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

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Current plans for lunar surface exploration include small pressurized rovers ("Lunar Electric Rovers") that are quickly ingressed and egressed with minimal consumables losses:

- Cabin: 8 PSI, 32% O₂, 68% N₂

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.

The new operational concept of multiple short EVAs necessitates short purge times and short prebreathes to ensure rapid egress with minimal loss of consumables.

Preliminary analysis has begun to evaluate the potential benefits of intermittent recompression, variable pressure EVA suits and Nitrox breathing mixtures in enabling reduced purge and prebreathe durations.
Suit Port Egress and Ingress Procedures

Egress Procedures
1. Don Suit (8.0 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)

Egress Time: 11 min ± 3 min

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

Ingress Procedures
1. Engage Suit Port (red)
2. Vestibule press to 8.0 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

Ingress Time: 5 min ± 1 min
Intermittent Recompressions (IR) during saturation decompression 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

Previous modeling work and empirical human and animal data indicate that IR between EVA suit pressure (≤4.3 psia, 100% O₂) and cabin pressure (8 psia, 32% O₂) may reduce decompression stress

IR has been shown to decrease decompression stress in humans and animals (Pilmanis et al. 2002, Møllerløkken et al. 2007)

During recompressions:
- Reversed N₂ concentration gradient during recompression means that N₂ 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 N₂ diffusion gradient
- Because the volume of gas in the bubbles is small compared to the volume of gas in surrounding tissues, the N₂ elimination from the bubbles does not significantly increase N₂ tissue tension
Abbreviated Suit Purge: Mass and Time Savings

- EVA suits are purged of N₂ prior to depressurization to achieve ≥ 95% O₂
  - 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

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
Abbreviated Suit Purge: Decreased Off-Gassing Gradient

- As described, an abbreviated purge saves gas and crew time, but decreases the N\textsubscript{2} off-gassing gradient because suit O\textsubscript{2} reaches only 80% compared with 95% O\textsubscript{2} achieved during an 8 minute purge.

- However, the benefit of 95\% O\textsubscript{2} vs. 80\% O\textsubscript{2} for denitrogenation is reduced when initial is saturation pressure is 8 PSI (LER) vs. 14.7 PSI (ISS) as there is a smaller change in off-gassing gradient.
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%)

\[
\frac{dR}{dt} = \frac{\alpha D}{h(r,t)} \left( P_a - vt + \frac{2\gamma}{1 + \frac{4}{3} \pi r^3 M} \right) - \frac{P_a - vt + \frac{4\gamma}{3r} + \frac{8}{3} \pi r^3 M}{P_{\text{Total}} - P_{\text{metabolic}}} + \frac{rv}{3}
\]

\( t = \) Time (sec)
\( a = \) Gas Solubility (mL gas)/(mL tissue))
\( D = \) Diffusion Coefficient (cm²/sec)
\( h(r,t) = \) Bubble Film Thickness (cm)
\( P_a = \) Initial Ambient Pressure (dyne/cm²)
\( v = \) Ascent/Descent Rate (dyne/cm² cm³)
\( g = \) Surface Tension (dyne/cm)
\( M = \) Tissue Modulus of Deformability (dyne/cm² cm³)
\( P_{\text{Total}} = \) Total Inert Gas Tissue Tension (dyne/cm²)
\( P_{\text{metabolic}} = \) Total Metabolic Gas Tissue Tension

Data Set: In-Water Decompression on Air

<table>
<thead>
<tr>
<th>Index</th>
<th>Log-Likelihood</th>
<th>( x^2 )</th>
<th>p-value</th>
<th>( x^2 )</th>
<th>p-value/df</th>
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</thead>
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<tr>
<td>Null set</td>
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<td>n/a</td>
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<td>Bubble Growth Index</td>
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<td>&lt;0.001</td>
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<td>0.77/8</td>
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<td>Relative Super-saturation</td>
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<td>10.8</td>
<td>.001</td>
<td>19.4</td>
<td>0.08/12</td>
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<td>Exposure Index</td>
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<td>47.9</td>
<td>&lt;0.001</td>
<td>30.5</td>
<td>0.00/9</td>
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</table>

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 1-7
  - n=345, 57 DCS cases
  - 16.5% DCS, 41.4% VGE
- Prebreathe staged decompressions, all with exercise at altitude and includes data points at 10.2, 6.0, and 4.3PSI
- Does not include adynamic data
- 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
Objectives & Methods

♦ Part I: Compare super-saturation in the brain and spinal cord (5 and 10 minute half-time compartments) and tissue tensions in 40 minute compartments, where most of the body’s inert gas is located, for the following conditions:
  - 15-minute 80% O₂, 20% N₂ prebreathe @ 6.0 PSIA, Sat @ 8.0 PSI, 32% O₂, 68% N₂
  - 40-minute 95% O₂, 5% N₂ prebreathe @ 10.2 PSIA, Sat @ 10.2 PSI, 26.5% O₂, 73.5% N₂

♦ Part II: Use TBDM to estimate DCS Risk under the following scenarios:
  - Purge cases:
    - 8 minute, 95% O₂ suit purge
    - 2 minute, 80% O₂ suit purge
  - EVA cases:
    - 3 x 2 hr EVAs separated by 60 min at cabin pressure (8 PSI, 32% O₂, 68% N₂)
    - 1 x 8 hr EVA

♦ Assumptions:
  - Crew begin saturated at 8 PSI, 32% O₂ / 68% N₂
  - Purge performed at 8 PSI
  - 1 minute post-purge depress to 6 PSI
  - 15 minutes prebreathe completed at 6 PSI (EVA may begin during this time)
  - Depress to 4.3 PSI at 5,000 FPM after 15 min at 6.0 PSI
  - Repress from 4.3 PSI to 6.0 PSI at 5,000 FPM
Comparison of 15 minute 80% O$_2$ 6.0 PSI prebreathe vs. 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):
  • 4.0 PSI after 40 minutes @ 95% O$_2$
  • 4.37 PSI after 15 minutes @ 80% O$_2$ (incl. 2 min purge and 1 min depress)

→ 15 minute 80% O$_2$ prebreathe eliminates CNS supersaturation and provides N$_2$ elimination approximately equivalent to standard 40 min 95% O$_2$ prebreathe from 10.2 PSI.
Results: Part II

- 15% DCS Risk
- 8hr Continuous EVAs
- 95% O2, 8hr EVA
- 80% O2, 8hr EVA
Results: Part II

The graph shows the relationship between time (in hours) and bubble growth index for different oxygen levels and EVAs types. The lines represent:

- **Red Line**: 95% O2, 8hr EVA
- **Blue Line**: 80% O2, 8hr EVA
- **Dashed Line**: 80% O2, 3x2hr EVAs with 1hr between

The y-axis represents the bubble growth index, while the x-axis represents time in hours. The graph includes a horizontal line indicating a 15% DCS risk level.
In this analysis:

- 80% O₂ vs. 95% O₂ during an 8-hr continuous EVA increased DCS Risk by 2.2%
- 1 hr Recompressions between 3x2 hr EVAs performed with 80% O₂ reduced decompression stress by 2.8% compared with an 8-hr continuous EVA with 95% O₂

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).

Recent analog field test data demonstrated that crewmembers performing multiple EVAs from an LER achieved 57% greater performance while using 61% less EVA time than when performing continuous EVAs using an unpressurized rover.

→ Actual decompression benefits of LERs may be even more significant

In case an EVA lasts longer than planned, variable pressure suits will allow an in-suit intermittent recompression back to 6 PSI without ingressing the LER. Supplemental suit purge (increased suit O₂ %) could also be performed.

At 80% O₂, 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 ppO₂) but still maintaining a higher ppO₂ than the nominal cabin environment (2.4-2.6 PSI ppO₂)
Discussion


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.

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.
• 45 min additional time (i.e. 60 min total) at 6.0 PSI required at beginning of first EVA only
  - 45 min also required to match P(DCS) for continuous 8hr EVAs
• Or, 35 min additional time at 6.0 PSI required prior to all EVAs
AVERAGE BUBBLE GRADE AS A FUNCTION OF TIME

DAY 1
LUNCH AT 10.2 PSIA

N = 12  
10.2 psia CURRENT PROTOCOL

N = 35  
10.2 psia 6.0 HOUR EVA PROTOCOL

DAY 2
LUNCH AT 10.2 PSIA
NO BUBBLES

DAY 3
LUNCH AT 10.2 PSIA
NO BUBBLES

AVERAGE VENOUS BUBBLE GRADE

EXPOSURE TIME LINE (HOURS)
Intermittent Recompression, Bubble Model incorporating Hill’s Assumption of Profuse Tissue Bubble Nucleation

1. Decompression stress goes down with time for A?
2. Decompression stress higher on C than B or A?

Fig. 4. Exposures A, C with high tissue bubble density and mass balance.
### DCS and VGE Incidence from Repetitive EVA Exposure

Unlike repetitive diving, repetitive EVA results in lower decompression stress.

<table>
<thead>
<tr>
<th></th>
<th>First 3 hr test at 4.3 psia</th>
<th>Second 3 hr test at 4.3 psia</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TR360</td>
<td>DCS</td>
</tr>
<tr>
<td>Day 1</td>
<td>1.68</td>
<td>1/12</td>
</tr>
<tr>
<td>Day 2</td>
<td>1.37</td>
<td>0/12</td>
</tr>
<tr>
<td>Day 3</td>
<td>1.35</td>
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</table>
The objective of Part II was to use the Tissue Bubble Dynamics Model (TBDM) (5) to estimate of crew time saved per 6 months = 6.0 PSI prebreathe with 40 minute 95% O₂. The following assumptions were made: (5) Modeling work (1,2) and empirical human (3) and animal (4) data indicate that these intermittent recompressions between EVA suit pressure (4.3 PSI) and cabin pressure (8 PSI) reduce the risk of central neurological DCS. To within acceptable limits while preserving rapid egress capability is an essential component of the entire LER concept. Typical 8 min suit purges, to achieve 95% O₂ suit breathing mixture, result in significant gas losses and unproductive crew time. A 2 min purge to ~80% O₂ 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.

RESULTS

Part I: Comparison of 15 minute 80% O₂, 6.0 PSI prebreathe with 40 minute 95% O₂, 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% O₂
- 4.37 PSI after 15 minutes @ 80% O₂ (incl. 2 min purge and 1 min depress)
- Fifteen minutes at 80% O₂, 6.0 PSI, before a 4.3 PSI EVA prevents supersaturation in the brain and spinal cord (5- and 10-min half-time components) and reduces tissue stresses in fast half-time components (4.37 min) where the majority of whole-body Nitrogen is located, to approximately the levels (4.37 vs. 4.00 PSI) achieved during a standard Shuttle/ISS staged prebreathe protocol.

Part II: Comparison of DCS Risk for 80% O₂ with Intermittent Recompression vs. 95% O₂ Continuous EVA

- 80% O₂, 95% O₂ during an 8 hr continuous EVA increased DCS Risk by 2.2%
- The recompressions between 3x2 hr EVAs performed with 80% O₂ reduced decompression stress by 2.8% compared with an 8 hr continuous EVA with 95% O₂.

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 TBDM-calculated BGI for the two altitude conditions (one 120-min altitude exposure at 8 PSI, one 30 min altitude exposure at 4.37 PSI) are also shown, which reduced decompression stress (Bubble Growth Index – BGI) comparison of the continuous EVA performed using 95% O₂ vs. 80% O₂ at 14.7 PSI (ISS) as there is a smaller change in off-gassing gradient (Fig. 4). However, the empirical data detailed in Figures 5-6 suggest that this is not the case.

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.
- Future research is needed to characterize and optimize intermittent recompression and Nitrox breathing mixes 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

REFERENCES


