POTENTIAL FIFTY PERCENT REDUCTION IN SATURATION DIVING DECOMPRESSION TIME USING A COMBINATION OF INTERMITTENT RECOMPRESSION AND EXERCISE.

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Introduction- 50% Reduction in Saturation Decompression Time

- Recent resurgence in saturation diving driven by Hurricane damage and other operational factors
- Few significant improvements to saturation diving decompression methods over the past two decades
- Conventional saturation decompression protocols use linear decompression rates that become progressively slower at shallower depths, consistent with gas bubble control vs. dissolved gas elimination kinetics.

DEPTH		RATE	
MSW	FSW	Travel in MSW	Travel in FSW
0 – 15	0 – 50	1 MSW per hour (60 min/MSW)	3 FSW per hour
16 – 30	51 – 100	1.2 MSW per hour (50 min/MSW)	4 FSW per hour
31 – 60	101 – 200	1.5 MSW per hour (40 min/MSW)	5 FSW per hour
61 – 457	201 – 1500	2 MSW per hour (30 min/MSW)	6 FSW per hour

- Intermittent recompression during saturation decompression previously proposed as a method for decreasing decompression stress and time (Gernhardt,1982,1989).
  - Gas bubbles respond to changes in hydrostatic pressure on a time scale much faster than the tissues.
  - Faster and uniform ascent rates accelerate inert gas washout, short recompression periods to control bubble growth
  - Exploits surface tension to increase bubble- tissue diffusion gradients across the long decompression profile

Introduction

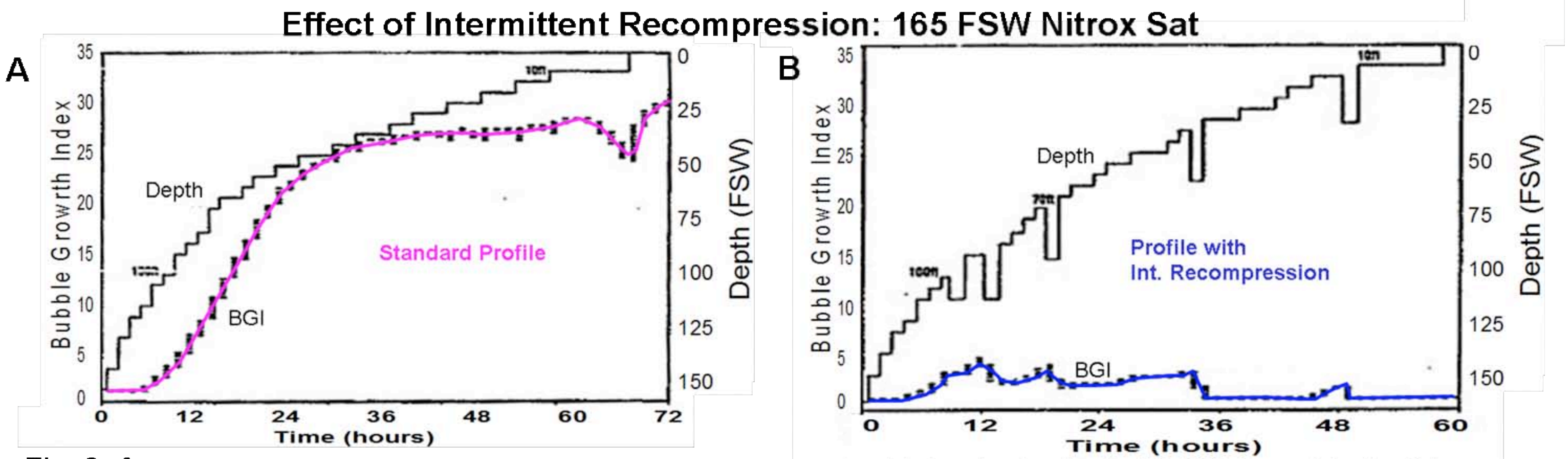

Fig. 3. A: 165 FSW saturation on Nitrox, decompressed to 45 FSW using an experimental staged protocol (ppO_2=0.5 ATA), then switched to air for remaining decompression. 50% DCS (n=10) observed with the 4000 minute protocol (7). Protocol modified to 7000 minutes (4.86 days) for operations.

B: Same decompression protocol as in A, but modified to include intermittent recompression (without exercise) achieves a faster ascent time (2.43 days) with lower decompression stress (Bubble Growth Index, or BGI), demonstrating the theoretical advantage of intermittent recompression.

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

r = Bubble Radius (cm)
t = Time (sec)
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)
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g = Surface Tension (dyne/cm)
M = Tissue Modulus of Deformability (dyne/$cm^2 \cdot cm^3$)
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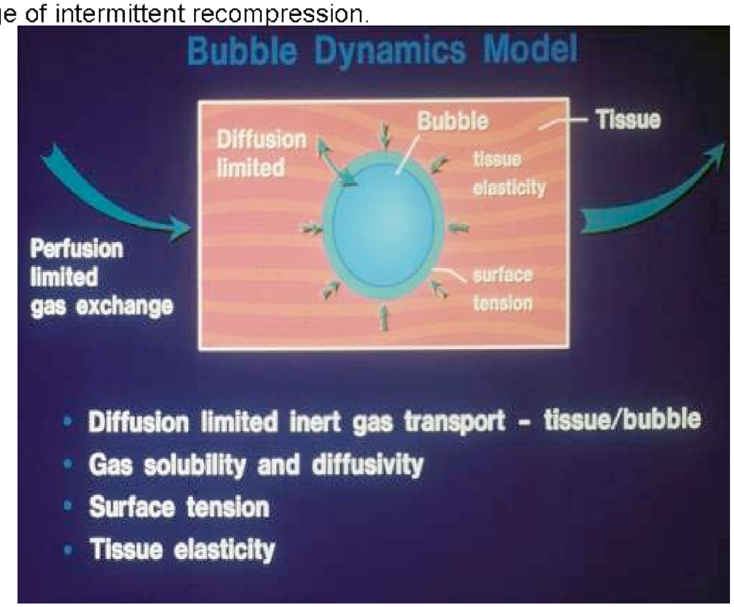
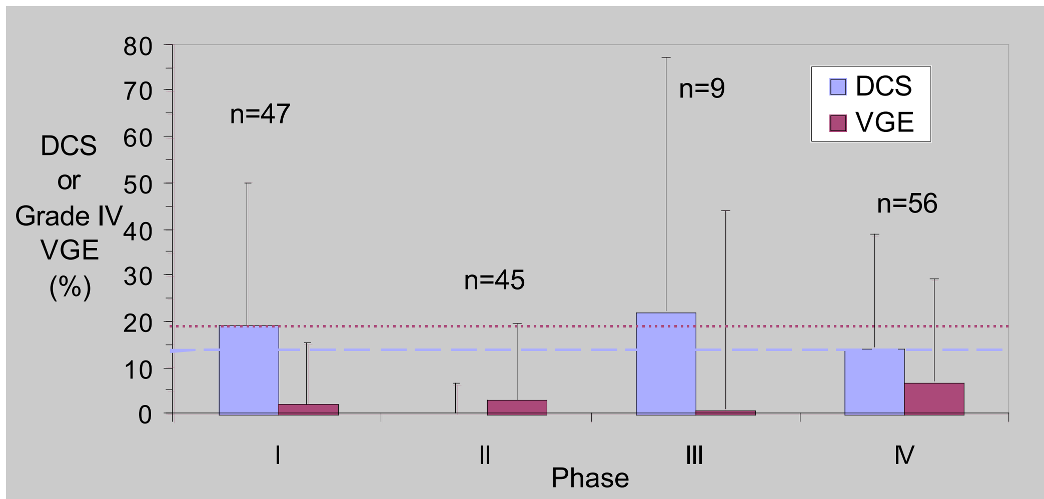


NASA Exercise Prebreathe Trials

- The NASA prebreathe reduction program (Multi-center study- NASA, Duke, DRDC, UT Hermann) demonstrated that exercise during Oxygen prebreathe resulted in a 50% reduction (2-h vs. 4-h) in the saturation decompression time from 14.7 to 4.3 PSI and a significant reduction in decompression sickness (DCS: 0 vs. 23.7%).
- **Combining exercise with intermittent recompression, which controls gas phase growth and eliminates supersaturation before exercising, may enable even more efficient saturation decompression schedules than intermittent recompression alone.**



Phase I-IV - 2 hr oxygen prebreathe exercise protocols

METHODS

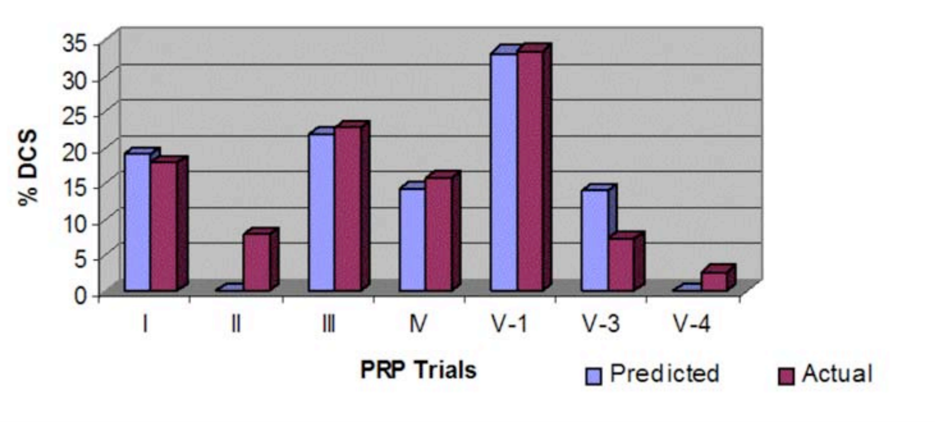
Tissue Bubble Dynamics Model (TBDM)

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

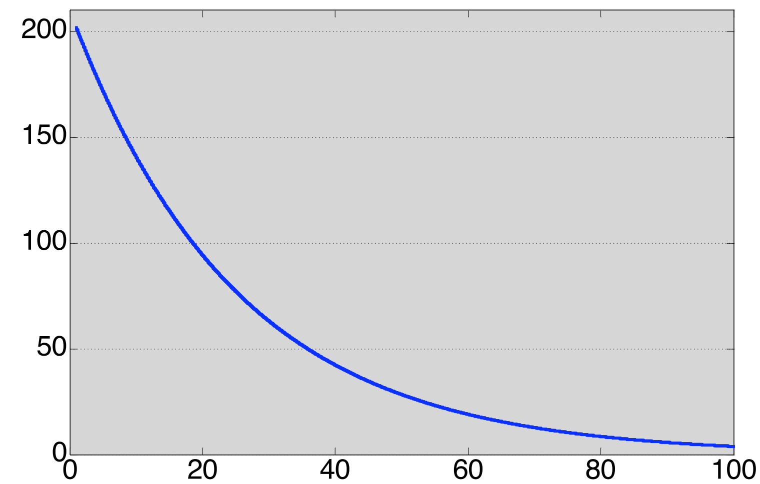
Significant prediction ($p < 0.001$) and goodness of fit (Hosmer-Lemeshow: p=.77) with 430 cases of DCS in 6437 laboratory dives for TBDM. **Used operationally in over 25,000 dives**

- TBDM used in conjunction with NEPM that relates tissue inert gas exchange rate constants to exercise (mL O2/kg-min), to develop decompression schedules from saturation at depths from 45 feet sea water (FSW) to 400 FSW.

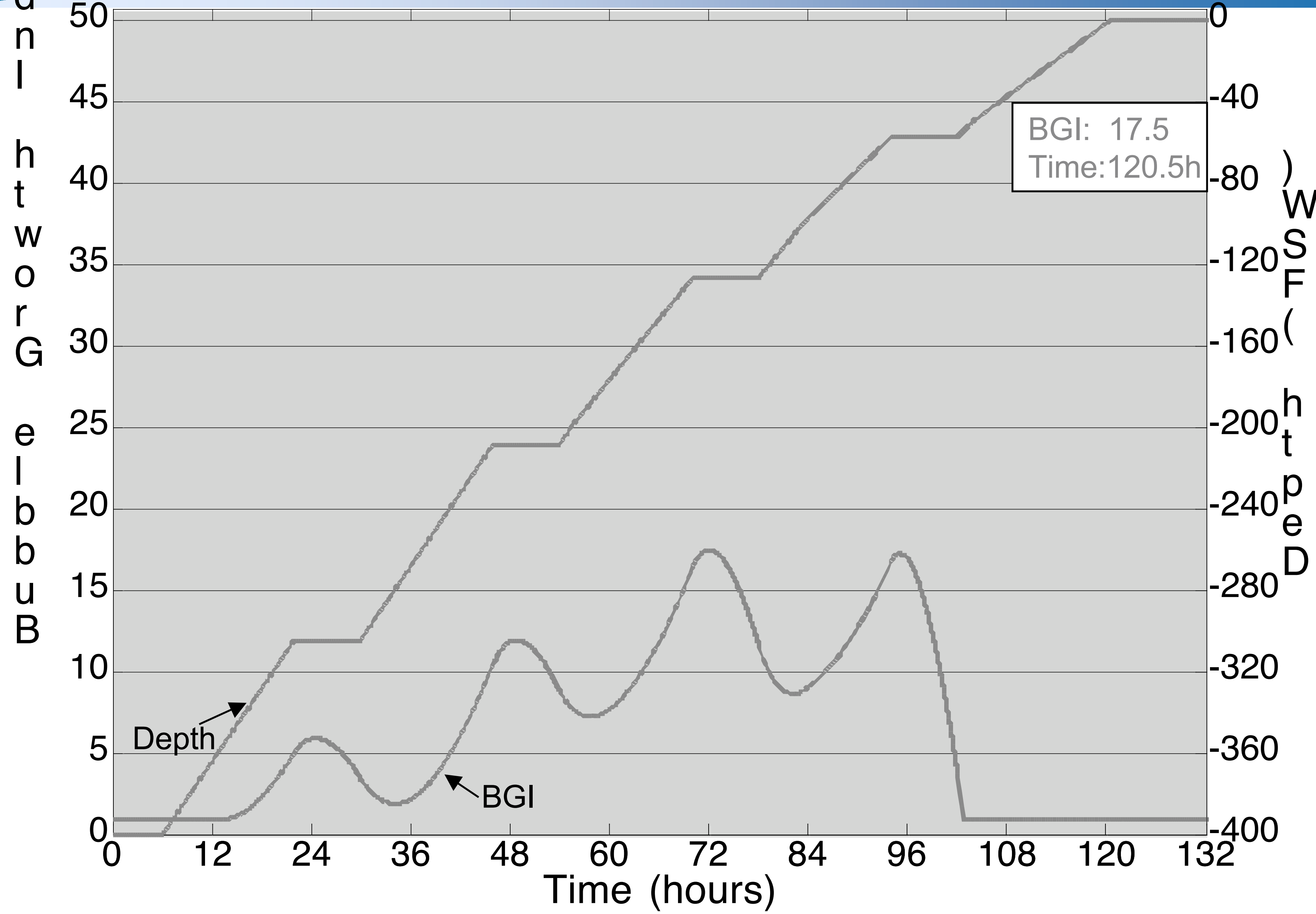
NASA Exercise Prebreathe Model (NEPM)



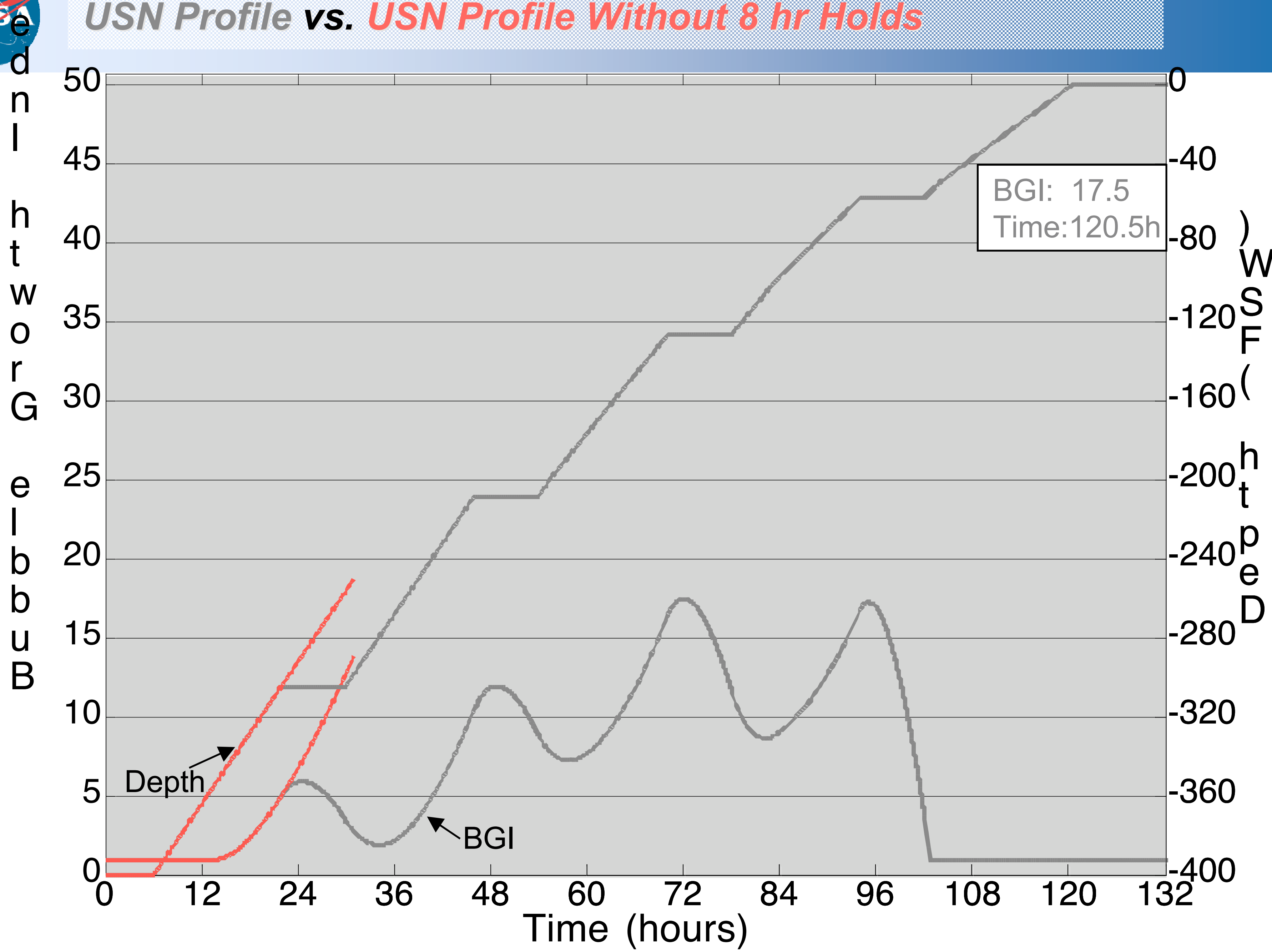
k = 1 / (*e*-_x * C). Logistic regression was used to fit the _ and C constants to DCS incidence in 159 altitude exposures with 39 cases of DCS (6). Significant prediction ($p < 0.001$) and goodness of fit (Hosmer-Lemeshow: p=.70) with 22 cases of DCS in 159 altitude exposures for NEPM (Hosmer-Lemeshow p=.70). **Used operationally in over 40 spacewalks**



USN 400 FSW Heliox Sat Decompression Profile



USN Profile *vs.* USN Profile Without 8 hr Holds



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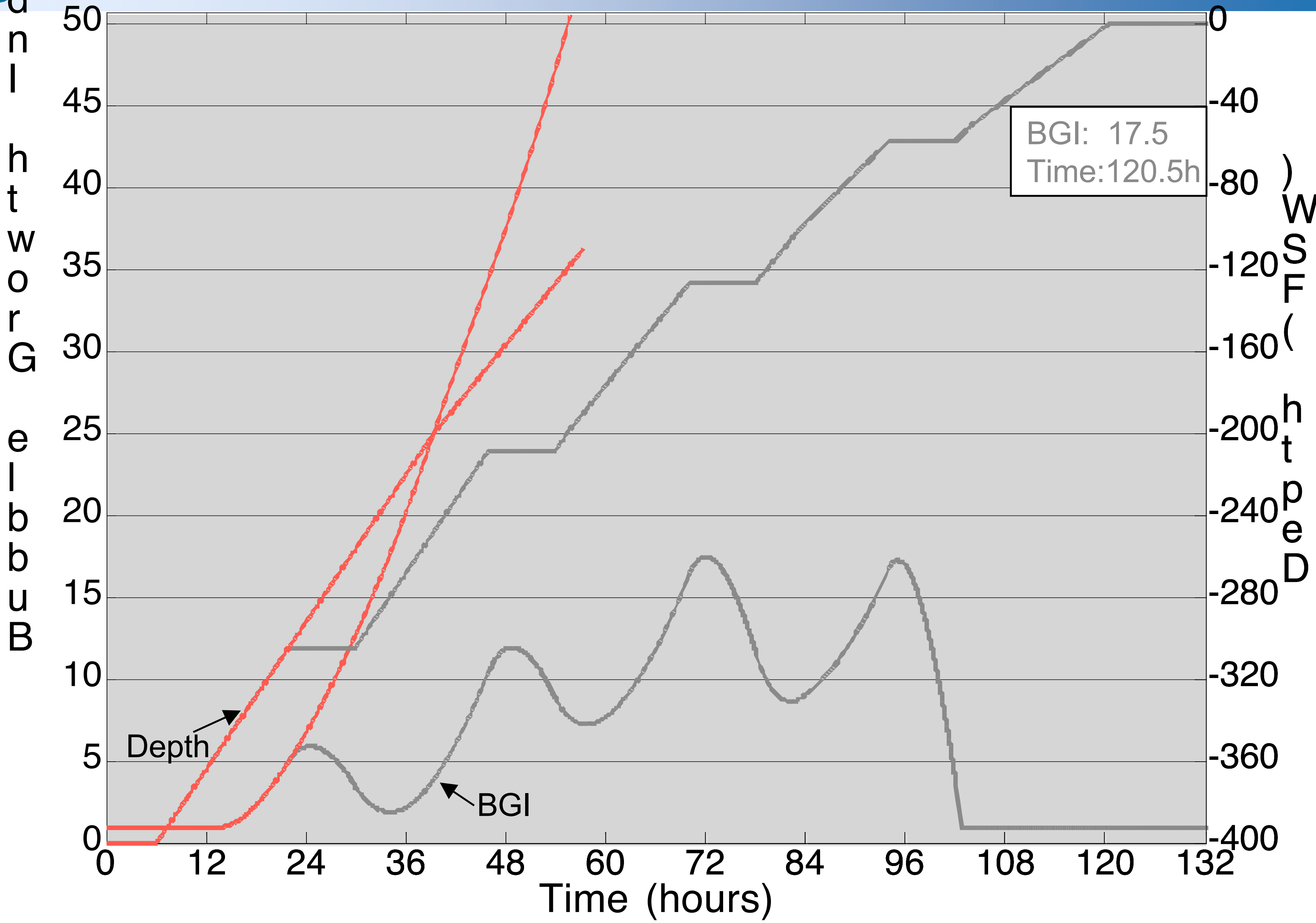
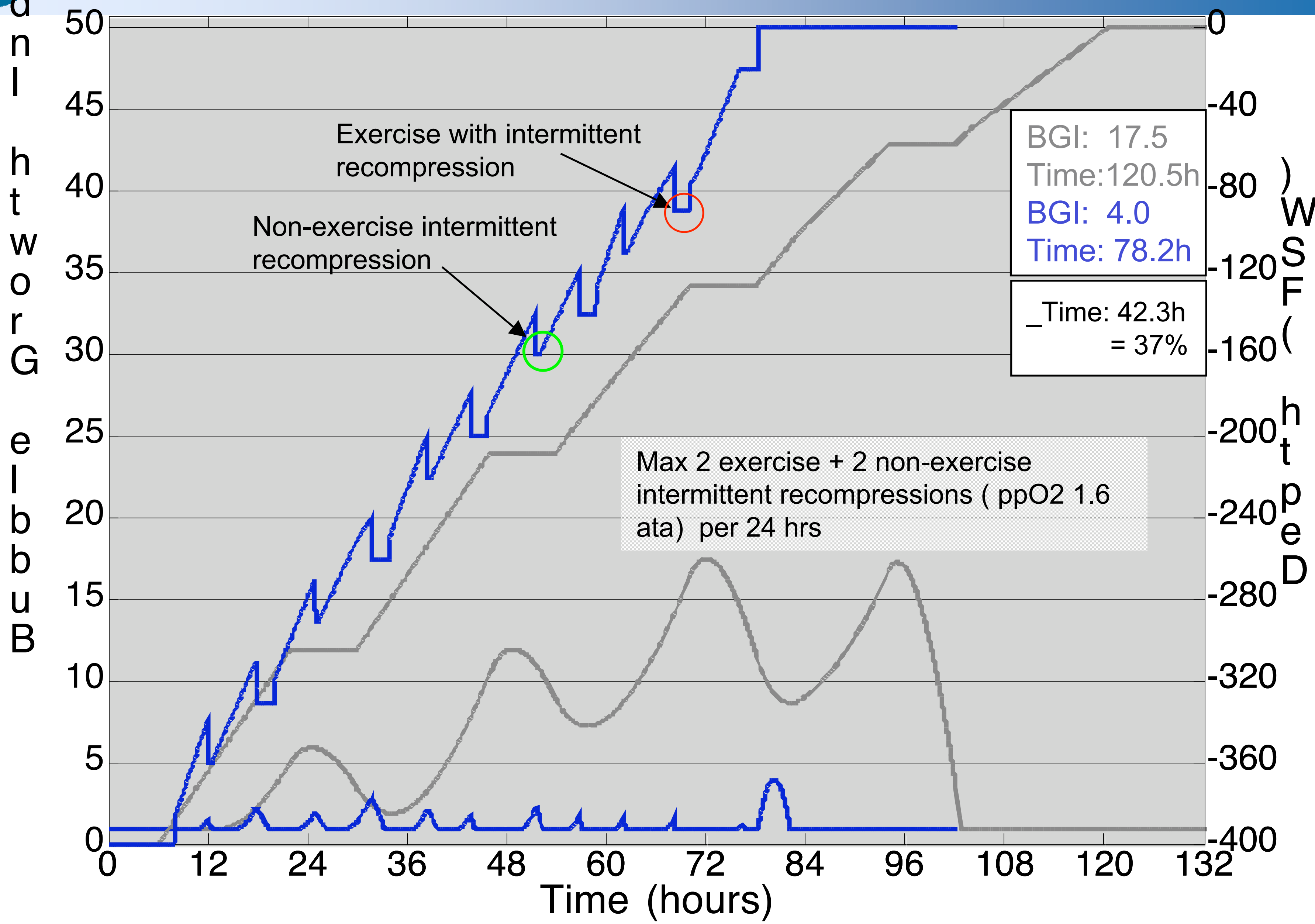
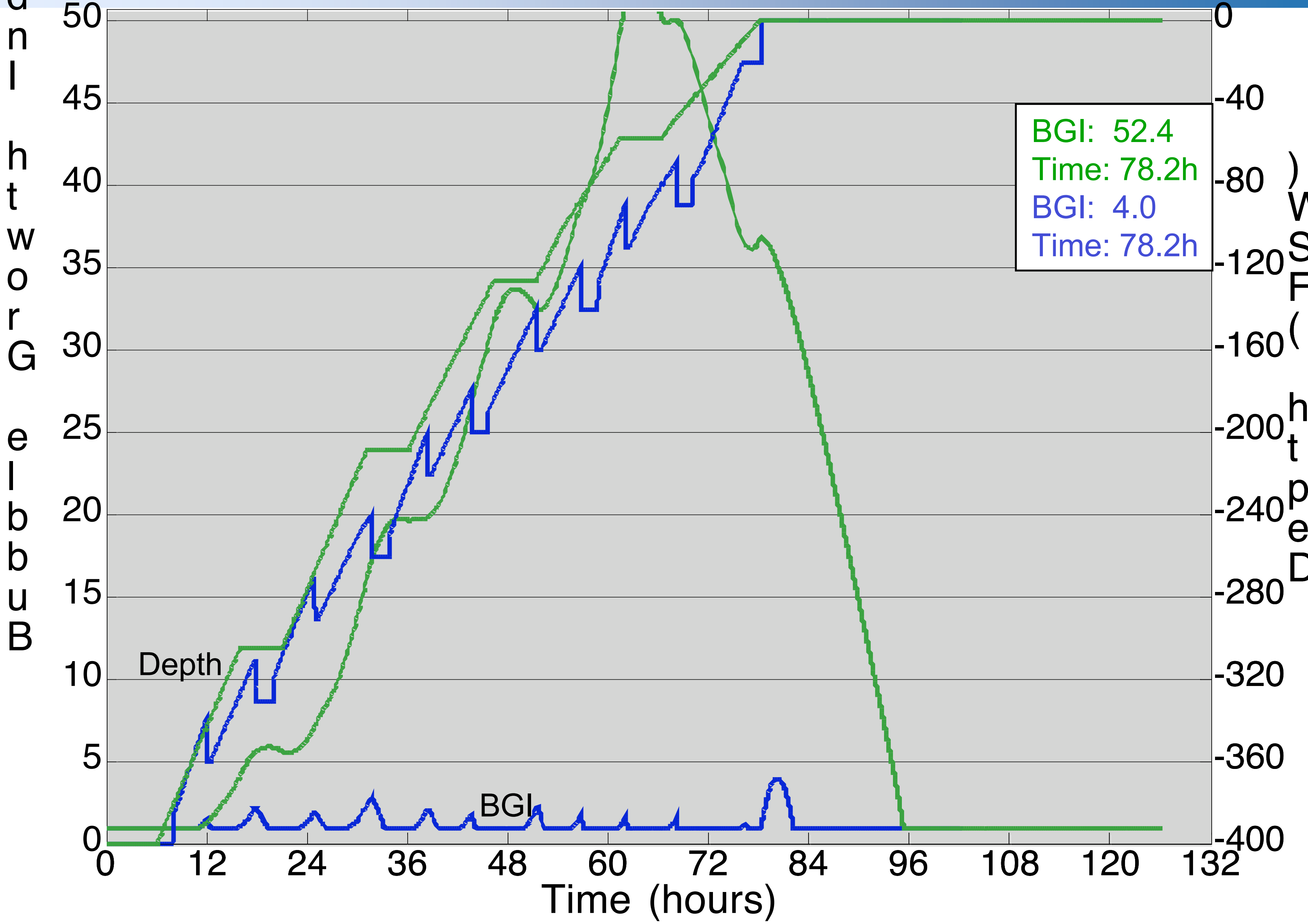


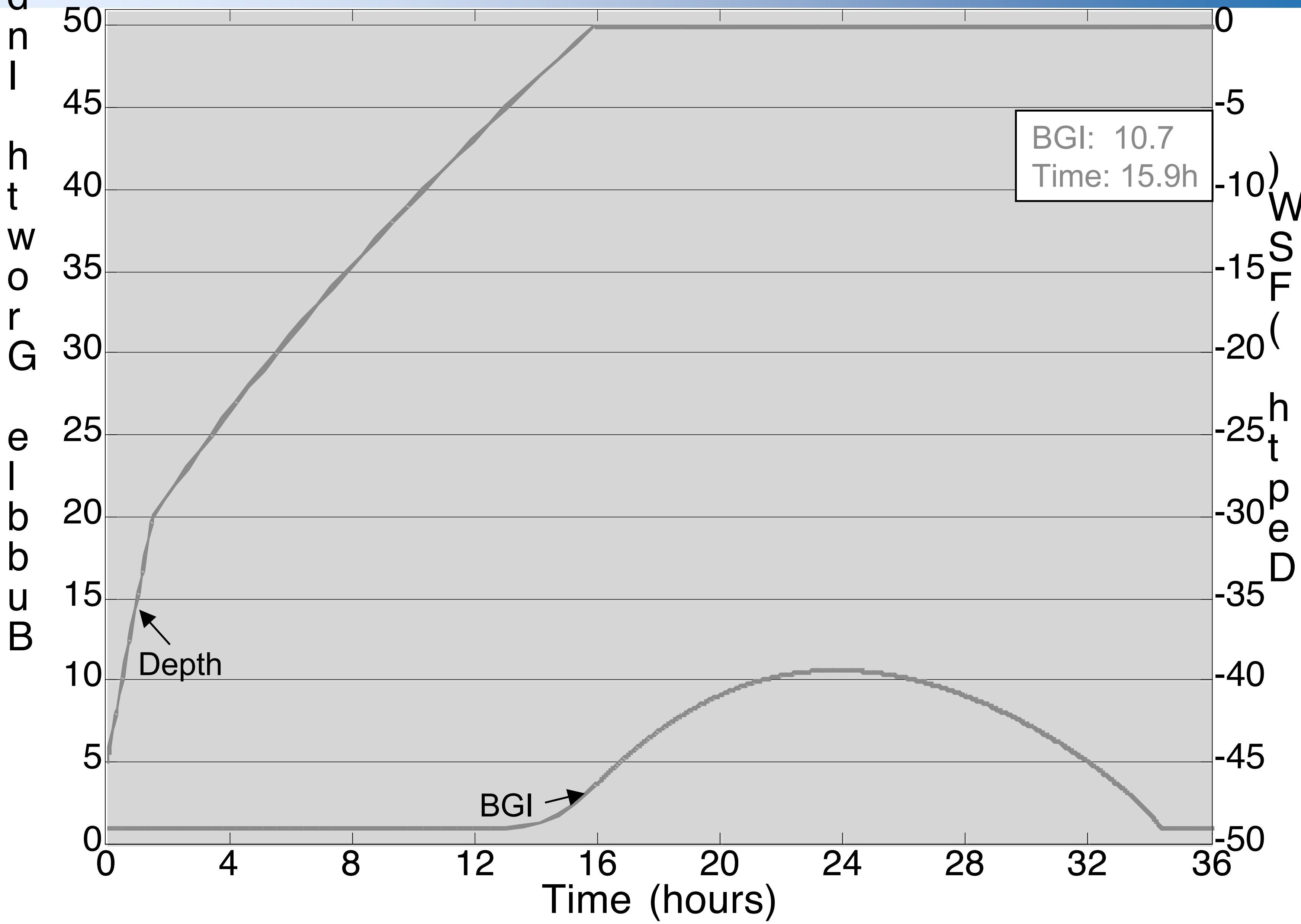
USN Profile vs. *Intermittent Recompression + Exercise Countermeasures (IRECM)*



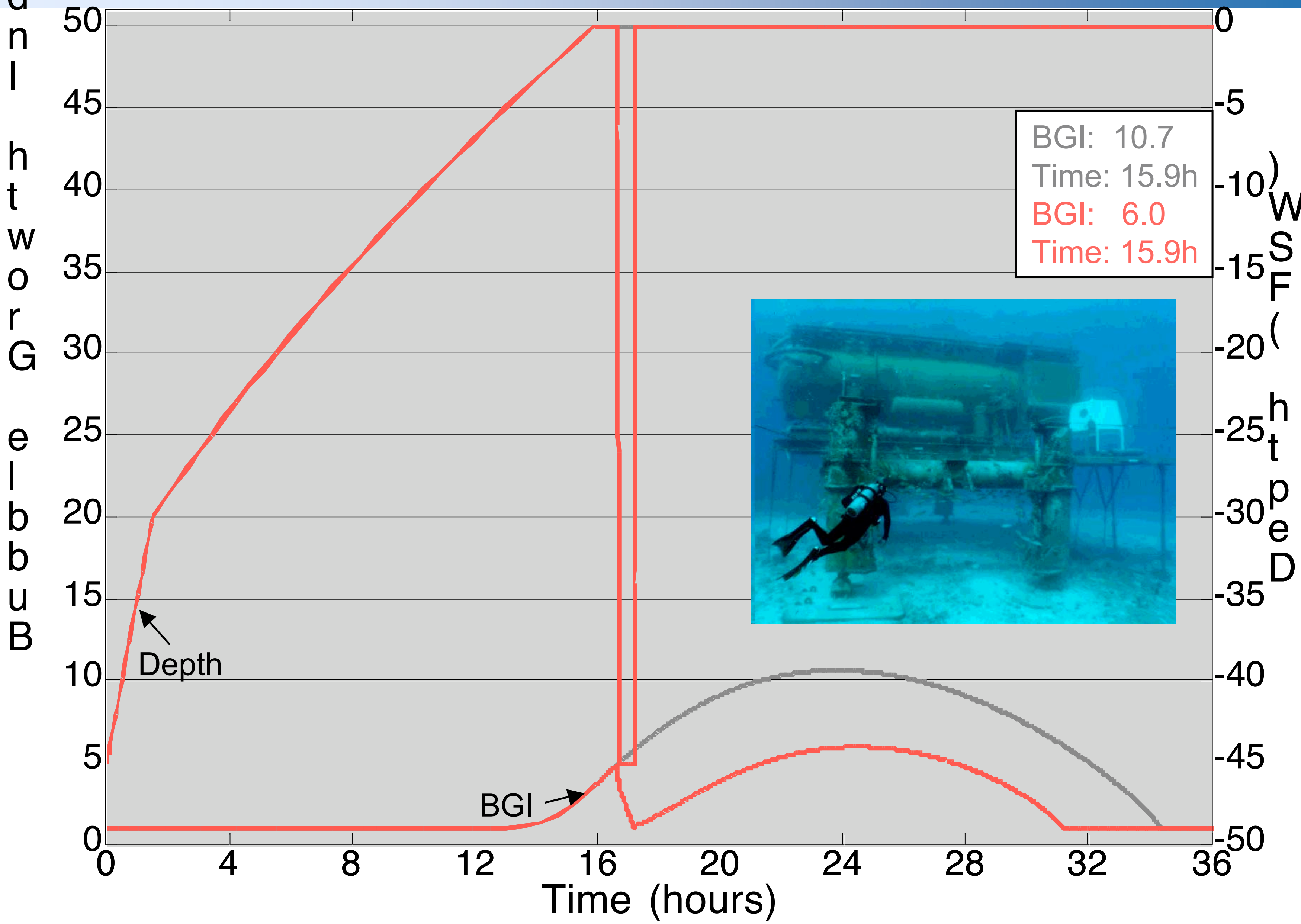
IRECM vs. *USN Profile Time-and-O_2-matched*



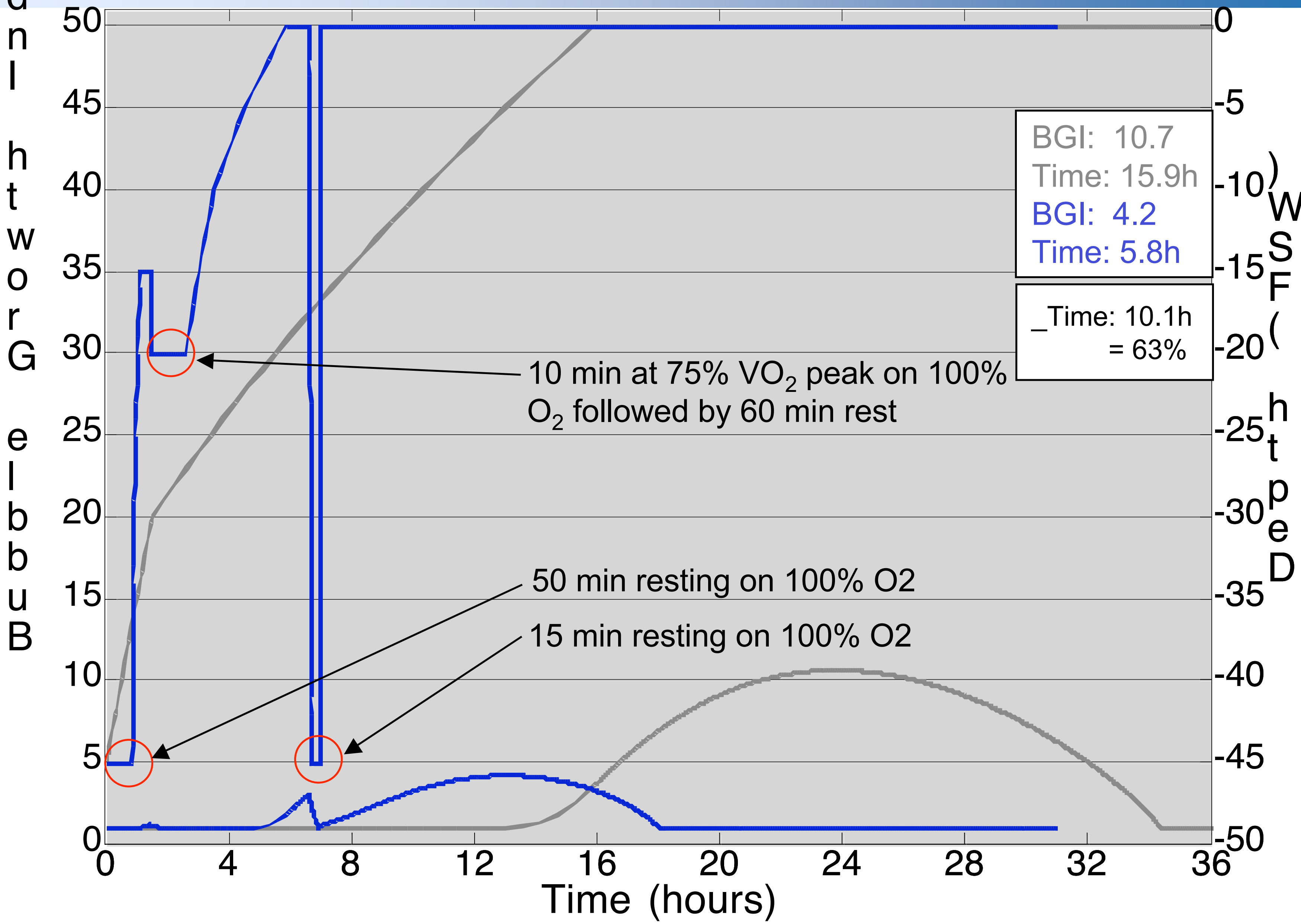
NOAA 45 FSW Air Sat Decompression Profile



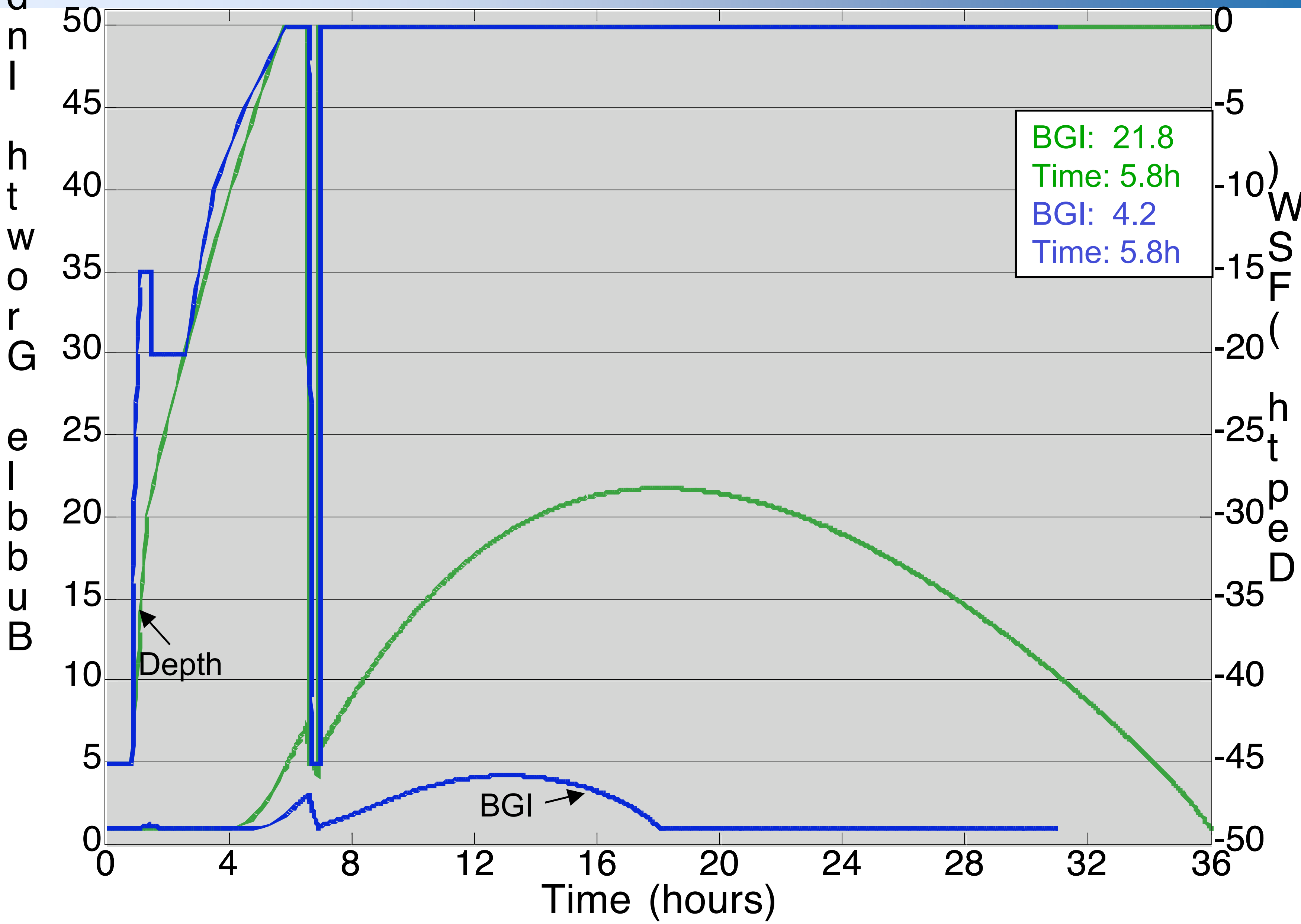
NOAA Profile *vs.* NOAA Profile With 45 FSW Air Recompression



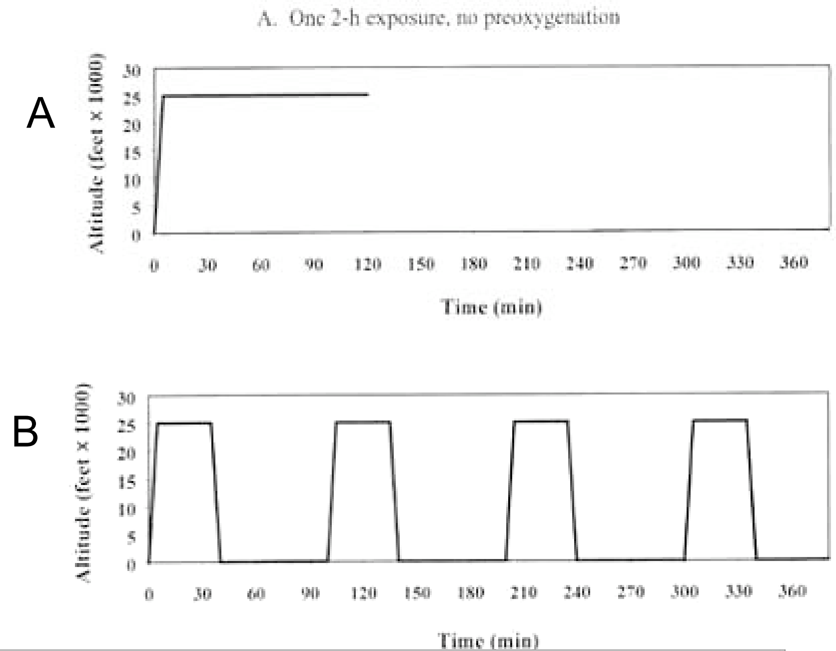
NOAA Profile vs. IRECM

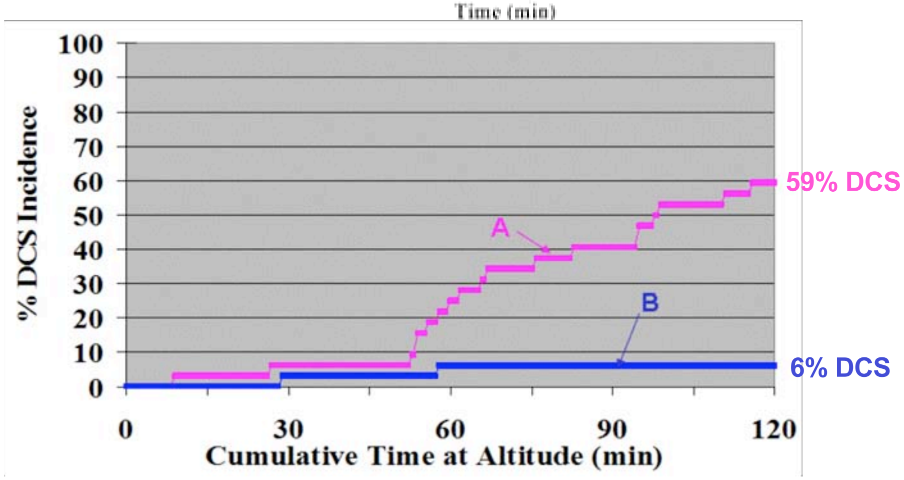


IRECM vs. *NOAA Profile Time-and-O_2-matched*

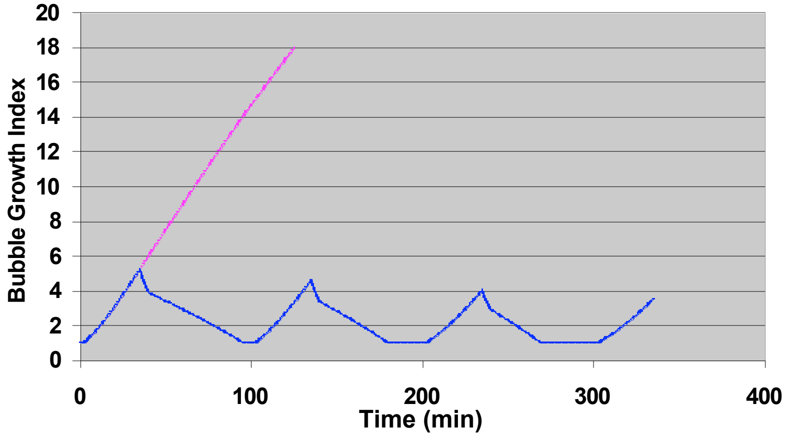


Discussion





DCS Incidence

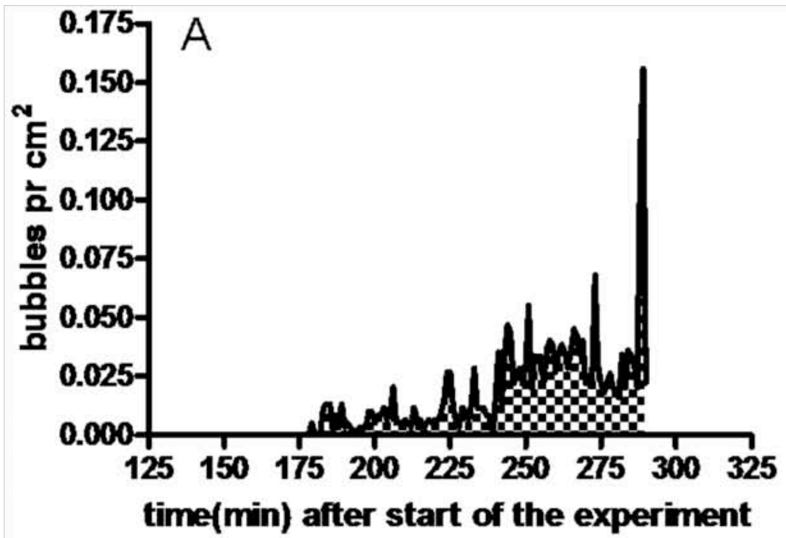


TBDM Predictions

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.

Discussion

Without Intermittent Recompression



With Intermittent Recompression

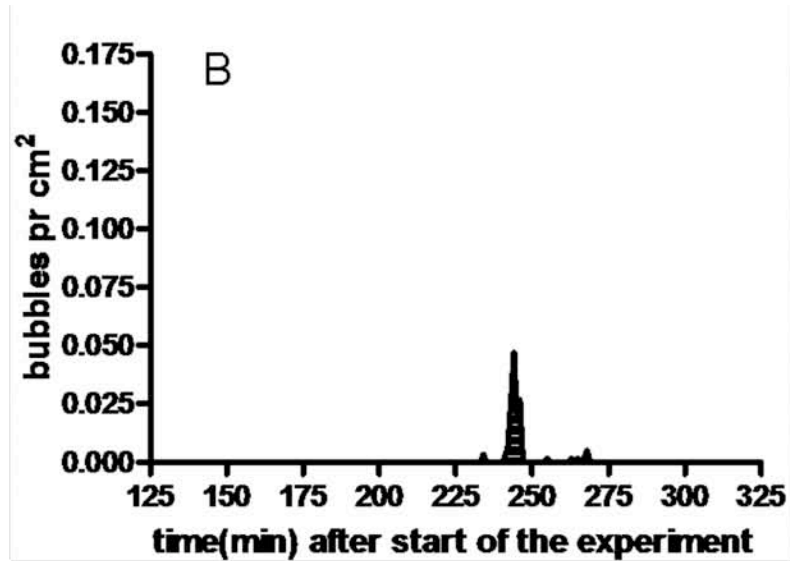


Fig. 10. Two groups of six pigs were compressed to 121 FSW with 90 minutes bottom time and were then decompressed following one of two decompression procedures; either with a 5-min 12 FSW recompression at the end of the three last decompression stops (experimental group), or without such recompression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

Conclusions

- Theoretical reductions in saturation times of up to 63% with lower decompression stress using Intermittent Recompression and Exercise (IRECM) have been demonstrated
- Intermittent recompression has been shown to decrease decompression stress in humans and animals.
- Exercise during enriched 02 breathing with no tissue supersaturation has been shown to decrease decompression stress and time.
- Further research is needed to characterize and optimize these combined countermeasures across a wider range of depths and practical operational conditions
- These countermeasures offer significant safety, operational and economic advantages
- Laboratory validation trials should precede operational implementation.

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Exercise Prebreathe with Ambulatory and Non-Ambulatory Subjects

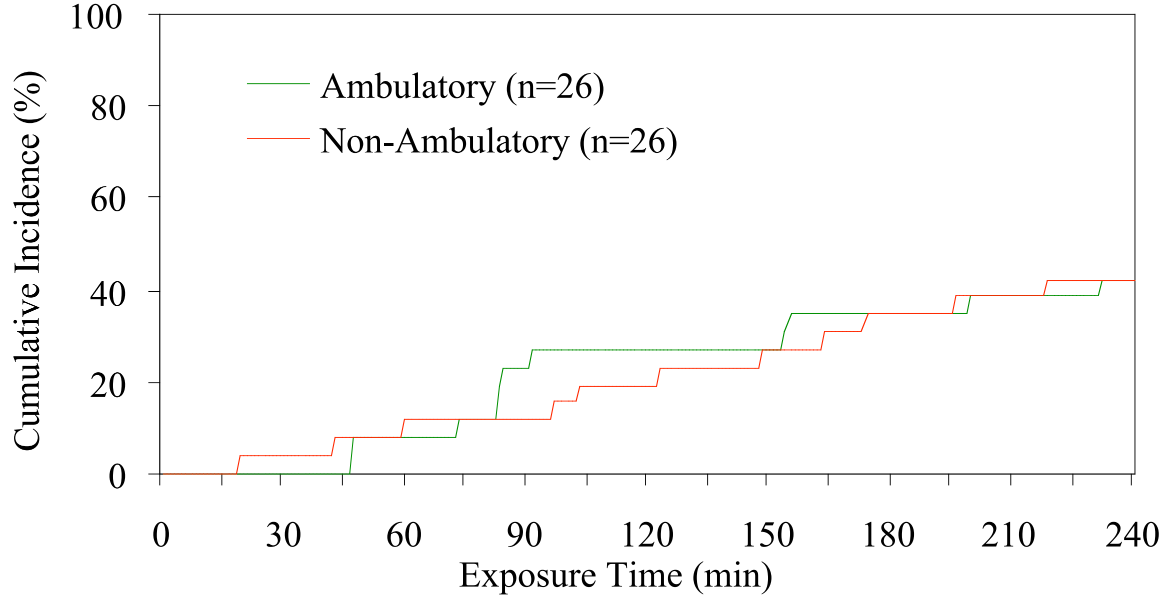
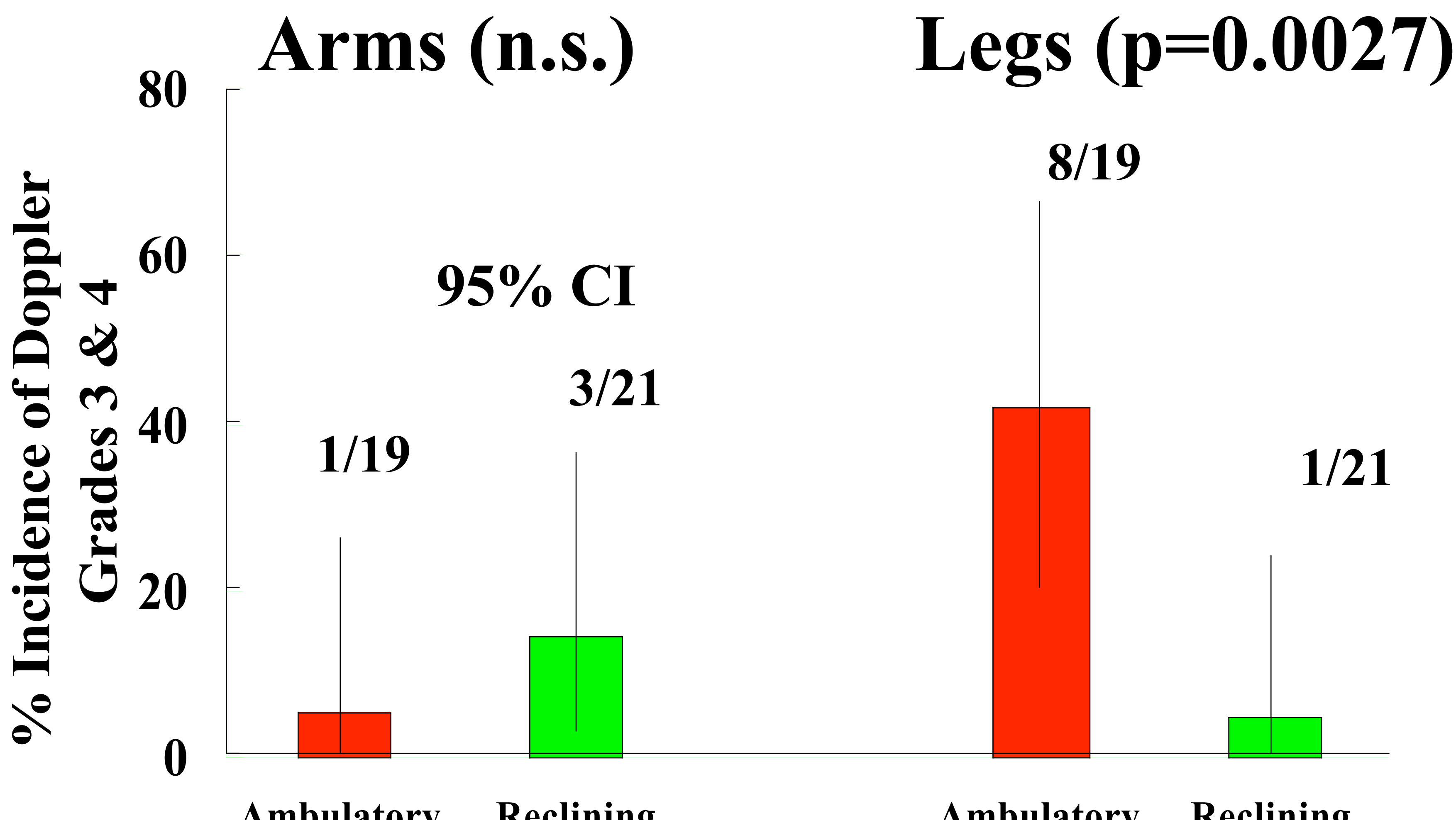
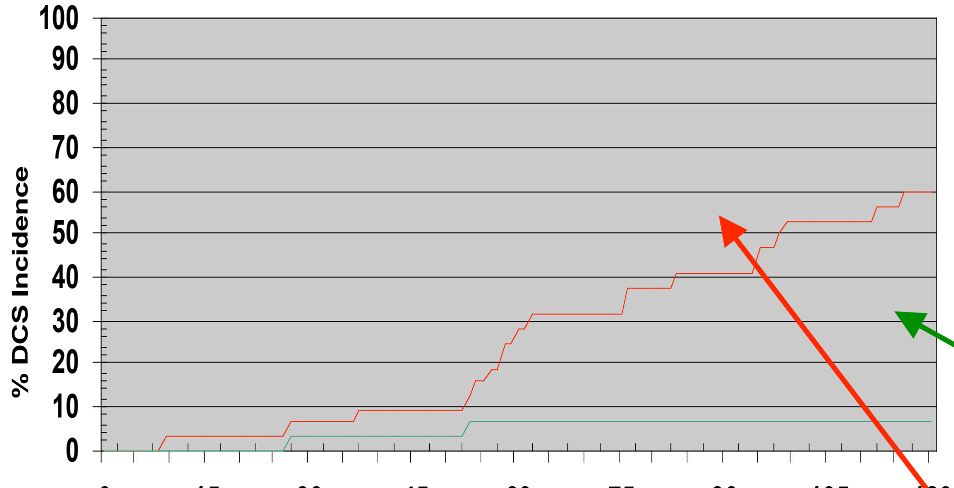


Figure 6. DCS in one hour 02 prebreathe with 10 minutes high intensity exercise- Ambulatory and Non Ambulatory subjects.

VGE & Micro-gravity simulation (Duke)

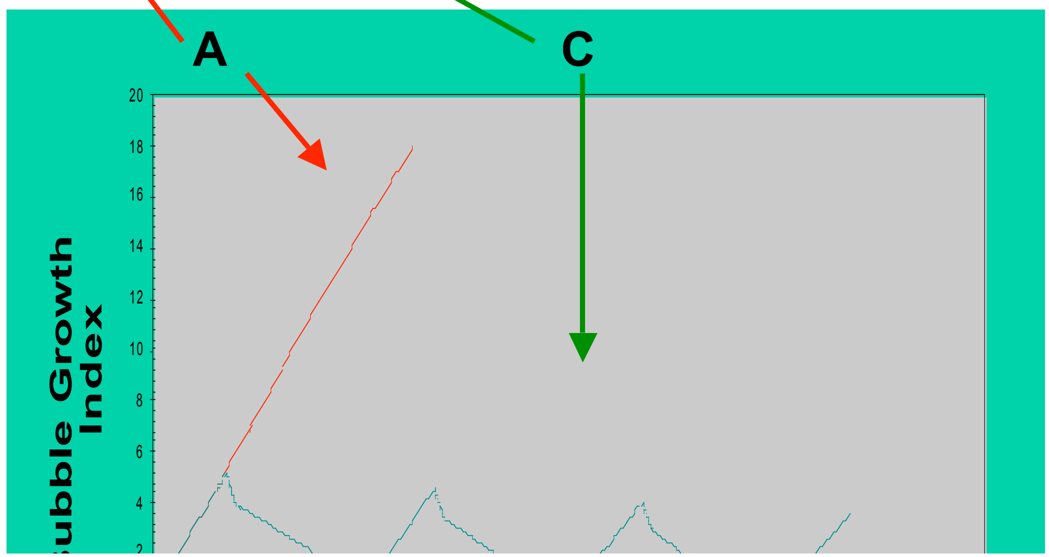


Intermittent Recompression



Kendall's coefficient of concordance (tau-b) between nonparametric cumulative hazard function values and the bubble growth index (BGI) was high (Kendall's tau-b=0.80, p<0.0001) (profiles A,B and C combined), indicating that the increased BGI is strongly associated with increased risk of differences in DCS incidence in each profile.

To the specific impact of BGI on DCS risk, a Cox proportional hazard model (4,5) was fit to the data to test the null hypothesis: "BGI has no effect on the hazard function." We estimated that the hazard for DCS increases by a factor of about 1.58, (95% confidence interval (0.98-2.58) for each unit increase in BGI. Standard errors were adjusted (robust estimation methodology [6]) to account for 32 people performing three separate profiles vs. 96 separate observations



Intermittent Recompression, Bubble Model incorporating Hills assumption of profuse tissue bubble nucleation

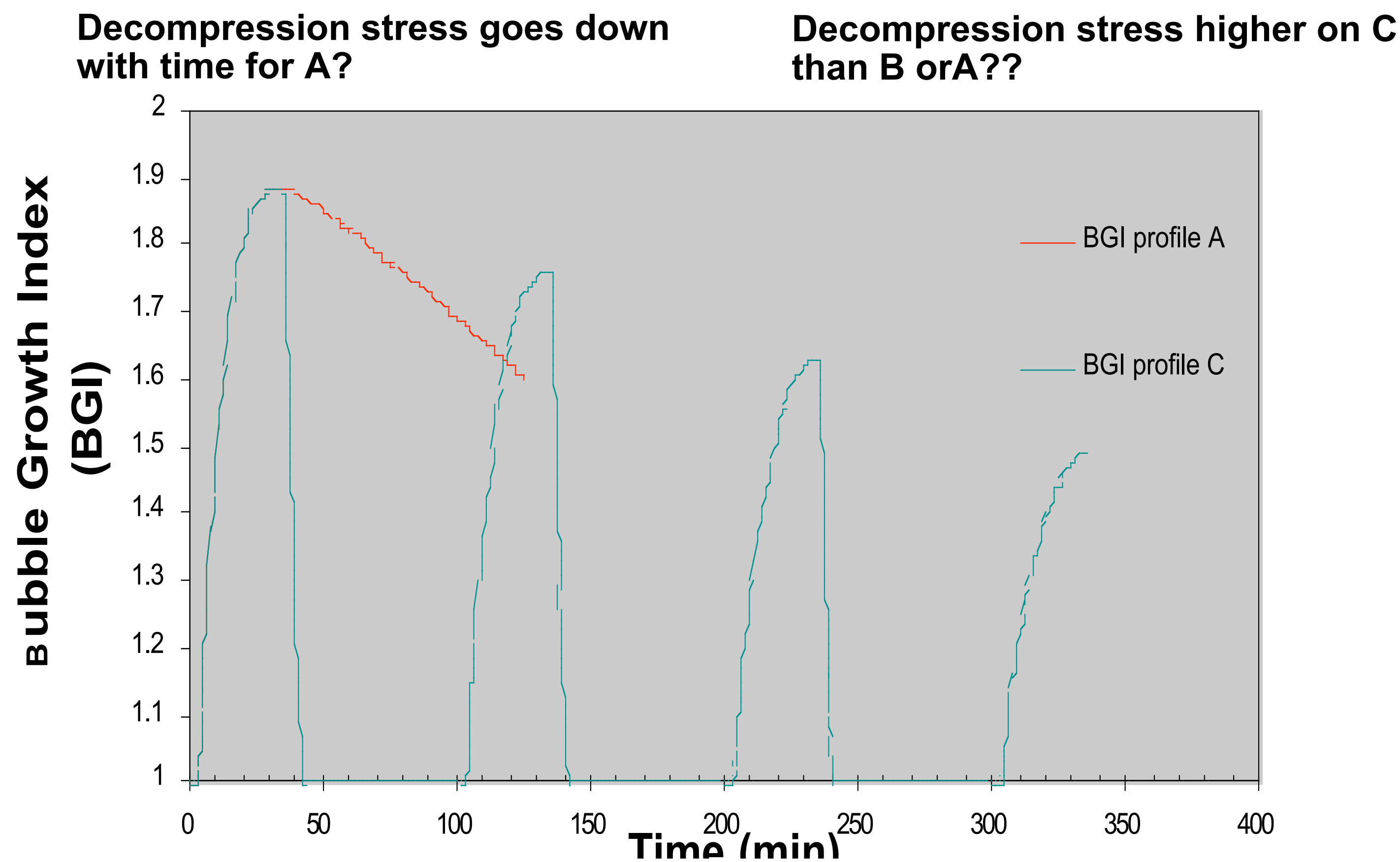


Fig. 4. Exposures A,C with high tissue bubble density and mass balance.

Tissue Bubble Dynamics Model (TBDM)

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r = Bubble Radius (cm)
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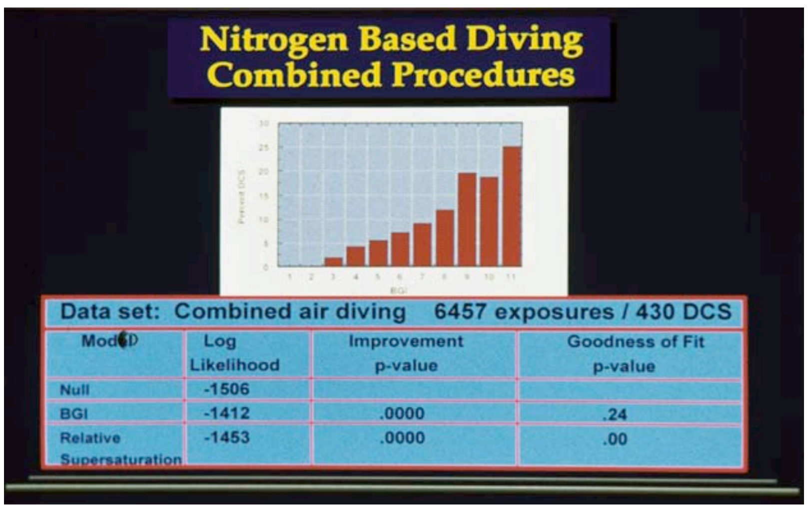
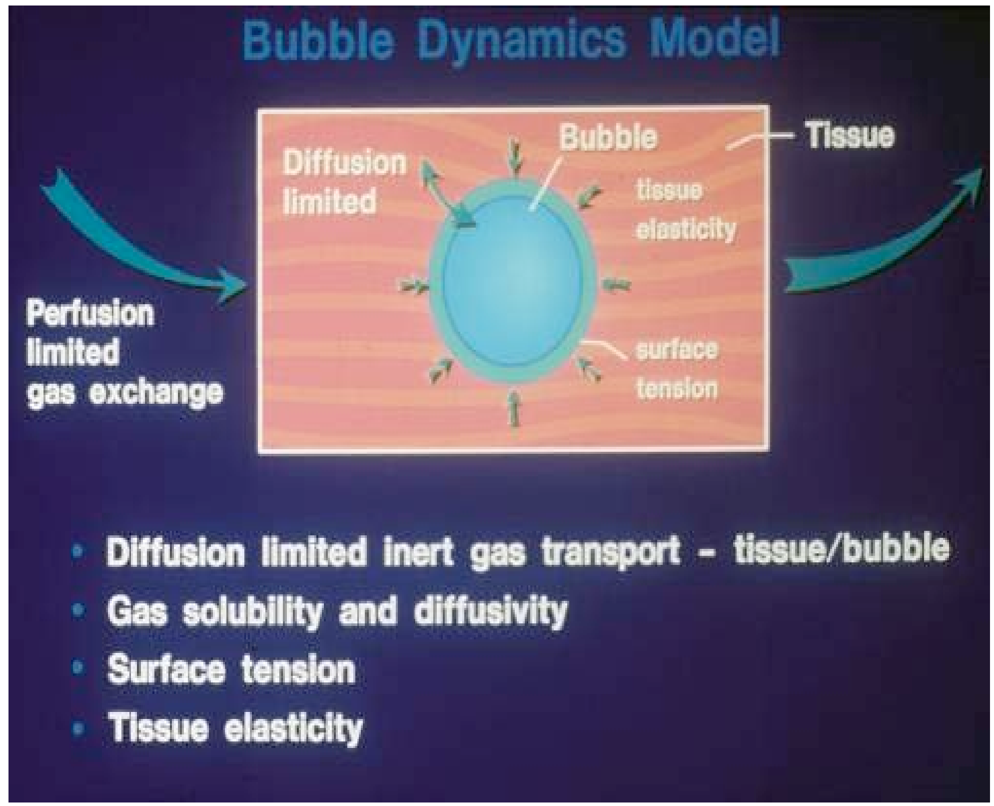
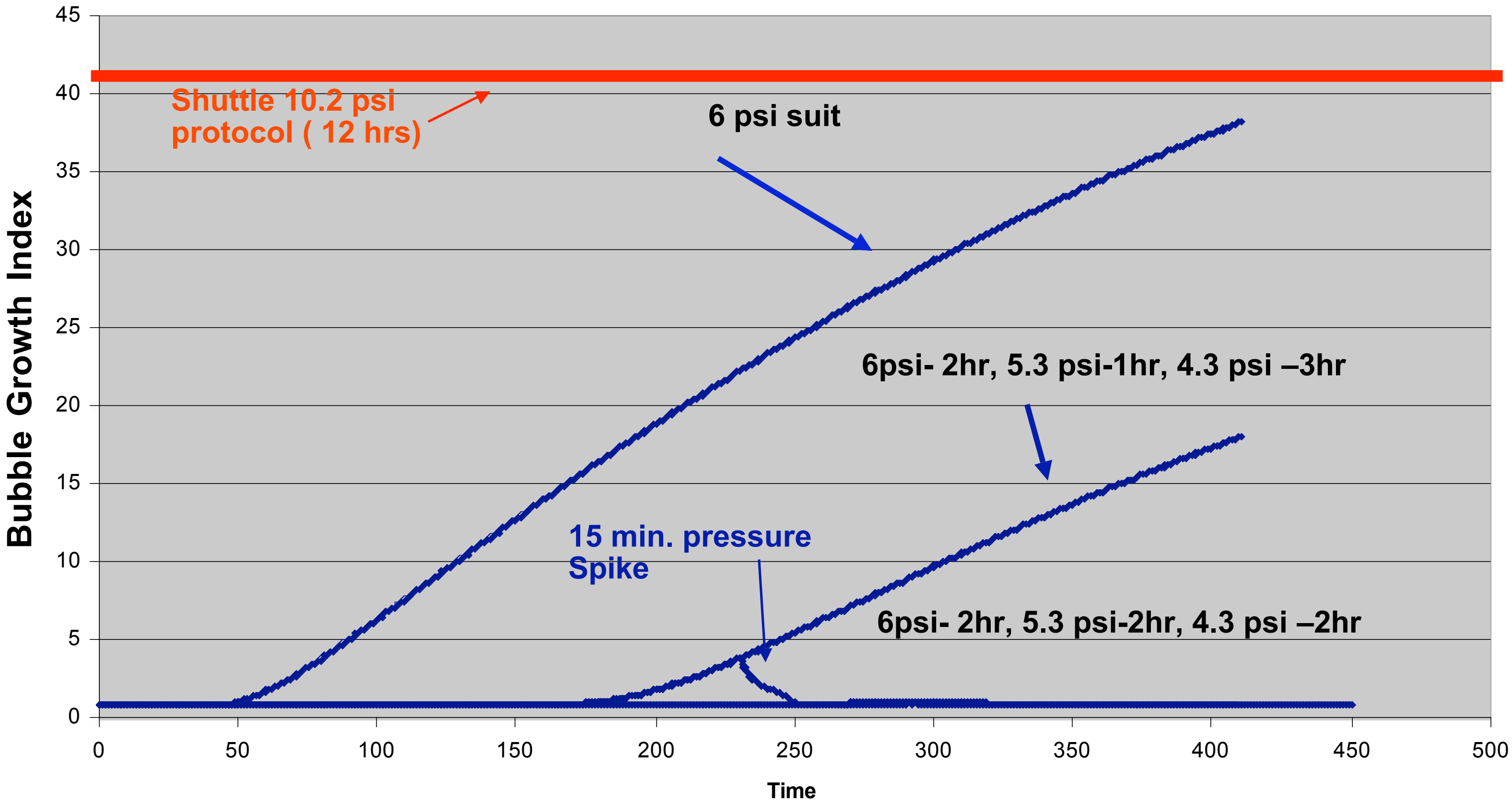




Tissue Bubble Dynamics Model (TBDM) Implications for Variable Pressure Suits

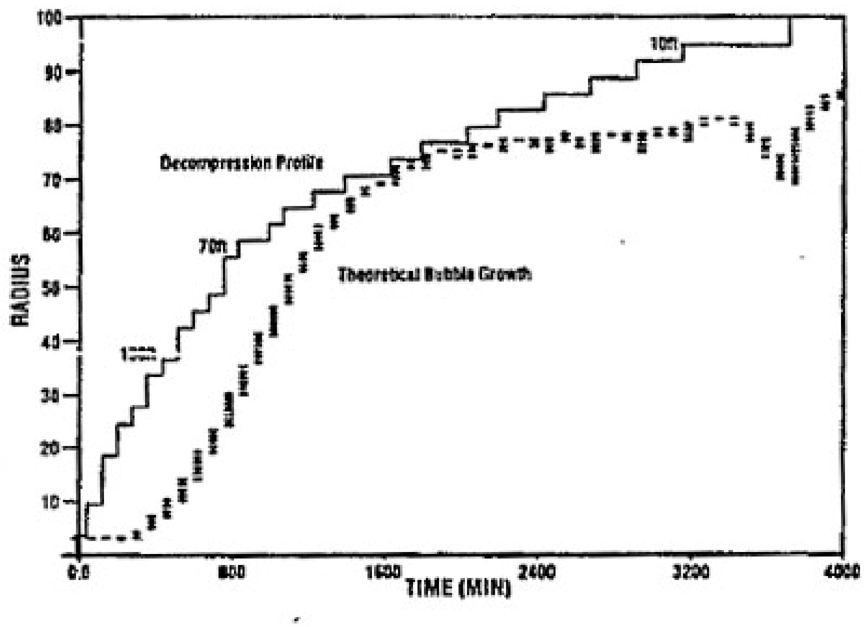
4.3 psi variable pressure suit from 9.5 psi, 30% 02 Habitat

all options have 45 minute prebreathe (use 360 minute half-time tissue with metabolic gases)

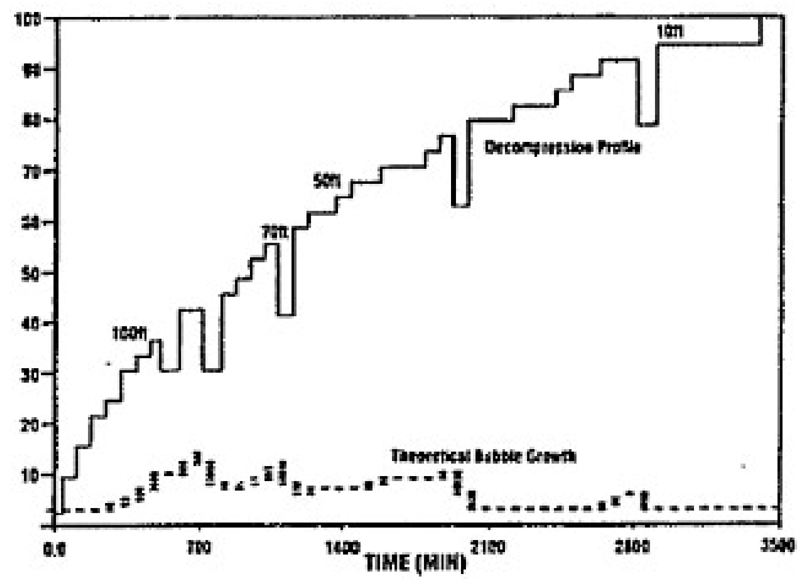


Intermittent Recompression from 165 FSW Nitrox Saturation Dive

A.



B.

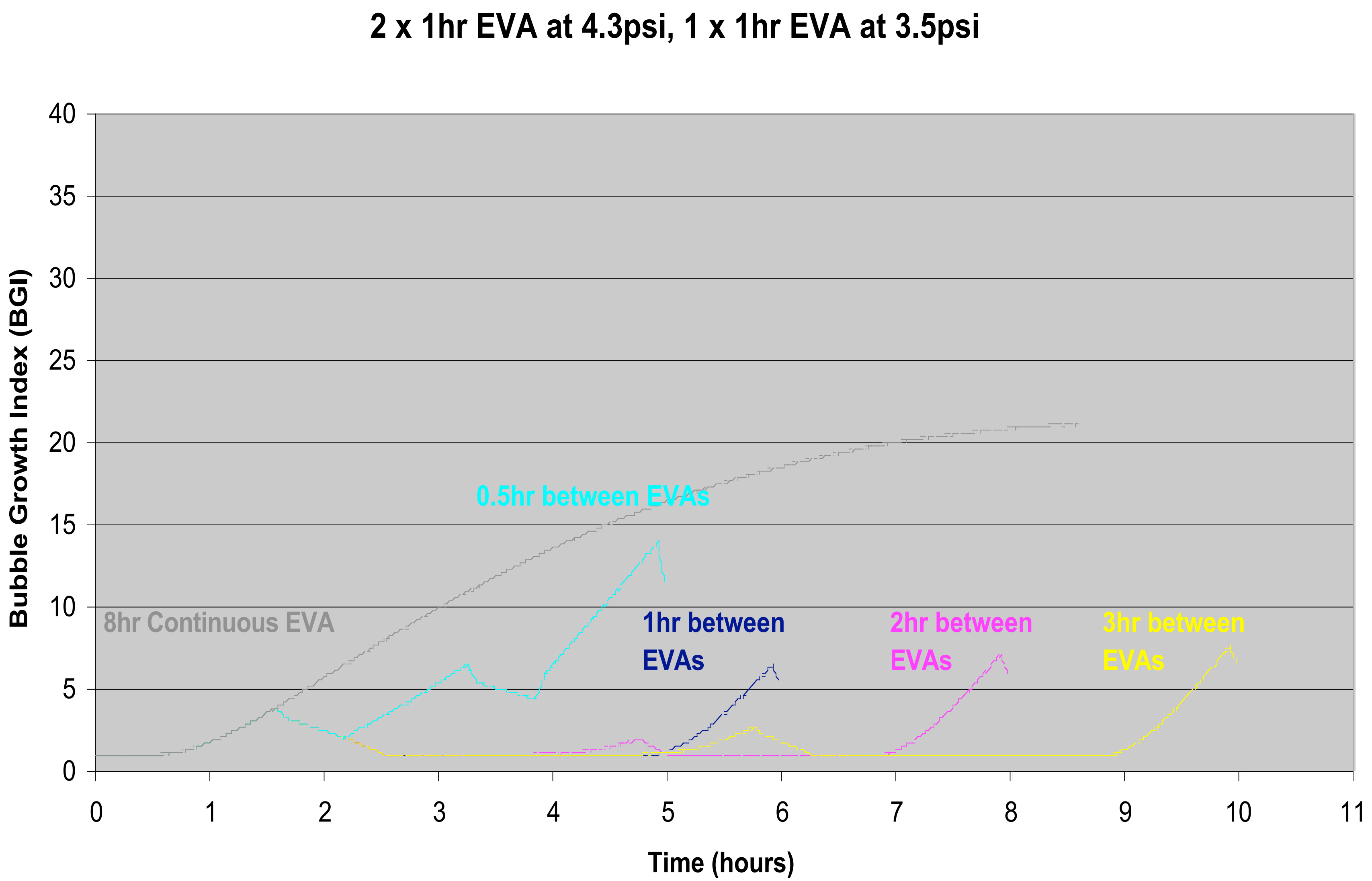


A. 10 divers saturated (165 FSW) on Nitrox and decompression on experimental staged protocol (pp02=.5 ATA) to 45 FSW, then switched to air for remaining decompression (7). (Peterson)

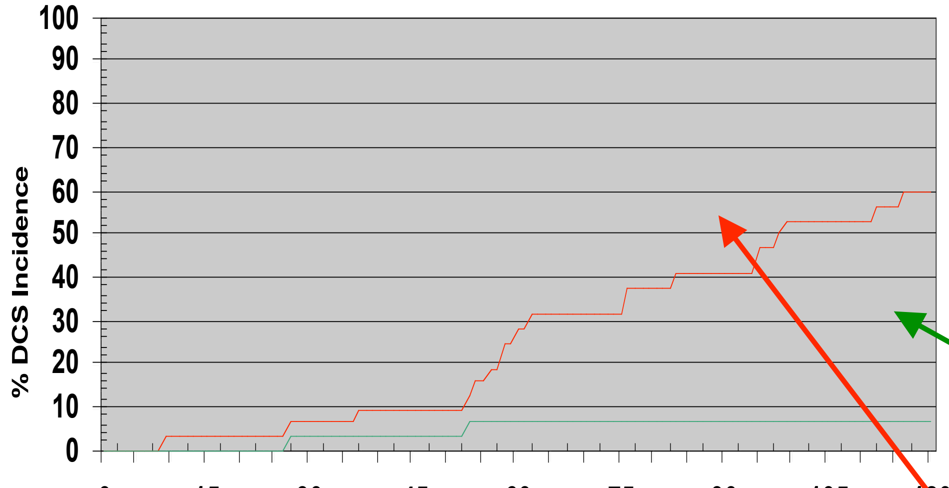
50% DCS with the 4000 minute protocol. Protocol modified to 7000 minutes (4.86 days) for operations

B. Theoretical advantage of intermittent recompression in 3500 minute protocol (2.43 days)

Variable Pressure EVA - lower suit pressure and less decompression stress



Intermittent Recompression



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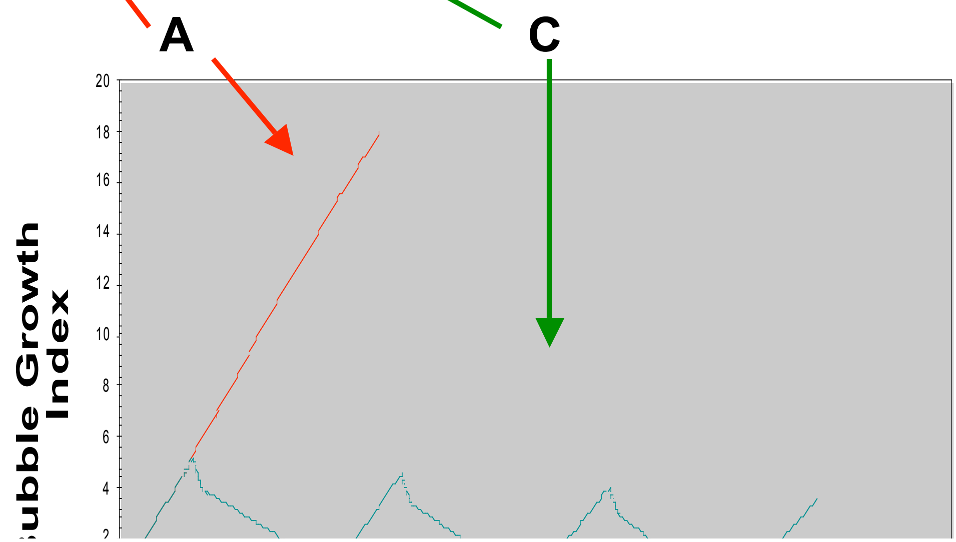
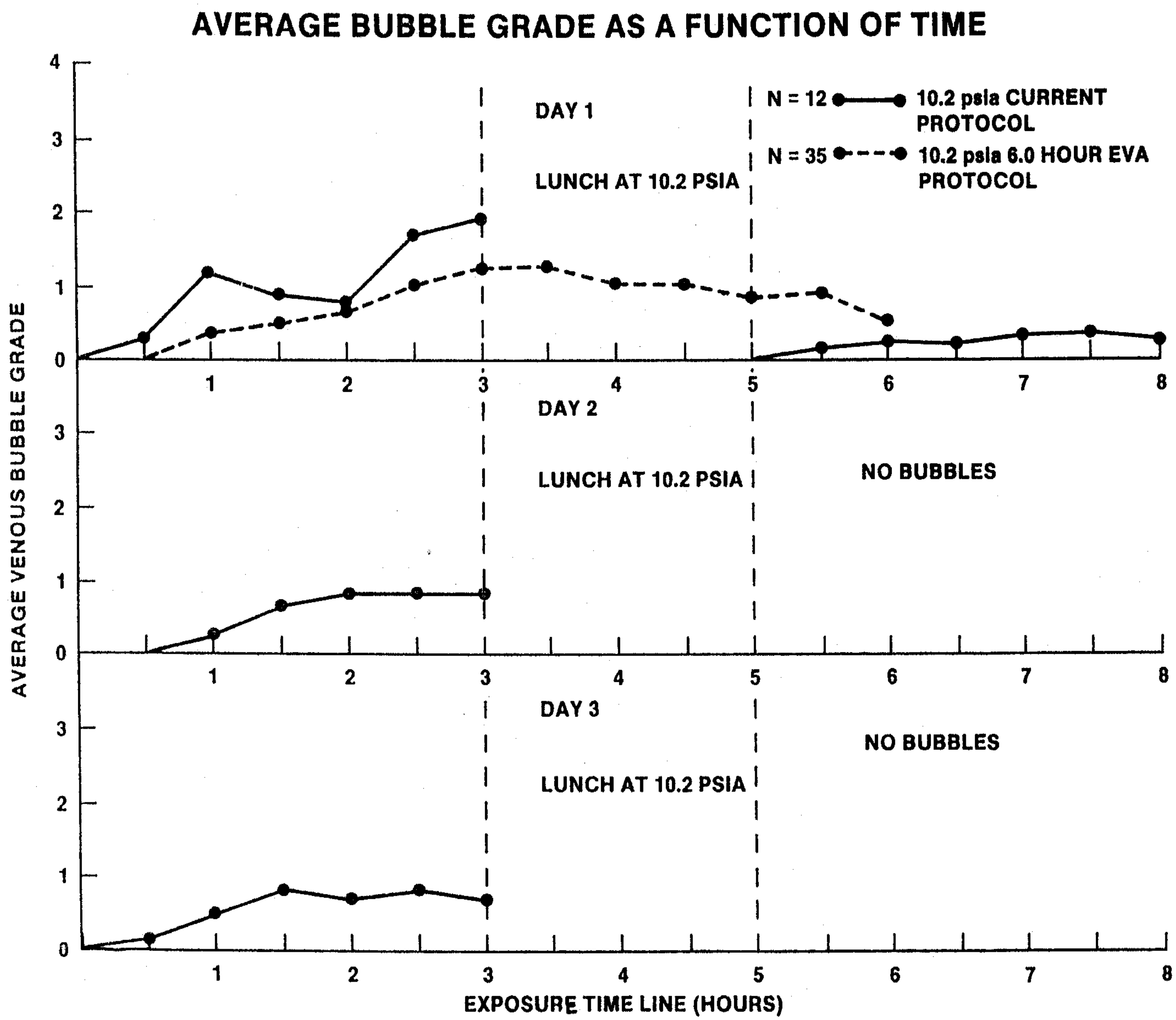


Repetitive EVAs



DCS and VGE incidence from repetitive EVA exposure

		First 3 hr test at 4.3 psia				Second 3 hr test at 4.3 psia		
	TR360	**DCS**	**VGE**	**Grades**	**TR360**	**DCS**	**VGE**	**Grades**
Day 1	1.68	1/12	7/12	2,2,3,4, 4,4,2	1.12	0/12	2/12	4,1
Day 2	1.37	0/12	4/12	3,3,2,4	0.95	0/12	0/12	all 0
Day 3	1.35	0/12	4/12	3,3,2,4	0.94	0/12	0/12	all 0

Unlike repetitive diving repetitive EVA results in lower decompression stress