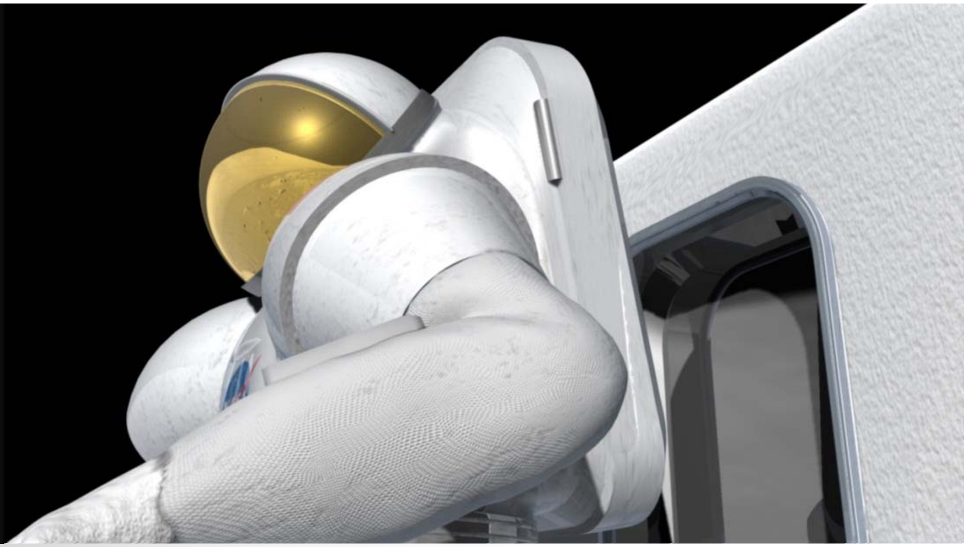


Fifteen-minute Extravehicular Activity Prebreathe Protocol Using NASA's Exploration Atmosphere (8.2 psia / 34% O_2)

Andrew F. J. Abercromby, Ph.D.[1]
Michael L. Gernhardt, Ph.D.[2]
Johnny Conkin, Ph.D.[3]

[1] Wyle Laboratories, Inc., Houston, TX
[2] NASA Johnson Space Center, Houston, TX
[3] Universities Space Research Association, Houston, TX

Introduction – Exploration Atmosphere

- Current engineering and physiological constraints such as oxygen purge and prebreathe requirements make EVAs costly in terms of crew time and consumables
- NASA recently adopted an exploration atmosphere (Expl. Atm.) of 8.2 psia, 34% oxygen (O_2), 66% nitrogen (N_2) for future spacecraft that will be used for high-frequency EVAs
  - This is a change from the previously defined Expl. Atm. of 8.0 psia, 32% O_2, 68% N_2, recommended in 2006 by the Exploration Atmospheres Working Group
- When combined with suit ports that enable rapid ingress and egress with minimal gas losses, the reduced ppN_2 of the new Expl. Atm. potentially enables multiple extravehicular activities (EVAs) in a single day or a single 8-hour EVA, depending on mission needs
- However, existing ISS and Shuttle O_2 prebreathe protocols are not applicable to the new Expl. Atm.
- **➔ New O_2 prebreathe protocols must be developed that provide adequate protection against DCS while minimizing crew time and consumables usage**

Background – Suit Port Egress & Ingress Procedures

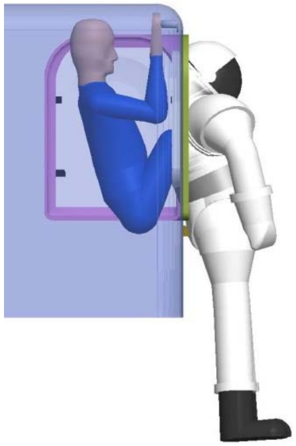
Egress Procedures

1. Don Suit (8.2 PSI)
2. Close/lock hatch (blue)
3. Mode to PRESS (6.0 PSI)
4. 2 min leak check in suit
5. Purge 2 min
6. Mode to EVA (6.0 PSI)
7. Start prebreathe clock
8. Vestibule depress to 3.5 PSI
9. Leak Check 1 min
10. Vestibule depress to 0.0 PSI
11. Release Suit Port (red)

Depress suit to 4.3 PSI 15 mins after start of prebreathe clock

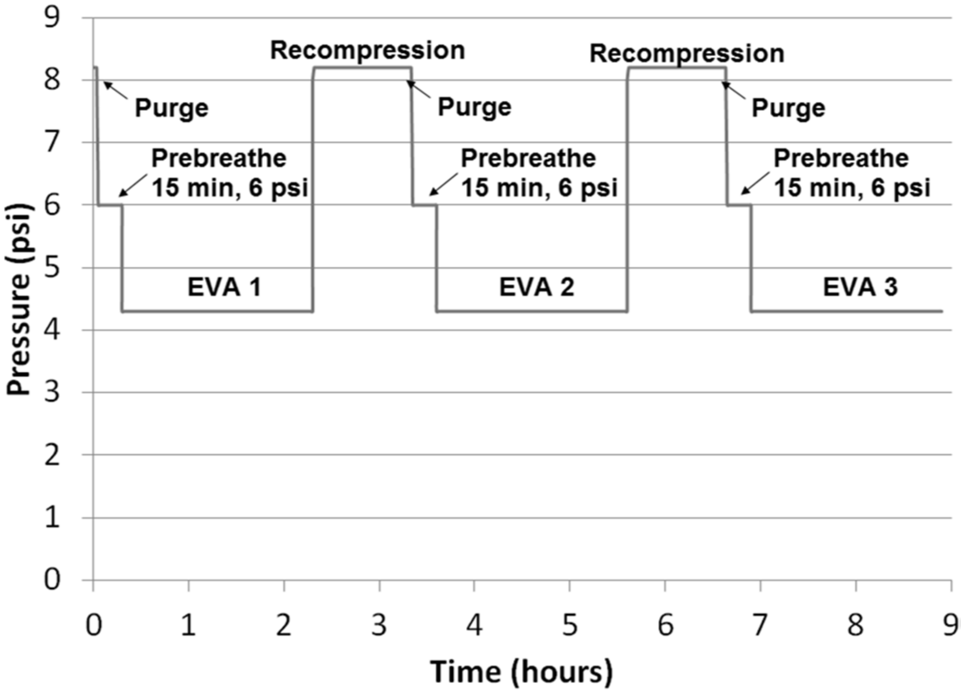
Ingress Procedures

1. Engage Suit Port (red)
2. Vestibule press to 8.2 PSI
3. Leak Check 1 min
4. Vestibule-Cabin press equalization
5. Vestibule-Cabin-Suit equalization
6. Open PLSS lock
7. Open hatch (blue)
8. Close PLSS lock
9. Egress suit



Background – Intermittent Recompression

- **Performing multiple EVAs per day results in intermittent recompressions (IR)**
- **IR during saturation decompression previously proposed as a method for decreasing decompression stress and time** *(Gernhardt,1988)*
- **IR has been shown to decrease decompression stress in humans and animals** *(Pilmanis et al. 2002, Møllerløkken et al. 2007)*



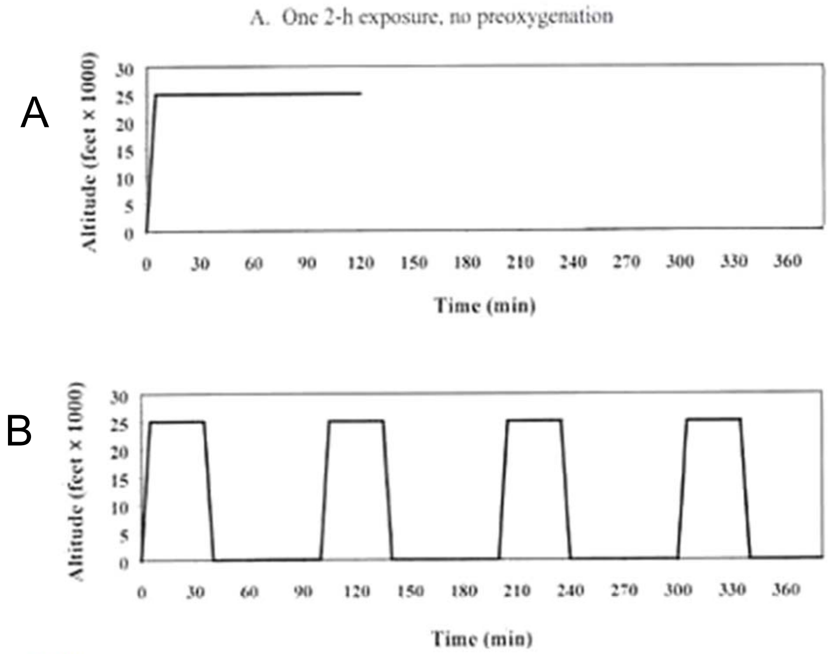
- ***During recompressions:***
  - ***Reversed N_2 concentration gradient during recompression means that N_2 reuptake from blood into the tissues slowly begins***
  - ***At the same time, increased hydrostatic pressure rapidly reduces the size of the bubbles such that the pressure due to surface tension inside the bubble increases, causing a higher bubble-to-tissue N_2 diffusion gradient***
  - ***Because the volume of gas in the bubbles is small compared to the volume of gas in surrounding tissues, the N_2 elimination from the bubbles does not significantly increase N_2 tissue tension***

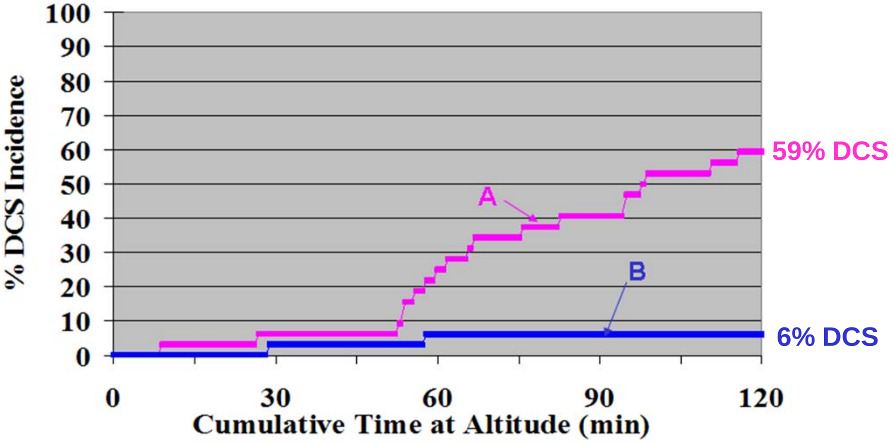
Gernhardt, M.L. Mathematical modeling of tissue bubble dynamics during decompression. *Advances in Underwater Technology, Ocean Science and Offshore Engineering, Volume 14: Submersible Technology. Society for Underwater Technology,* 1988.

Pilmanis A.A., et al.. The effect of repeated altitude exposures on the incidence of decompression sickness. Aviat Space Environ Med; 73: 525-531, 2002.

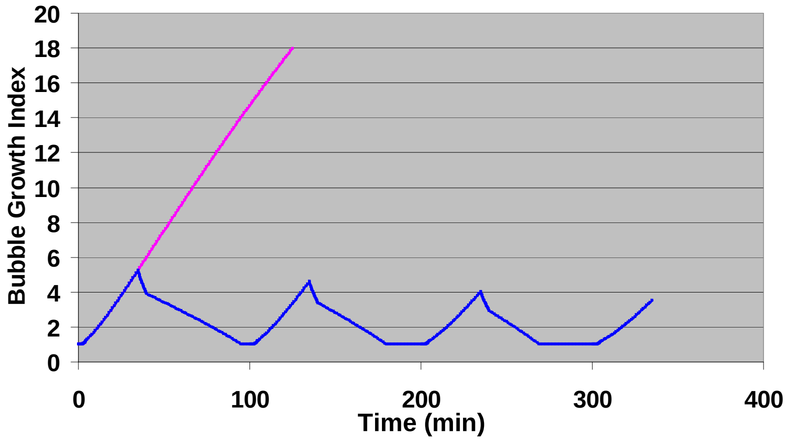
Møllerløkken A, et al. Recompression during decompression and effects on bubble formation in the pig. Aviat Space Environ Med; 78:557-560, 2007.

Background – Intermittent Recompression





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.

Background – Intermittent Recompression

Without Intermittent Recompression

With Intermittent Recompression

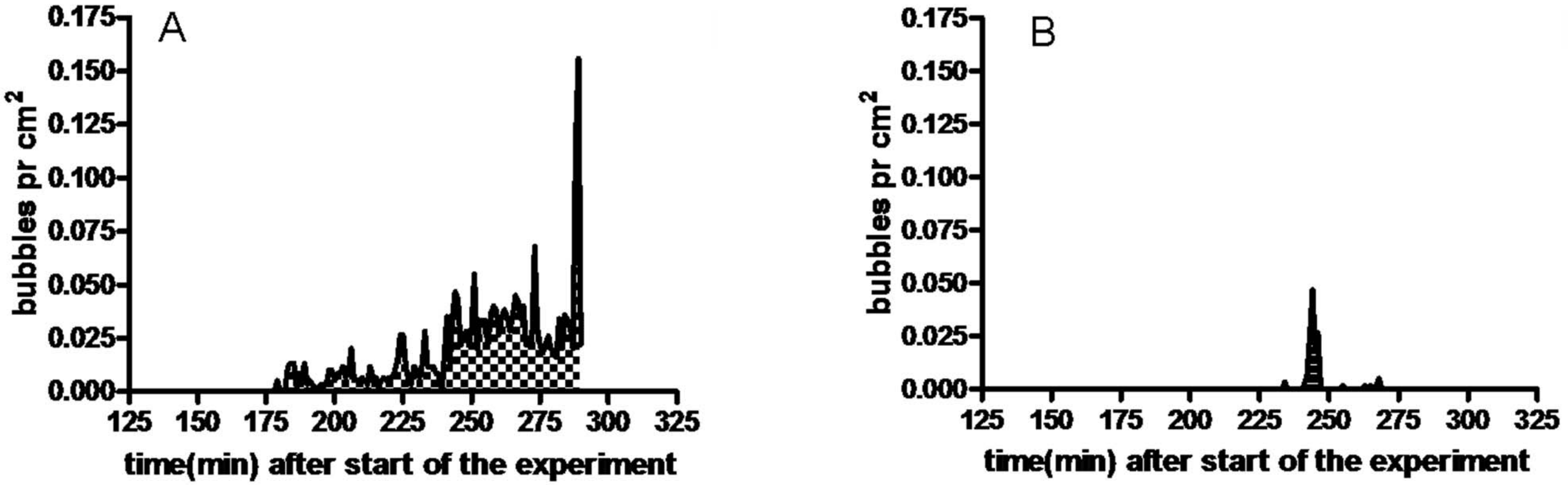


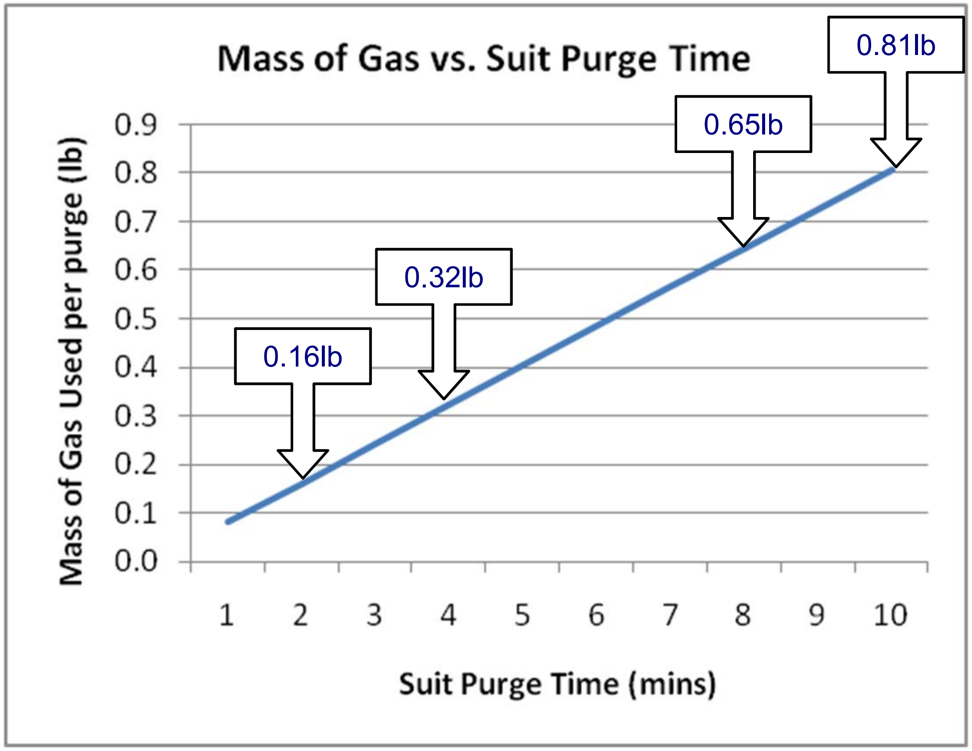
Fig. 10. Two groups of six pigs were compressed to 121 FSW with 90 minutes bottom time and were then decompressed following one of two decompression procedures; either with a 5-min 12 FSW recompression at the end of the three last decompression stops (experimental group), or without such recompression (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.*

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

Background:
Abbreviated Suit Purge – Mass and Time Savings

- EVA suits are purged of N_2 prior to depressurization to achieve ≥ 95% O_2
  - Purge requires ~ 8 minutes and uses 0.65 lb gas per purge per suit
- In an airlock, most of this gas is reclaimed but with a suit port this gas is vented to vacuum

  → Shortening the purge will expedite vehicle egress & save gas
- A 2 min purge saves ~0.48 lb gas and 6 minutes of crew time per person per egress compared with a standard 8 min purge



Cumulative Gas and Crew Time Saved by Abbreviated Purge

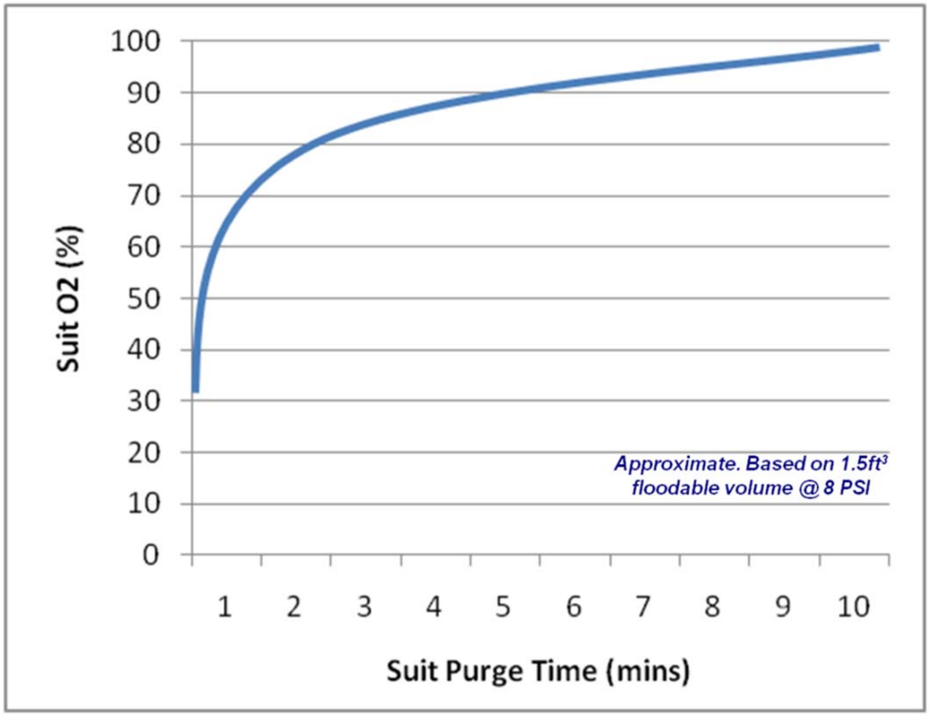
6 month mission, 4 crew, 3 egresses /day, 6 days/week:

- **900 lb gas + tankage = 1800 lb (819 kg)**
- **Over 31 hours of crew time saved**

Background:
Abbreviated Suit Purge – Decreased Off-Gassing Gradient

- An abbreviated purge saves gas and crew time, but decreases the tissue N_2 off-gassing gradient because suit O_2 reaches only 80% compared with 95% O_2 achieved during an 8 minute purge

- However, the benefit of 95% O_2 vs. 80% O_2 for denitrogenation is reduced when initial saturation pressure is 8.2 psi, 34% O_2 (Expl. Atm.) vs. 14.7 psi 21% O_2 (ISS) as there is a smaller change in off-gassing gradient



Approximate. Based on 1.5ft³ floodable volume @ 8 PSI

	Initial Saturation Atmosphere	EVA Suit Prebreathe Atmosphere	Off-Gassing Gradient	Difference in Gradient (80% O2 vs 95% O2)
ISS	14.7 psia @ 20.8% O_2, 79.2% N_2	15.6 psia @ 95.0% O_2, 5.0% N_2 15.6 psia @ 80.0% O_2, 20.0% N_2	10.8 psi 8.5 psi	2.3 psi
ISS Staged	10.2 psia @ 26.5% O_2, 73.5% N_2	11.1 psia @ 95.0% O_2, 5.0% N_2 11.1 psia @ 80.0% O_2, 20.0% N_2	6.9 psi 5.3 psi	1.7 psi
Exp. Atm. (MMSEV)	8.2 psia @ 34.0% O_2, 66.0% N_2	6.0 psia @ 95.0% O_2, 5.0% N_2 6.0 psia @ 80.0% O_2, 20.0% N_2	5.1 psi 4.2 psi	0.9 psi

Objectives

1. **Use NASA human decompression data collected from 1982 to 1998 to develop a probability model for DCS based on the TBDM biophysical model of bubble growth in a unit volume of tissue**

2. **Use the TBDM DCS probability model to:**
   1. estimate the probability of DCS (*P(DCS)*) for a notional 15-minute suit port prebreathe protocol,
   2. compare estimated *P(DCS)* for 95% vs. 80% O_2 suit atmosphere, and
   3. compare estimated *P(DCS)* for continuous EVAs and intermittent EVAs

3. **Compare N_2 tissue tensions in 5-, 10-, 20-, and 40-minute half-time compartments after a 15-minute suit port prebreathe protocol with tensions in the same compartments after a standard Space Shuttle staged prebreathe protocol in which no DCS cases have been reported.**

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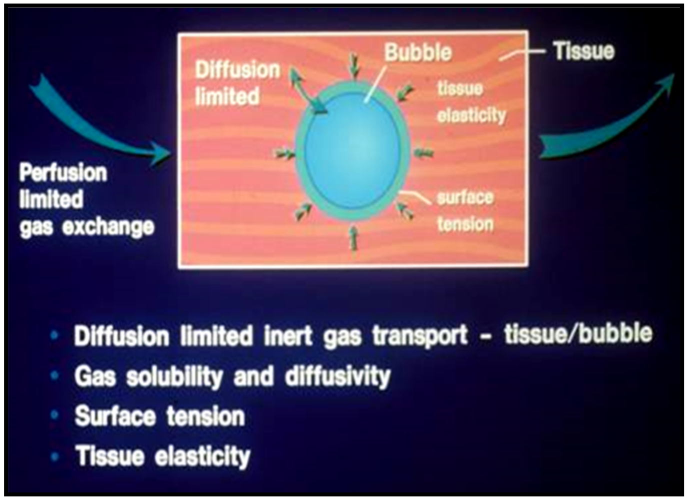
Tissue Bubble Dynamics Model (TBDM)

- **Decompression stress index based on tissue bubble growth dynamics** *(Gernhardt, 1991)*
  - Original statistical analysis of 6437 laboratory dives (430 DCS cases) compared predictions of the TBDM to Workman M-value and the Hempleman PrT index. TDBM predictions (Bubble Growth Index) yielded best log-Likelihood and Hosmer-Lemeshow Goodness-of-Fit Test
  - Used operationally in more than 25,000 dives with extremely low DCS incidence (< 0.1%)



- 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/$cm^2 \cdot cm^3$)
g = Surface Tension (dyne/cm)
M = Tissue Modulus of Deformability (dyne/$cm^2 \cdot cm^3$)
P_{Total} = Total Inert Gas Tissue Tension (dyne/cm^2)
$P_{metabolic}$ = Total Metabolic Gas Tissue Tension

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.

Logistic Regression

Logistic Regression

- Logistic regression quantitatively relates the TBDM Bubble Growth Index (BGI) to a % DCS risk based on existing altitude DCS data
- Performed using DCS and VGE data from NASA Bends Tests 1-11b
  - *n* = 668, 84 DCS cases
  - 12.5% DCS, 33.8% VGE
- Prebreathe staged decompressions, all with exercise at altitude and includes data points at 10.2, 6.5, 6.0, and 4.3 psi
- **BGI provided significant prediction of DCS and VGE data (*p* < 0.0001)**
- **Hosmer-Lemeshow Goodness-of-Fit statistic: *p*=.26 for DCS, indicating a good fit of the data**
  - For Hosmer-Lemeshow statistic, *p* > .05 rejects the hypothesis that there is a significant difference between the model predictions and the observed data

$$P(DCS) = \frac{\exp(B_0 + B_1 * BGI)}{\left[1 + \exp(B_0 + B_1 * BGI)\right]}$$

Parameter	Coefficient	Asymptotic SE	Z-score	*p*-value	95% CI
B_0	-3.477	0.300	-11.61	<0.001	-4.06 to -2.89
B_1	0.0499	0.0079	6.27	<0.001	0.034 to 0.065

TBDM DCS Probability Model

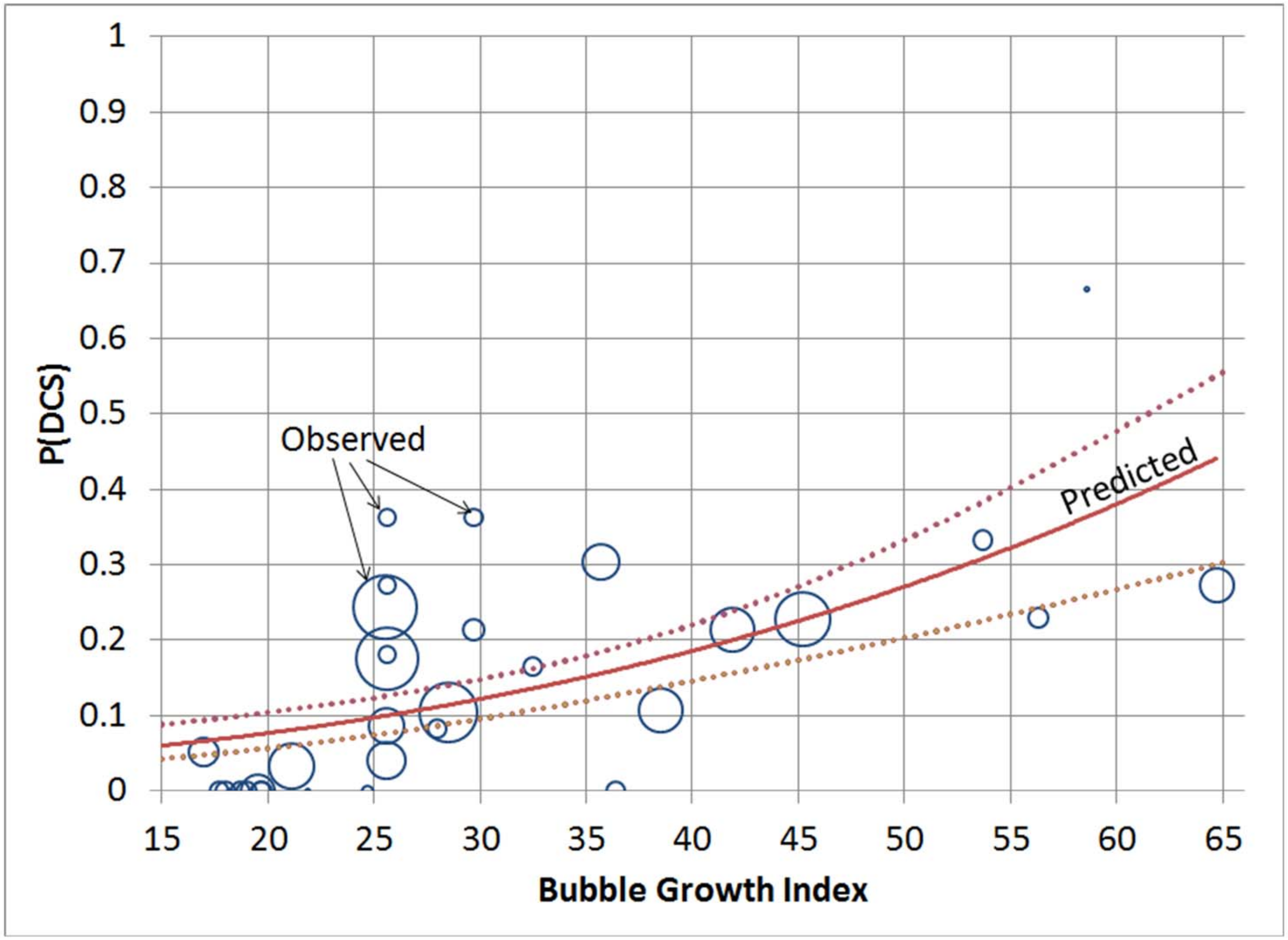


Figure 1. Observed and predicted group DCS incidence from 37 tests shows a moderate correlation with BGI. 33 of 37 tests are shown (4 tests with sample size < 10 were omitted). Circle diameter reflects sample size. The *P(DCS)* and upper and lower 95% CIs are the best-fit predictions over a range of tested BGIs. Predictions are not shown for BGI < 15 units due to absence of data in that range.

TBDM DCS Probability Model

- TBDM DCS Probability Model was used to estimate *P(DCS)* for the 10.2 psi Shuttle staged protocol that was ground tested by 35 test subjects with 22.8% reporting DCS and used operationally 296 times with no reported DCS.

Observed versus model-predicted DCS incidence for Shuttle staged prebreathe protocol. 'As Flown' timelines are based on detailed timelines available from 53 EVAs.

Protocol	Sample	Predicted DCS	Observed DCS
Ground Trial	35	0.23 (0.18-0.28)	0.228
As Flown	296	0.15 (0.12-0.18)	0.000

- Discrepancy between ground and flight exposures due in part to additional 25 minutes prebreathe that occurred during spaceflight due to suit purge, leak check, and a slow ascent to final EVA pressure
- Absence of lower-body activity and weight-bearing in microgravity before and during EVA also likely to have reduced the risk of Type I DCS in the lower body and, when combined with the additional on-orbit prebreathe, may have reduced on-orbit decompression stress to the low levels at which our models provide very conservative estimates of *P(DCS)*.

Objectives

1. **Use NASA human decompression data collected from 1982 to 1998 to develop a probability model for DCS based on the TBDM biophysical model of bubble growth in a unit volume of tissue**

2. **Use the TBDM DCS probability model to:**
   1. estimate the probability of DCS (*P(DCS)*) for a notional 15-minute suit port prebreathe protocol,
   2. compare estimated *P(DCS)* for 95% vs. 80% O_2 suit atmosphere, and
   3. compare estimated *P(DCS)* for continuous EVAs and intermittent EVAs

3. **Compare N_2 tissue tensions in 5-, 10-, 20-, and 40-minute half-time compartments after a 15-minute suit port prebreathe protocol with tensions in the same compartments after a standard Space Shuttle staged prebreathe protocol in which no DCS cases have been reported.**

Prebreathe Protocols Compared

Table 1. EVA protocols with different combinations of IR and O_2 breathing mixtures using the new exploration atmosphere. In all cases the balance of the gas is N_2.

Protocol A: Continuous EVA, 80% O_2

Step	Duration (min)	Pressure (psi)	O_2 %
1 Saturated		8.2	34
2 Purge	0:02	8.2	80
3 Depress	0:01	8.2 → 6.0	80
4 Prebreathe*	0:15	6.0	80
5 Depress	0:01	6.0 → 4.3	80
6 EVA	8:00**	4.3	80

Protocol B: Continuous EVA, 95% O_2

Step	Duration (min)	Pressure (psi)	O_2 %
1 Saturated		8.2	34
2 Purge	0:08	8.2	95
3 Depress	0:01	8.2 → 6.0	95
4 Prebreathe*	0:15	6.0	95
5 Depress	0:01	6.0 → 4.3	95
6 EVA	8:00**	4.3	95

Protocol C: 3 x 2 hr EVAs, 80% O_2

Step	Duration (min)	Pressure (psi)	O_2 %
1 Saturated		8.2	34
2 Purge	0:02	8.2	80
3 Depress	0:01	8.2 → 6.0	80
4 Prebreathe*	0:15	6.0	80
5 Depress	0:01	6.0 → 4.3	80
6 EVA	2:00	4.3	80
7 Repress	0:02	4.3 → 8.2	34
8 Hold	1:00	8.2	34
Repeat Steps 2-8 twice, for 3 total EVAs			

Protocol D: 3 x 2 hr EVAs, 95% O_2

Step	Duration (min)	Pressure (psi)	O_2 %
1 Saturated		8.2	34
2 Purge	0:08	8.2	95
3 Depress	0:01	8.2 → 6.0	95
4 Prebreathe*	0:15	6.0	95
5 Depress	0:01	6.0 → 4.3	95
6 EVA	2:00	4.3	95
7 Repress	0:02	4.3 → 8.2	34
8 Hold	1:00	8.2	34
Repeat Steps 2-8 twice, for 3 total EVAs			

* EVA can begin at 6 psi at the start of prebreathe, with suit pressure being dropped to 4.3 psi 15 mins after start of prebreathe clock.

** *P(DCS)* was calculated after 6 hours and after 8 hours of continuous EVA.

TBDM Comparison of Prebreathe Protocols

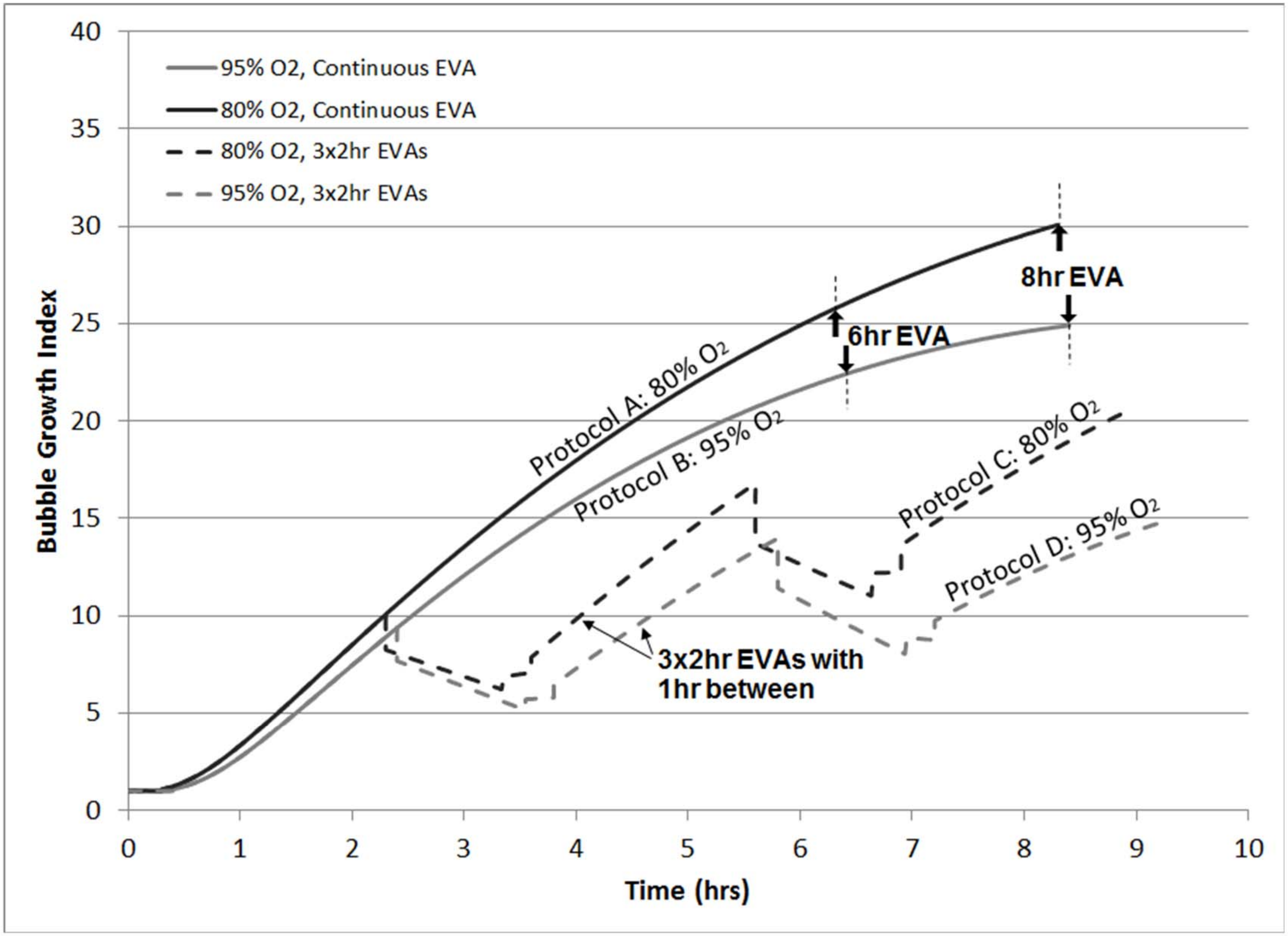


Figure 1. **Bubble growth index profiles for Protocols A-D. Peak BGI from these BGI profiles were used to estimate *P(DCS)* using the TBDM DCS Probability Model (Table 1).The BGI after 6 hours and 8 hours of EVA are indicated for Protocols A and B; note that the temporal offset is due to the longer duration purge for Protocol B than for protocol A.**

Objectives

1. **Use NASA human decompression data collected from 1982 to 1998 to develop a probability model for DCS based on the TBDM biophysical model of bubble growth in a unit volume of tissue**

2. **Use the TBDM DCS probability model to:**
   1. **estimate the probability of DCS (*P(DCS)*) for a notional 15-minute suit port prebreathe protocol,**
   2. compare estimated *P(DCS)* for 95% vs. 80% O_2 suit atmosphere, and
   3. compare estimated *P(DCS)* for continuous EVAs and intermittent EVAs

3. **Compare N_2 tissue tensions in 5-, 10-, 20-, and 40-minute half-time compartments after a 15-minute suit port prebreathe protocol with tensions in the same compartments after a standard Space Shuttle staged prebreathe protocol in which no DCS cases have been reported.**

TBDM DCS Probability Model Comparison of Protocols

Table 1. *P(DCS)* as estimated by the TBDM DCS Probability Model. Superscript letters indicate Protocols A-D.

	80% O_2	95% O_2	*Difference*
Continuous 8-hr EVA	0.121 [A]	0.097 [B]	0.024
Continuous 6-hr EVA	0.097 [A]	0.084 [B]	0.013
3 × 2-hr EVAs	0.079 [C]	0.061 [D]	0.018
Difference: 8 hr vs. 6 hr	0.023	0.012	
Difference: 8 hr vs. 3 × 2 hr	0.041	0.035	
Difference: 6 hr vs. 3 × 2 hr	0.018	0.023	
Difference: 8 hr 95% O_2 vs. 3 × 2 hr 80% O_2:			0.017
Difference: 6 hr 95% O_2 vs. 3 × 2 hr 80% O_2:			0.005

- **Model estimates of *P(DCS)* for Protocols A-D ranged from 6.1% to 12.1%**
  - No cases of Type II DCS observed in 244 tests with 7692 exercising subjects until the incidence of Type I DCS exceeded 15%. **(Gernhardt, 2008)**

Gernhardt, M. L. "Overview of Shuttle and ISS Exercise Prebreathe Protocols and ISS Protocol Accept/Reject Limits," Prebreathe Protocol for Extravehicular Activity Technical Consultation Report; 96-125; (NASA/TM-2008-215124);, 2008.

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Effect of Abbreviated Purge (80% vs. 95% O_2)

Table 1. *P(DCS)* as estimated by the TBDM DCS Probability Model. Superscript letters indicate Protocols A-D.

	80% O_2	95% O_2	*Difference*
Continuous 8-hr EVA	0.121^{A}	0.097^{B}	0.024
Continuous 6-hr EVA	0.097^{A}	0.084^{B}	0.013
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Difference: 8 hr 95% O_2 vs. 3 × 2 hr 80% O_2:			0.017
Difference: 6 hr 95% O_2 vs. 3 × 2 hr 80% O_2:			0.005

- Differences in estimated DCS risk ranged from 0.5% to 2.4%.
- Nominal EVA suit leakage at joints and bearings will increase O_2 concentration
  → assumption of 80% O_2 for the entire EVA duration is conservative
- 80% O_2 after 2 minutes of purge may also be conservative
- Decompression benefits of multiple EVAs per day may compensate for the slight increase in *P(DCS)* resulting from the abbreviated purge.
- Note: The 15-minute prebreathe protocol described in this paper does not *require* an abbreviated purge

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Effect of Intermittent Recompression

Table 1. *P(DCS)* as estimated by the TBDM DCS Probability Model. Superscript letters indicate Protocols A-D.

	80% O_2	95% O_2	*Difference*
Continuous 8-hr EVA	0.121^{A}	0.097^{B}	0.024
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Difference: 8 hr vs. 6 hr	0.023	0.012	
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Difference: 6 hr vs. 3 × 2 hr	0.018	0.023	
Difference: 8 hr 95% O_2 vs. 3 × 2 hr 80% O_2:			0.017
Difference: 6 hr 95% O_2 vs. 3 × 2 hr 80% O_2:			0.005

- Model predictions suggest that IR during may reduce decompression stress by 1.8% to 2.3% for 6 hours of total EVA time
  - Pressurized mobility and rapid EVA capability can increase productivity by 57% while reducing the EVA time required to conduct exploration by 61%, further reducing decompression stress
- Increased hydrostatic pressure reducing bubble growth combined with the possibility of performing the same amount of work using less EVA time makes the capability of performing multiple shorter EVAs significantly enhancing for future exploration missions.

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Comparison of N_2 Tissue Tensions

- Ending ppN2 for the 5-, 10-, and 20- minute compartments < 4.3 psi, avoiding the risk of supersaturation upon depress to final suit pressure.
  - 5- and 10-min compartments represent brain and spinal cord, which are well denitrogenated by the end of longer conventional prebreathe protocols.
- Ending ppN_2 of 40-min compartment is 4.35 psi vs. 4.00 psi for the Shuttle staged protocol
  - Tensions in fast compartments (≤ 40 min), where majority of whole-body N_2 is located, reduced to approx levels achieved during standard Shuttle staged prebreathe protocol for which no cases of DCS were reported.

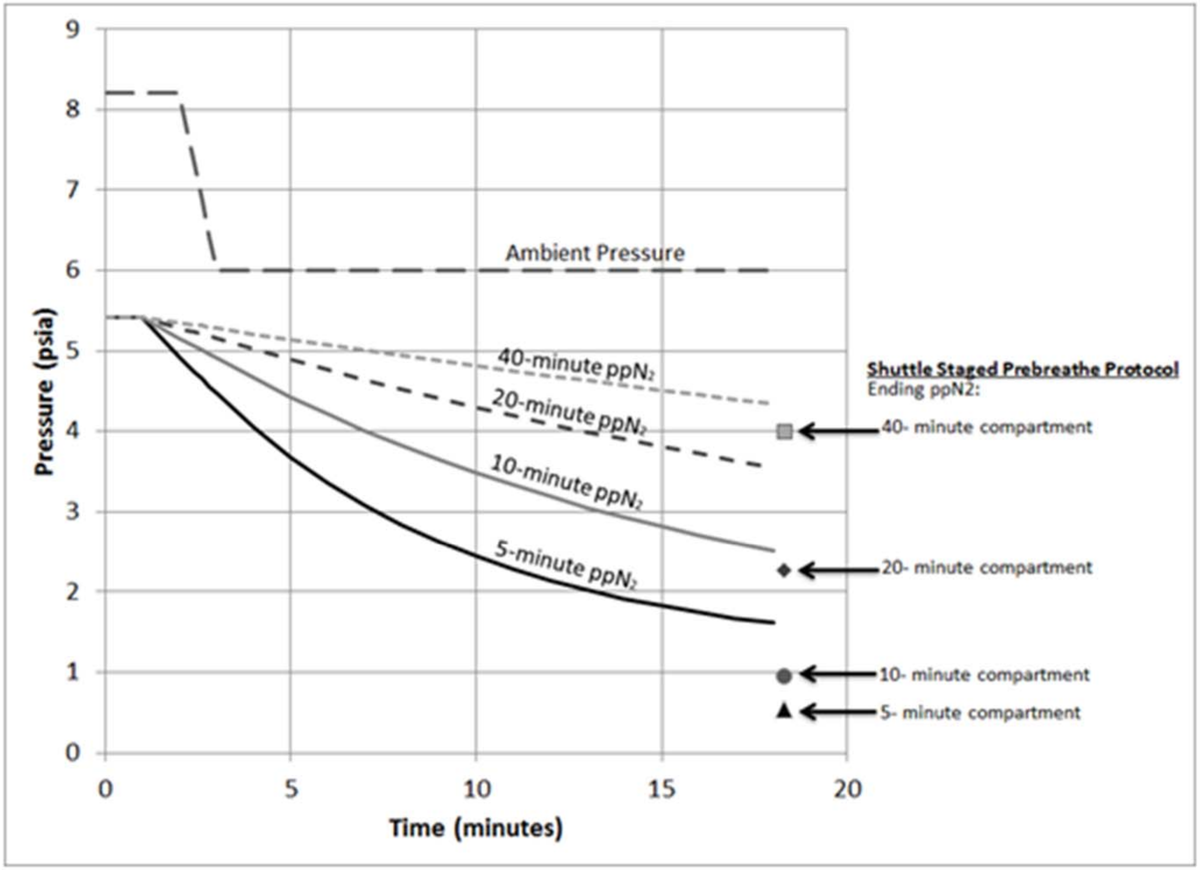

Figure 1. Nitrogen tissue tensions calculated for 5-, 10-, 20-, and 40-minute half-time compartments during 2-minute purge, 1-minute depress to 6.0 psi, and 15-minute 80% O_2 prebreathe beginning from saturation at 8.2 psi, 34% O_2, 66% N_2. Ending ppN_2 for the Shuttle staged prebreathe protocol is also shown for comparison (40-minute 95% O_2 prebreathe beginning from saturation at 10.2psi, 26.5% O_2, 73.5% N_2).

Conclusions (1 of 2)

1. A TBDM DCS probability model based on an existing biophysical model of inert gas bubble growth provides significant prediction and goodness-of-fit with 84 cases of DCS in 668 human altitude exposures.
2. Model predictions suggest that 15-minute O_2 prebreathe protocols used in conjunction with suit ports and an 8.2 psi, 34% O_2, 66% N_2 atmosphere may enable rapid EVA capability for future exploration missions with the risk of DCS ≤ 12%.
   - EVA could begin immediately at 6.0 psi, with crewmembers decreasing suit pressure to 4.3 psi after completing the 15-minute in-suit prebreathe.
3. Model predictions suggest that intermittent recompression during exploration EVA may reduce decompression stress by 1.8% to 2.3% for 6 hours of total EVA time
   - The penalty of N_2 reuptake during intermittent recompressions may be outweighed by the benefit of decreased bubble size.

Conclusions (2 of 2)

5. Savings in gas consumables and crew time may be accumulated by abbreviating the EVA suit N_2 purge to 2 minutes (20% N_2) compared with 8 minutes (5% N_2) at the expense of an increase in estimated decompression risk of up to 2.4% for an 8-hour EVA.
   - Increased DCS risk could be offset by IR or by spending additional time at 6 psi at the beginning of the EVA.
   - Savings of 0.48 lb of gas and 6 minutes per person per EVA corresponds to more than 31 hours of crew time and 1800 lb of gas and tankage under the Constellation lunar architecture.
6. Further research is needed to characterize and optimize breathing mixtures and intermittent recompression across the range of environments and operational conditions in which astronauts will live and work during future exploration missions.
7. Development of exploration prebreathe protocols will begin with definition of acceptable risk, followed by development of protocols based on models such as ours, and, ultimately, validation of protocols through ground trials before operational implementation.