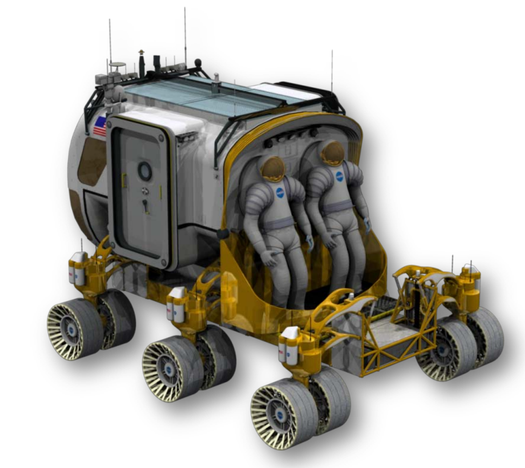
USE OF VARIABLE PRESSURE SUITS, INTERMITTENT RECOMPRESSION AND NITROX BREATHING MIXTURES DURING LUNAR EXTRAVEHICULAR ACTIVITIES



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INTRODUCTION

- NASA's plans for lunar surface exploration include small pressurized rovers ("Lunar Electric Rovers") at 8.0 PSIA, 32% O_2, 68% N_2 with suit ports that enable rapid ingress and egress with minimal gas losses. This capability enables crewmembers to perform multiple short extravehicular activities (EVAs) at different locations in a single day versus a single 8-hr EVA. Development and validation of a prebreathe protocol that reduces the risk of decompression sickness (DCS) risk to within acceptable levels while preserving rapid egress capability is an essential component of the entire LER concept.
- Modeling work (1,2) and empirical human (3) and animal (4) data indicate that these intermittent recompressions between EVA suit pressure (4.3 PSIA) and cabin pressure (8 PSIA) reduce decompression stress.
- Typical 8-min suit purges, to achieve 95% O_2 suit breathing mixture, result in significant gas losses and unproductive crew time. A 2-min purge to ~80% O_2 addresses these issues but may increase DCS risk.
- An analysis using the Tissue Bubble Dynamics Model (5) was conducted to determine whether the increase in decompression stress resulting from an abbreviated suit purge would be offset by the decrease in decompression stress offered by intermittent recompression.

METHODS

- A validated Tissue Bubble Dynamics Model (TBDM) was used to predict DCS risk using 80% and 95% O_2 breathing mixtures during three 2-hr EVAs (4.3 PSIA) separated by 1-hr recompressions to cabin pressure (for driving between EVA sites) versus a single 8-hr EVA.
- Part I: Experience from altitude DCS suggests that some degree of enriched O_2 prebreathing is necessary to reduce the risk of central neurological DCS. The objectives of Part I of the analysis were i) to ensure that the proposed LER prebreathe protocol would eliminate super-saturation in the neurological tissues (brain and spinal cord, half-times approx. 5 - 10 minutes), and ii) to compare tissue tensions in ≤40 minute compartments, where the majority of whole-body nitrogen is located, with an established Shuttle staged prebreathe protocol in which no DCS cases have been reported.
  - LER Protocol: 15-minute 80% O_2, 20% N_2 @ 6.0 PSIA , Sat @ 8.0 PSI, 32% O_2, 68%N_2
  - Shuttle Protocol: 40-minute 95% O_2, 5% N_2 @ 10.2 PSIA , Sat @ 10.2 PSI, 26.5% O_2, 73.5%N_2
- Part II: The objective of Part II was to use the Tissue Bubble Dynamics Model (TBDM) (5) to estimate DCS Risk under the following scenarios:
  - Purge cases:
    - 8 minute, 95% O_2 suit purge
    - 2 minute, 80% O_2 suit purge
  - EVA cases:
    - 3 x 2 hr EVAs separated by 60 mins at cabin pressure (8.0 PSI, 32% O_2 / 68% N_2)
    - 1 x 8 hr EVA
- The following assumptions were made:
  - Crew begin saturated at 8 PSI, 32% O_2 / 68% N_2
  - Purge performed at 8 PSI
  - 1 minute post-purge depress to 6.0 PSI
  - 15 minutes prebreathe completed at 6.0 PSI (EVA may begin during this time)
  - Depress to 4.3 PSI at 5,000 FPM after 15 mins at 6.0 PSI
  - Repress from 4.3 PSI to 6.0 PSI at 5,000 FPM

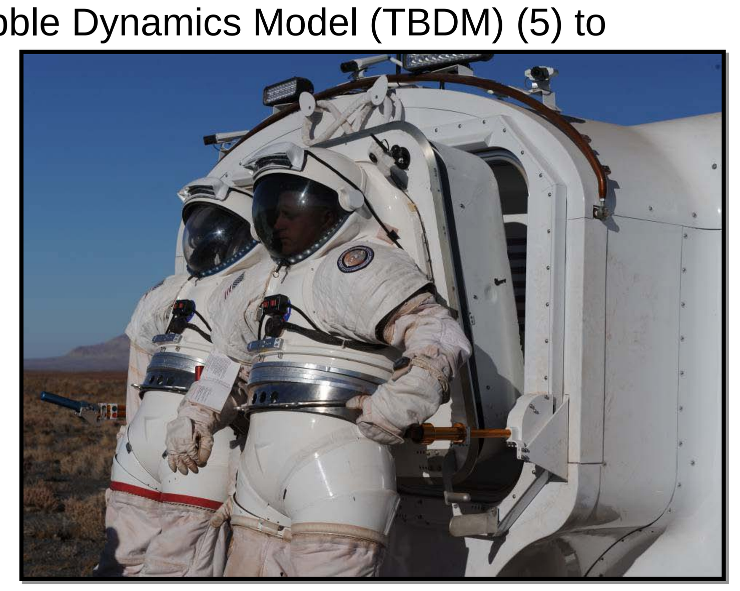

Fig. 1. Prototype LER suit ports being developed by NASA. The LER rover concept relies heavily on safe and efficient suit purge and prebreathe protocols to minimize gas losses and enable rapid vehicle egress.

- The TBDM model provides significant prediction ($p < 0.001$) and goodness of fit with 430 cases of DCS in 6437 laboratory dives (Table 1) and has been used operationally in over 25,000 dives.

Tissue Bubble Dynamics Model (TBDM) (5)

Bubble Growth Equation:

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

r = Bubble Radius (cm)
t = Time (sec)
α = 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/$cm^2 \cdot cm^3$)
γ = 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

Table 1. A 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 (Table 1).

Data Set: In-Water Decompression on Air		Test for Improvement		Test for Goodness of Fit	
Index	**Log-Likelihood**	**x^2**	**p-value**	**x^2**	**p-value/ df**
Null set	-529	n/a	n/a	n/a	n/a
Bubble Growth Index	**-498**	**62.8**	**<0.001**	**4.8**	**0.77/8**
Relative Super-saturation	-524	10.8	.001	19.4	0.08/12
Exposure Index	-505	47.9	<0.001	30.5	0.00/9

- Logistic regression was used to quantitatively relate the TBDM Bubble Growth Index (BGI) to a % DCS risk based on existing altitude DCS data. The Logistics Regression was performed using DCS and VGE data from NASA Bends Tests 1-7 (n=345, 57 DCS cases, 16.5% DCS, 41.4% VGE). All data included prebreathe staged decompressions, all with exercise at altitude and included data points at 10.2, 6.0, and 4.3 PSI.
  - BGI provided significant prediction of DCS and VGE data ($p < 0.01$)
  - Hosmer-Lemeshow Goodness-of-Fit statistic: p=.35 for DCS, p=.55 for VGE, 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).

RESULTS

Part I: Comparison of 15 minute 80% O_2 6.0 PSI prebreathe with 40 minute 95% O_2 10.2 PSI Prebreathe

- 5- and 10-min Tissues (brain and spinal cord):
  → Supersaturation eliminated
- 40 min Tissues (most of body's inert gas):
  → 4.00 PSI after 40 minutes @ 95% O_2
  → 4.37 PSI after 15 minutes @ 80% O_2 (incl. 2min purge and 1 min depress)

- Fifteen minutes at 80% O_2, 6.0 PSIA, before a 4.3 PSIA EVA prevents supersaturation in the brain and spinal cord (5- and 10-min half-time compartments) and reduces tissue tensions in fast half-time compartments (≤ 40-min), where the majority of whole-body Nitrogen is located, to approximately the levels (4.37 vs. 4.00 PSIA) achieved during a standard Shuttle/ISS staged prebreathe protocol.

Part II: Comparison of DCS Risk for 80% O_2 with Intermittent Recompression vs. 95% O_2 Continuous EVA

- 80% O_2 vs. 95% O_2 during an 8-hr continuous EVA increased DCS Risk by 2.2%
- 1-hr Recompressions between 3x2-hr EVAs performed with 80% O_2 *reduced* decompression stress by 2.8% compared with an 8-hr continuous EVA with 95% O_2

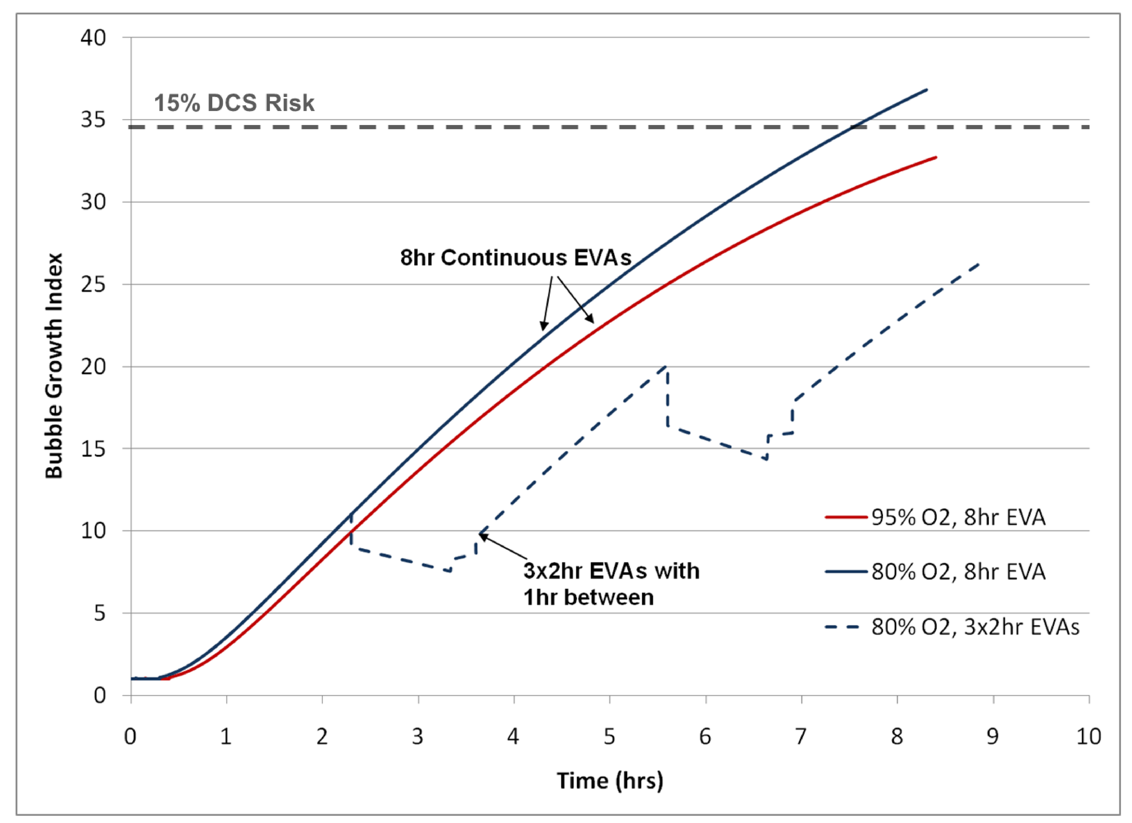

Fig. 2. (right) Theoretical decompression stress (Bubble Growth Index – BGI) comparison of 8-hr continuous EVAs performed using 95% O_2 and 80% O_2. 3x2-hr EVAs on 80% O_2 separated by 1-hr intermittent recompressions are also shown, which reduced decompression stress below the 95% O_2 continuous EVA case and within the current definition of acceptable DCS risk.

DISCUSSION

- The TBDM model predicts that the benefits of intermittent recompression may enable shortening of the suit purge time with significant crew time and consumables benefits while also reducing decompression stress.
  – The model indicates that intermittent recompressions reduce decompression stress by limiting the bubble growth time and size, resulting in a higher bubble to tissue diffusion gradient due to the effects of surface tension (Laplace's Law).
- 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. Thus, shortening the purge will expedite vehicle egress and 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:
- **900lb gas + tankage = 1800 lb (819kg) per 6 months**
- **Over 31 <u>hours</u> of crew time saved per 6 months**

- In the event that an EVA lasts longer than planned, variable pressure suits allow an in-suit intermittent recompression back to 6.0 PSI without ingressing the LER. Supplemental suit purge (increased suit O_2 %) could also be performed.
- At 80% O_2, 4.3 PSIA crewmembers will be hyperoxic. In the event of a suit leak, the Secondary Oxygen Pack (SOP) will maintain the suit at ~3.6 PSI, making crew only mildly hypoxic (2.9 PSI ppO_2) but still maintaining a higher ppO_2 than the nominal cabin environment (2.4-2.6 PSI ppO_2).
- An abbreviated purge decreases the N_2 off-gassing gradient because suit O_2 reaches only 80% compared with 95% O_2 achieved during an 8 minute purge (Fig. 3). However, the benefit of 95% O_2 vs. 80% O_2 for denitrogenation is reduced when initial saturation pressure is 8.0 PSI (LER) vs. 14.7 PSI (ISS) as there is a smaller change in off-gassing gradient (Fig. 4).

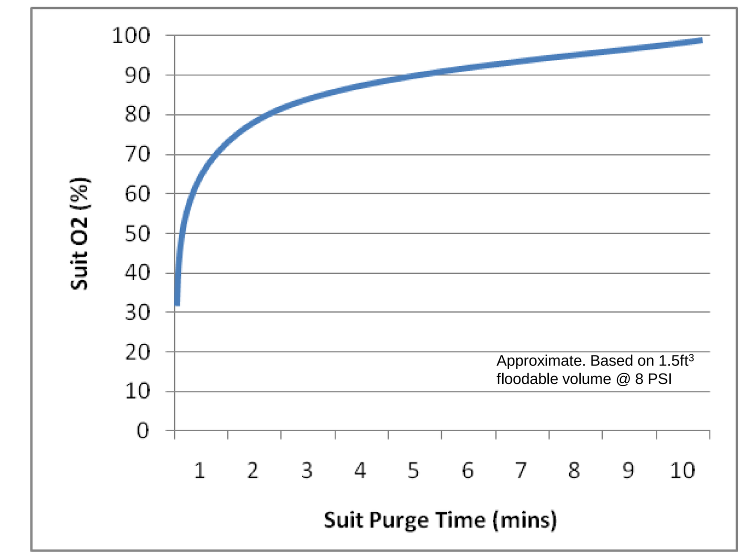

Fig. 3. Suit O_2 concentration as a function of suit purge time.

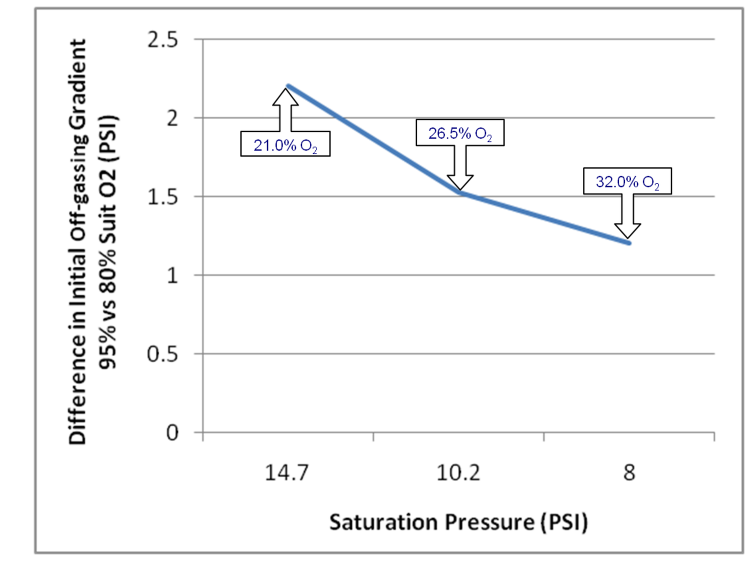

Fig. 4. Decreasing benefit of 95% vs. 80% O_2 prebreathe on initial N_2 off-gassing gradient as a function of decreasing saturation pressure.

- The TBDM predictions are based on the assumption that the volume of gas in the bubble is small compared to the volume of gas in surrounding tissue. This assumption is supported by experimental evidence from human (3) and animal (4) decompression trials. If tissues were profusely nucleated, resulting in many small bubbles, then tissue tensions would reduce as the bubbles grow, with the effect of decreasing off-gassing gradients. In this case, the larger quantity of gas in the numerous small bubbles would simply redistribute into the tissue during the recompression, resulting in an equivalent decompression penalty and no decompression benefit. However, the empirical data detailed in Figures 5-6 suggest that this is not the case.

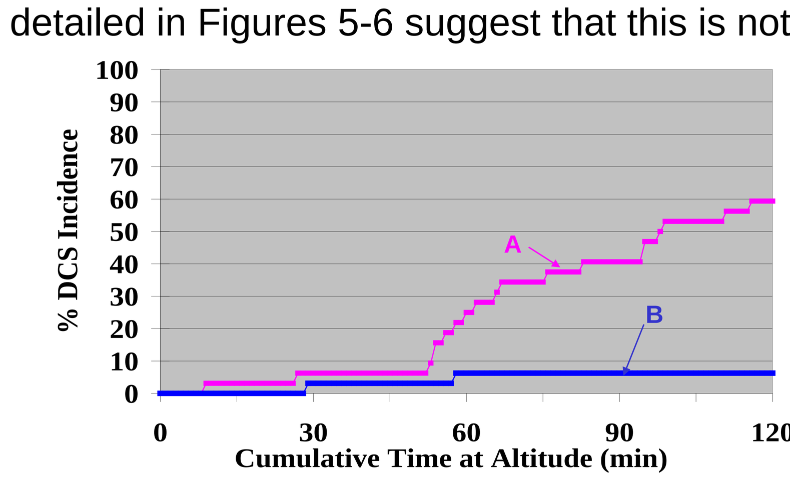

Fig. 5. The percentage of cumulative DCS onset incidence plotted vs. cumulative time at altitude for the two conditions: **A** (one 120-min altitude exposure with no ground-level preoxygenation), and **B** (four 30-min altitude exposures to the same simulated altitude, but with 1-hr ground-level intervals breathing air; no prebreathing).
From Pilmanis et al. (3) by permission.

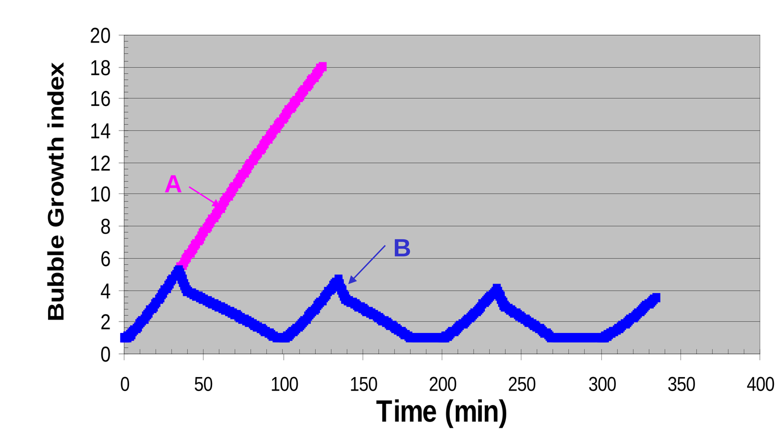

Fig. 6. The TBDM-calculated BGI for the two altitude decompression conditions described in Figure 5. The intermittent recompressions in profile B control bubble growth resulting in a maximum BGI of 5 in profile B compared with 18 in profile A. The benefits of intermittent recompression predicted by the TBDM are consistent with the observed DCS incidence in Figure 5.

CONCLUSIONS

- Variable pressure suits combined with the ability to perform multiple shorter EVAs may enable prebreathe protocols that save several tons of gas and hundreds of hours of crew time over the duration of the next lunar program
- Further research is needed to characterize and optimize intermittent recompression and Nitrox breathing mixtures across the range of environments and operational conditions in which astronauts will live and work during future lunar exploration
- Laboratory validation trials should precede operational implementation

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