora JM, Fitzpatrick DT, Conkin J. Extravehicular Activities (Chap. 5.4). In: Risin D, Stepaniak PC, eds. *Biomedical Results of the Space Shuttle Program*. Washington, DC: U.S. Government Printing Office, NASA/SP-2013-607, 2013; 315-26.
- Gerth, W, Ruterbusch, V, Long, E. The Influence of Thermal Exposure on Diver Susceptibility to Decompression Stress. NEDU-TR-06-07, November 2007.
- Hart KR. Decompression sickness in aerospace medicine: the development of an onboard treatment facility for the shuttle-orbiter. The University of Texas Health Science Center at Houston. June 1979
- Krause KM, Pilmanis AA. The effectiveness of ground-level oxygen for treatment of altitude decompression sickness in human research subjects. *Aviat Space Environ Med* 2000; 71:115-8.
- Muehlberger PM, Pilmanis AA, Webb JT, Olson JE. Altitude decompression sickness symptom resolution during descent to ground-level. *Aviat Space Environ Med* 2004; 75:496-99.
- Pilmanis AA, Webb JT, Balldin UI, Conkin J, Fischer JR. Air break during preoxygenation and risk of altitude decompression sickness. *Aviat Space Environ Med*. 2010 Oct;81(10):944-50. doi: 10.3357/ase.2819.2010. PMID: 20922886.
- Pristipino et al, European position paper on the management of patients with patent foramen ovale. Part II - Decompression sickness, migraine, arterial deoxygenation syndromes and select high-risk clinical conditions. *EuroIntervention* 2021;17:e367-e375.
- Ryles MT, Pilmanis AA. The initial signs and symptoms of altitude decompression sickness. *Aviat Space Environ Med* 1996; 67:983-89.

Waligora JM. Chronology of events and documents relating to the risk of decompression sickness in the shuttle and space station programs. In-house report, Houston: Johnson Space Center, July 17, 2000 (to be submitted to NTRS).

JPD1800.2B:

<http://server-mpo.arc.nasa.gov/services/CDMSDocs/Centers/JSC/Dirs/JPD/JPD1800.2B.pdf>