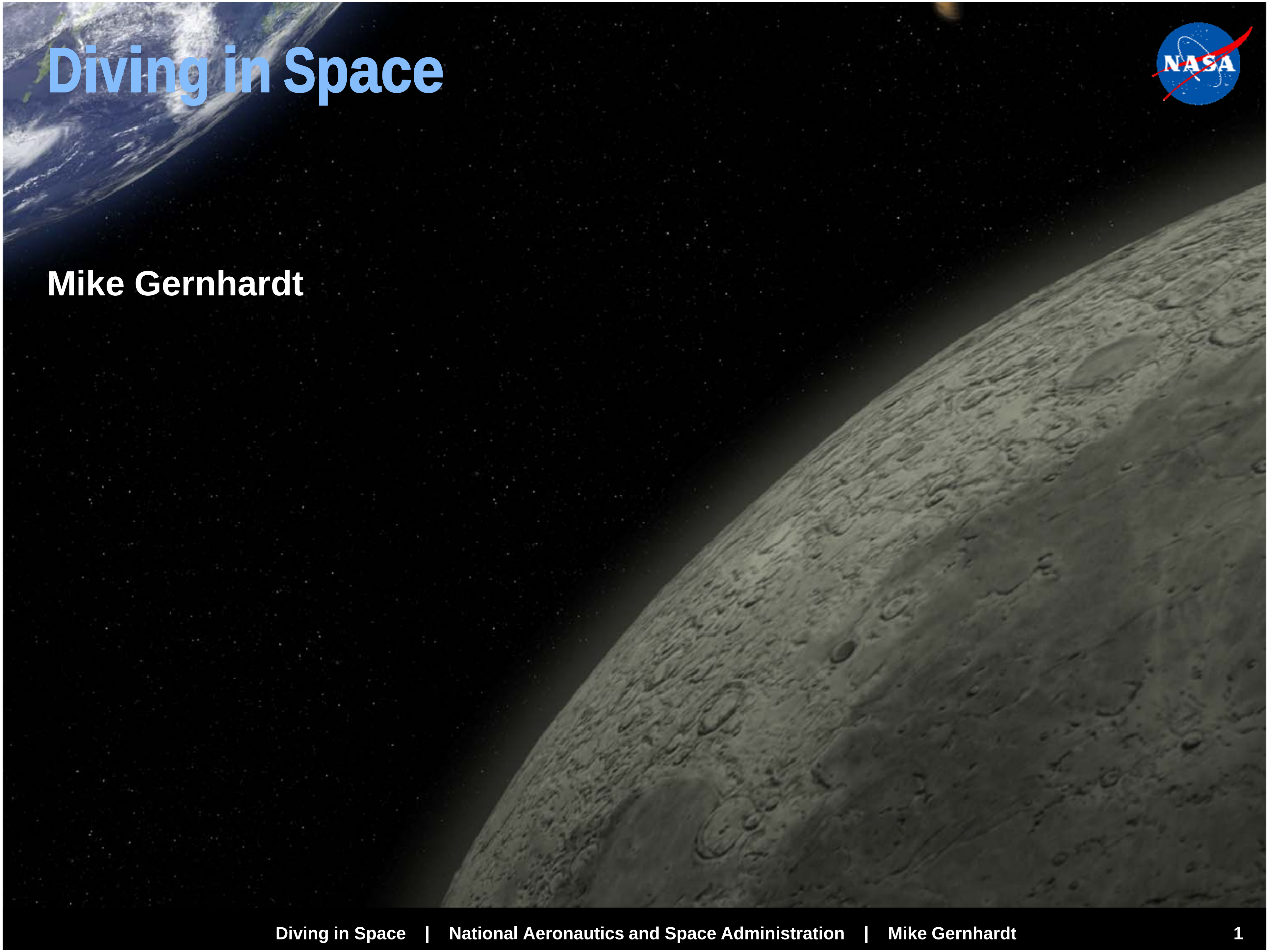


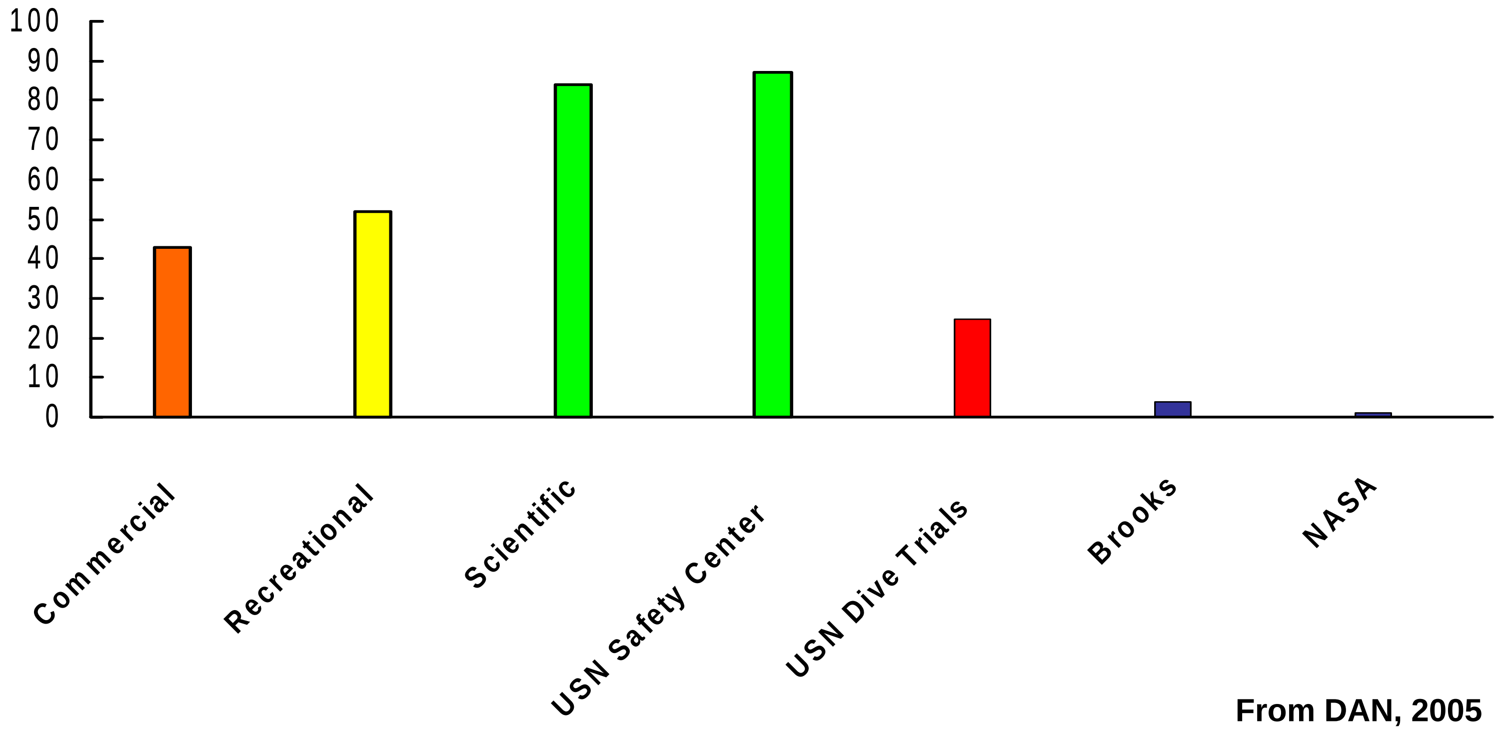
# Diving in Space

Mike Gernhardt

# Biomedical and Technological Challenges of EVA

- **Decompression** (denitrogenation required to work in low pressure suit (4.3 psi))
- **Thermoregulation** (-120°C to + 120°C)
- **Nutrition** (200 kcal/hr requirement)
- **Hydration** (1 liter/EVA)
- **Waste Management**
- **Radiation**
- **Micrometeoroids and Orbital Debris**
- **Suit Trauma**
- **Mobility/Dexterity:** current pressurized suits reduce mobility and dexterity
- **Visibility**

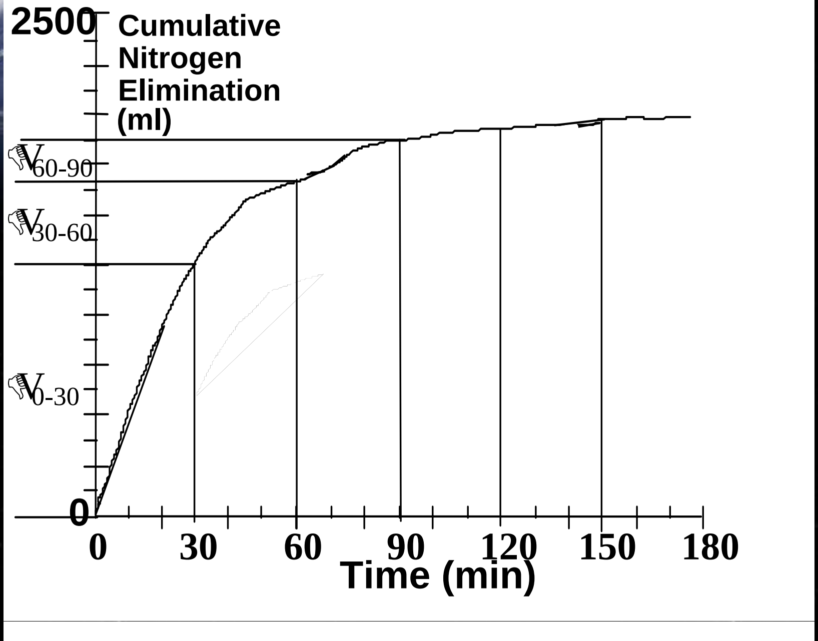
# Type II DCS – Percentage of All DCS vs. Diving Methods

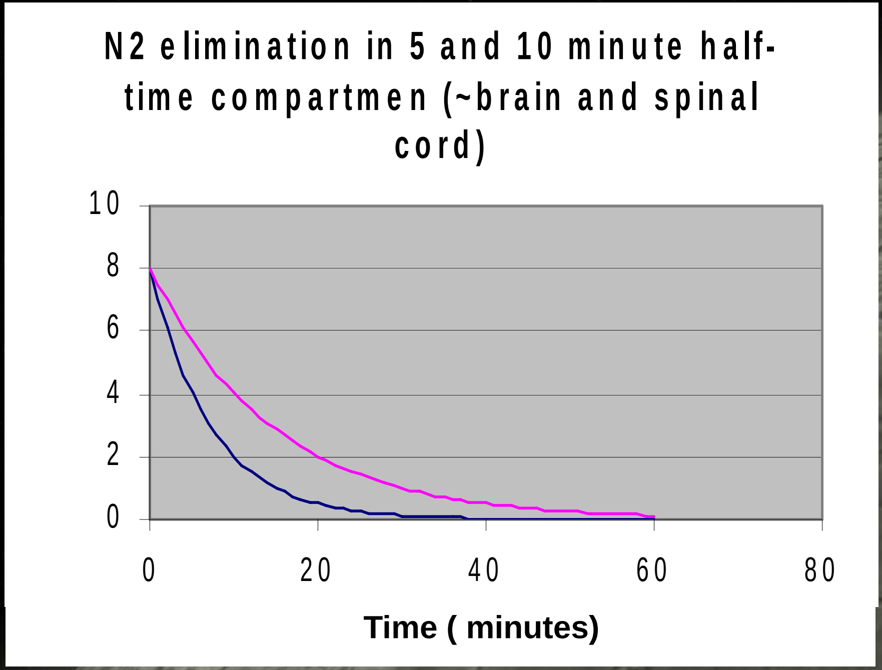


From DAN, 2005

- Character of Altitude DCS Different from Diving DCS
- Undersaturated Neurological Tissues
- “Softer Bubbles” Metabolic Gases

# Altitude DCS - Nitrogen Elimination during Oxygen Prebreathe

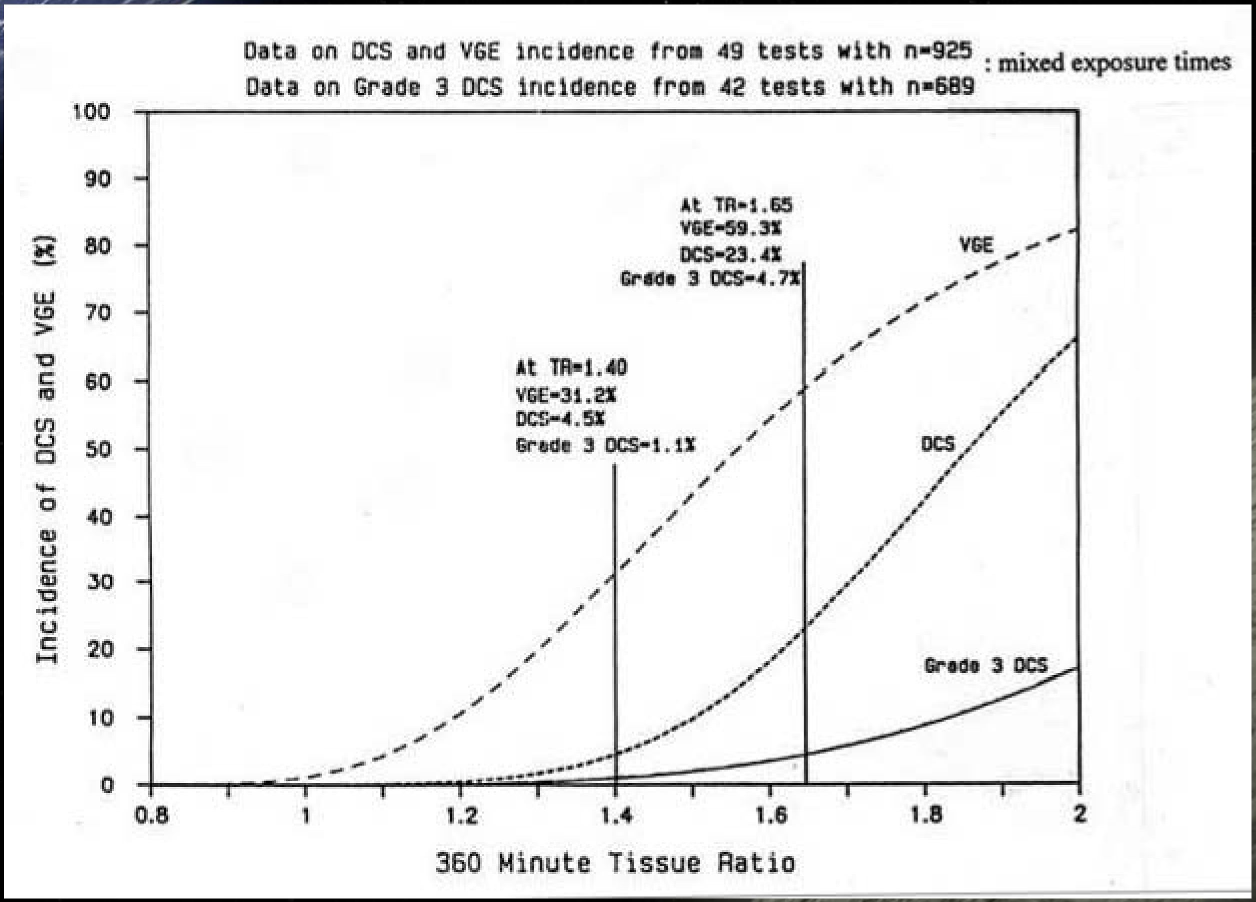




- **Over 50% of nitrogen eliminated in first 30 minutes**
- **Brain, spinal cord Halftime ~ 5-10 minutes, muscle and skin halftimes**
    - **15-25 minutes at resting conditions**
- **Resting prebreathe reaches point of diminishing return for reducing pain only DCS**
- **Type II DCS incidence higher on “Zero Prebreathe”**

Gerth, W.A., R.D. Vann, N.E. Leatherman, and M.D. Feezor. 1987. Effects of microgravity on tissue perfusion and the efficacy of astronaut denitrogenation for EVA. Aviat. Space Environ. Med. 58(9, Suppl.): A100-105

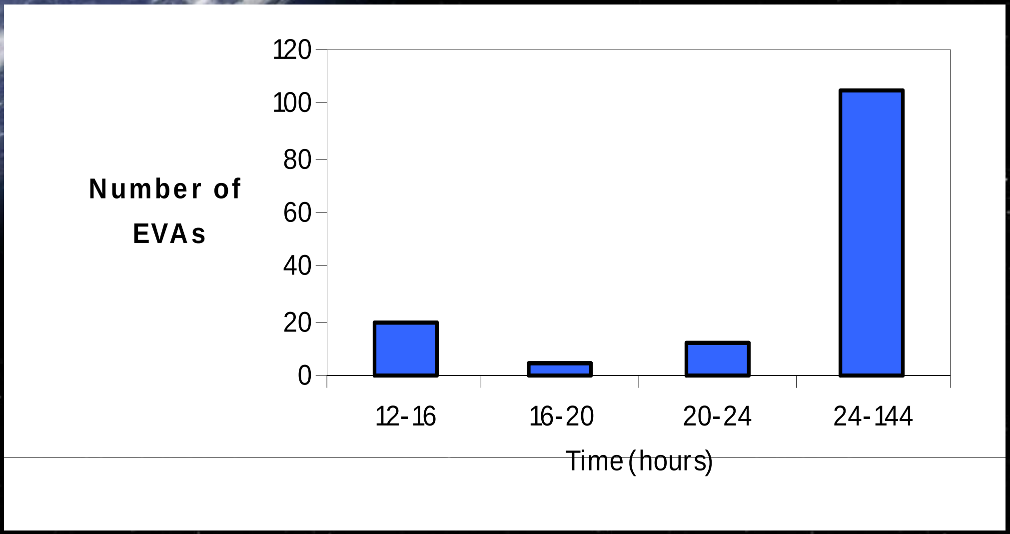
# Shuttle Pre-breathe Ground Studies



**Two Pre-breathe protocols approved for flight operation**

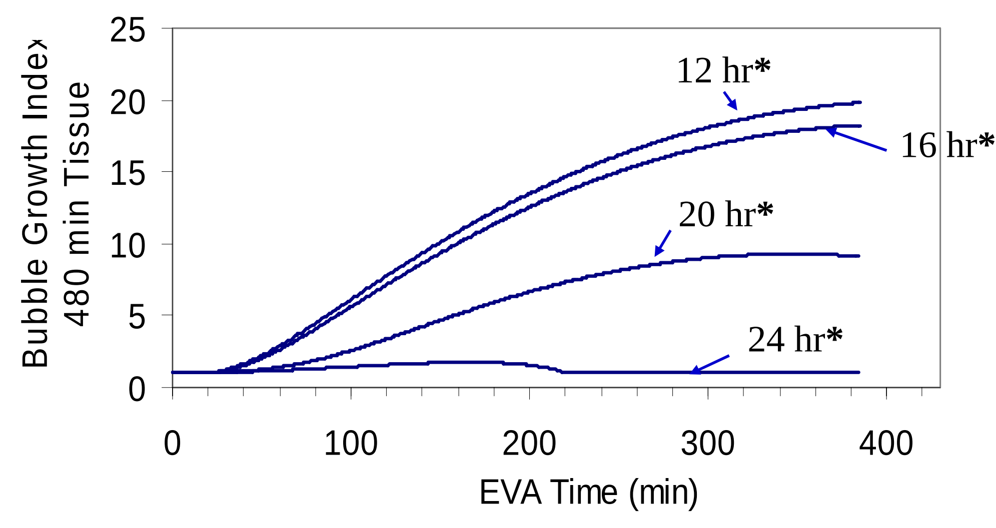
- **4 hour in-suit resting oxygen pre-breathe**
- **12 hr 10.2 psi staged decompression procedure**
- **R value ( tissue tension (360)/suit pressure)= 1.65**

# Flight Experience Shuttle 10.2 psi Staged Protocol – Zero DCS



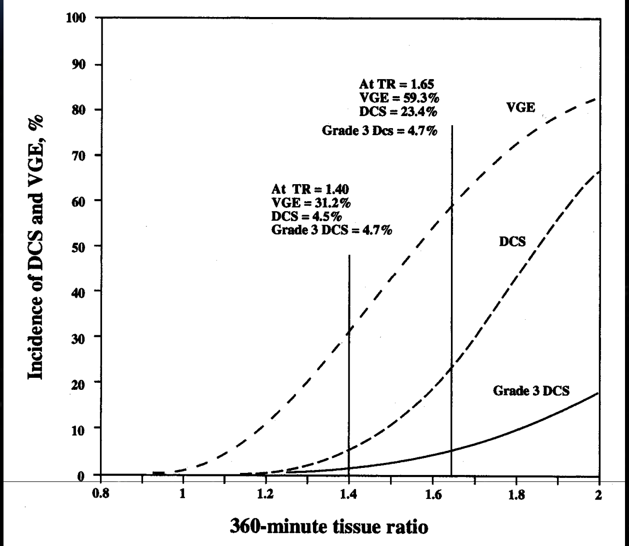
Time at 10.2 psi prior to shuttle EVA

Theoretical Tissue Bubble growth as a function of 10.2 exposure time



# Defining and Controlling Risk in Operational Research Programs – Example of Prebreathe Reduction Program (PRP)

## Background



**Shuttle Prebreathe Ground Trials (~ 25% DCS, ~ 5% symptoms that would terminate an EVA.) Acceptable Risk?**

**- 4 hour prebreathe**

**- 10.2 psi staged protocol**

**- 146 EVAs exposures with no reports of DCS**

## ISS Overnight Campout

**Limitations**

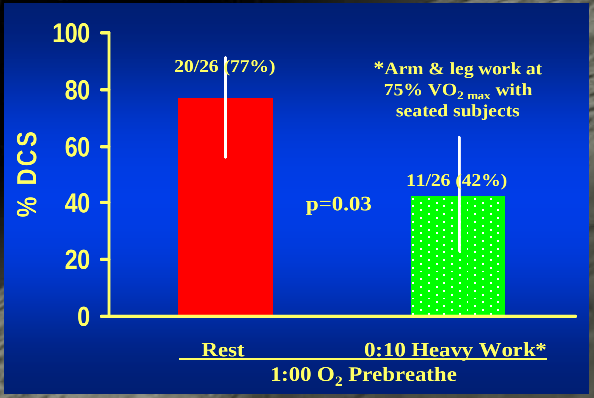
**•Timeline, back to back EVAs,**

**•02 usage,ISS 02 concentration**

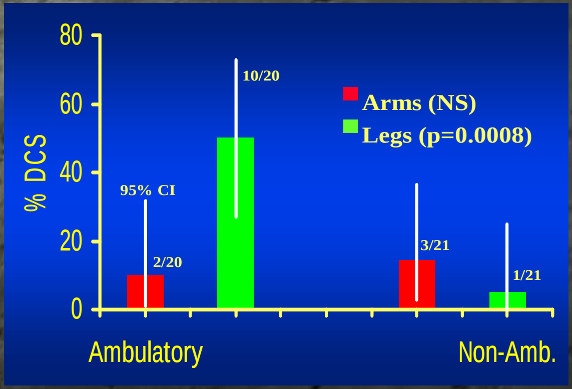
**•crew isolation and comfort**

## Enabling Counter Measure Research

## ( NASA TRL 3/4)



**USAF prebreathe exercise**



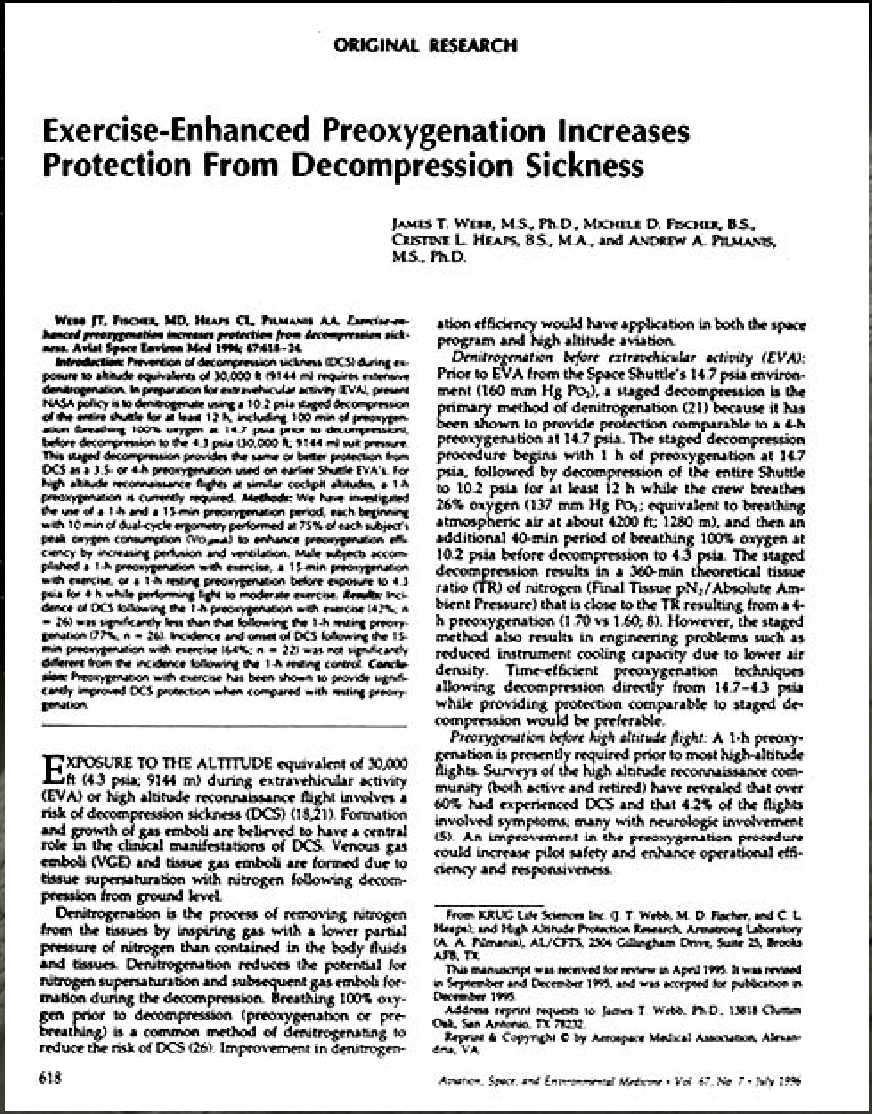
**Duke, NASA micro-gravity simulation ( non ambulation)**

# Enabling Research

Air Force Research Laboratory

Brooks AFB, Texas

Dual-Cycle Ergometer used for Exercise-Enhanced Prebreathe



ORIGINAL RESEARCH

## Exercise-Enhanced Preoxygenation Increases Protection From Decompression Sickness

James T. Webb, M.S., Ph.D., Michele D. Fischer, B.S., Cristine L. Heaps, B.S., M.A., and Andrew A. Pilmanis, M.S., Ph.D.

Webb JT, Fischer, MD, Heaps CL, Pilmanis AA. *Exercise-enhanced preoxygenation increases protection from decompression sickness.* Aviat Space Environ Med 1996; 67:618–24.

**Introduction:** Prevention of decompression sickness (DCS) during exposure to altitude equivalents of 30,000 ft (9144 m) requires extensive denitrogenation. In preparation for extravehicular activity (EVA), present NASA policy is to denitrogenate using a 10.2 psia staged decompression of the entire shuttle for at least 12 h, including 100 min of preoxygenation (breathing 100% oxygen at 14.7 psia prior to decompression), before decompression to the 4.3 psia (30,000 ft; 9144 m) suit pressure. This staged decompression provides the same or better protection from DCS as a 3.5- or 4-h preoxygenation used on earlier Shuttle EVA's. For high altitude reconnaissance flights at similar cockpit altitudes, a 1-h preoxygenation is currently required. **Methods:** We have investigated the use of a 1-h and a 15-min preoxygenation period, each beginning with 10 min of dual-cycle ergometry performed at 75% of each subject's peak oxygen consumption ($\dot{V}O_{2peak}$) to enhance preoxygenation efficiency by increasing perfusion and ventilation. Male subjects accomplished a 1-h preoxygenation with exercise, a 15-min preoxygenation with exercise, or a 1-h resting preoxygenation before exposure to 4.3 psia for 4 h while performing light to moderate exercise. **Results:** Incidence of DCS following the 1-h preoxygenation with exercise (42%, n = 26) was significantly less than that following the 1-h resting preoxygenation (77%, n = 26). Incidence and onset of DCS following the 15-min preoxygenation with exercise (64%; n = 22) was not significantly different from the incidence following the 1-h resting control. **Conclusion:** Preoxygenation with exercise has been shown to provide significantly improved DCS protection when compared with resting preoxygenation.

EXPOSURE TO THE ALTITUDE equivalent of 30,000 ft (4.3 psia; 9144 m) during extravehicular activity (EVA) or high altitude reconnaissance flight involves a risk of decompression sickness (DCS) (18,21). Formation and growth of gas emboli are believed to have a central role in the clinical manifestations of DCS. Venous gas emboli (VGE) and tissue gas emboli are formed due to tissue supersaturation with nitrogen following decompression from ground level.

Denitrogenation is the process of removing nitrogen from the tissues by inspiring gas with a lower partial pressure of nitrogen than contained in the body fluids and tissues. Denitrogenation reduces the potential for nitrogen supersaturation and subsequent gas emboli formation during the decompression. Breathing 100% oxygen prior to decompression (preoxygenation or prebreathing) is a common method of denitrogenating to reduce the risk of DCS (26). Improvement in denitrogenation efficiency would have application in both the space program and high altitude aviation.

*Denitrogenation before extravehicular activity (EVA):* Prior to EVA from the Space Shuttle's 14.7 psia environment (160 mm Hg $PO_2$), a staged decompression is the primary method of denitrogenation (21) because it has been shown to provide protection comparable to a 4-h preoxygenation at 14.7 psia. The staged decompression procedure begins with 1 h of preoxygenation at 14.7 psia, followed by decompression of the entire Shuttle to 10.2 psia for at least 12 h while the crew breathes 26% oxygen (137 mm Hg $PO_2$; equivalent to breathing atmospheric air at about 4200 ft; 1280 m), and then an additional 40-min period of breathing 100% oxygen at 10.2 psia before decompression to 4.3 psia. The staged decompression results in a 360-min theoretical tissue ratio (TR) of nitrogen (Final Tissue $pN_2$/Absolute Ambient Pressure) that is close to the TR resulting from a 4-h preoxygenation (1.70 vs 1.60; 8). However, the staged method also results in engineering problems such as reduced instrument cooling capacity due to lower air density. Time-efficient preoxygenation techniques allowing decompression directly from 14.7–4.3 psia while providing protection comparable to staged decompression would be preferable.

*Preoxygenation before high altitude flight:* A 1-h preoxygenation is presently required prior to most high-altitude flights. Surveys of the high altitude reconnaissance community (both active and retired) have revealed that over 60% had experienced DCS and that 4.2% of the flights involved symptoms, many with neurologic involvement (5). An improvement in the preoxygenation procedure could increase pilot safety and enhance operational efficiency and responsiveness.

---

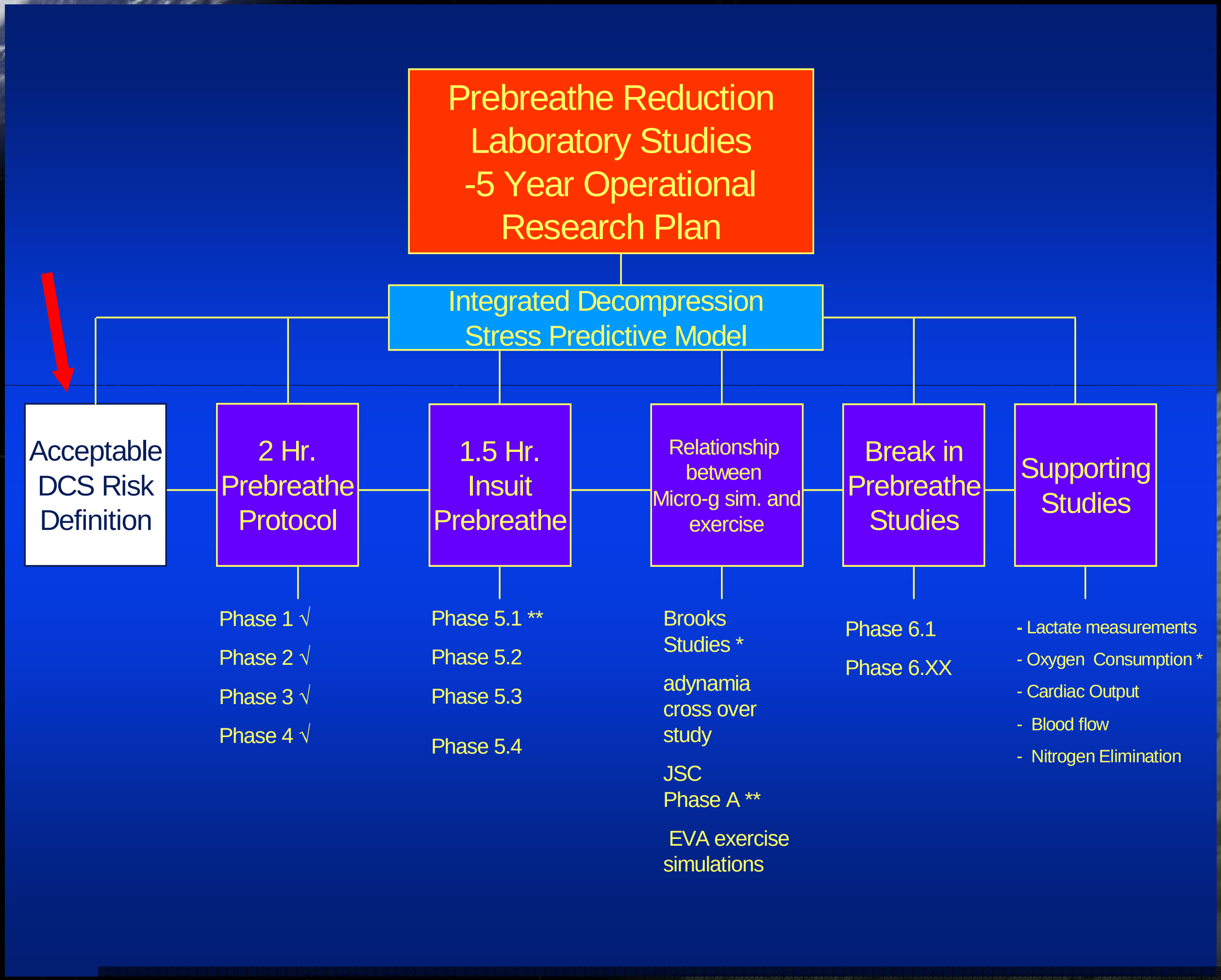
From KRUG Life Sciences Inc. (J. T. Webb, M. D. Fischer, and C. L. Heaps); and High Altitude Protection Research, Armstrong Laboratory (A. A. Pilmanis), AL/CFTS, 2504 Gillingham Drive, Suite 25, Brooks AFB, TX.

This manuscript was received for review in April 1995. It was revised in September and December 1995, and was accepted for publication in December 1995.

Address reprint requests to: James T. Webb, Ph.D., 13818 Chittim Oak, San Antonio, TX 78232.

10 minutes 75% V02peak, 88% lower body, 12% upper body

# Prebreathe Reduction Program



Prebreathe Reduction Laboratory Studies -5 Year Operational Research Plan

Integrated Decompression Stress Predictive Model

Acceptable DCS Risk Definition

2 Hr. Prebreathe Protocol
- Phase 1 √
- Phase 2 √
- Phase 3 √
- Phase 4 √

1.5 Hr. Insuit Prebreathe
- Phase 5.1 **
- Phase 5.2
- Phase 5.3
- Phase 5.4

Relationship between Micro-g sim. and exercise
- Brooks Studies *
- adynamia cross over study
- JSC Phase A **
- EVA exercise simulations

Break in Prebreathe Studies
- Phase 6.1
- Phase 6.XX

Supporting Studies
- Lactate measurements
- Oxygen Consumption *
- Cardiac Output
- Blood flow
- Nitrogen Elimination

- Start by defining acceptable DCS risk for ISS mission and developing accept/reject limits for countermeasure trials
- Early development focused on delivering acceptable/effective counter measure
- Later development focused on increased efficiency and improved scientific understanding of counter measure mechanisms

Accept: DCS ≤ 15% and Grade IV VGE ≤ 20% , @ 95% C.I

Reject: DCS ≥ 15% or Grade IV VGE ≥ 20% , @ 70% C.I

# Multi-Center Study: NASA, Duke, DCIEM, Hermann UT

Exercise 10 mins @ 75% V02$_{peak}$
And/or light exercise (160-253 Kcal/hr)

2hr oxygen prebreathe

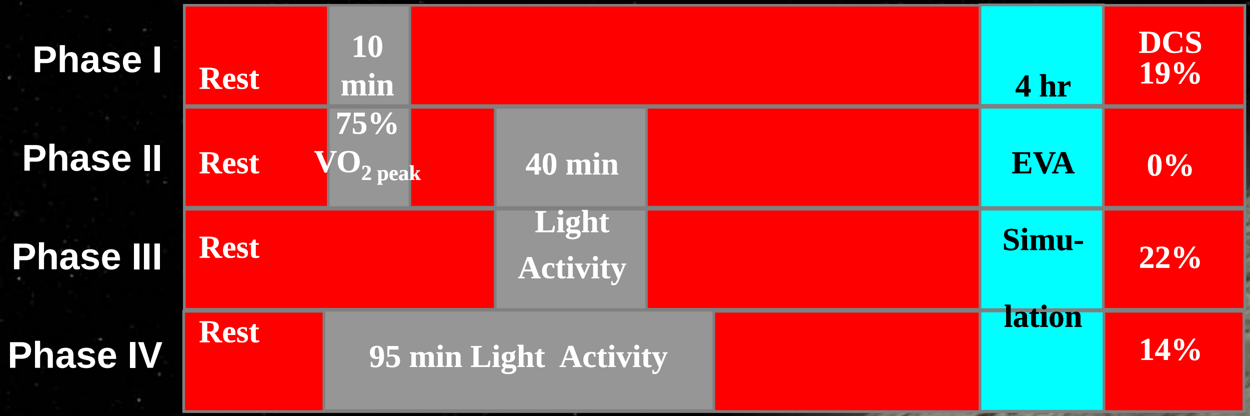
Micro-gravity simulation
( non-ambulation)

Simulated EVA exposure at
4.3 psi 4 hrs

Use of “Suit Simulator” for
EVA Exercise

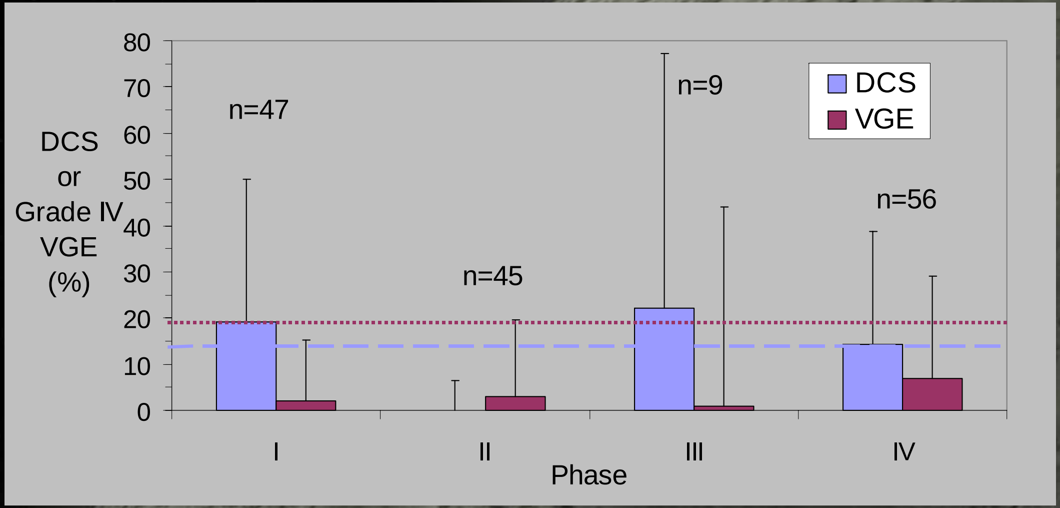
# Prebreathe Trials

- **High intensity exercise (75% peak oxygen consumption [$VO_{2\ peak}$])**
- **Low intensity activity (5.8 mL·kg$^{-1}$·min$^{-1}$ $VO_2$)**
- **Neither High or low intensity exercise was acceptable**
- **Coupling High with low intensity exercise was acceptable**



| | | | | | |
|---|---|---|---|---|---|
| **Phase I** | Rest | 10 min 75% $VO_{2\ peak}$ | | 4 hr EVA Simu-lation | DCS 19% |
| **Phase II** | Rest | 10 min 75% $VO_{2\ peak}$ | 40 min Light Activity | | 0% |
| **Phase III** | Rest | | 40 min Light Activity | | 22% |
| **Phase IV** | Rest | 95 min Light Activity | | | 14% |

PRP Phase I-IV 2 hr oxygen prebreathe exercise protocols

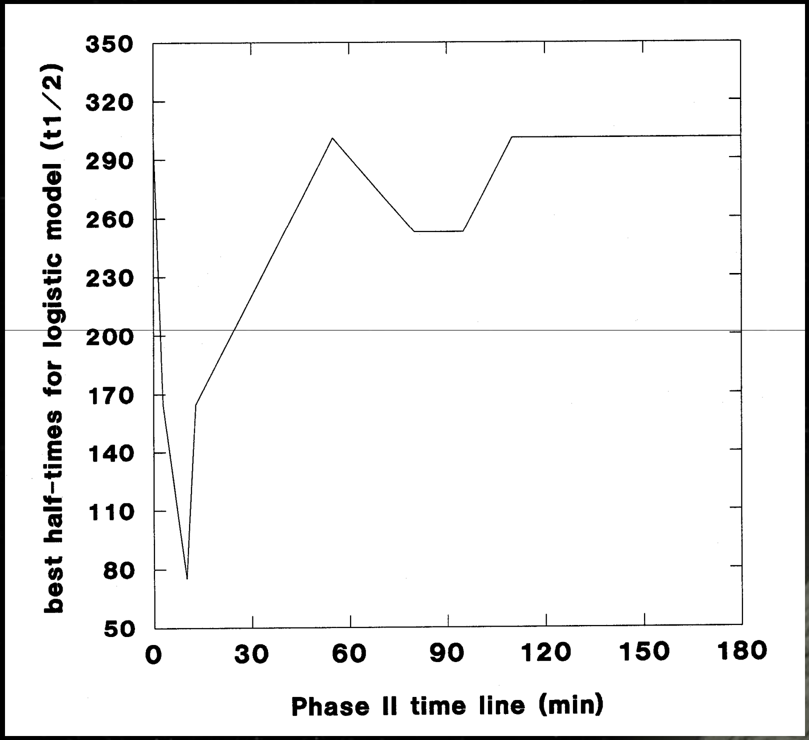


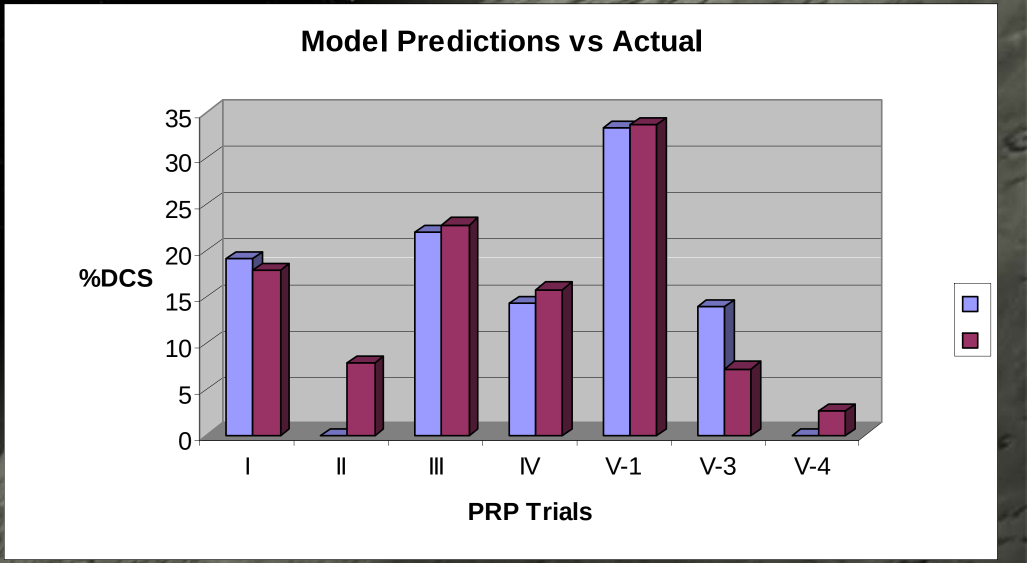
**DCS and Grade IV VGE observations** (shown with 95% upper confidence limit bars dashed lines indicating accept levels for DCS and VGE incidences)

# Exercise and Inert Gas Kinetics

$$P1N2 = P0 + (1 - \exp - k1t) * (Pa - P0),$$

$$k1 = [(1 / \exp(-\lambda * mL*kg^{-1}*min^{-1})) / 519.37].$$



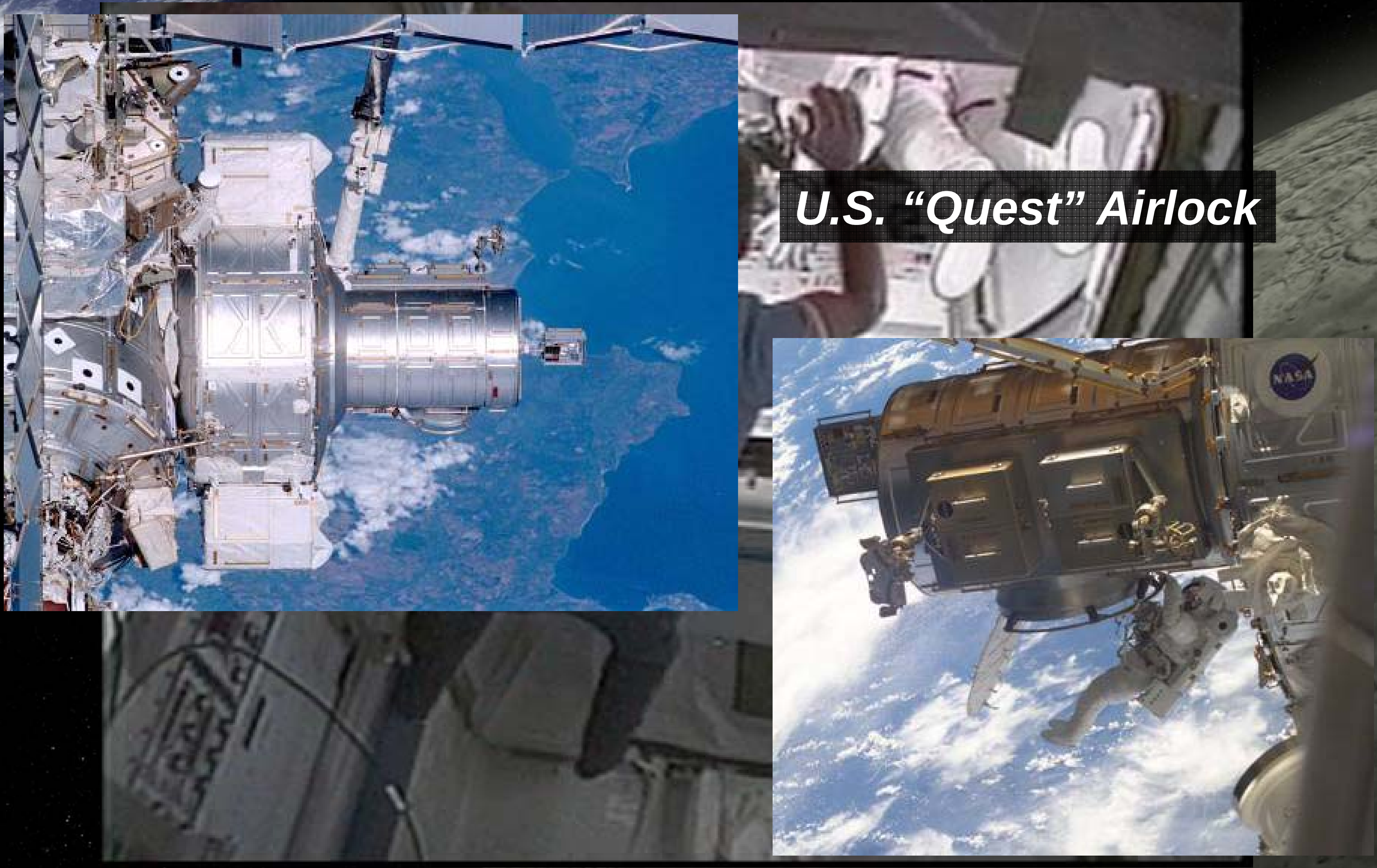


Hosmer-Lemshow Goodness of fit statistic = 2.188 with 5 degrees of freedom, p = 0.82 ( significance > .05)

# Exercise Prebreathe Protocol: Experience to Date

- Overview- The exercise prebreathe protocol has been used successfully on 34 EVAs from the International Space Station (ISS)- no DCS
  - Five Shuttle assembly flights and two increment EVAs
    - Starting in July 2001
  - These assembly missions would have been difficult or impossible to execute as base-lined, without the protocol

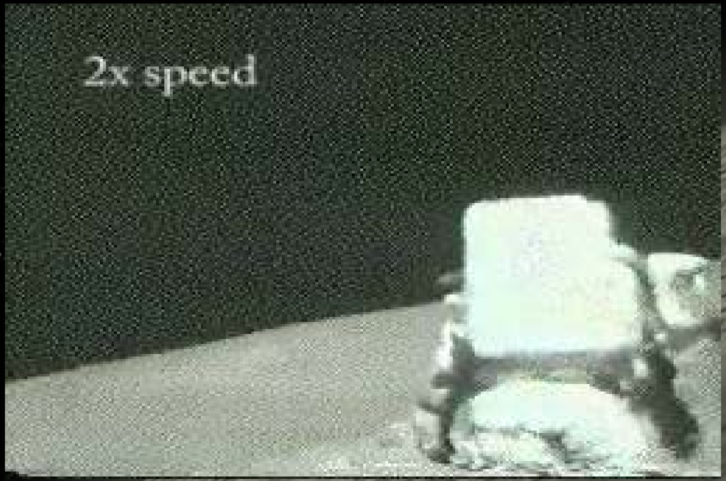
# A United States Airlock: Doorway to Space

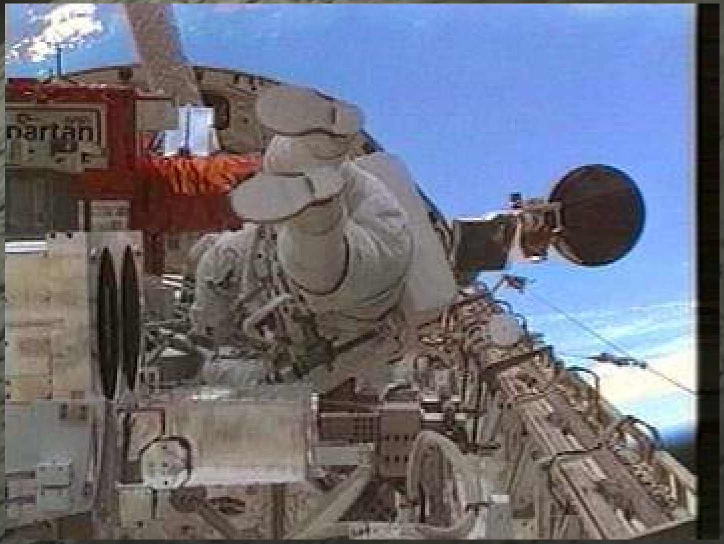


U.S. “Quest” Airlock

# The Challenge of Moving Past Apollo

- Apollo was a remarkable human achievement
- Fewer than 20 EVAs, maximum of three per mission
- Constellation Program, up to 2000 EVAs over the 10 year Lunar program
- Limited mobility, dexterity, center of gravity and other features of the suit required significant crew compensation to accomplish the objectives. It would not be feasible to perform the constellation EVAs using Apollo vintage designs
- The vision is to develop an EVA system that is low overhead and results in close to (or better than) one g shirt sleeve performance i.e. “ A suit that is a pleasure to work in, one that you would want to go out and explore in on your day off”
- Lunar EVA will be very different from earth orbit EVA – a significant change in design and operational philosophies will be required to optimize suited human performance in lunar gravity

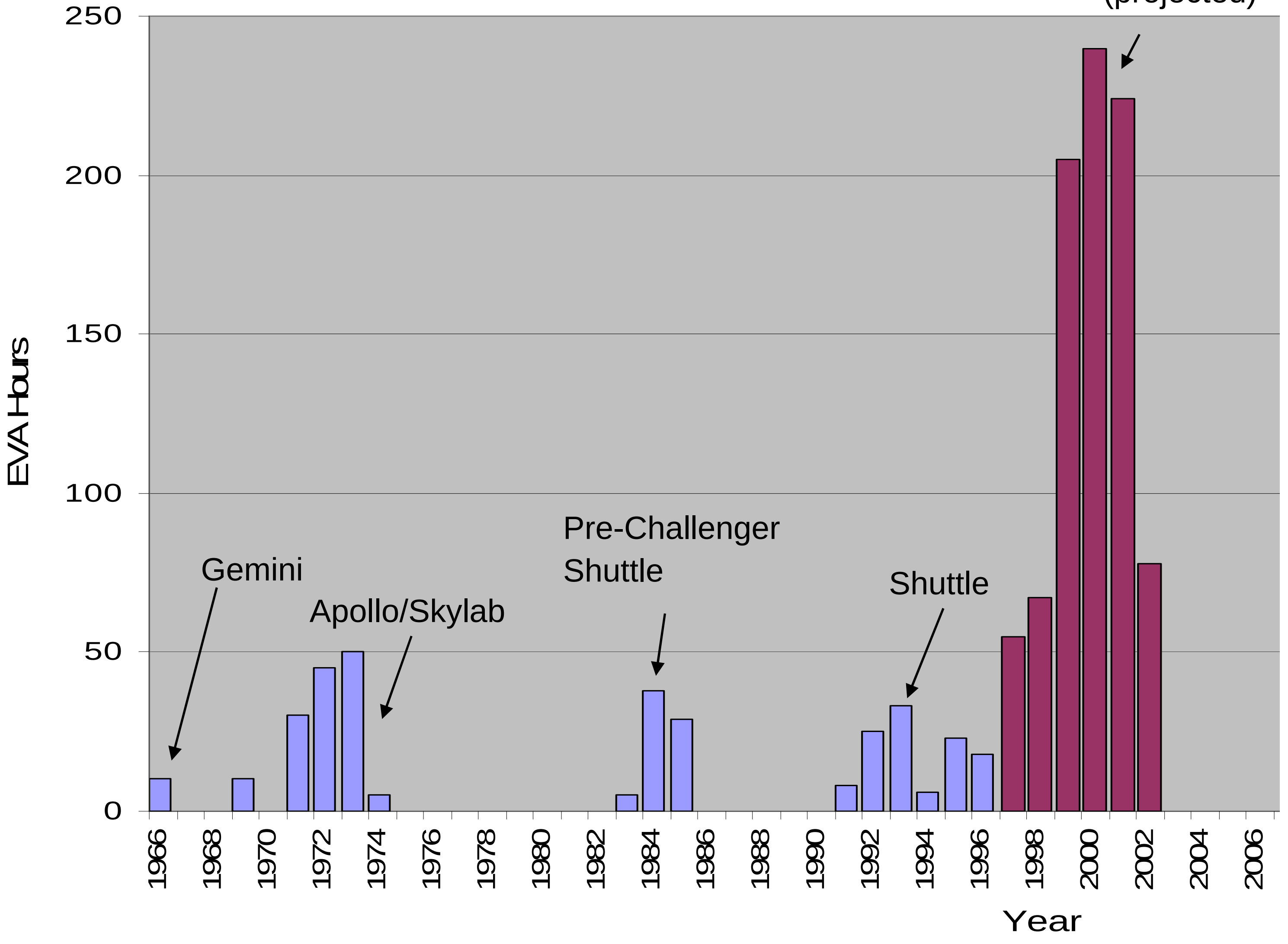




# Challenges for EVA on the Moon

- **Dealing with risk and consequences of a significant Solar Particle Event (SPE)**
- **Long duration missions with three 8hr EVAs per person per week**
  - Apollo suits were used no more than 3 times
  - Individual crewmembers might perform up to 76 EVAs in a 6-month mission
  - Suit-induced trauma currently occurs with even minimal EVA time
- **With Apollo style un-pressurized rover (UPR), exploration range is limited by EVA sortie time and 10 km walkback constraint**
  - Science community input that optimal scientific return within this range could be accomplished within ~ 30 days of EVA
  - Two UPRs could extend exploration range up to 15-20 km (crew-day limited)
- **Apollo highlighted the importance of dust control for future long duration missions**
- **Increased Decompression Sickness (DCS) risk and prebreathe requirements associated with 8 psi 32% $O_2$ cabin pressure versus Apollo with 5 psi 100% $O_2$**
- **The high frequency EVA associated with the projected lunar architectures will require significant increases in EVA work efficiency (EVA prep time/EVA time)**

# “The Wall of EVA”



**“The Wall”**

ISS Construction
(projected)

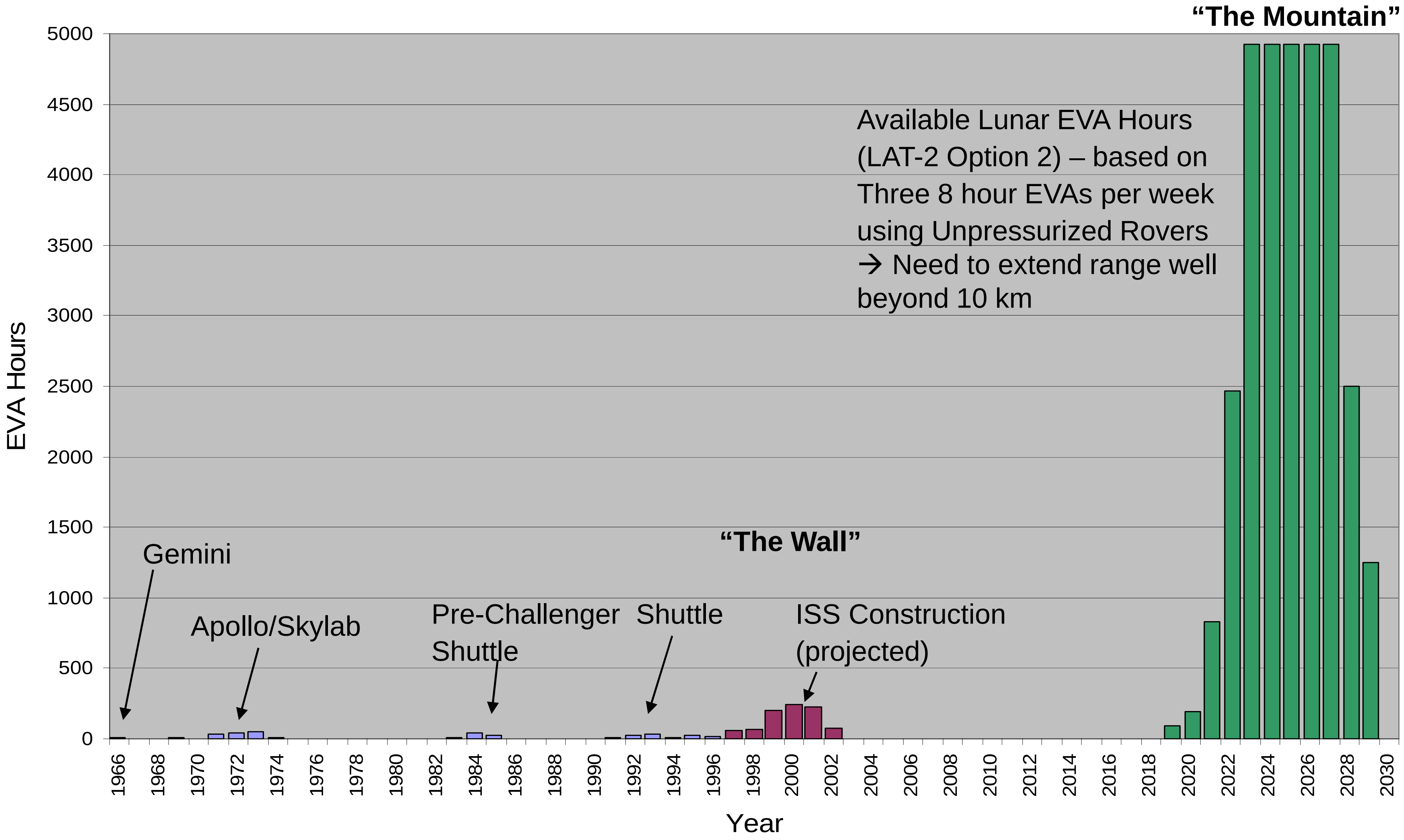
Gemini

Apollo/Skylab

Pre-Challenger
Shuttle

Shuttle

# "The Mountain of EVA"

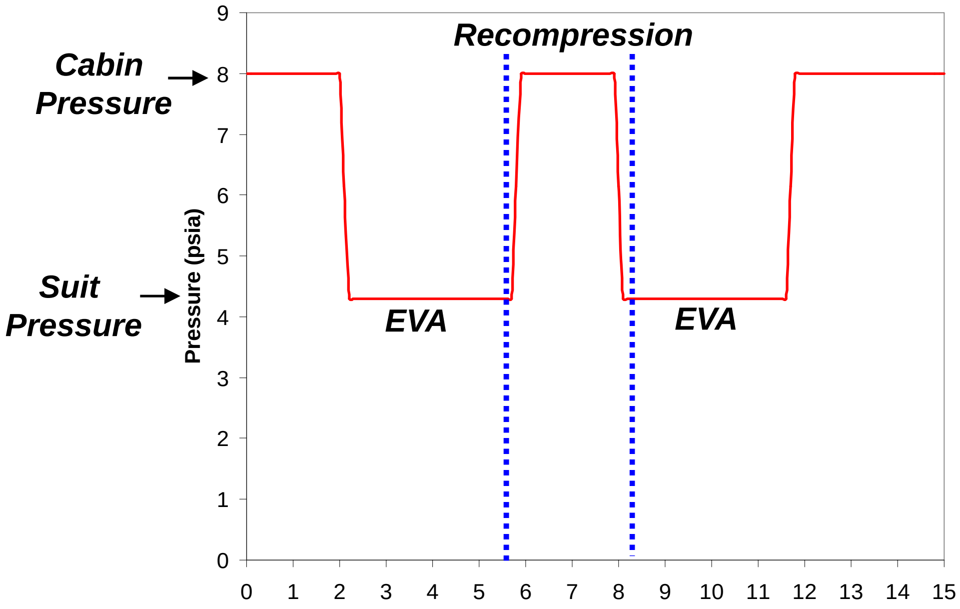


# Intermittent Recompression - Background

- **Current plans for lunar surface exploration include Small Pressurized Rovers (SPRs) that are quickly ingressed and egressed with minimal loss of consumables**

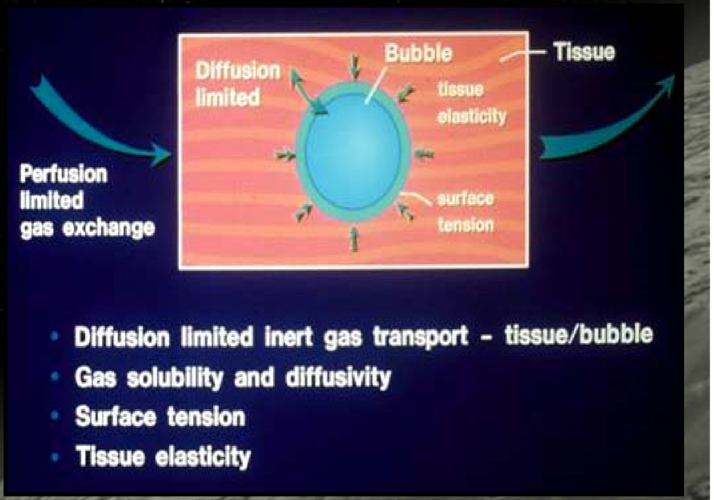
- **This capability enables crew members to perform multiple short extravehicular activities (EVAs) at different locations in a single day versus a single 8-hr EVA**

- **Previous modeling work and empirical human and animal data indicate that the intermittent recompressions may reduce decompression stress**



# Tissue Bubble Dynamics Model (TBDM)- Provides Significant Prediction and Fit of Diving and Altitude DCS Data

- Decompression stress index based on tissue bubble growth dynamics *(Gernhardt, 1991)*
- *Diving: n*=6437 laboratory (430 DCS cases)
  - *Logistic Regression Analysis: p <0.01*
  - *Hosmer-Lemeshow Goodness of Fit = 0.77*
- *Altitude: n=345 (57 DCS, 143 VGE)*
  - *Logistic Regression Analysis (DCS): p <0.01*
  - *Logistic Regression Analysis (VGE): p <0.01*
  - *Hosmer-Lemeshow Goodness of Fit (DCS): p = 0.35*
  - *Hosmer-Lemeshow Goodness of Fit (VGE): p = 0.55*



- Diffusion limited inert gas transport - tissue/bubble
- Gas solubility and diffusivity
- Surface tension
- Tissue elasticity

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

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

tion of a Decompression Stress Index Based on Tissue Bubble Dynamics. Ph.D dissertation, University of

# Intermittent Recompression - Background

- Intermittent recompression during saturation decompression was previously proposed as a method for decreasing decompression stress and time ***(Gernhardt,1988)***
  - Gas bubbles respond to changes in hydrostatic pressure on a time scale much faster than the tissues
- Intermittent recompression (IR) has been shown to decrease decompression stress in humans and animals ***(Pilmanis et al. 2002, Møllerløkken et al. 2007)***

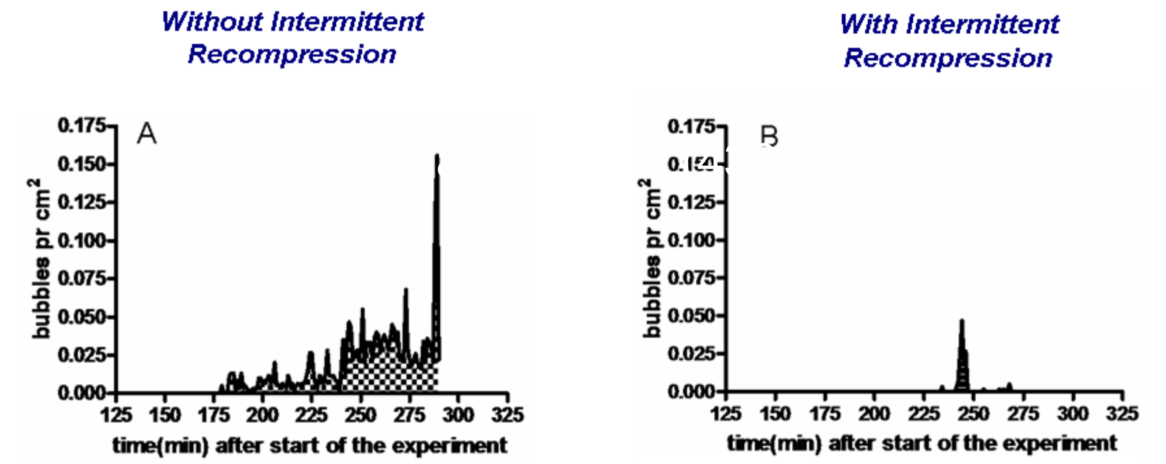


**Fig. 10.** Two groups of six pigs were compressed to 121 FSW with 90 minutes bottom time and were then decompressed following one of two decompression procedures; either with a 5-min 12 FSW recompression at the end of the three last decompression stops (experimental group), or without such recompression (control group). The control profile was a USN profile for this exposure, where the stop times were reduced by 50% as pilot studies showed that the standard USN profile produced very few bubbles. The average number of venous gas bubbles measured in the pulmonary artery during the decompression is shown for the control group (A) and the experimental group (B). The results indicate significantly fewer bubbles in the experimental group than in the control group ($p<.0001$). *From Møllerløkken et al. (5) by permission.*

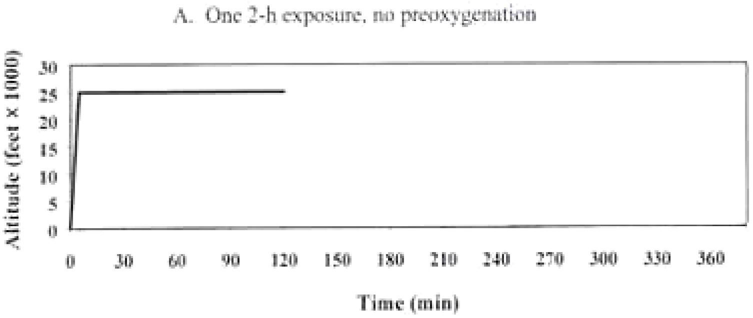
Gernhardt, M.L. Mathematical modeling of tissue bubble dynamics during decompression. *Advances in Underwater Technology, Ocean Science and Offshore Engineering, Volume 14: Submersible Technology. Society for Underwater Technology,* 1988.

Pilmanis A.A., Webb J.T., Kannan N., Balldin U. The effect of repeated altitude exposures on the incidence of decompression sickness. Aviat Space Environ Med; 73: 525-531, 2002.

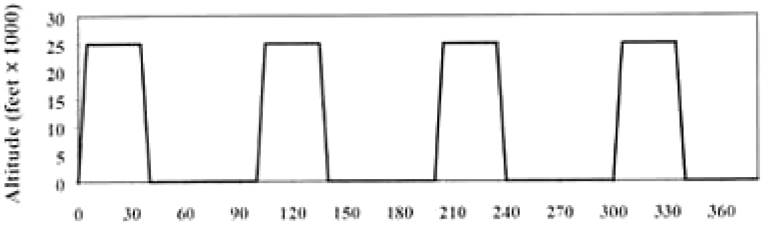
Møllerløkken A, Gutvik C, Berge VJ, Jørgensen A, Løset A, Brubakk AO. Recompression during decompression and effects on bubble formation in the pig. Aviat Space Environ Med; 78:557-560, 2007.

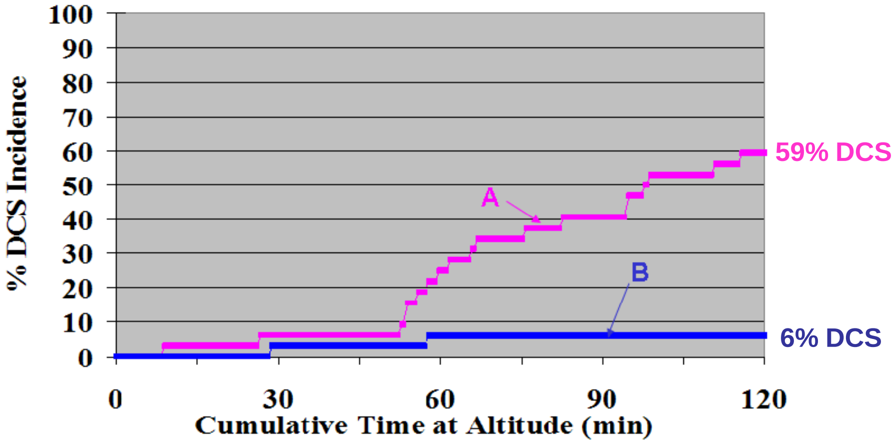
# Discussion

A

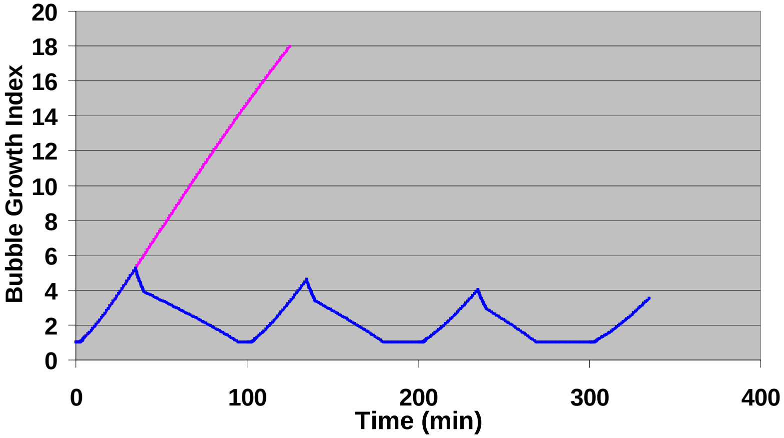


B





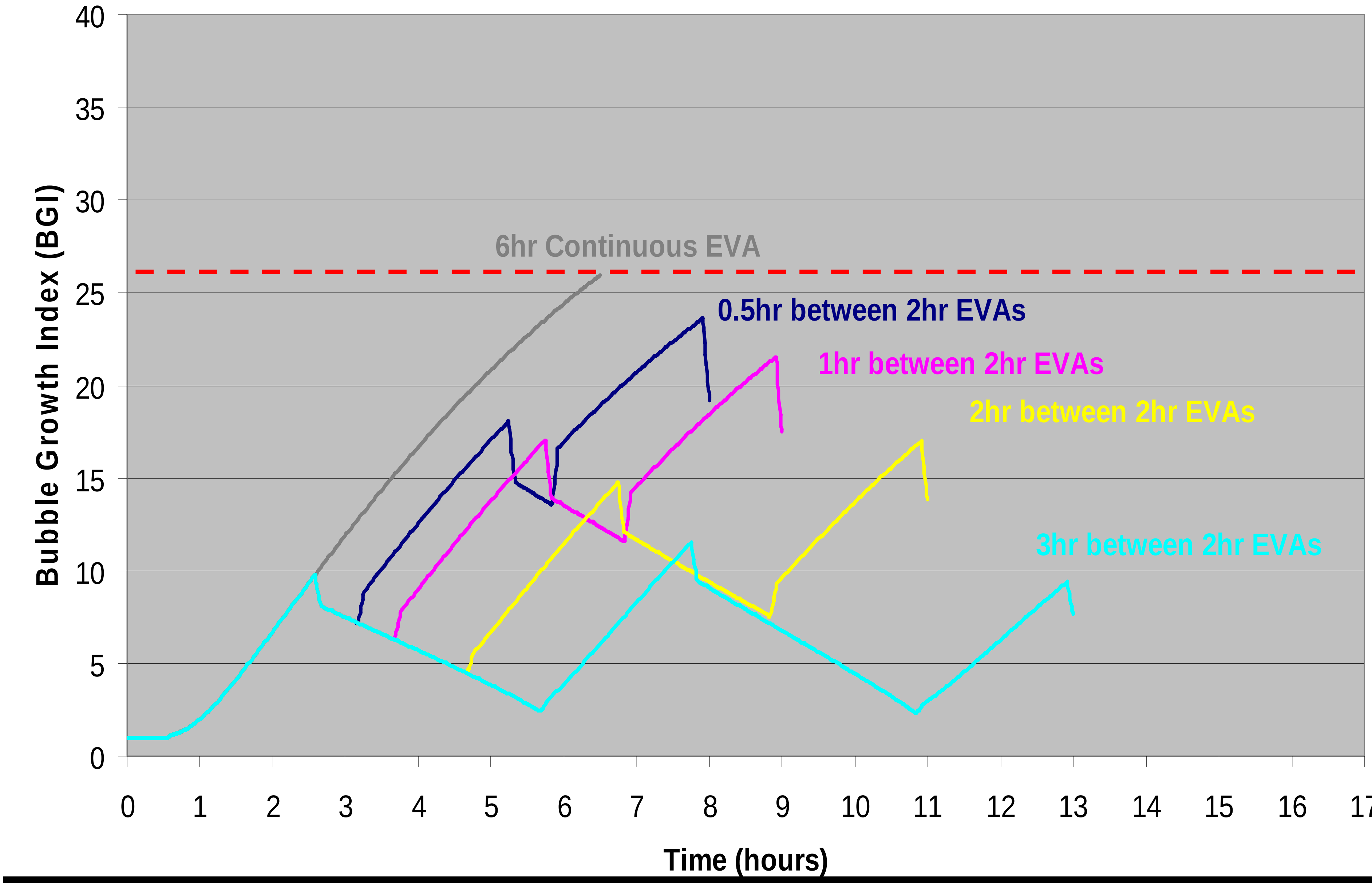
DCS Incidence



TBDM Predictions

Pilmanis A.A., Webb J.T., Kannan N., Balldin U. The effect of repeated altitude exposures on the incidence of decompression sickness. Aviat Space Environ Med; 73: 525-531, 2002.

# Intermittent Recompression - 3 x 2hr EVA at 4.3 psi



# Floating Through the Terminator in the Sea Space Continuum