REDUCTION OF DECOMPRESSION STRESS IN ARTEMIS EVAS USING SUITPORTS, VARIABLE PRESSURE SUITS, AND INTERMITTENT RECOMPRESSION

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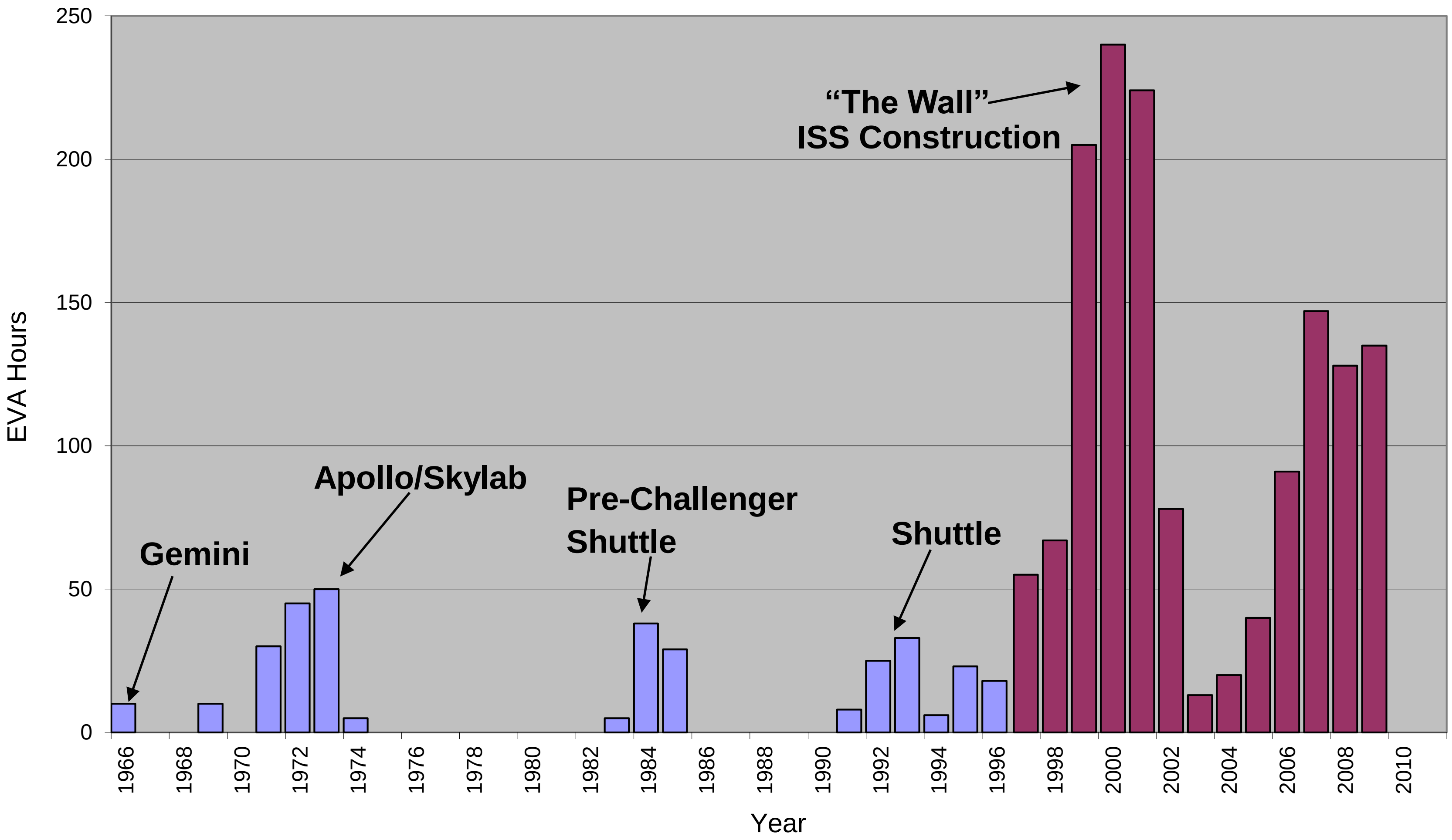
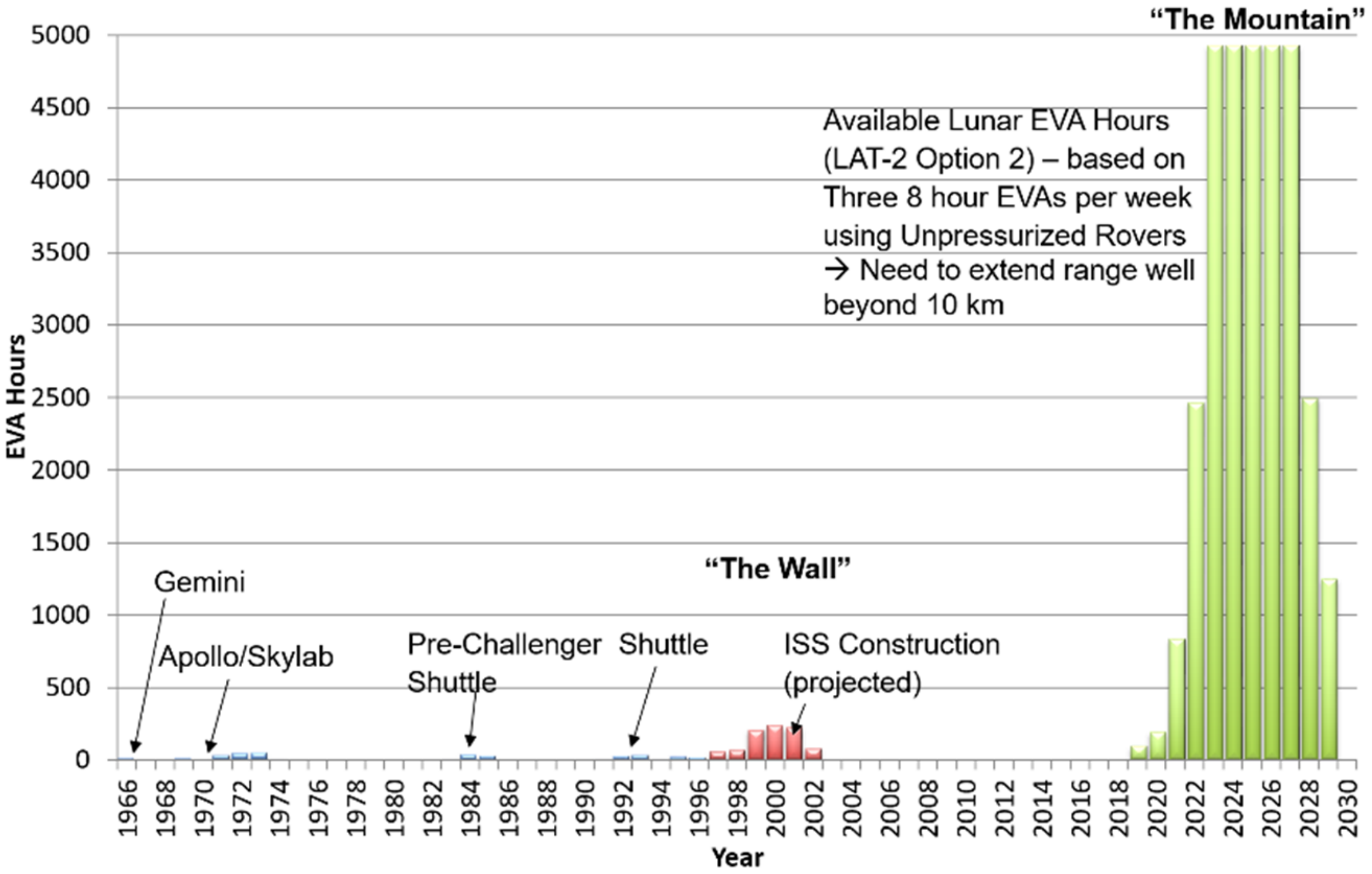
"The Wall of EVA"



- At the beginning of ISS assembly and maintenance we were projected to have the "wall" of EVA where in a period of <10yrs we were going to do more EVAs than in the previous history of NASA
  - For ISS EVA was just a tool to assemble and maintain the ISS, whereas the primary purpose of ISS was to perform microgravity research at 1 atmosphere (Earth as control environment)

Constellation Era: “The Mountain of EVA”



- During the Constellation program where the goal was to have a permanent human presence on the moon, the plans drove out “the mountain” of EVA.
    - It was clear that we needed a paradigm change in how we do EVAs to accomplish the goals of Constellation
    - Unlike ISS the primary purpose of EVA in the Artemis program is to perform science exploration.

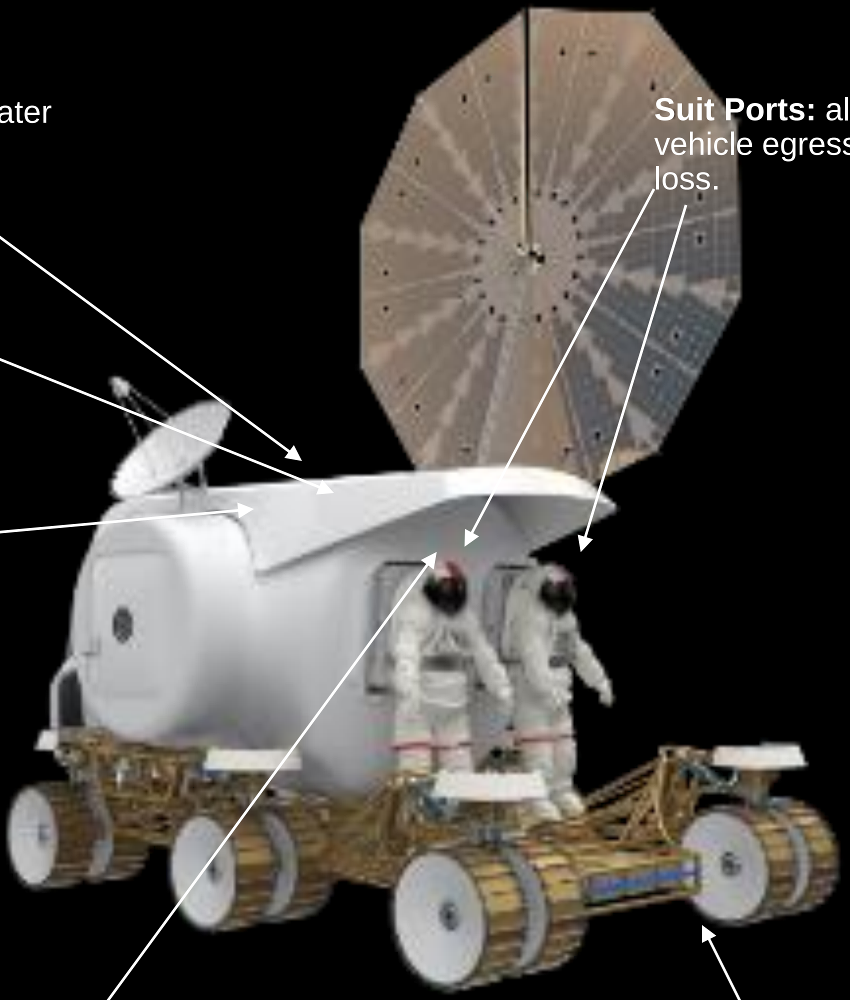
Pressurized Rover (PR) Design Features - Cabin Pressurized at 8.2 psia / 34% O2

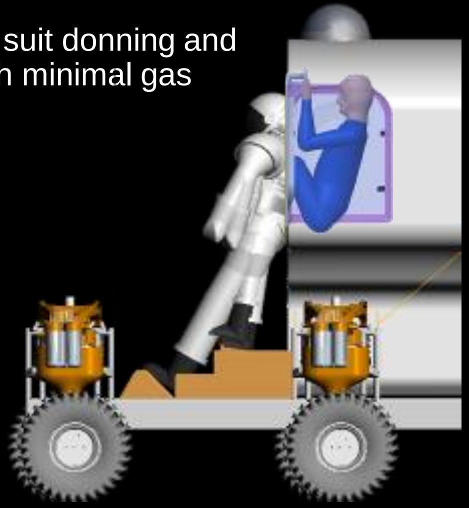
Radiator on Roof: allows refreezing of fusible heat sink water on extended sorties

Suit Ports: allows suit donning and vehicle egress with minimal gas loss.

ECLSS system with heavy commonality with PLSS (e.g., swingbeds, pumps, blowers, etc)

SPE / Fusible Heat Sink: cabin surrounded by 5.4 cm frozen water provides SPE protection. Same ice is used as a fusible heat sink, rejected heat energy by melting ice vs. evaporating water to vacuum.





Aft Driving Station: enables crew to drive rover while EVA (not shown)

Suit Shelter: retractable shelter protects EVA suits from dust, radiation and micrometeorites.

Work Package Interface: allows attachment of modular work packages e.g. winch, cable reel, backhoe, crane

Note: All computer illustrated images of surface mobility elements in this presentation are for illustrative purposes only and do not reflect actual designs.

Suitports Concept of Operations

1. Crewmember opens the bulkhead hatch which envelopes the suit hatch and PLSS

2. Open the suit hatch and begin ingress

3. Ingress partway into suit

4,5. Once part way into the suit, crewmember reaches back to mate LCVG connections to PLSS

6. Crewmember secures suit harness and tightens to ensure comfortable suit mass load transfer and index crewmember to suit so torse moves efficiently with crewmember movement.

7. Once ingressed, utilize suitport procedure on outside display to close bulkhead hatch which closes the suit hatch.

8. Once hatches are closed crewmember closes overcenter lever on suit to rotate suit hatch dogs into place.

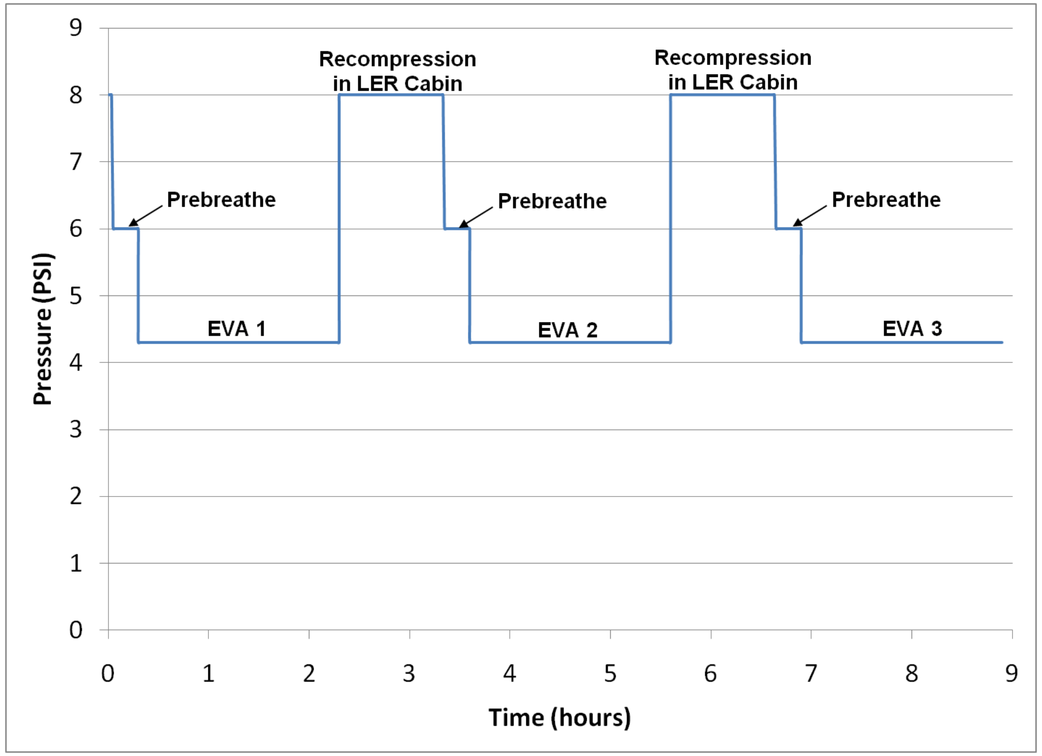
Suitports enable multiple EVAs at different locations and reduce EVA time to only that necessary to accomplish science and sampling activities


NASA

Background: Intermittent Recompression

- Intermittent Recompressions (IR) during saturation decompression was previously proposed as a method for decreasing decompression stress and time *(Gernhardt,1980)*
  - Gas bubbles respond to changes in hydrostatic pressure on a time scale much faster than the tissues absorb nitrogen

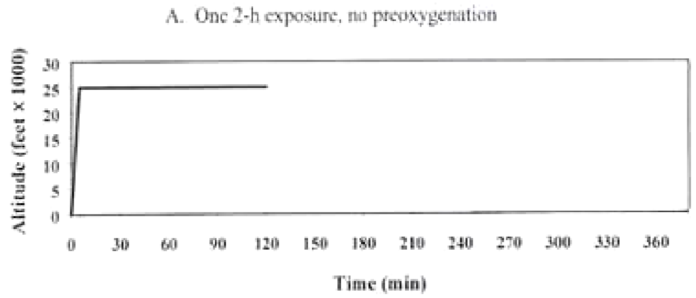
- Previous modeling work and empirical human and animal data indicate that IR between EVA suit pressure (≤4.3 psia, 100% O_2) and cabin pressure (8 psia, 32% O_2) may reduce decompression stress



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

Supporting Data from U.S. Air Force Studies

A



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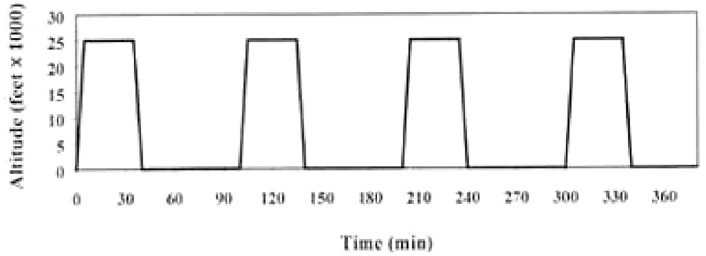
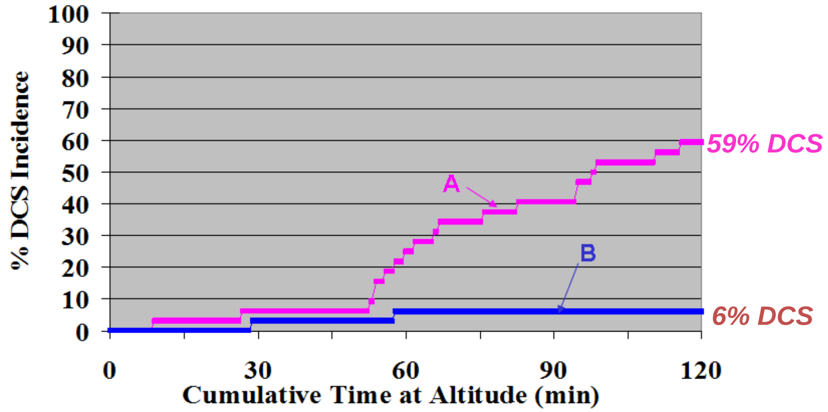
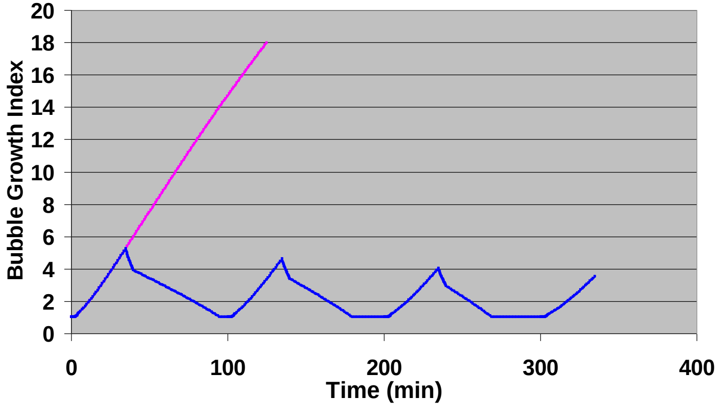




DCS Incidence



TBDM Predictions

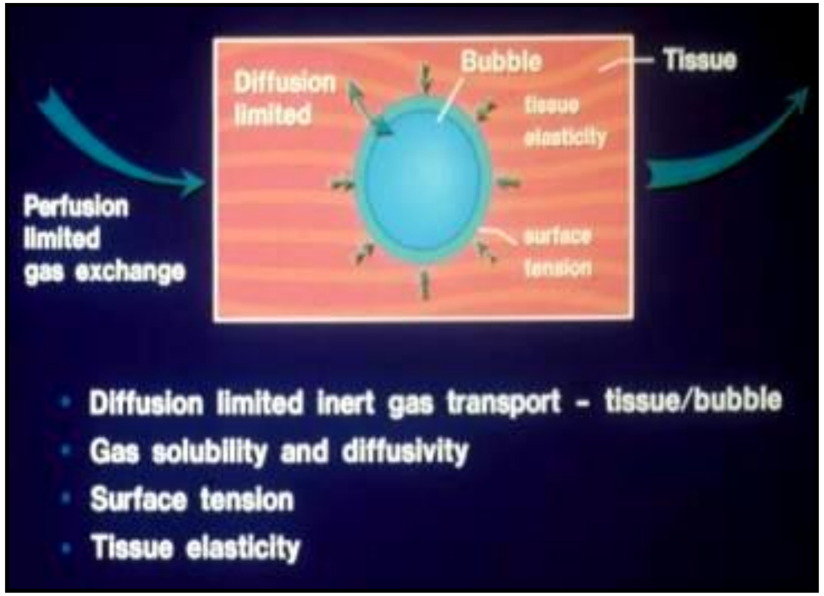
Pilmanis A.A., Webb J.T., Kannan N., Balldin U. The effect of repeated altitude exposures on the incidence of decompression sickness. Aviat Space Environ Med; 73: 525-531, 2002.

Methods: Tissue Bubble Dynamics Model

- **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*

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

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



♦ The Oceaneering and Subsea international decompression tables where based on the tissue bubble dynamics model (TBDM), with millions of safe dives performed using these decompression tables which enable much longer bottom times than the USN tables.

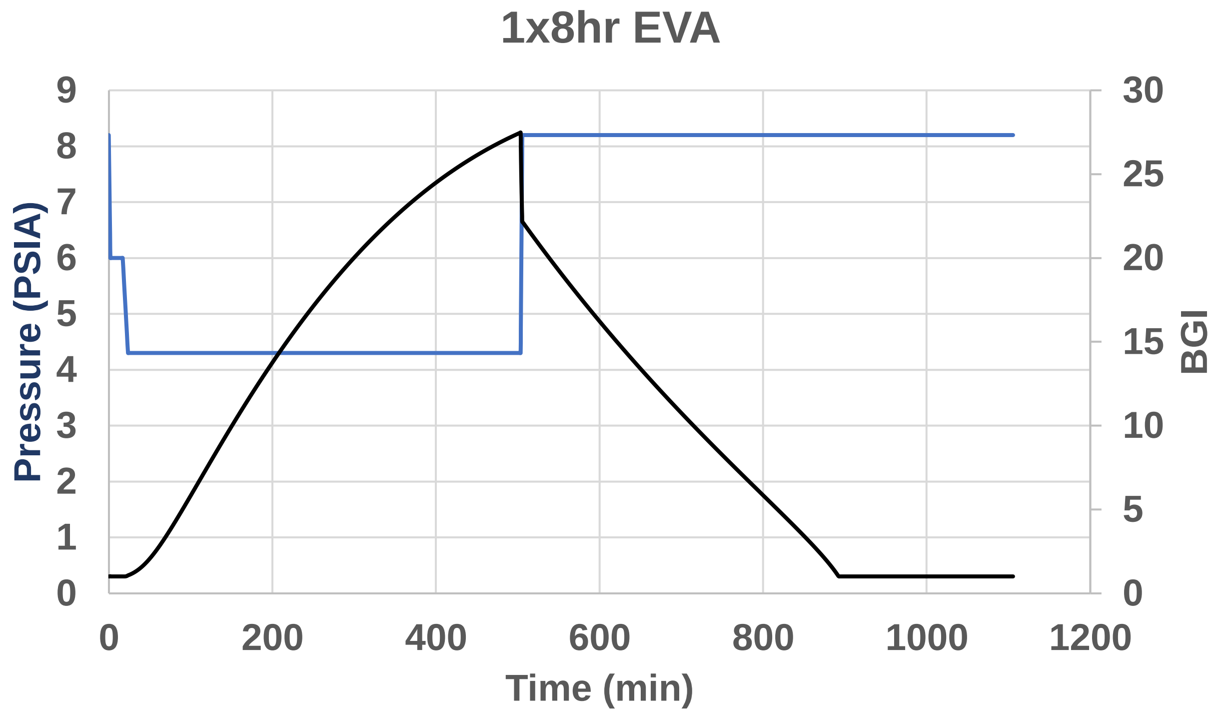
♦ The fact that the model was parameterized using literature based parameters and not from maximum likelihood estimation of the parameters from “training data sets”.

- This approach has a demonstrated ability to extrapolate to other forms of decompression exposure as evidenced by the ability to significantly predict and fit DCS data from diving to altitude exposures using the same set of parameters.

Results Model Predictions – 1x8hr EVA from the Exploration Atmosphere with a 15min Prebreathe

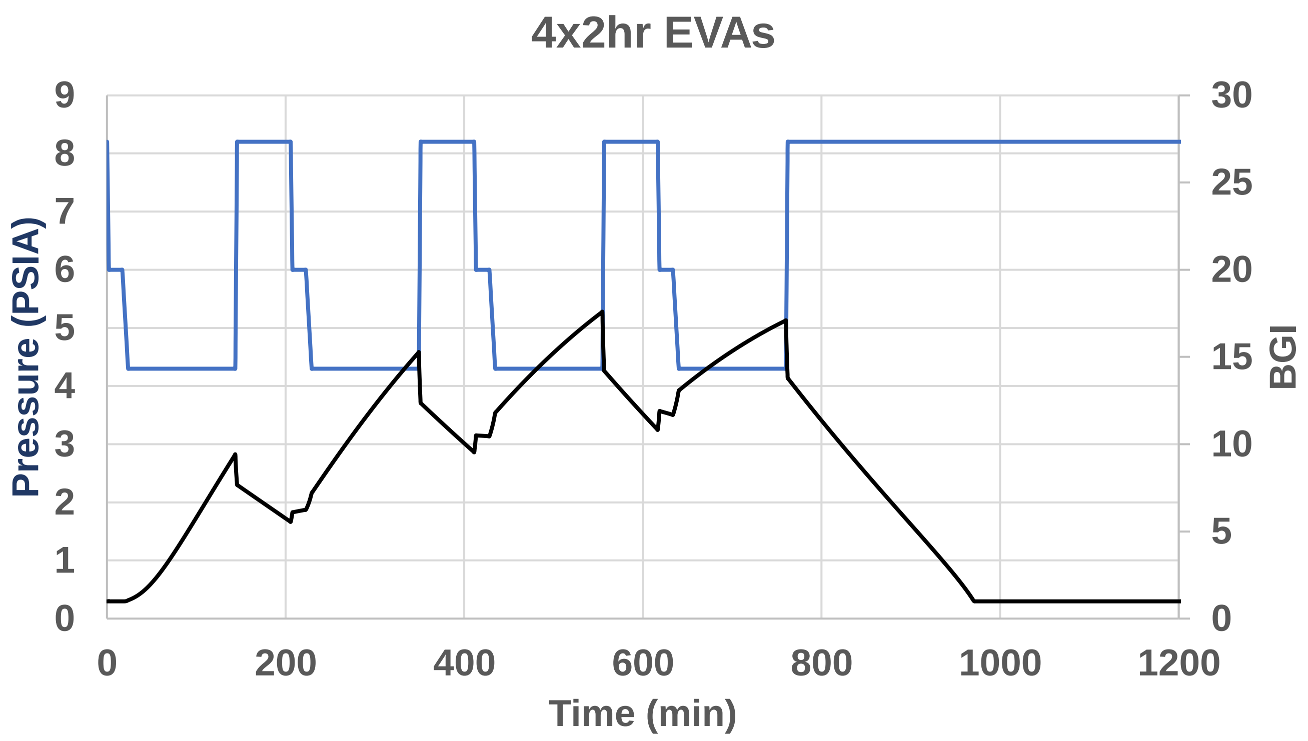
- **Profile:**
  1. Saturated at 8.2 psia / 34% O2
  2. 2 min depress to 6 psia (85% O2)
  3. Hold 15 min at 6 psia
  4. 0.26 psi/min depress to 4.3 psia (breathe down)
  5. 8 hr EVA at 4.3 psia
  6. 2 min repress to 8.2

Max % DCS = 10.9%



Results Model Predictions – 4x2hr EVAs from the Exploration Atmosphere with a 15min Prebreathe

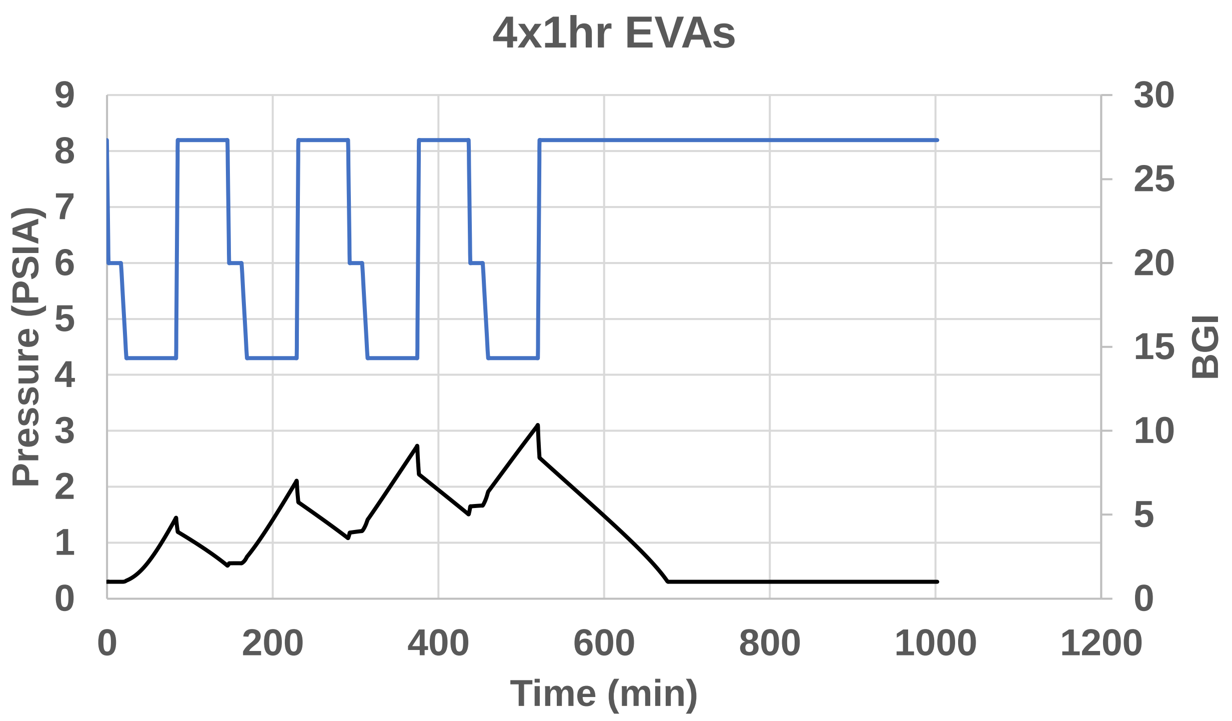
- **Profile:**
  1. Saturated at 8.2 psia / 34% O2
  2. 2 min depress to 6 psia (85% O2)
  3. Hold 15 min at 6 psia
  4. 0.26 psi/min depress to 4.3 psia (breathe down)
  5. 2 hr EVA at 4.3 psia
  6. 2 min repress to 8.2
  7. 1 hrs hold at 8.2 psia
  8. Repeat 2 – 7



Max % DCS = 6.9%

Results Model Predictions – 4x1hr EVAs from the Exploration Atmosphere with a 15min Prebreathe

- **Profile:**
  1. Saturated at 8.2 psia / 34% O2
  2. 2 min depress to 6 psia (85% O2)
  3. Hold 15 min at 6 psia
  4. 0.26 psi/min depress to 4.3 psia (breathe down)
  5. 1 hr EVA at 4.3 psia
  6. 2 min repress to 8.2
  7. 1 hrs hold at 8.2 psia
  8. Repeat 2 – 7



Max % DCS = 4.9%

Risk of DCS associated with highest 1-min metabolic rate

- **These predictions were based on logistic regression of the TBDM with DCS data associated with ambulatory EVA simulations with average metabolic rates of ~800 BTU/hr**

- **The metabolic rates associated with Artemis lunar surface operations are anticipated to be up to 2000 BTU/hr.**
  - With peak 2-min metabolic rates of up to 70% VO2 max (~30ml/kg-min based on a VO2 max of 42 ml/kg-min)

- **Previous decompression studies at Brooks AFB* have shown a high correlation between peak 1-min metabolic rate and DCS. And a poor correlation with average metabolic rate.**

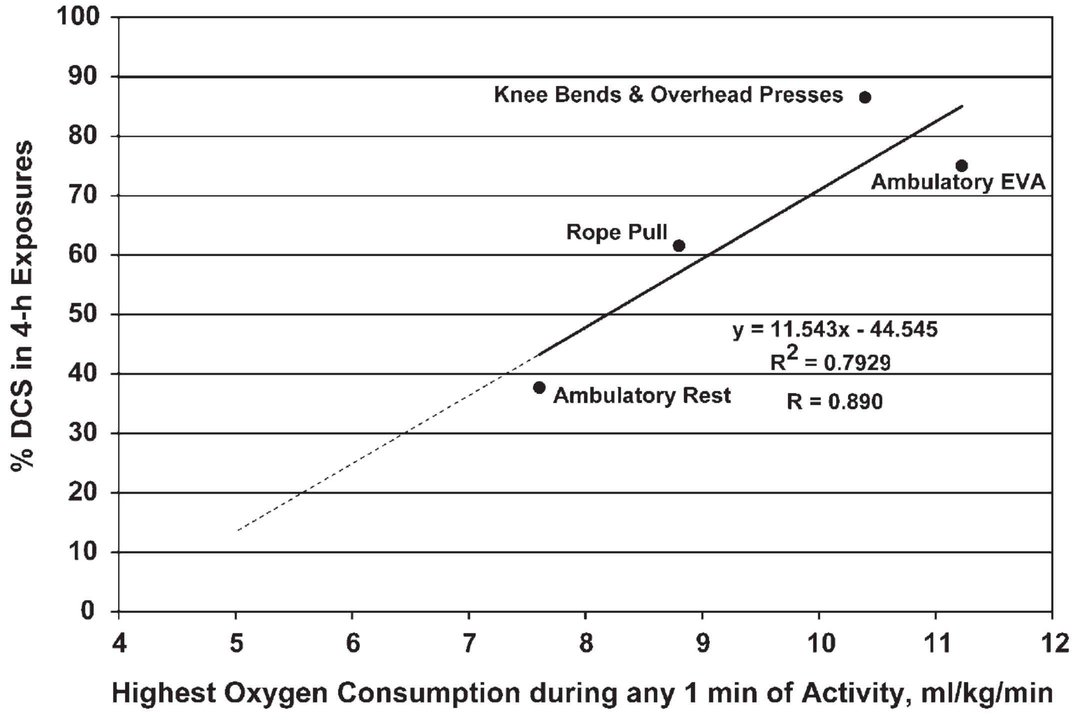


Fig. 1. % DCS as a function of highest $\dot{V}O_2$ in any 1 min of activity.

Webb, James T., Larry P. Krock, and Michael L. Gernhardt. "Oxygen consumption at altitude as a risk factor for altitude decompression sickness." Aviation, space, and environmental medicine 81.11 (2010): 987-992.

Risk of DCS associated with highest 1-min metabolic rate

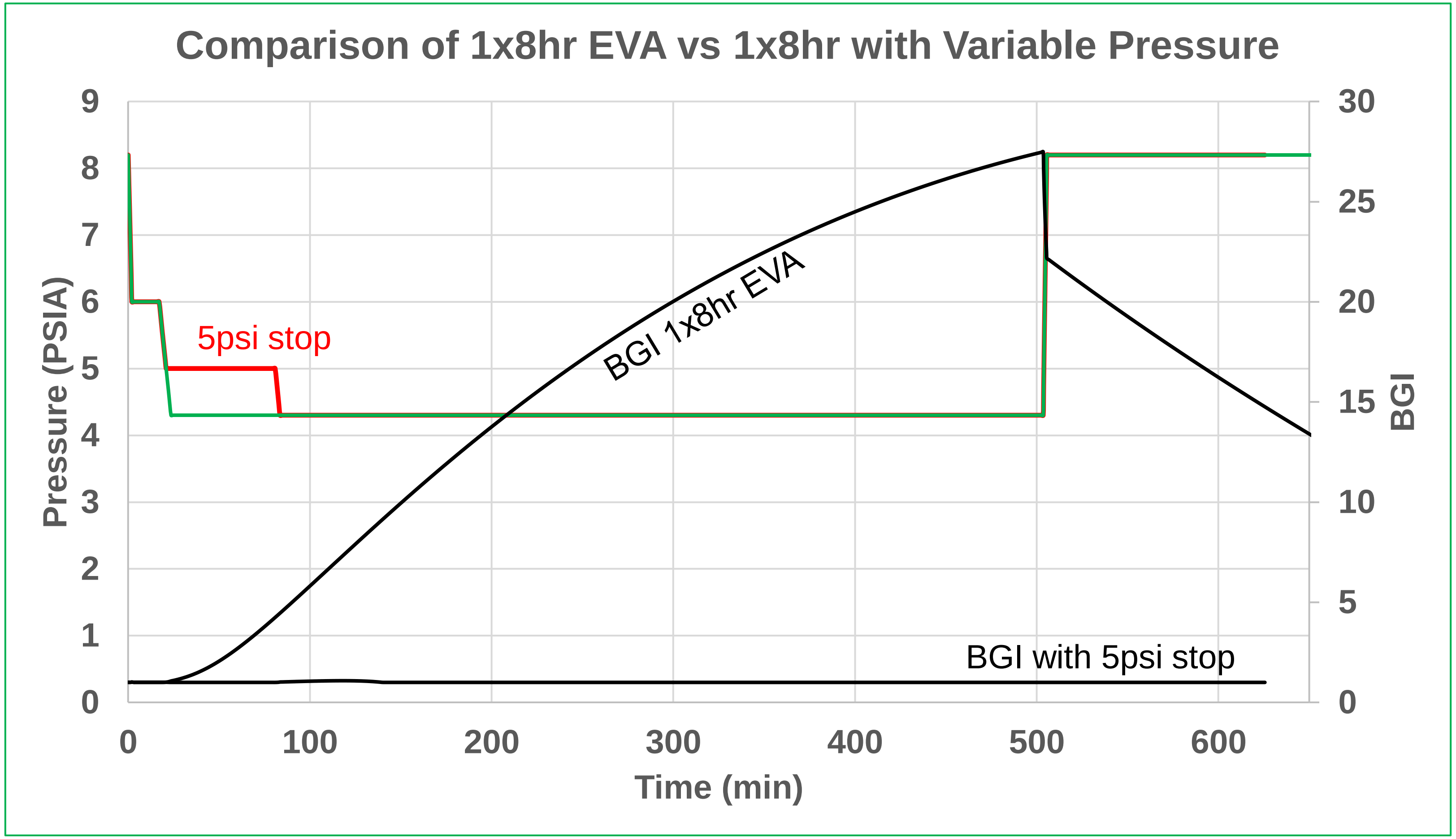
- **The Artemis EVA profiles with peak metabolic rates of ~30ml/kg-min are higher than have ever been studied at Brooks or NASA in the past 40yrs.**
  - The maximum metabolic rates in the historical data have been ~12 ml/kg-min

- **It is likely that the bubble model for DCS predictions for these higher metabolic rates grossly understates the risk and that EVAs may need to be conducted with initial periods of higher suit pressure (~5 psi vs 4.3 psi)**

$$P_{Bubble} = P_{Ambient} + P_{Surface\ Tension} + P_{Tissue\ Deformation}$$

- **When the tension of nitrogen in the tissue is higher than the pressure of gas in the bubble, nitrogen will diffuse into the bubble resulting in bubble growth**
  - **With the limiting 360minute half-time tissue if the tension of gas in the tissue is even 0.1 psi higher than the pressure of gas in the bubble, the bubbles will continue to grow for a long period of time.**
- **Only when the tissue nitrogen tension falls below the bubble pressure will nitrogen begin to diffuse out of the bubble into the tissues resulting in a slow bubble resolution.**

Results Model Predictions – 4x1hr EVAs from the Exploration Atmosphere with a 15min Prebreathe



- **Performing a variable pressure EVA where after the initial short prebreathe there is an additional 60min at 5 psi prior to depressing to a final suit pressure of 4.3 psi results in no predicted bubble growth**
  - **The additional time at 5 psi will likely not have any operational impact**
  - **Even though no bubble growth is predicted the model is calibrated with much lower metabolic rates and testing will need to be performed to validate the profile.**

Summary

- The decompression stress associated with the multiple short EVAs is less than a single long EVA because bubbles have less time to grow through a time-dependent diffusion-limited process.
- Recompression to cabin pressure resolves bubbles on a time scale much faster than the rate limiting 360min half-time tissue on-gasses nitrogen. Therefore, a series of EVAs with intermittent recompression to cabin pressure should lower the DCS risk
- These DCS risk predictions, using the logistic regression calibrated to 800BTU/hr, are likely to understate the DCS risk of Artemis EVAs which are anticipated to have peak metabolic rates up to ~2000 BTU/hr.

Backup

Risk of DCS associated with highest 1-min metabolic rate

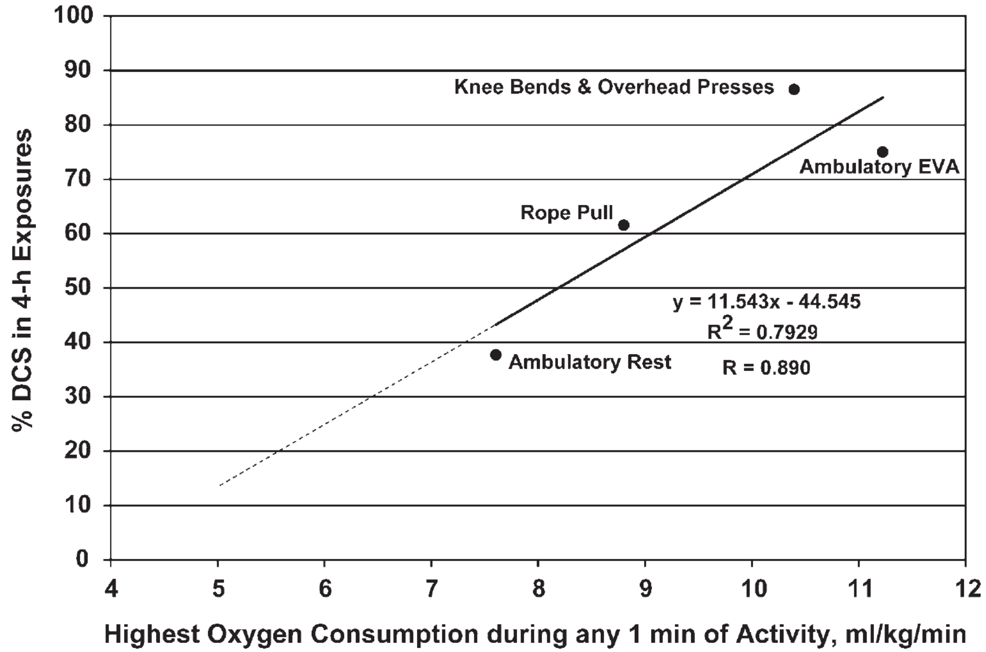


Fig. 1. % DCS as a function of highest $\dot{V}O_2$ in any 1 min of activity.

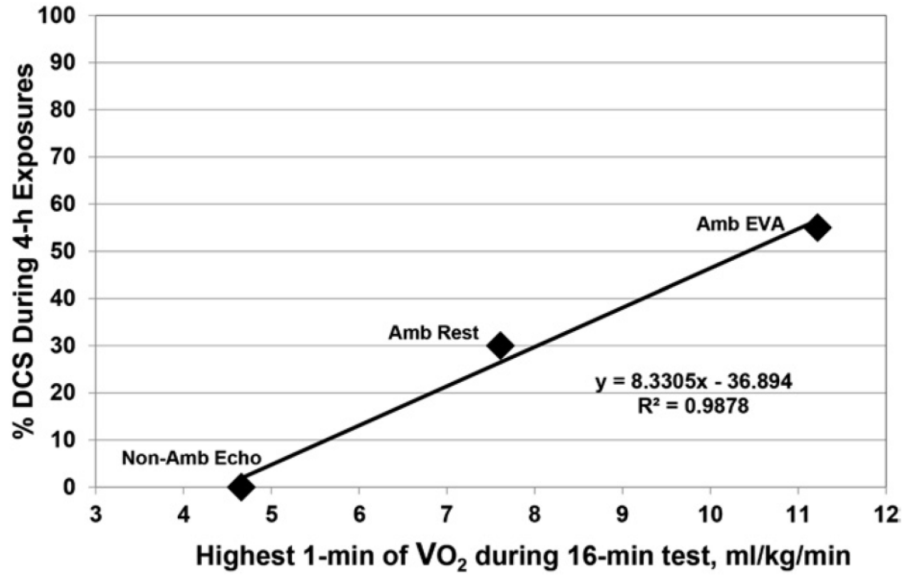


Fig. 1. DCS during zero-prebreathe, 4-h exposures of men to 22,500 ft (6858 m; 314 mmHg; 6.1 psia; r = 0.99). As reported in Webb,[33] 22 male subjects accomplished both Amb Rest and Amb EVA oxygen consumption determinations. For the current study, 20 additional subjects accomplished the Non-Amb Echo exposures.

- **Webb's analysis and subsequent human test shows that peak 1min met rate correlates significantly better with DCS than the average metabolic rate.**