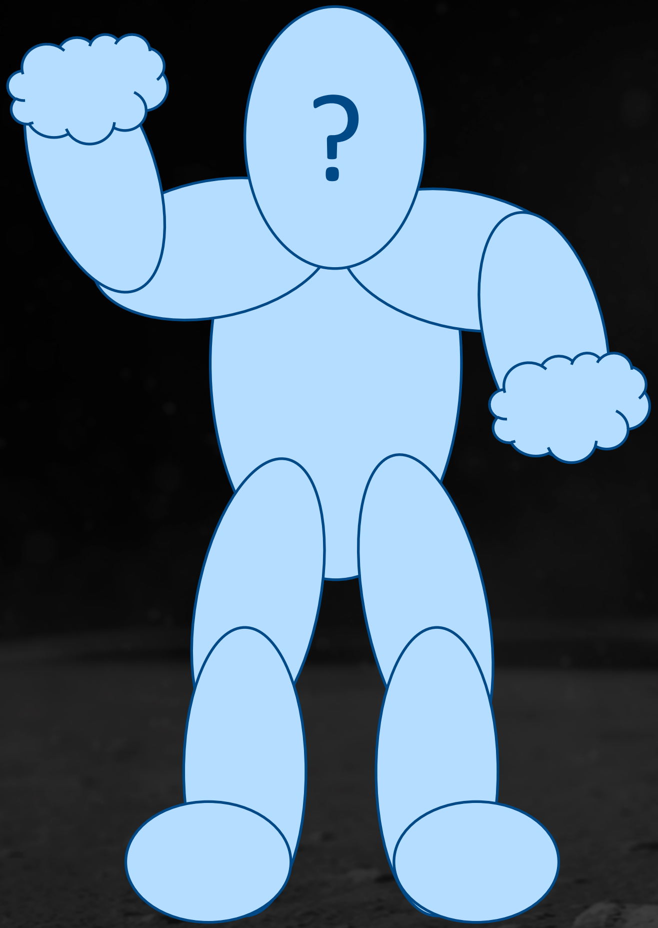
Variable Pressure Spacesuits and Human Performance Implications

Spaceflight Human Optimization and Performance (SHOP) Summit

April 17-19, 2024

Jason Norcross

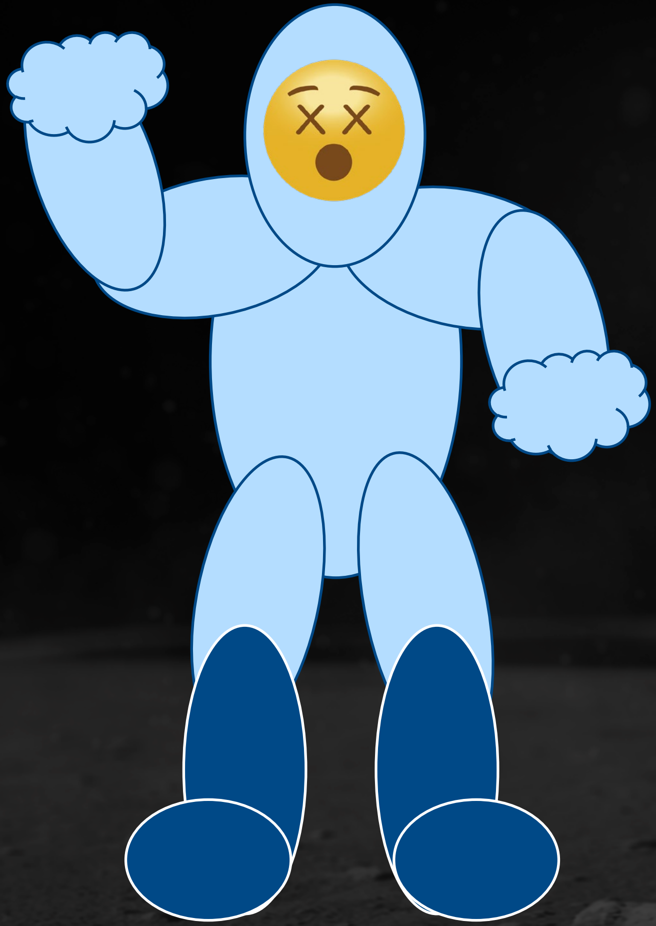
Suit Pressure Selection – Where to Start?



What is the minimum suit pressure?

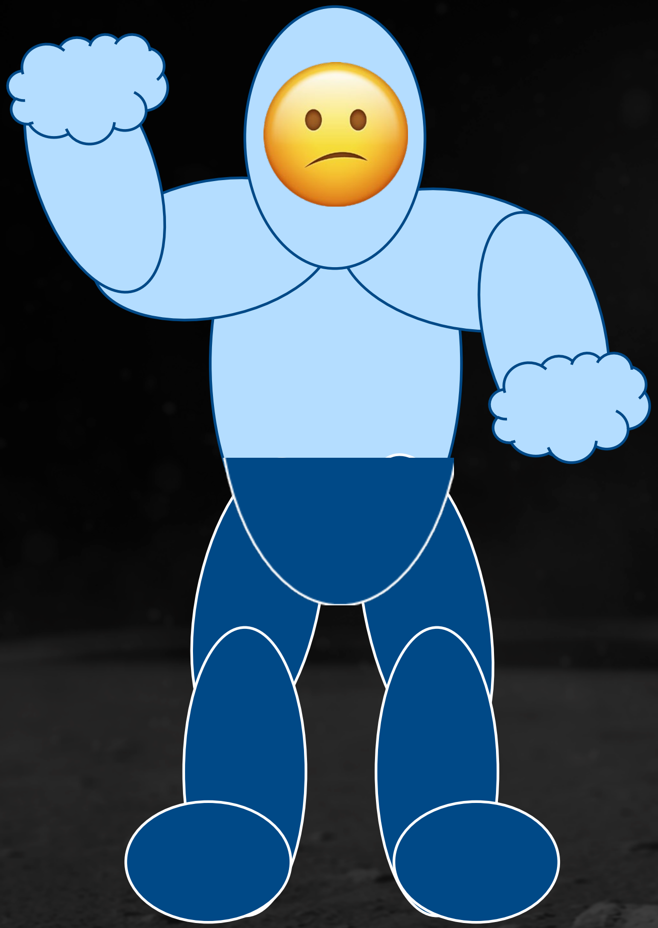
All Pressures assume >95% O_2

Suit Pressure Selection



> 1.0 PSI prevents Ebullism

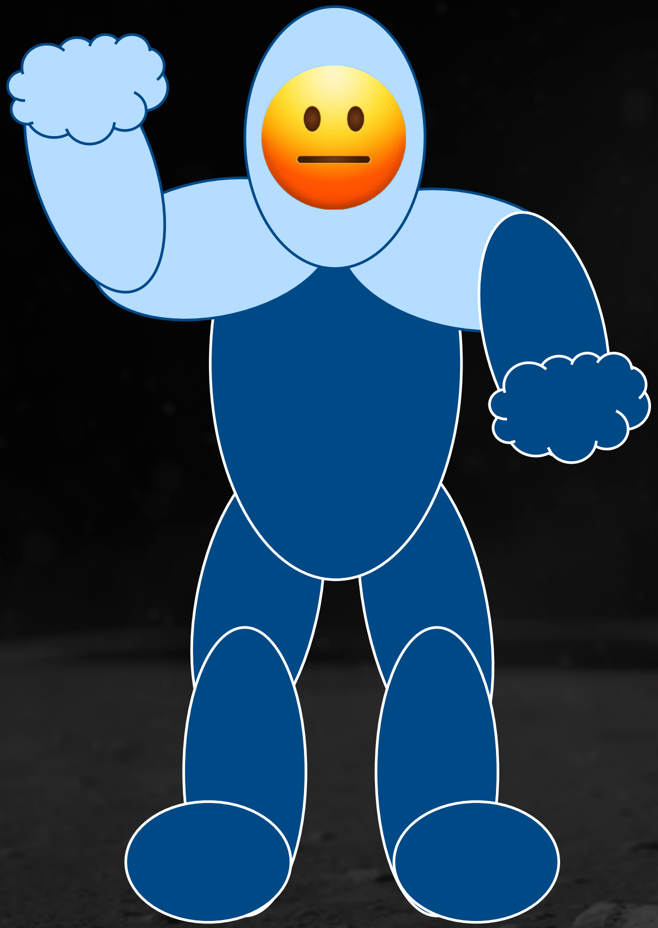
Suit Pressure Selection



> 2.2 PSI allows ~ 30 min TUC
> Avoids Life Threatening Hypoxia

> 1.0 PSI prevents Ebullism

Suit Pressure Selection

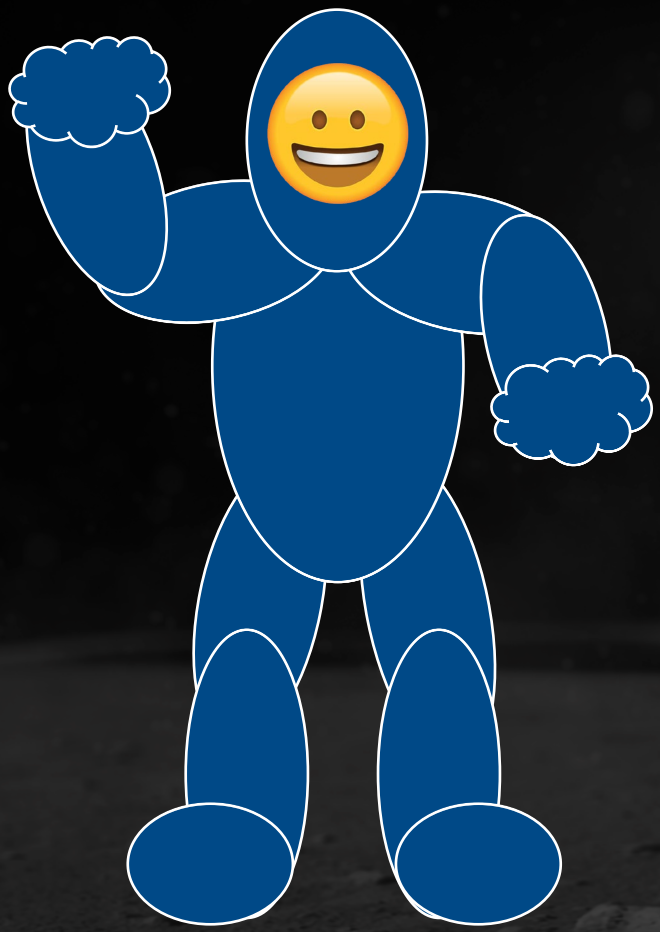


> 3.2 PSI avoids Severe Hypoxia

> 2.2 PSI allows ~ 30 min TUC
Avoids Life Threatening Hypoxia

> 1.0 PSI prevents Ebullism

Suit Pressure Selection



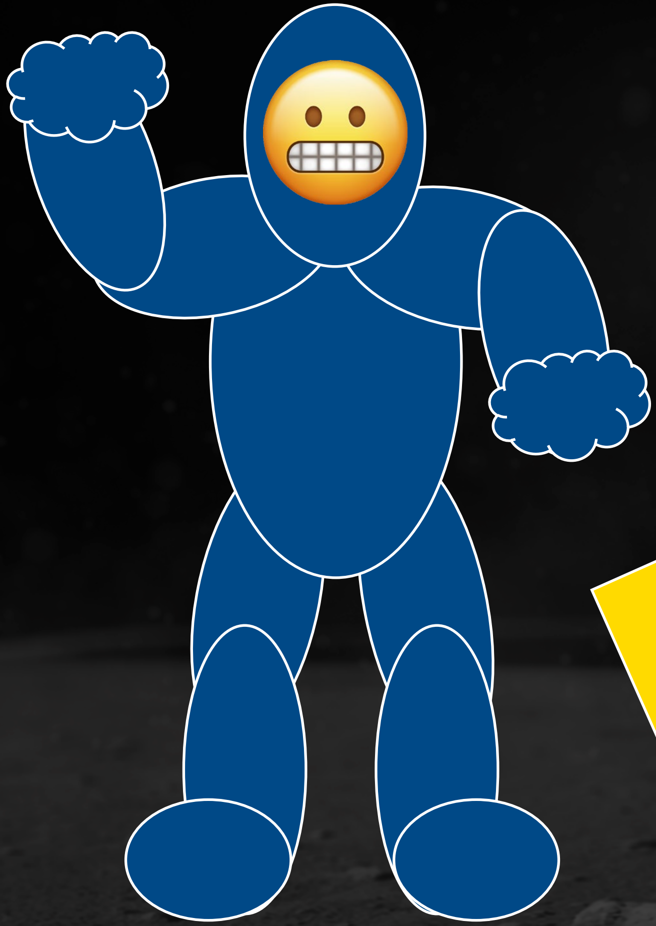
> 4.1 PSI provides Normoxia

> 3.2 PSI avoids Severe Hypoxia

> 2.2 PSI allows ~ 30 min TUC
Avoids Life Threatening Hypoxia

> 1.0 PSI prevents Ebullism

Suit Pressure Selection



> 4.1 PSI provides No

> 3.2 PS

0 min TUC

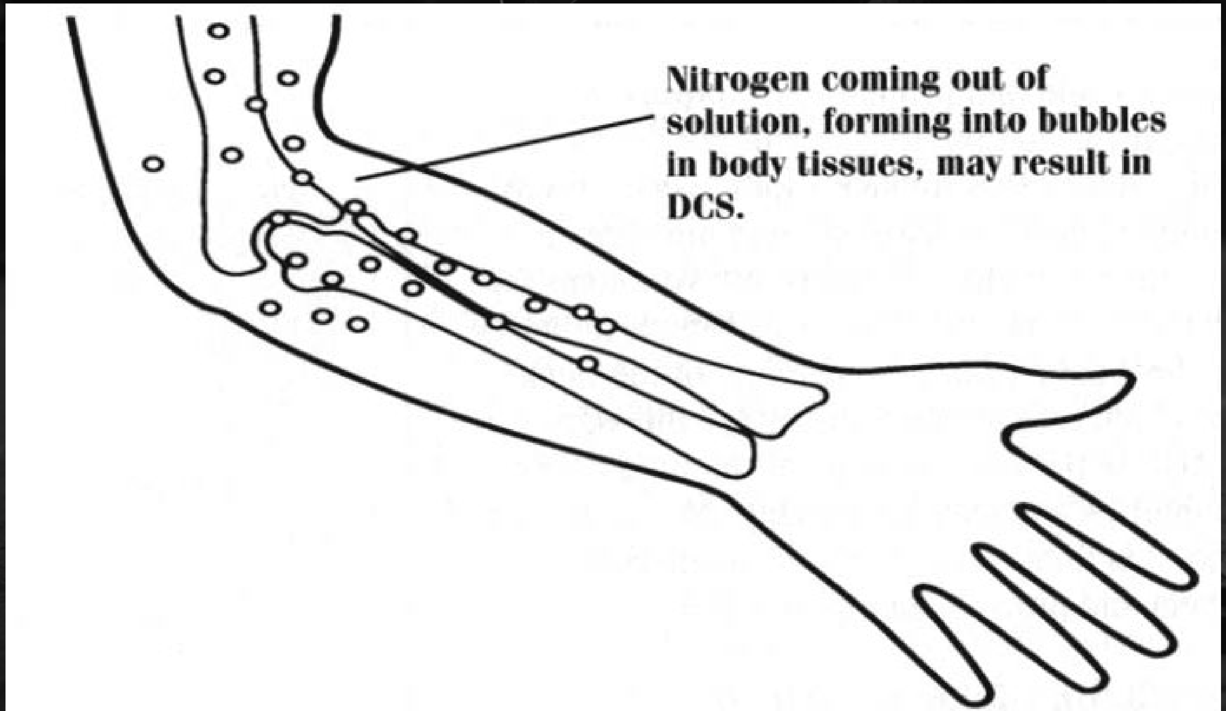
reatening Hypoxia

> 1.0 PSI prevents Ebullism

None of these pressures address decompression sickness (DCS)

What is DCS?

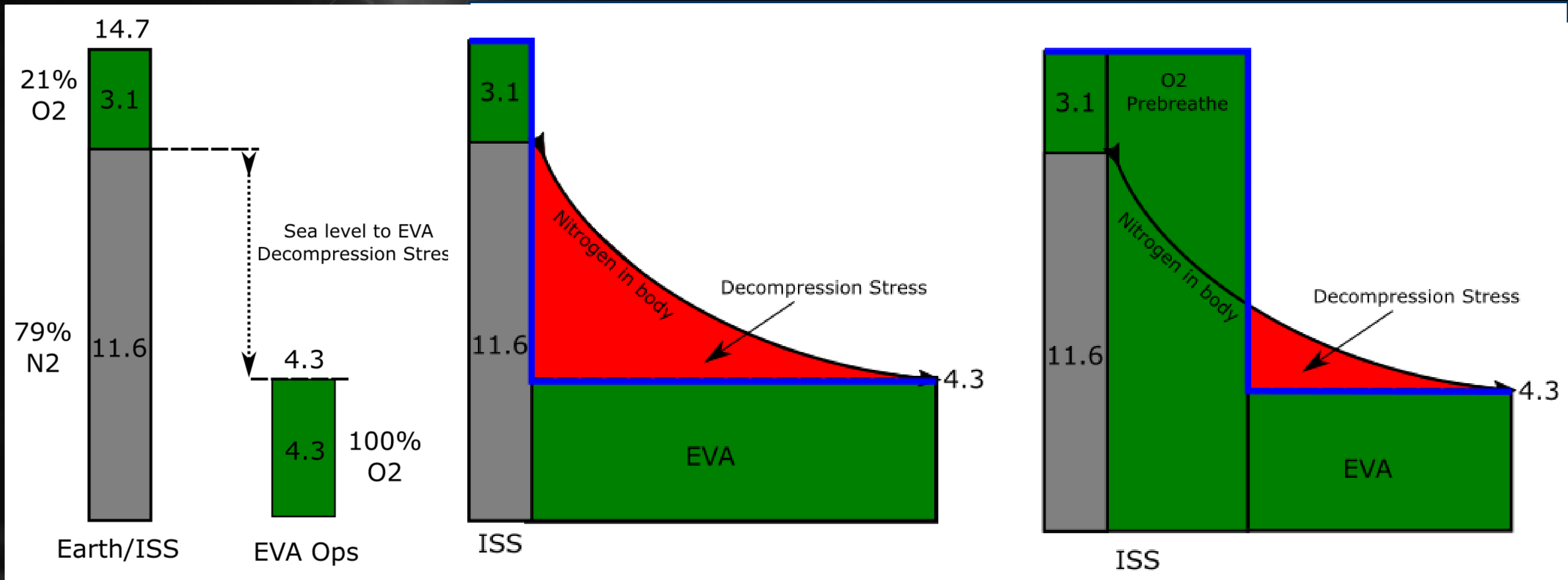
- Decreasing ambient pressure causes a release of nitrogen dissolved in tissues which may result in bubble formation and DCS
  - **Venous Gas Emboli (VGE)** are "silent bubbles" (no symptoms or clinical findings) that can be detected by Doppler; Grade IV VGE is the most severe form and is correlated with risk of DCS
  - **Mild Type I DCS:** Joint pain; single extremity tingling or numbness; mild skin symptoms
  - **Serious Type II DCS:** Central neurological or cardiopulmonary symptoms; can be life-threatening



Conditions for Decompression Sickness (DCS)

- ❖ Decrease in Pressure
- ❖ Change in Phase State

- ❖ Supersaturation
  - Tissue pN2 > Ambient Pressure



- ❖ High workload/ambulation = higher risk
- ❖ Too much bubbling: Decompression Sickness
  - Type I DCS: Mild/Joint pain
  - Type II DCS: Severe/life threatening
  - Any DCS = loss of EVA objectives

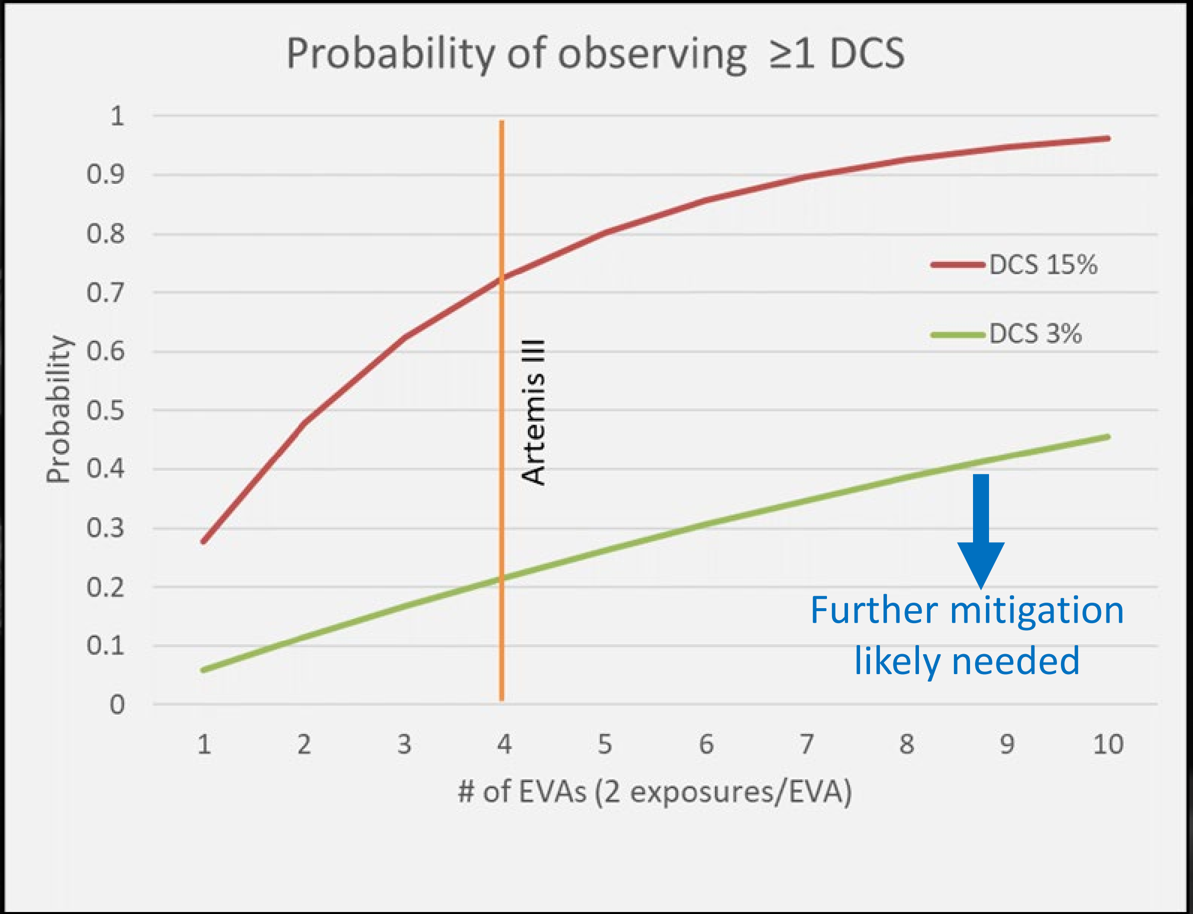
DCS is Both a Health and Mission Risk

- Overarching medical and operational philosophy is that it is always better to **prevent** DCS than to treat DCS
- Mission Risk - DCS symptoms would most likely occur during an EVA and result in EVA termination, additional crew time/resources to treat DCS, and subsequent loss of mission objectives

Artemis Mission Impacts from DCS

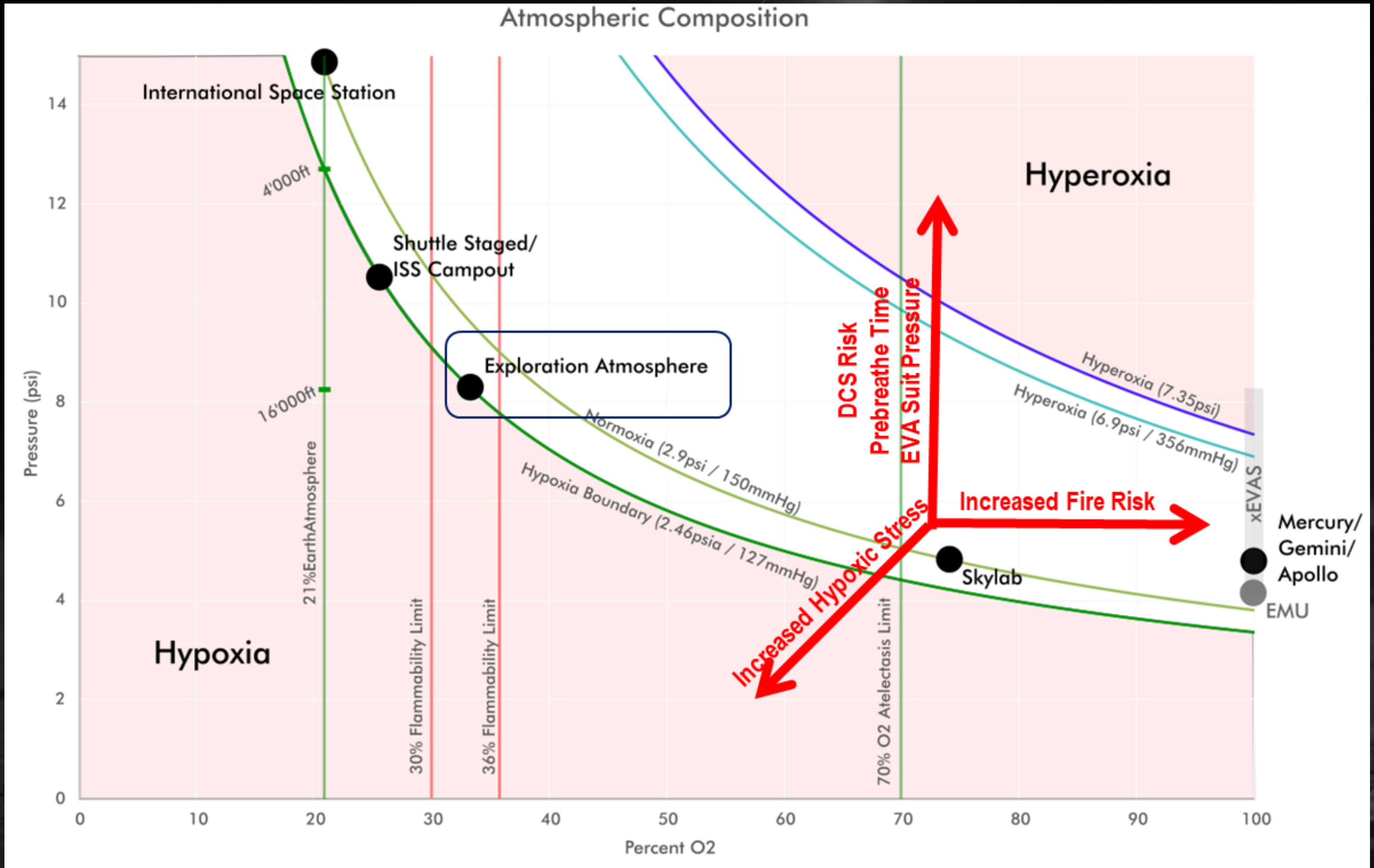
- Ground-based study estimates:
  - Exp Atm testing is aiming for success with minimum prebreathe and heavy EVA simulation
  - ~3% per person per EVA risk for 2 crewmembers, across 4 EVAs is ~22% chance for mission
- Type I DCS hit requires 24-hr downtime after successful treatment for
  - Evolved gas phase resolution
  - Secondary tissue injury recovery
- Two Type 1 DCS hits or a Type II DCS hit would end the EVA portion of the mission

Artemis mission success likely requires a very low per EVA DCS risk, but this must be balanced against the costs to further reduce the risk



Step 1 – Cabin Atmosphere Selection

- Exploration Atmosphere Working Group[1,2] suggested 8.2psia / 34% O_2 environment
  - Compromise between **flammability, hypoxia, DCS risk, prebreathe time** – but forward work not funded



[1] *Recommendations for Exploration Spacecraft Internal Atmospheres: The Final Report of the NASA Exploration Atmospheres Working Group. NASA/TP-2010-216134*

[2] *Norcross J, Norsk P, Law J, Arias D, Conkin J, et al. Effects of the 8 psia / 32% O2 Atmosphere on the Human in the Spaceflight Environment. NASA/TM-2013-217377*

Cabin Atmosphere and Suit Pressure History

Apollo

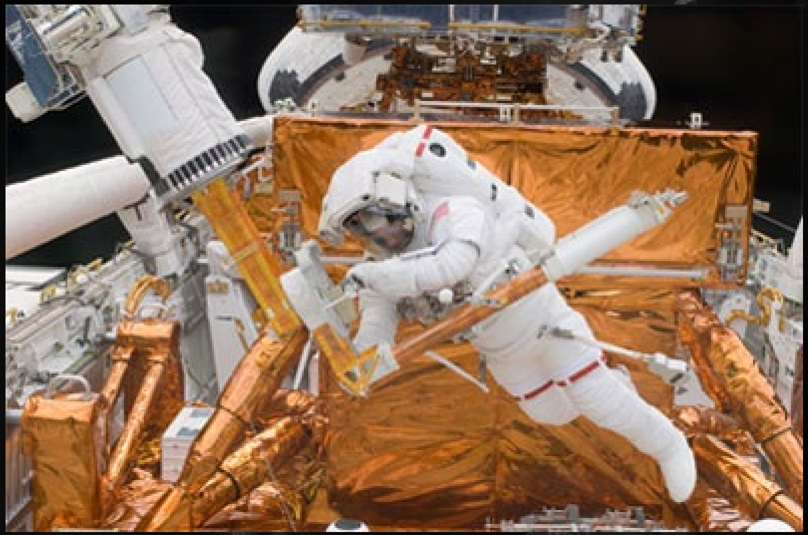
14.7 psia / 21% O_2 on Pad
3-hr PB on launch pad

*DCS Experienced Here

5 psia / 100% O_2 Cabin
3.7-4.0 psid suit pressure

- Minimum pressure to avoid hypoxia
- *No Nitrogen = No PB*

Shuttle



14.7 psia / 21% O_2 Cabin
Suit pressure increased to 4.1-4.3 psid
4-hour pre-EVA PB required

- Used only 6 times due to crew dislike

Shuttle retroactively certified to
10.2 psia / 26.5% O_2 Cabin
40-70 min in-suit PB pre-EVA

- *Efficient mitigation of DCS risk*

ISS

14.7 psia / 21% O_2 Cabin
Suit pressure kept at 4.3 psid
Hatches open for docked ops

- Same pressure for Shuttle and ISS

Prebreathe Reduction Program (PRP)

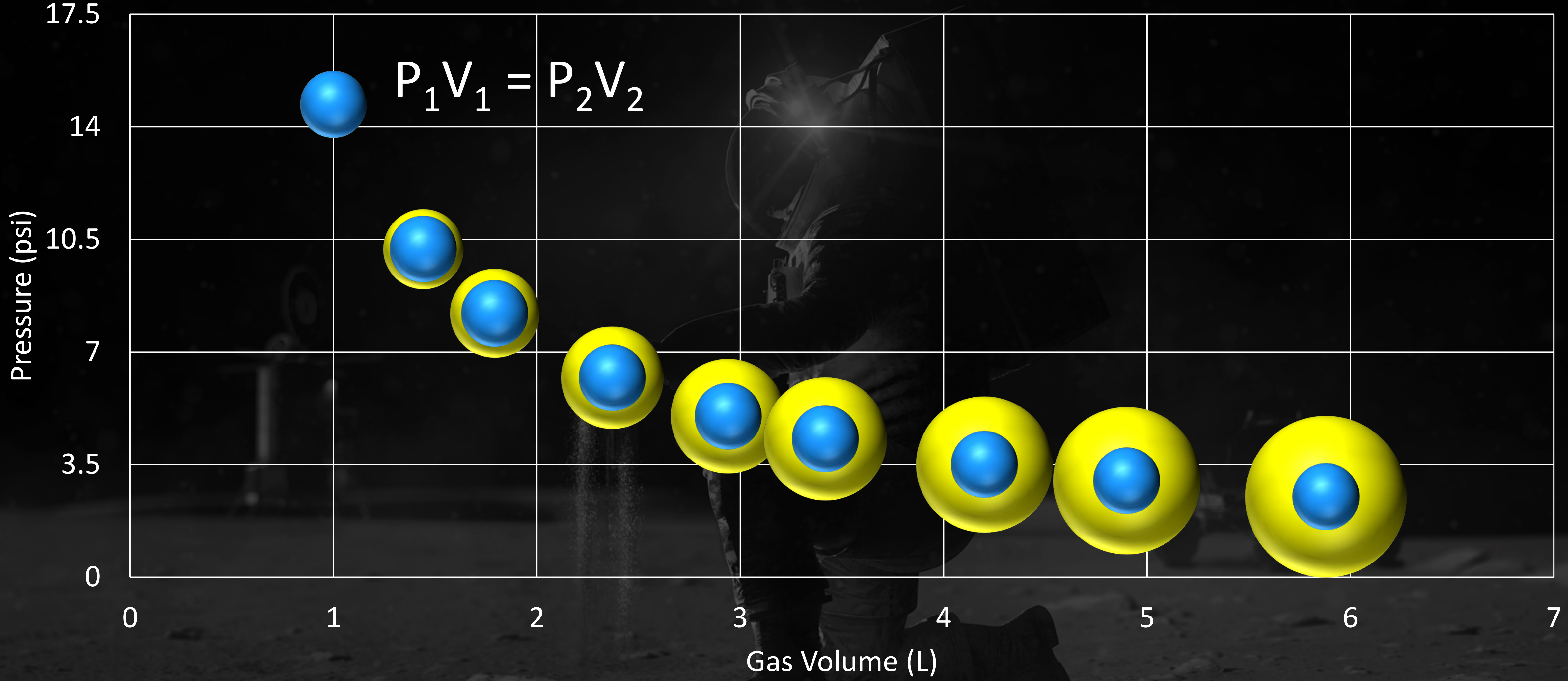
- Exercise (CEVIS), Campout, & ISLE Protocols
- Complex operational protocols require mask PB, airlock isolation, exercise, & ground support
- 5-6 hours total prep time prior to EVA considered acceptable for infrequent EVA

Step 2 – Suit Pressure Options

- NASA has historically used suit pressures between 3.7 and 4.3 psid for all US-led EVA operations – can we go to a higher pressure for Artemis?
  - Maintains normoxic environment
- Increasing the spacesuit pressure can reduce DCS risk and the required prebreathe duration (i.e., more time to explore on the moon)
- Concerns with higher suit pressure:
  - Increased EVA fatigue/mobility risk
    - Higher pressure/volume work
  - Increased consumable use (e.g., power, O_2)
- Current preference: maintain historical **4.3 psi EVA suit pressure**

Credit: Axiom Space
https://www.axiomspace.com/news/axemu-spacesuit-testing

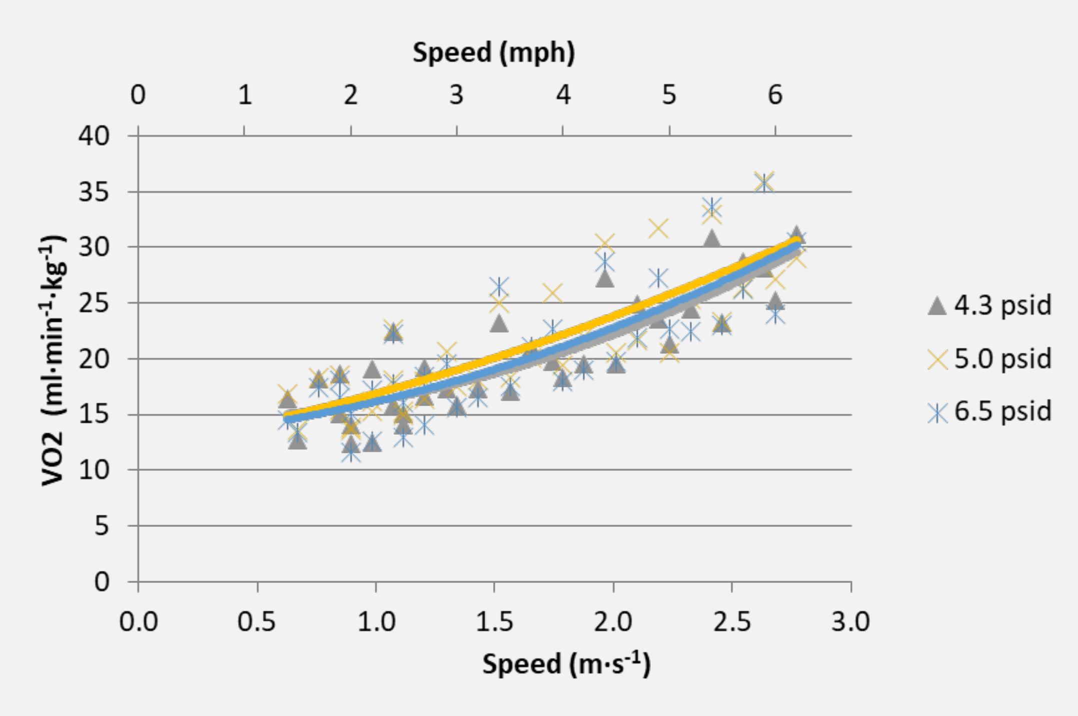
Boyle's Law Instantaneous Gas Volume of 1 Liter



Data with Suit Pressures > 4.3 psid

- Initial studies have shown that metabolic rate is not affected by suit pressures from 4.3-6.5 psid in MKIII suit with treadmill ambulation on POGO[1]
- Short durations at 8.0 psid during Z2 NBL testing provided positive feedback:

  "Test subjects stated that the gloves are the only discernable difference between operating the ZLTA configuration at 4.0 psid and 8.0 psid."
- 15 US crew have performed EVAs (some several) in Russian Orlan Suit at 5.8 psid
- Planetary EVA is full body vs all upper body microgravity EVA
  - Hand/forearm fatigue may be most impacted
  - Crew can be trained to prepare for these impacts
- Data is very limited on human performance implications



2024 Elevated Suit Pressure Testing in Work

[1]NASA/TP-2010-216115

Step 3 – Determine O_2 Prebreathe Duration

Approx. 1hr prebreathe estimated for 5psi suit pressure

No further prebreathe reduction for suit pressure > 5.5psi

Cabin pressure (psia)	Cabin O_2 (%)	P_IO_2 (mmHg)	EAA (feet)	Equilibrium $P_{tis}N_2$ (psia)	Estimated Prebreathe (mins)					
					4.3 psia	4.6 psia	4.9 psia	5.0 psia	5.2 psia	5.5 psia
9.8	28.0	128	4,000	7.05	150	105	65	55	25	0

*ALL SHOWN TIMES ARE UNVALIDATED MODEL ESTIMATES FROM **ONE MODEL**[1]

Note 1: EAA is equivalent air altitude, an indication of hypoxic stress.
Note 2: Computed acceptable probability of DCS [P(DCS)] for a 6-hour ambulatory EVA is approximately equivalent to ExAtm prebreathe protocol.
Note 3: Prebreathe time (min) is from end of purge to start of EVA at indicated suit pressure.
Note 4: Entire EVA is performed at indicated suit pressure.

[1] Conkin J, Kumar KV, Powell MR, Foster PP, Waligora JM. A probability model of hypobaric decompression sickness based on 66 chamber tests. *Aviat Space Environ Med* 1996; 67:176-83.

Atmospheric Impacts on Suit Pressure & PB Time (estimated)

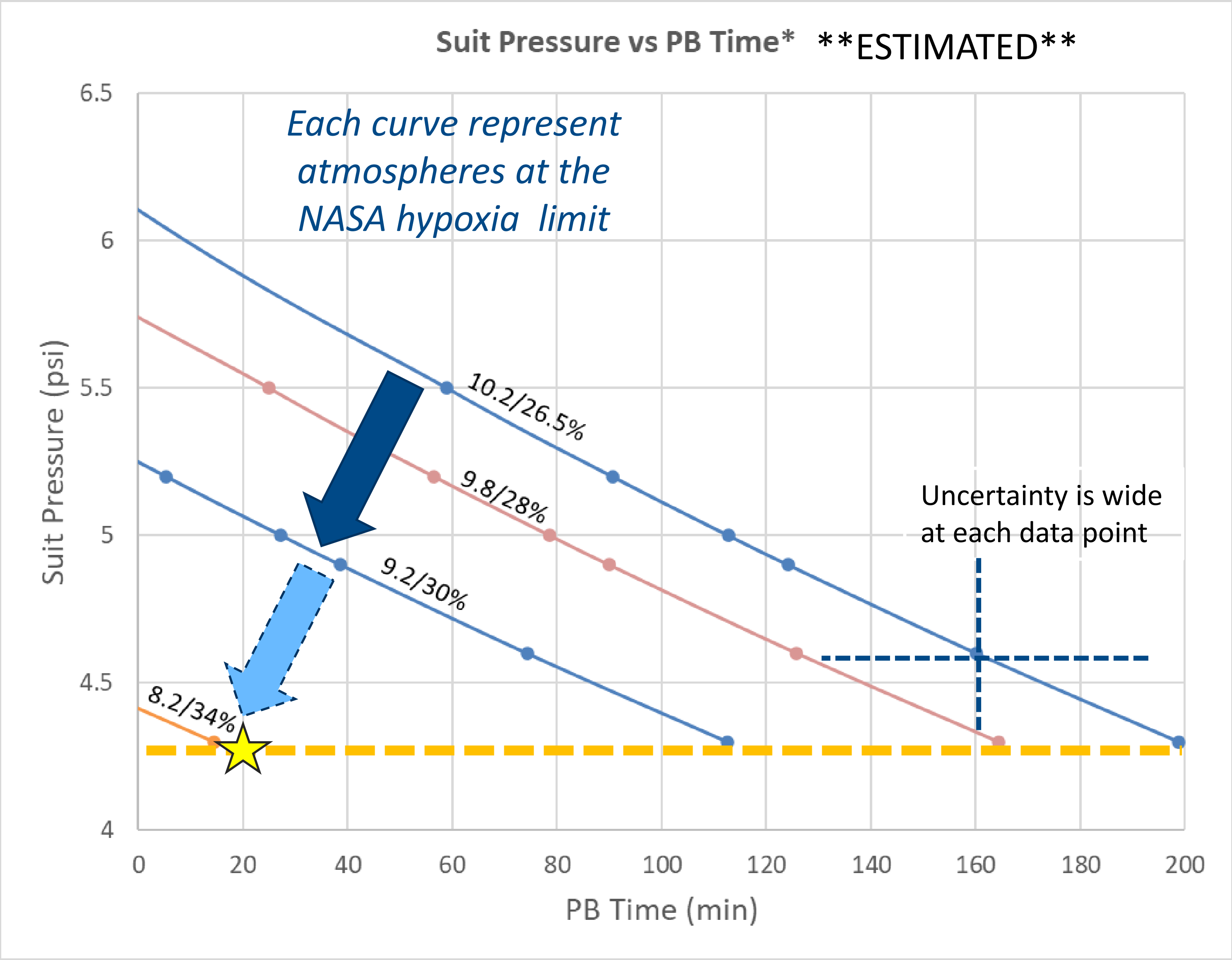
- Model* estimates to achieve 3% per person per EVA DCS Risk

Any movement toward the origin

- optimizes timeline efficiency
- minimizes consumables
- decreases human workload

Every incremental increase in O_2% drives us down and left towards less suit pressure and shorter prebreathe duration

★ Validated test point



*Conkin, J., Probability of Decompression Sickness and Venous Gas Emboli from 49 NASA Hypobaric Chamber Tests with Reference to Exploration Atmosphere,2020 NASA/TP-2020-220529
https://ntrs.nasa.gov/api/citations/20200004317/downloads/20200004317.pdf

Summary

- Suit pressure must first be sufficient to address hypoxia and sustain life
- But this minimum pressure will not address DCS
  - DCS is both a health and operations concern
- DCS should first be mitigated by engineering solutions including lowering N_2 cabin atmosphere to avoid human performance impacts
- Increasing suit pressure can greatly impact DCS risk and/or reduce necessary O_2 prebreathe time
  - BUT
- Human performance implications (workload, fatigue, injury risk) of operating at higher suit pressures are not well characterized

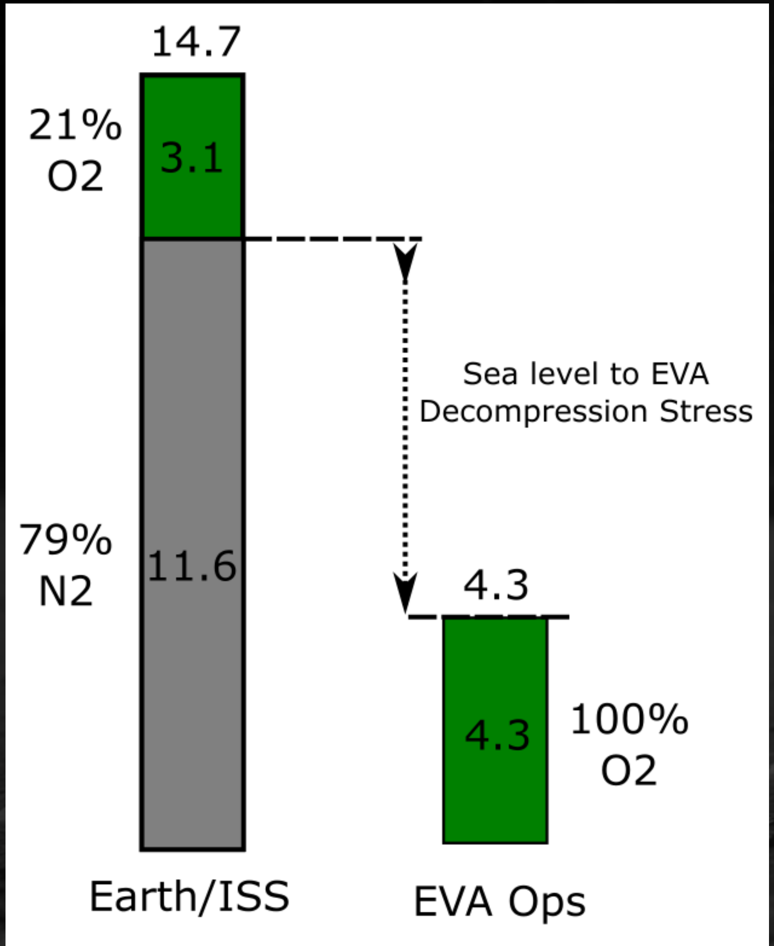
H3PO
HUMAN PHYSIOLOGY, PERFORMANCE, PROTECTION & OPERATIONS

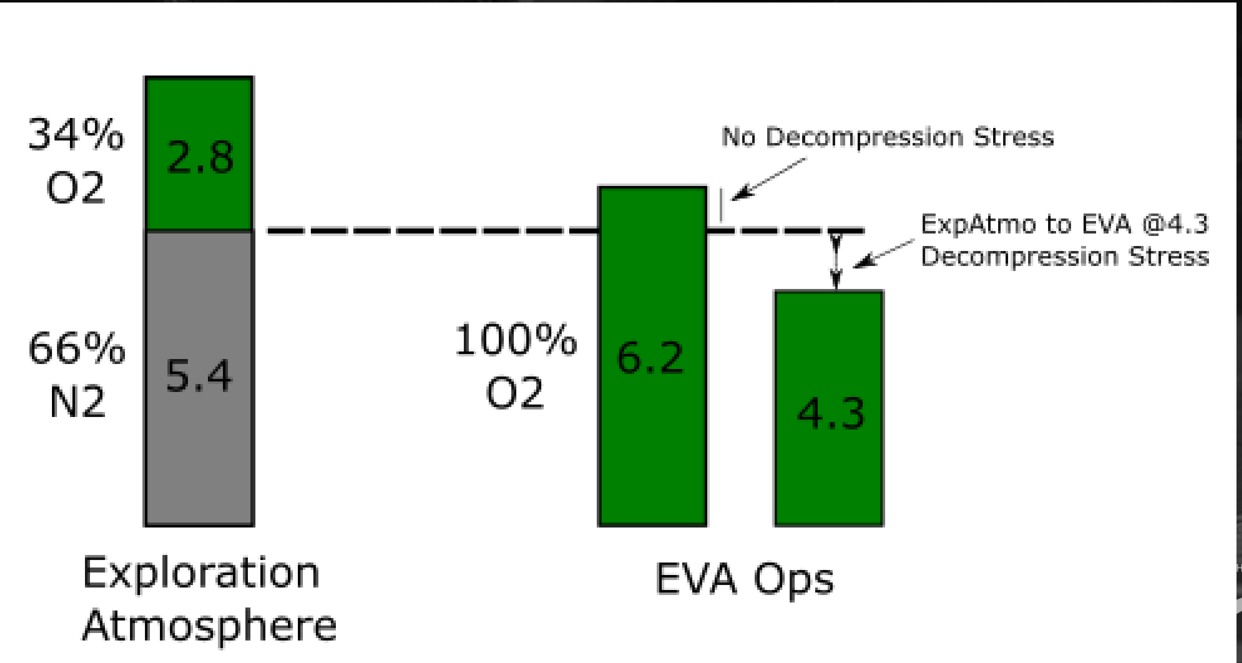
Thank you!

Suit Overpressure In-EVA Denitrogenation (formerly known as "Walking Prebreathe")

Suit pressure must exceed tissue ppN2

Vehicle Atmosphere	Tissue ppN2	Suggested Pressure Range
10.2 psia / 26.5% O2	**7.4 psi**	7.65-7.90 psid
9.8 psia / 28% O2	**7.05 psi**	7.30-7.55 psid
8.2 psia / 34% O2	**5.4 psi**	5.65-5.90 psid





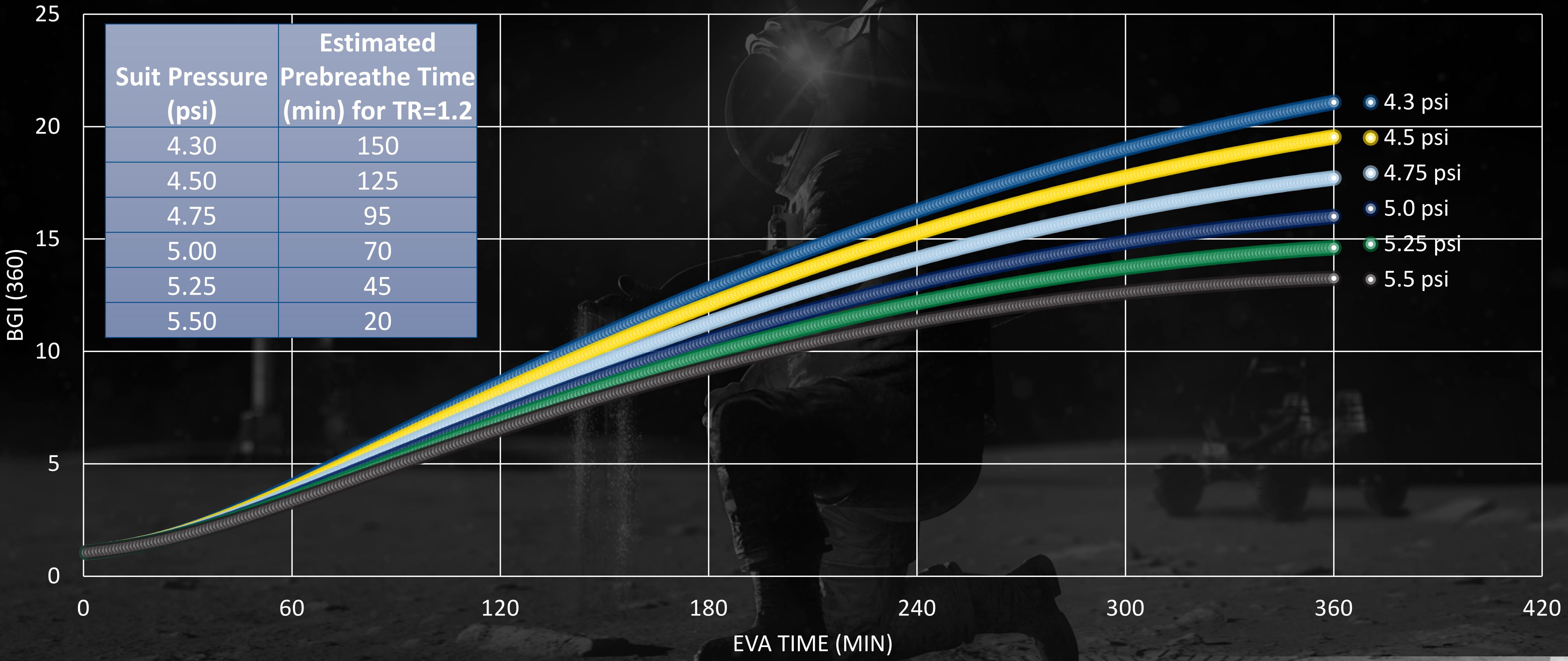
Duration of In-EVA Denitrogenation is dependent on many factors

1. starting atmosphere composition
2. terminal suit pressure
3. any PB that occurred during other operations

<u>There is no one size fits all solution</u>

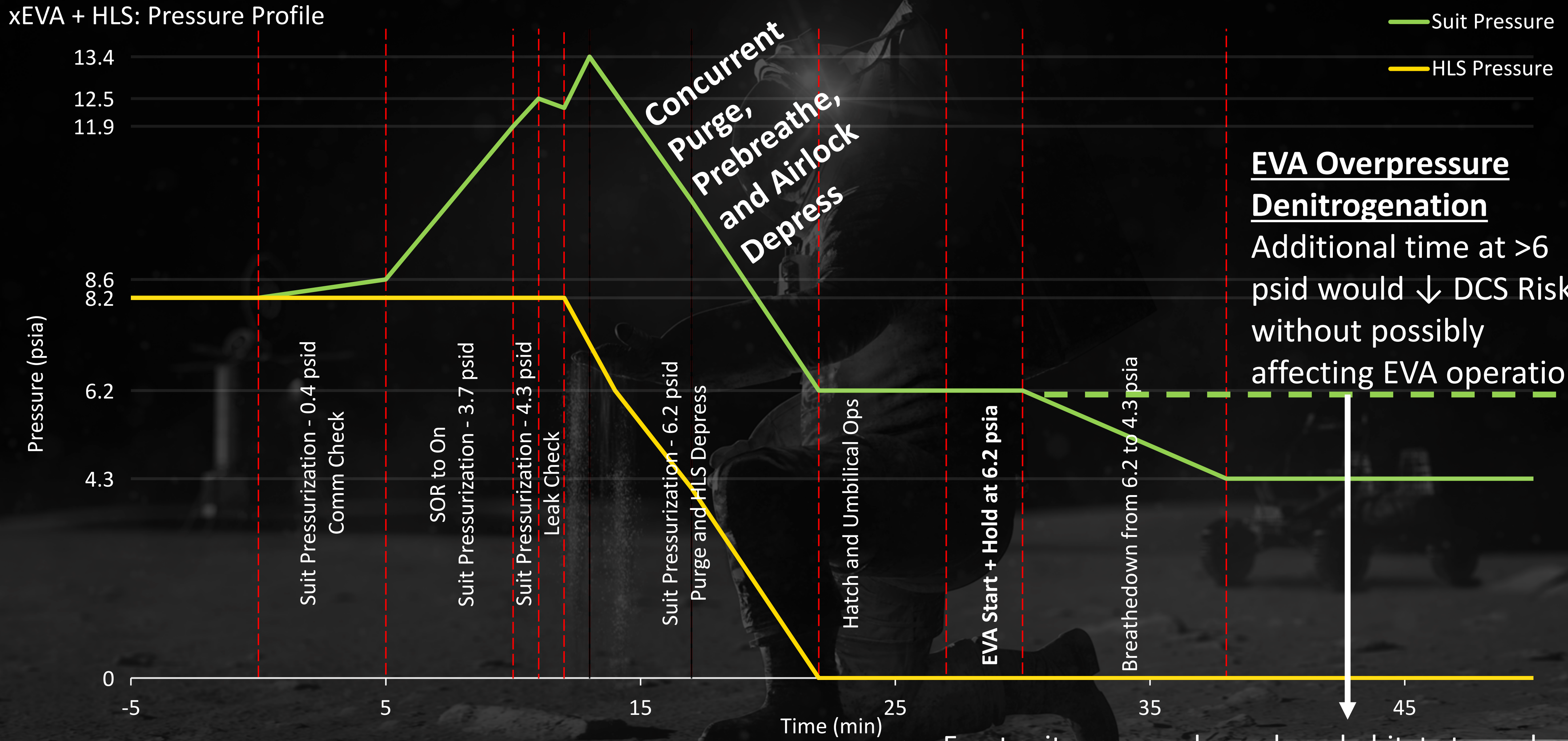
Modeled Bubble Growth During EVA

Even at same TR to start EVA, the higher suit pressure reduces modeled bubble growth



Suit Pressure (psi)	Estimated Prebreathe Time (min) for TR=1.2
4.30	150
4.50	125
4.75	95
5.00	70
5.25	45
5.50	20

Concurrent Operations



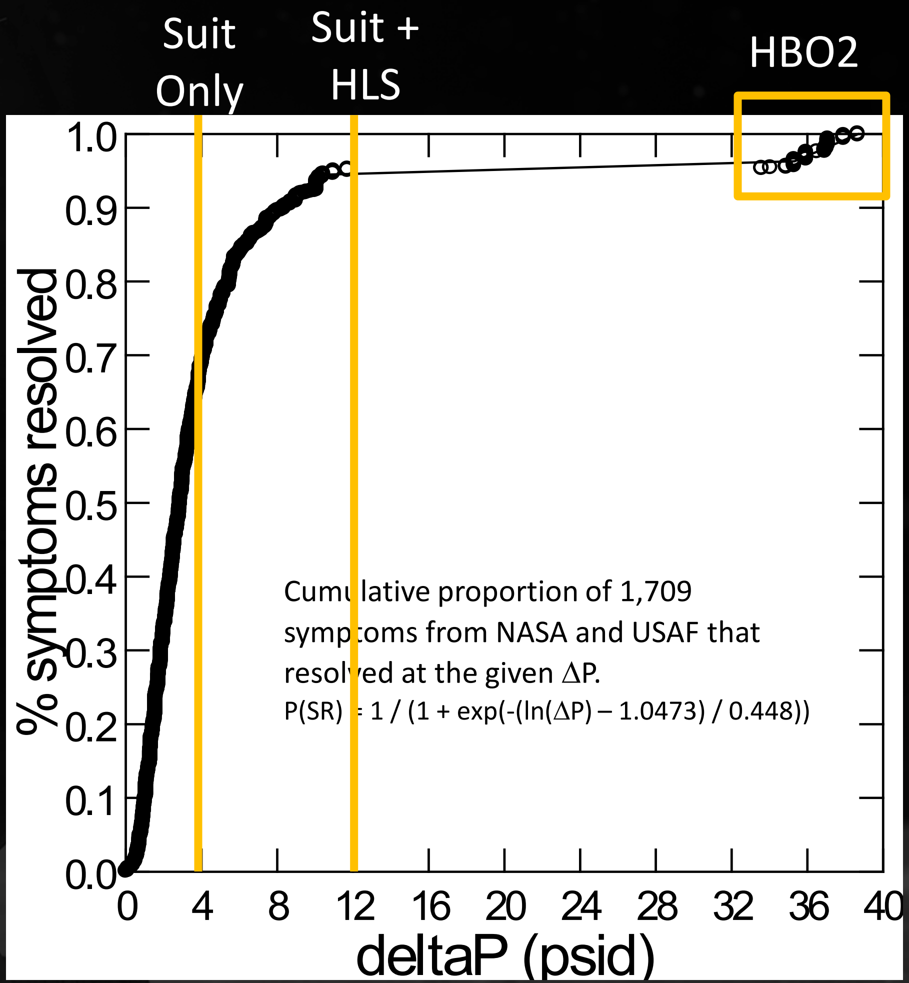
<u>EVA Overpressure Denitrogenation</u>

Additional time at >6 psid would ↓ DCS Risk without possibly affecting EVA operations

- Exact suit pressure depends on habitat atmosphere
- Example assumes 8.2/34 atmosphere

Principles of Altitude DCS Treatment

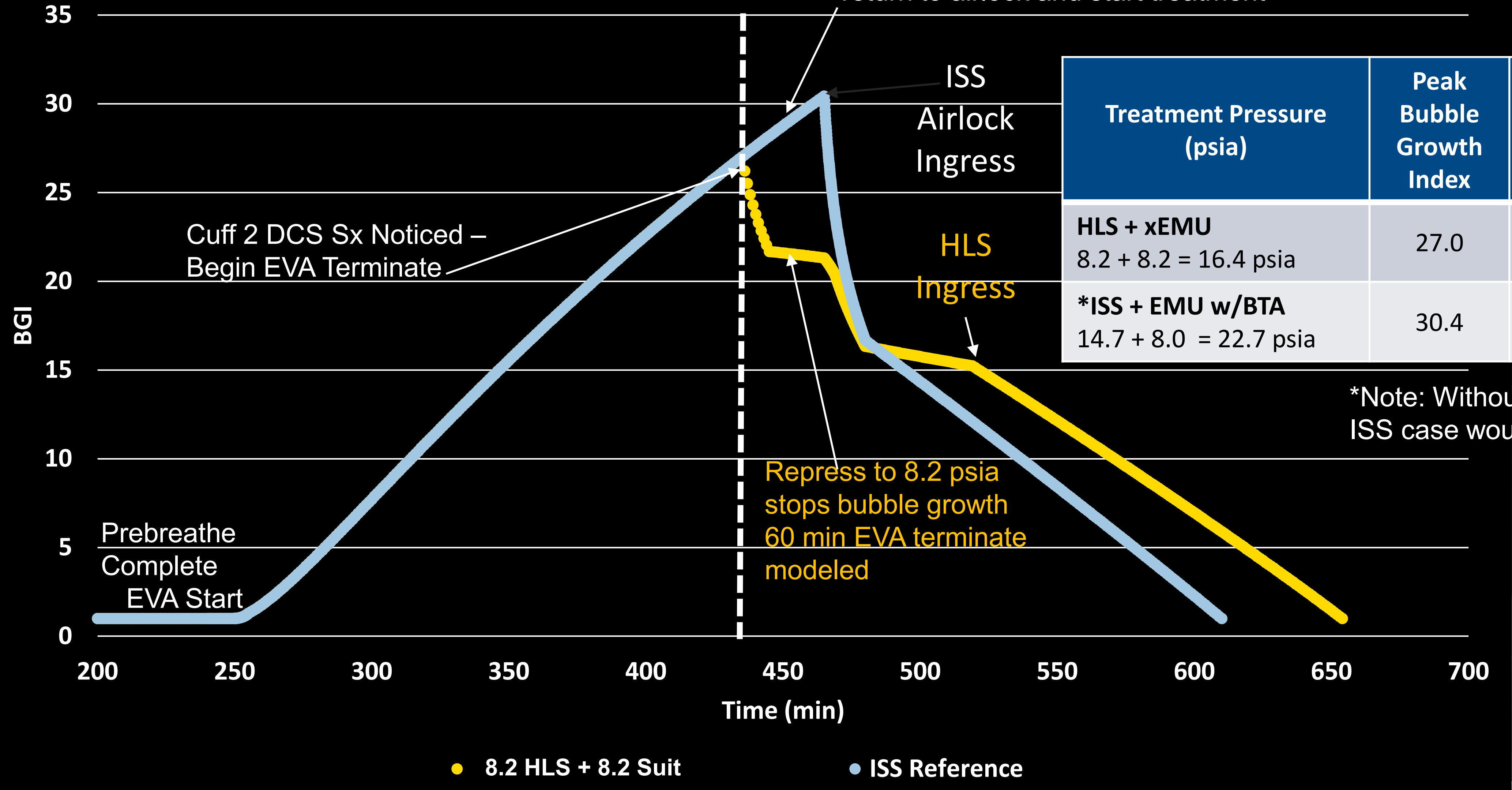
- Effective treatment for DCS and evolved gas includes
  1. Recognition of symptoms and early intervention
  2. Increasing atmospheric pressure
  3. Breathing >95% O_2
  4. Time to resolve a sign or symptom
- Pressurizing the suit within the habitat (suit pressure + habitat pressure) allows for additional pressure treatment capability (expected Ops)
- *When returning to sea level pressure (14.7 psia)*, empirical data exist to estimate the probability of symptom resolution



Conkin J, Abercromby AFJ, Dervay JP, Feiveson AH, Gernhardt ML, Norcross JR, Ploutz-Snyder R, Wessel JH, III. Hypobaric decompression sickness treatment model. Aerosp Med Hum Perform 2015; 86:508-17.

Bubble Dynamics* Comparison ISS vs Exploration Capabilities

Bubble continues growth in ISS case because it takes up to 30 min to return to airlock and start treatment



Treatment Pressure (psia)	Peak Bubble Growth Index	Time to Bubble Resolution from symptom onset (h:mm)
HLS + xEMU 8.2 + 8.2 = 16.4 psia	27.0	3:49 (60 min) 3:18 (30 min)
***ISS + EMU w/BTA** 14.7 + 8.0 = 22.7 psia	30.4	2:55

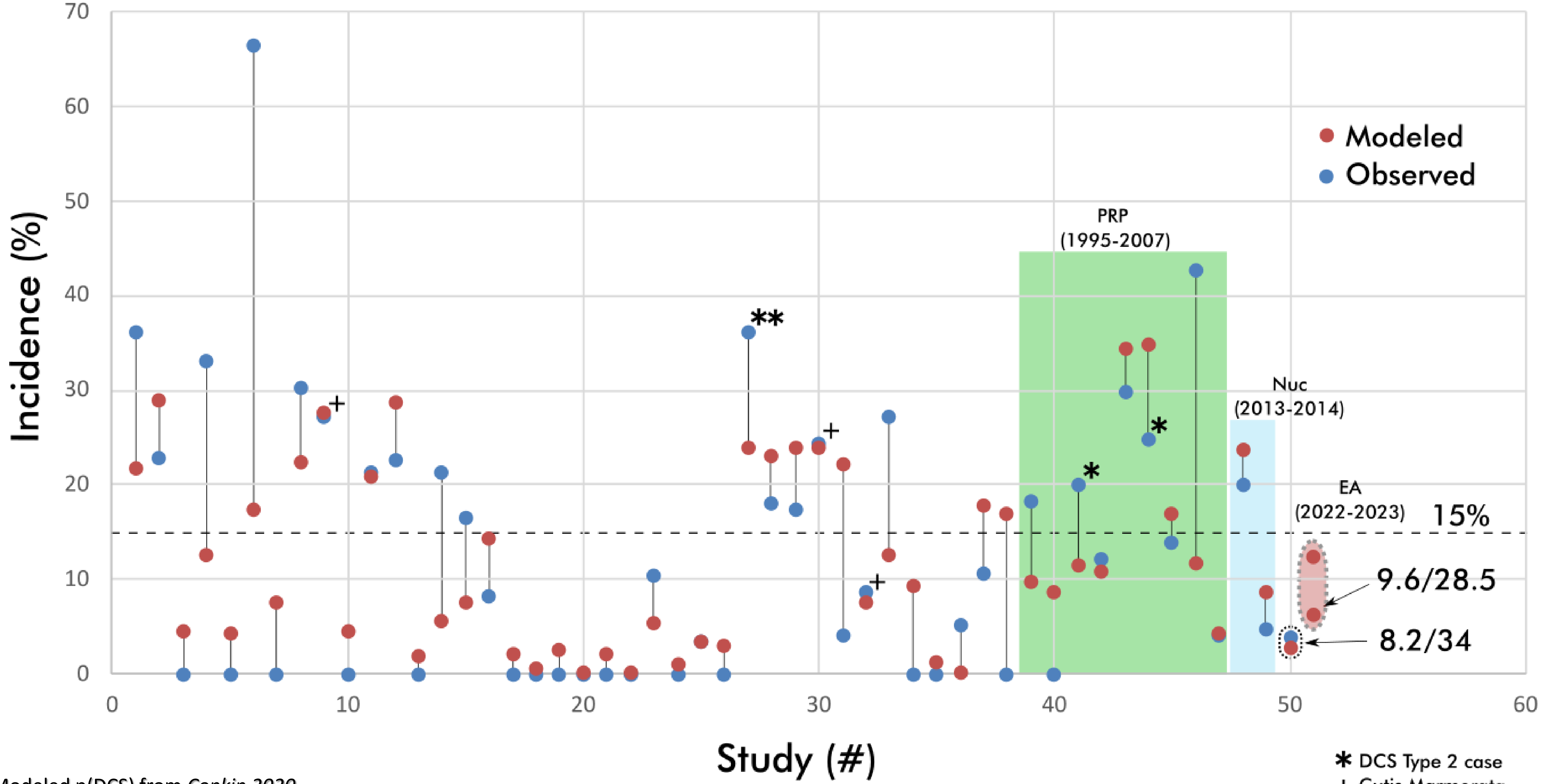
*Note: Without BTA usage, the ISS case would take longer

*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.

EHP Program Considerations

- Existing xEVAS suit pressure and operational requirements drive a variable pressure suit design
- Suit pressure selection history
  - 4.3 psi is sufficient to mitigate hypoxia, but not optimal for DCS
  - Experience at suit pressures >4.3 psi is limited but positive
- Variable pressure set points required for
  1. Nominal EVA operations at elevated pressure to reduce prebreathe
  2. Walking denitrogenation (DN2)
  3. Concurrent or suit independent operations – purge and airlock depressurization
  4. Immediate DCS treatment

NASA Historical Decompression Studies (1982-2023)



Modeled p(DCS) from *Conkin 2020*

✱ DCS Type 2 case
+ Cutis Marmorata