Implications of Operational Pressure on CSSE PGS Design

Ryan Lee

CSSE Pressure Garment

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Who Am I?

- Ryan Lee
  - Senior Project Engineer – ESCG/Barrios Tech.
  - Constellation Space Suit Element
    - Pressure Garment Subsystem
  - Education
    - M.S. Aerospace Engineering
      - Space Human Factors Curriculum
  - 7 years of advanced space suit design experience
  - 2 years of EMU training experience

My Daughter: Liberty

Why Am I Here?

- The Constellation Pressure Garment Subsystem (PGS) team performed a study to determine what the drivers would be for selecting an operating pressure in a space suit that meets Constellation requirements
- Presentation Goals
  - Review Study Objectives
  - Examine the Pressure Selection Problem
  - Review Historical Suit Pressure Selection
  - Present Recommendations Based on Study Results

Study Objectives

- Bound The Pressure Selection Problem
- Understand Historical PGS Pressure Selection Rationale
- Determine the Effects of Pressure Selection on PGS Design
- Recommend Operational Pressure Paradigm for CSSE PGS
  - Contingency and Nominal Suit pressures

The Pressure Selection Problem

The Pressure Selection Problem

- The pulmonary system is a pressure driven system
- The human body needs external pressure roughly equal to the pressure of inspired gases for physiological processes to work efficiently
- Pressurization with breathing gas makes sense
- In a pressure vessel the wall stress (σ) is directly proportional to the internal vessel pressure (p):

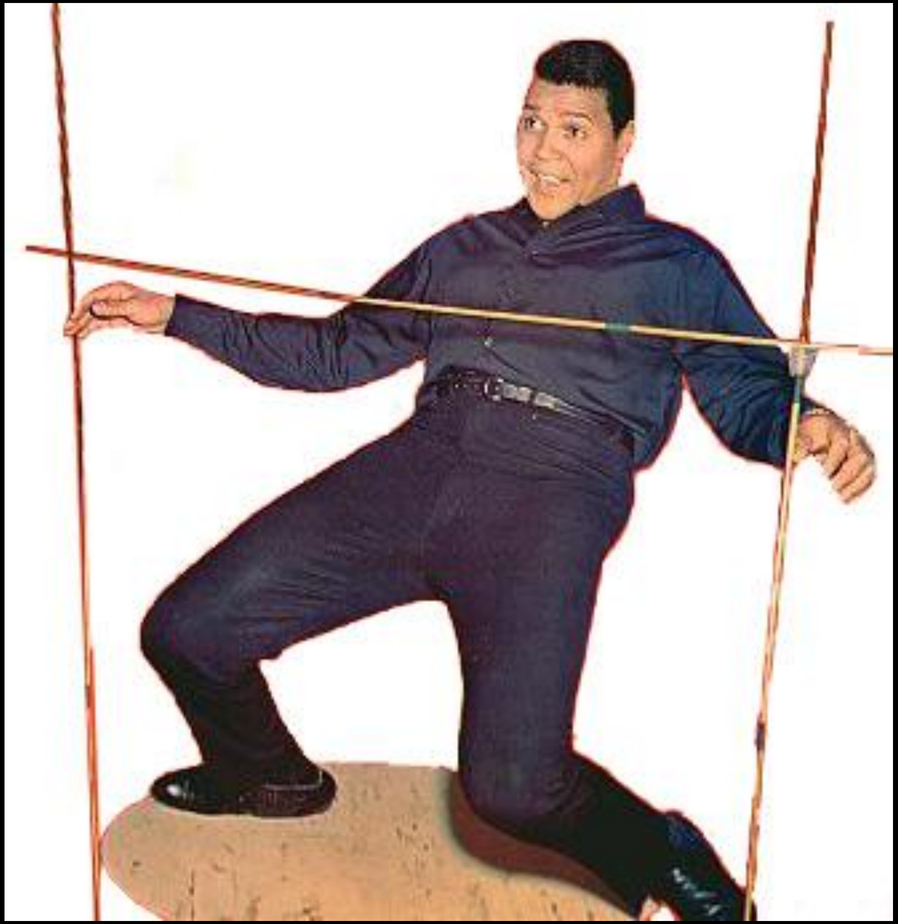
$$\sigma \alpha p$$

- Increased wall stress means increased wall stiffness
- The stiffer the walls of a pressure vessel the more difficult it is to flex
- Low pressure is more desirable for greater mobility

The Pressure Selection Problem

- Question:

How Low Can You Go?



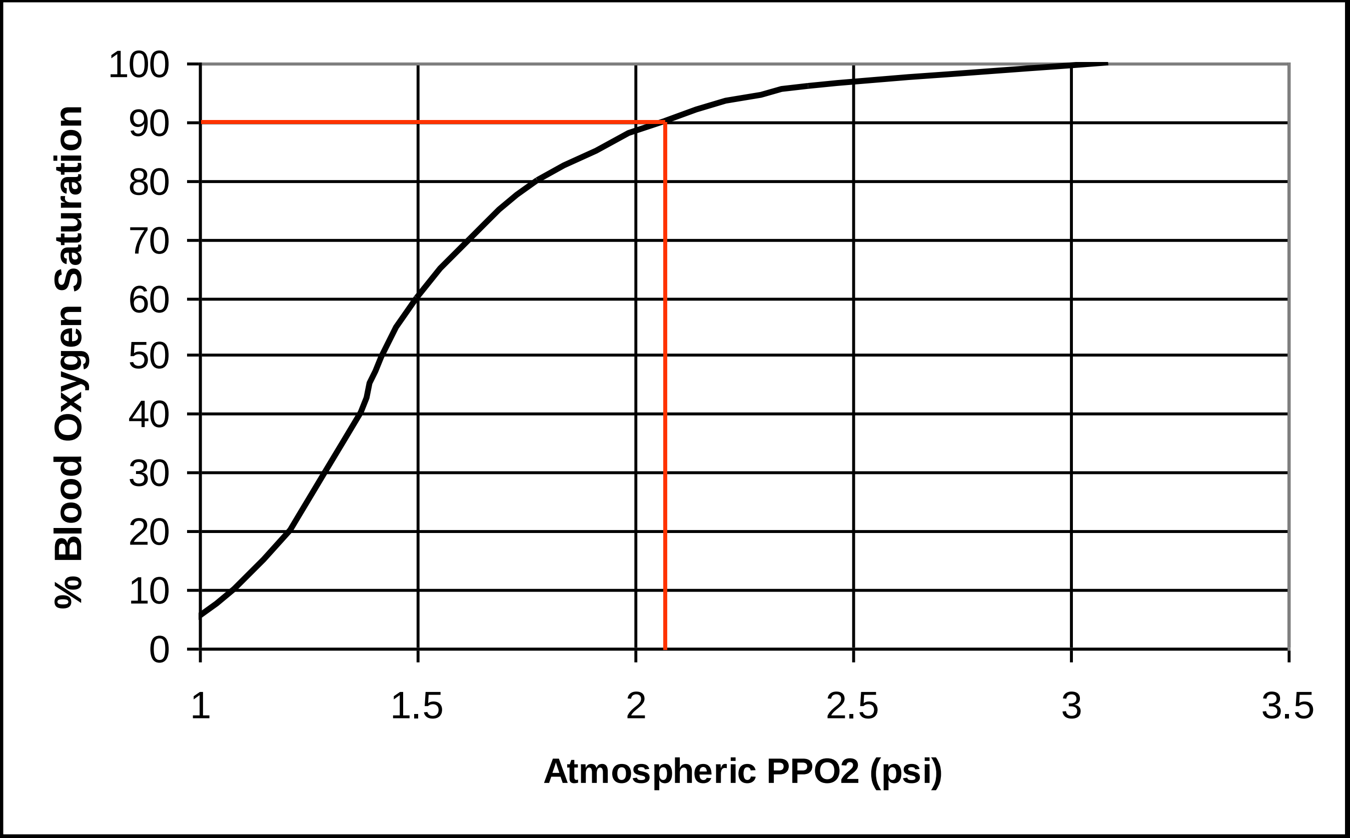
- Lower bound of design space, highest suit mobility

The Pressure Selection Problem

- Sea level atmosphere is a mix of O_2 and N_2 at 14.7 psi
- 21% is O_2 so PPO_2 is 3.1 psi
- In healthy, non-smoking people arterial blood is almost completely saturated with O_2 at sea level
- Doctors don’t recommend supplemental oxygen until blood saturation levels are lower than 90%
  - Hypoxic conditions begin to manifest

The Pressure Selection Problem

- Blood Oxygen Dissociation Curve (PPO_2 vs. Blood O_2 Saturation)



The Pressure Selection Problem

- 90% Blood O_2 saturation at 2.1 psi (10,000 ft.)
  - Represents lower bound of design space
- US EVAs currently performed at 4.3 psi
- Apollo EVAs performed at 3.7 psi
- Lowest ppO_2 allowed on ISS is 2.42 psi
  - During 10.2 psi airlock operations
- Recommended atmosphere for lunar ops is 8.0 psi w/ 32% O_2
  - ppO2 = 2.56 psi
- 2.5 psi is ppO_2 at 5500 ft. (Denver, Colorado)

The Pressure Selection Problem

Altitude: 14,196 ft   Atmospheric Pressure: 8.3 psi ppO_2: 1.7 psi

The Pressure Selection Problem

- Orion/Lunar spacecraft will operate with a mixed oxygen/nitrogen environment
- Both gasses will be dissolved in blood
- A decrease in pressure will cause a decrease in the concentration of nitrogen dissolved in the blood
- Excess gas normally expired through lungs
- If pressure difference is great enough some excess gas will remain in body tissues and organs
- Symptoms range from light pain, to impaired judgment, and even death
- This condition is called Decompression Sickness (DCS)

The Pressure Selection Problem

- Common way to track risk of DCS is by the ratio of body N_2 to final absolute suit pressure

$$R = \frac{N_{2Body}}{P_{Suit}}$$

- Higher R-Value = Greater Risk
- Research has demonstrated a 5% risk of minor DCS symptoms in 1-g environment at R=1.4
- U.S. EVAs performed at R~1.6
- Russian EVAs performed at R~1.8

The Pressure Selection Problem

- Depressing from Sea Level (14.7 psi)
  - Highest Constellation vehicle pressure condition
  - Atmospheric PPN_2 = 11.6 psi

PPN_2 Body (Psi)	P_{Suit} (Psi)	R-value	1g Risk of Minor Symptoms
11.6	11.6	1	None
11.6	9.7	1.2	<2%
11.6	8.3	1.4	~5%
11.6	7.3	1.6	~20%
11.6	6.4	1.8	~45%
11.6	4.3	2.7	Huge

The Pressure Selection Problem

- Upper design space boundary depends on acceptable risk
  - R=1.4 to 1.6 (suit pressure 7.3 psi - 8.3 psi)

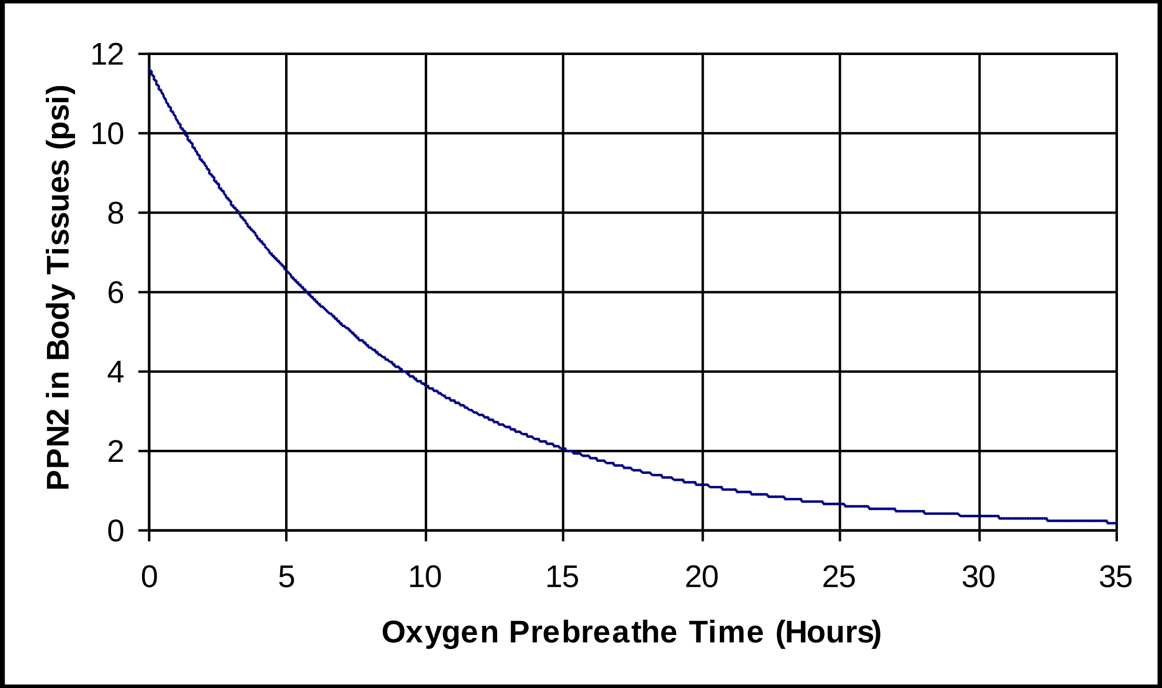
PPN_2 Body (Psi)	P_{Suit} (Psi)	R-value	1g Risk of Minor Symptoms
11.6	11.6	1	None
11.6	9.7	1.2	<2%
11.6	8.3	1.4	~5%
11.6	7.3	1.6	~20%
11.6	6.4	1.8	~45%
11.6	4.3	2.7	Huge

The Pressure Selection Problem

- Risk of DCS controlled by:
  - O_2 Pre-Breathe to Reduce PPN_2
    - Higher Initial R-value Means Longer Pre-Breathe
  - Reducing Cabin PPN_2 Prior to EVA
    - Reduced Overall Pressure, Higher PPO_2
  - Increase Suit Pressure
    - Suit performance decreases with suit pressure increase

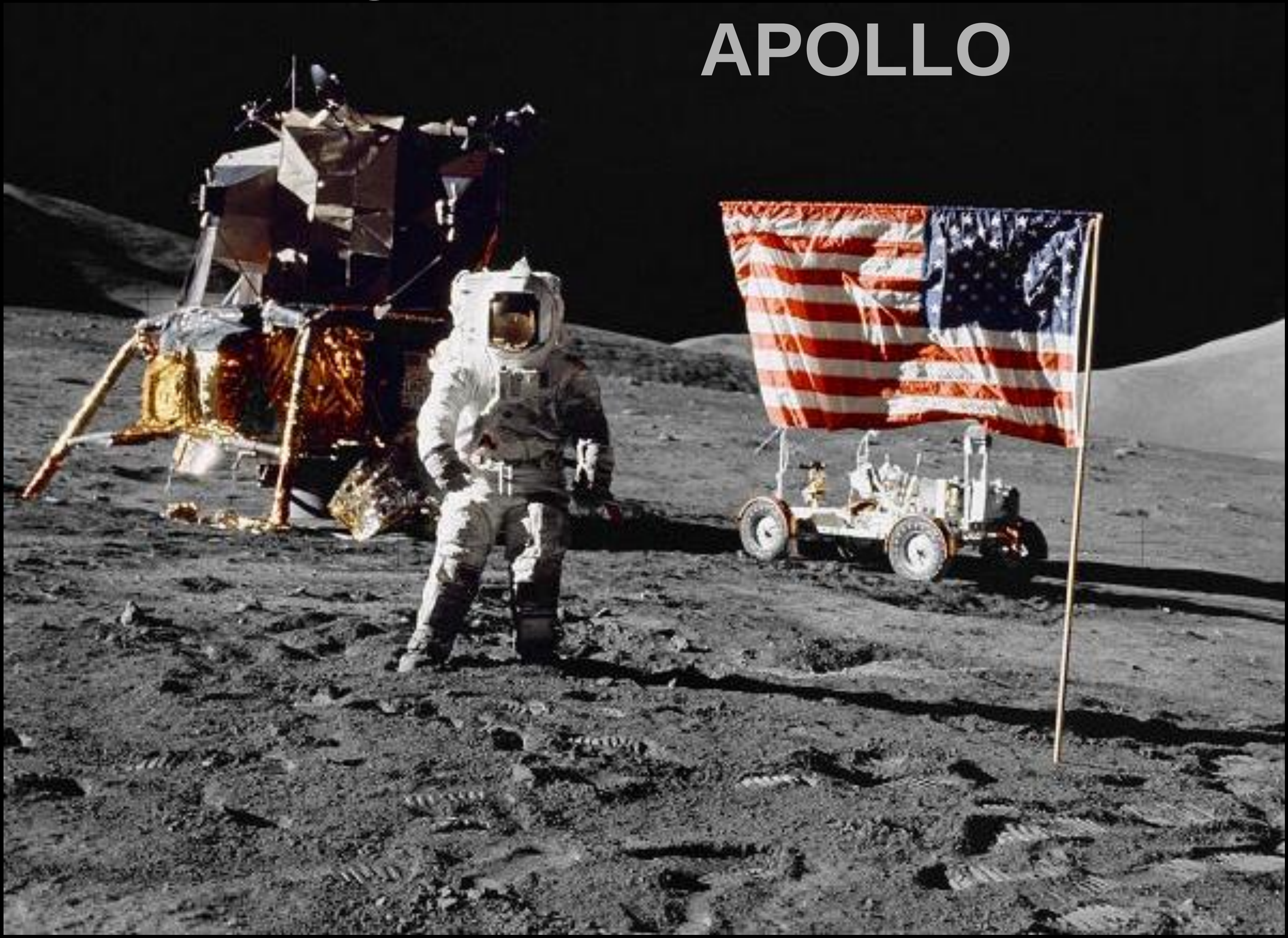
The Pressure Selection Problem

- PPN_2 is reduced by breathing O_2



- After 4 hours PPN_2 ~ 7.0 psi
- R-value for U.S. EVA = 7.0/4.3 = 1.63

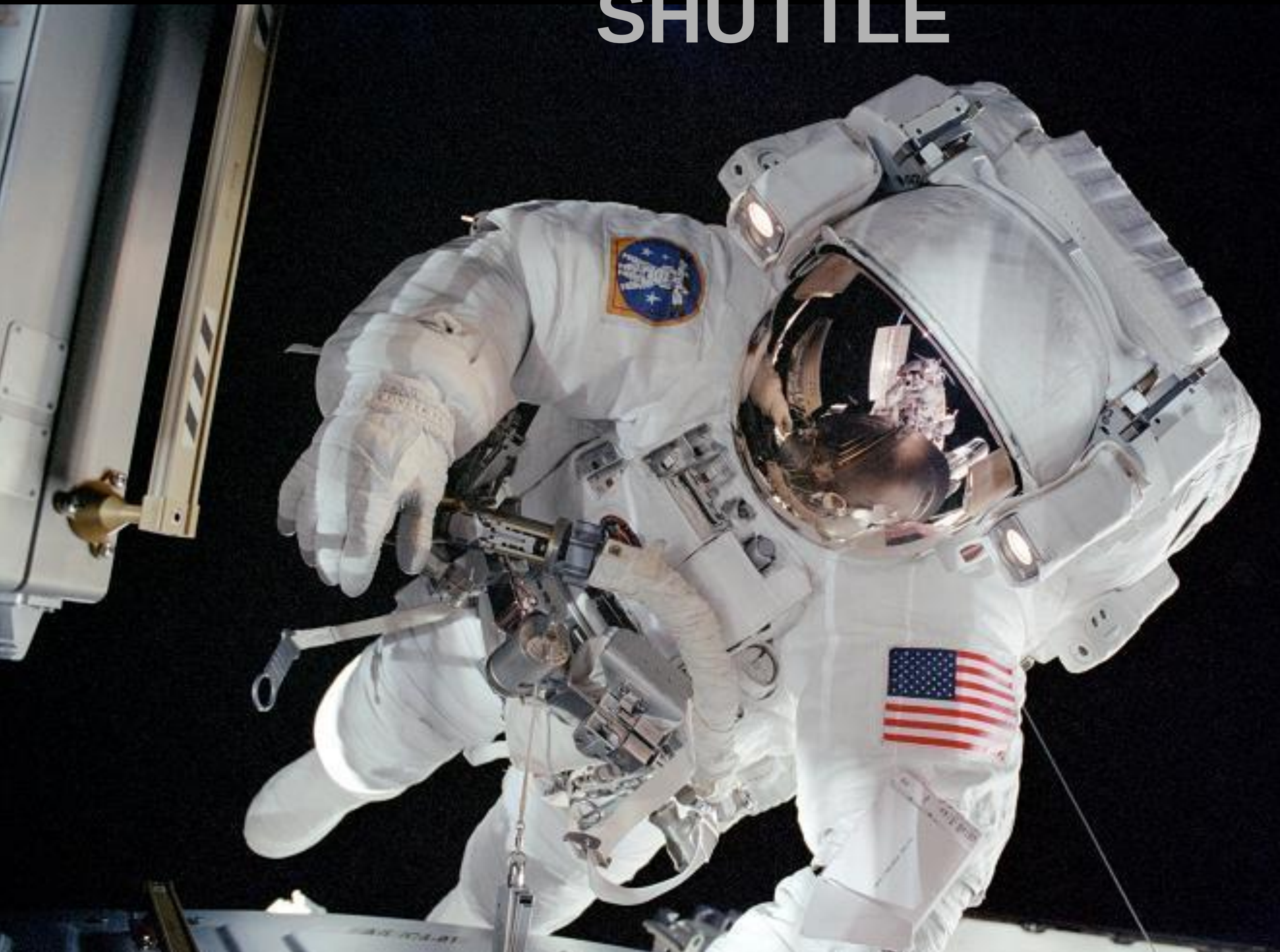
Solving the Pressure Problem: APOLLO



U.S. Pressure Selection – Apollo

- Apollo spacecraft operated with a pure oxygen cabin pressure of 5.0 psi
- Pure oxygen cabin meant no prebreathe required
- Maximizing mobility was prime concern while minimizing risk of hypoxia
- 3.1 psi was the starting minimum operational pressure
- Accounting for purge pressure drops, potential hardware failures, and emergency operations, the actual minimum nominal operating pressure was increased to 3.5 psi
- Accounting for the regulator error band, the final operating pressure for the Apollo spacesuit was 3.75   0.25 psi

Solving the Pressure Problem: **SHUTTLE**



U.S. Pressure Selection – Shuttle

- Decision was made to operate the Space Shuttle at sea-level pressure to account for future Space Station
- For zero prebreathe, an 8.3 psi suit was recommended in 1973 (R=1.4)
- NASA had no experience beyond Apollo suit pressure and considered an 8.3 psi program too expensive
- Shuttle program conceded to a minor pressure increase to 4.1   0.1 psi
- Because of the large pressure difference between cabin N_2 and suit pressure, pure oxygen prebreathe would be required

U.S. Pressure Selection – Shuttle

- Efforts to devise a means of prebreathe without the possibility of breaking protocol failed
- In 1980 NASA attempted to eliminate prebreathe with a procedure to decrease the spacecraft cabin pressure to 9.0 psi, 12 hours before EVA
- This decision required increasing the maximum allowable R-value to 1.6 (~20% risk of minor DCS symptoms)
- 9.0 psi was rejected because it would require a maximum 30% O_2 in the Shuttle cabin and it was only certified to 25.9%

U.S. Pressure Selection – Shuttle

- Astronaut Joe Kerwin, M.D. recommended decreasing the cabin pressure to 10.4 psi for 12 hours prior to EVA, and raising the EMU operational pressure to 4.3 psi
- His method produced an R-value of 1.78, which he tried to justify as safe based on DCS risk calculations using alveolar gas rather than expired gas concentrations
- This method was ultimately rejected

U.S. Pressure Selection – Shuttle

- In parallel, Hamilton Sundstrand engineers suggested reducing cabin pressure to 11.8 psi for 12 hours and increasing suit operational pressure to 5.8 psi
- This method would maintain an R-value of 1.6 and require no prebreathe
- An operational pressure increase to 5.8 psi would have required significant modifications to the EMU currently under production as a 4.1 psi suit
- Method was rejected for cost reasons

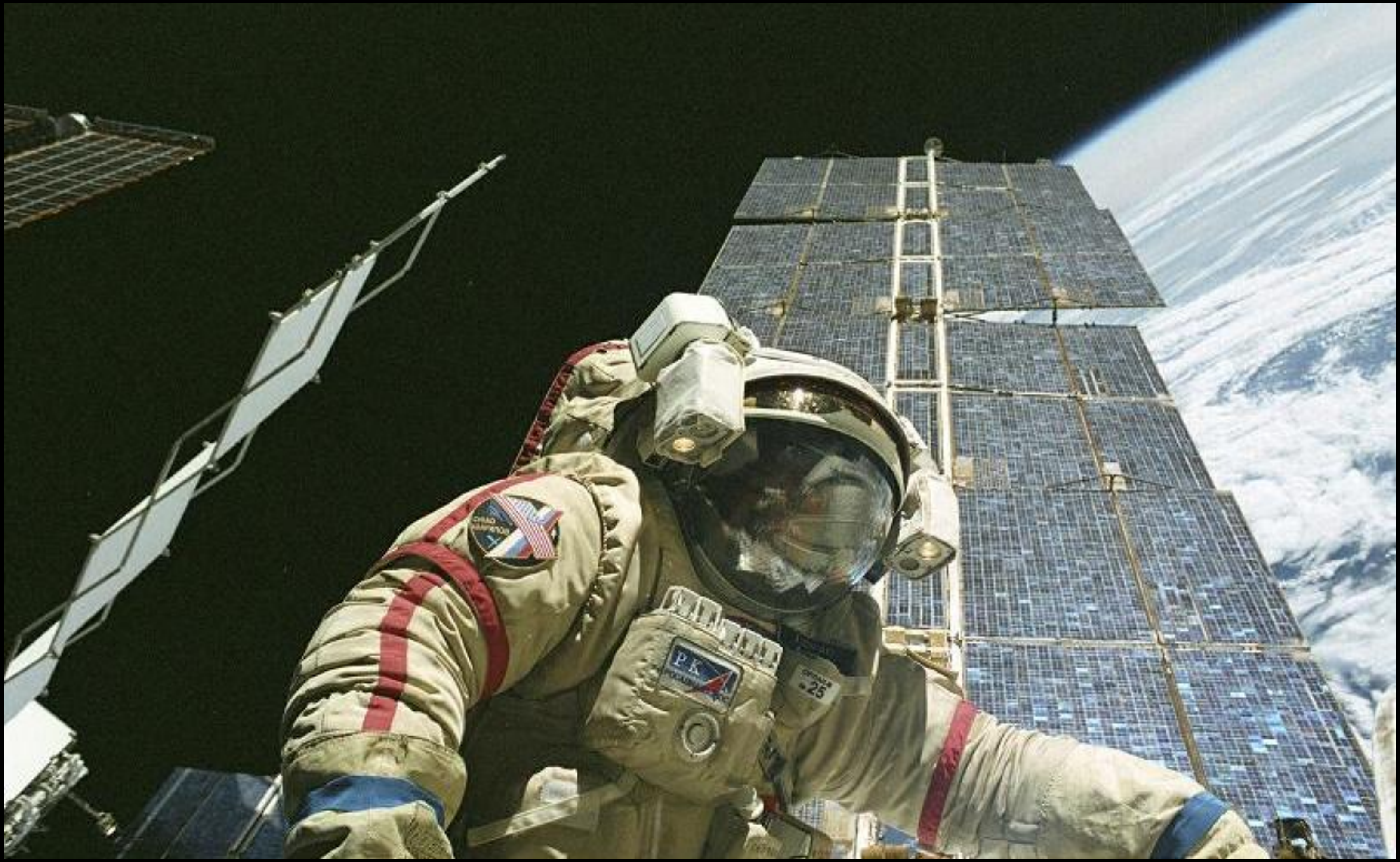
U.S. Pressure Selection – Shuttle

- In 1981 a JSC team suggested a hybrid approach of using both prebreathe and pressure manipulation
- The method required:
  - One hour of pure oxygen prebreathe prior to cabin depress
  - Cabin pressure would be reduced to 10.2 psi for 12 hours
  - 40 minutes of in-suit prebreathe prior to airlock depress
  - EMU operating pressure would be increased to 4.3 psi
  - Using an R-value of 1.6
- Method was accepted but not certified to use until 1984
- 3.5 hour in-suit prebreathe was used prior to method certification

U.S. Pressure Selection – Shuttle

- With the new prebreathe protocol (R-value of 1.6), models/testing predicted a 5% chance of serious DCS symptoms
- DCS treatment was now a consideration
- EMU had been certified to a proof pressure equal to 1.5 times the max operating pressure of 5.3 psi (maximum PPRV pressure), or 8.0 psi, without structural damage
- Bends Treatment Adapter (BTA) was developed that increased positive pressure relief to 8.8 psi max
- Procedure written to use suit as hyperbaric chamber for DCS treatment at 6.0 and 8.0 psi
- Suit taken to 8.0 psi cannot be reused until it has undergone an engineering evaluation

Solving the Pressure Problem: **ORLAN**



Russian Pressure Selection - Orlan

- Russian spacecraft have always operated at 14.7 psi
- Orlan pressure was chosen to minimize prebreathe
- Russian DCS testing was performed using subjects wearing space suits (U.S. testing was done in shirtsleeve environment)
- Tests resulted in an acceptable (~20% risk of minor DCS symptoms) R-value of 1.8
- A zero prebreathe suit with an R-value of 1.8 results in an operating pressure of: 11.6 psi / 1.8 = 6.4 psi
- 30 minutes of oxygen prebreathe prior to airlock depress was added
- Resulted in Orlan operating pressure of 5.8 psi

Solving the Pressure Problem: **CONSTELLATION**

The Pressure Selection Problem

- NASA Exploration Atmospheres Working Group Final Report Recommendations

Mission Phase	Nominal Cabin (psi)	Oxygen Concentration (%)	PPO_2 (psi)	PPN_2 (psi)
Launch/ISS	14.7	21	3.1	11.6
Lunar Coast	10.2	26.5	2.7	7.5
Lunar Surface	8.0	32	2.6	5.4

The Pressure Selection Problem

- Four Nominal Pressure Options Examined
  - Option 1: Minimum Operating Pressure – 2.5 psi
    - Maximize Suit Operating Characteristics
  - Option 2: Sea Level O2 Operating Pressure – 3.5 psi
    - Reduces Risk Associate with Option 1
    - Apollo History – Lessons Learned
  - Option 3: Zero Pre-Breathe Operating Pressure
    - Eliminate Pre-Breathe Operational Overhead
    - Would operate at a different pressures for each environment
  - Option 4: Minimal Pre-Breathe Operating Pressure
    - 20 minute pre-breathe
    - Minimal Overhead, Increased Suit Operability

The Pressure Selection Problem

- For Nominal Operations:

Pressure Option	Ambient Spacecraft Pressure (psi)	Nominal Operating Pressure (psi)	Prebreathe Time Required
Minimum O2	14.7 10.2 8.0	2.5 2.5 2.5	> 9 hrs to R=1.6 5.5 hrs to R=1.6 4.5 hrs to R=1.3*
Sea Level O2	14.7 10.2 8.0	3.5 3.5 3.5	> 6 hrs to R=1.6 2.5 hrs to R=1.6 1.8 hrs to R=1.3*
No Pre-Breathe	14.7 10.2 8.0	7.3 4.7 4.2	0 min to R=1.6 0 min to R=1.6 0 min to R=1.3*
Min Pre-Breathe	14.7 10.2 8.0	6.9 4.5 4.0	20 min to R=1.6 20 min to R=1.6 20 min to R=1.3*

* For Lunar EVA operations an R-value of 1.3 was recommended by the NASA Exploration Atmospheric Working Group

The Pressure Selection Problem

- Eliminated options 1 and 2:
  - Excessive prebreathe (greater than 40 minutes)
- Eliminated option 3:
  - Recognized advantages to allowing a small amount of prebreathe
  - EVA prep will likely always require some steps while pressurized
- Recognized EVA from 14.7 psi not required
  - ISS missions will perform EVAs from ISS A/L
  - Non-ISS missions will reduce cabin to 10.2 psi for a minimum of 36 hours prior to 0-g EVA

The Pressure Selection Problem

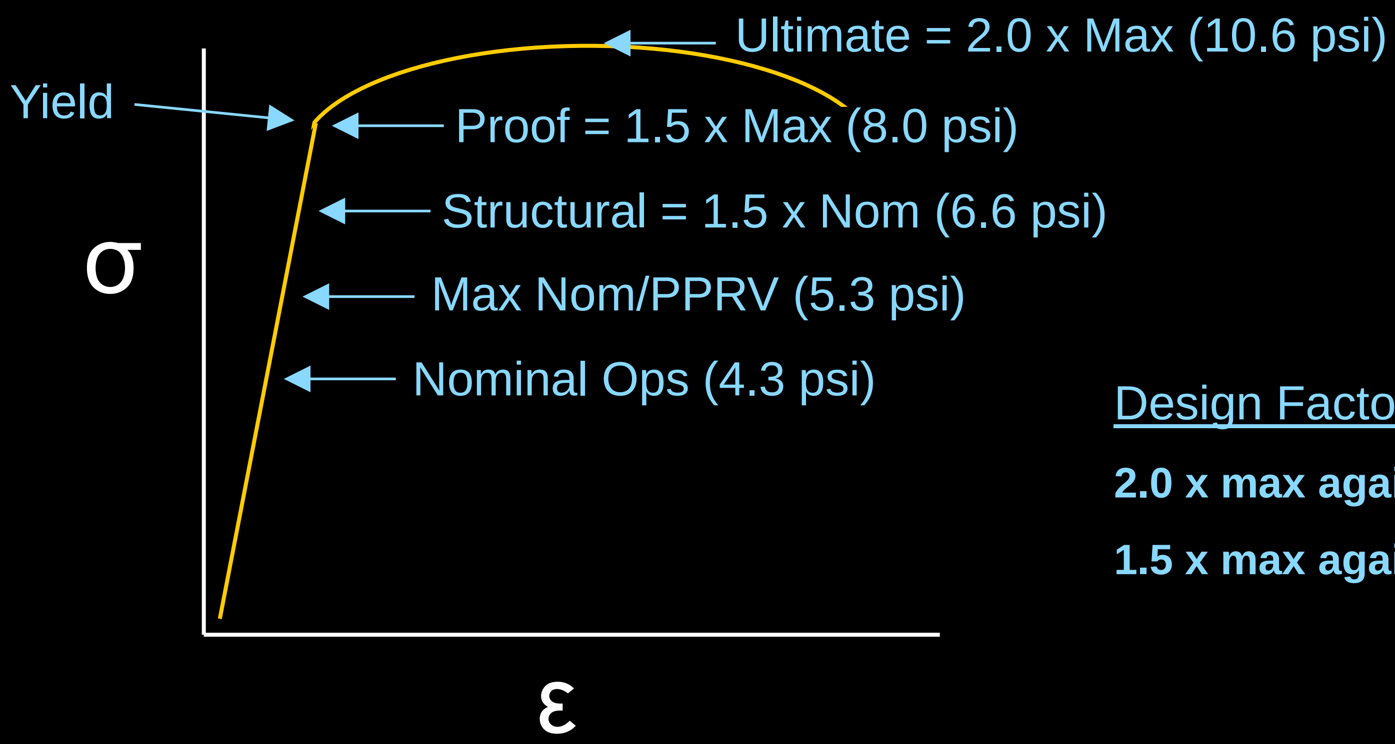
- For Nominal Operations:

Pressure Option	Ambient Spacecraft Pressure (psi)	Nominal Operating Pressure (psi)	Prebreathe Time Required
Min Pre-Breathe	10.2 8.0	4.5 4.0	20 min to R=1.6 20 min to R=1.3*

The Pressure Selection Problem

- Contingency operations – DCS Treatment:
  - EMU program uses an in-suit treatment pressure equivalent to suit ‘proof’ pressure
    - 8 psi, or 1.5 x max operating (relief valve) pressure (5.3 psi)
    - EMU is no-go for EVA prior to an engineering evaluation
  - ‘Structural’ pressure (1.5 x Nominal operating pressure: 6.6 psi) is used to check suit integrity after build up prior to flight

The Pressure Selection Problem



<u>Design Factors of Safety</u>

2.0 x max against ultimate

1.5 x max against yield

- At Issue are loads in the hoop direction
- Hoop stress is twice the plug load
- The only restraint in the hoop direction is the base restraint fabric

The Pressure Selection Problem

- Requirements guarantee no structural damage at proof pressure
- Beyond that there is no guarantee that permanent damage has not occurred
- For CSSE lunar case, engineering evaluation will not be possible
- Max DCS treatment pressure should not exceed suit 'structural' pressure
- Structural pressure should be greater than 6.0 psi (First Shuttle treatment pressure)

The Pressure Selection Problem

- Contingency Operations – Rapid Cabin Depress:
  - Worst case instantaneous cabin decompression would be from 14.7 psi
  - NASA flight surgeons state that 8 psi is the minimum emergency prebreathe pressure for cabin depress from 14.7 psi
    - Design driving: Suit must have a minimum proof pressure of 8.0 psi
  - This scenario would be mission ending, a one time use of the suit at 8.0 psi for this case would be acceptable

The Pressure Selection Problem

- For contingency operations:

Pressure Option	Ambient Spacecraft Pressure (psi)	Nominal Operating Pressure (psi)	Structural/ Max DCS Treatment Pressure (1.5 x Nom)	Max Operational Pressure* (PPRV Set) (psi)	Proof/Max Emergency Prebreathe Pressure (1.5 x Max)
Min Pre-Breathe	10.2 8.0	4.5 4.0	6.8 6.0	5.5 5.0	8.25 7.5

*Assumed Nominal Operating Pressure + 1.0 psi

- Minimum 4.3 psi required for 8.0 psi proof pressure
- Reduced Pressure Selection Design Space:
  - 4.5 psi for 0-g EVA with 20 minute prebreathe
  - 4.3 psi to meet contingency 8.0 psi case

PGS Team Recommendation

- Minimum single pressure paradigm that meets 8.0 psi emergency prebreathe pressure:

Pressure Option	Ambient Spacecraft Pressure (psi)	Nominal Operating Pressure (psi)	Structural/Max DCS Treatment Pressure (1.5 x Nom)	Max Operational Pressure (PPRV Set) (psi)	Proof/Max Emergency Prebreathe Pressure (1.5 x Max)	Prebreathe Time Required
Single Pressure	10.2 8.0 8.0	4.3 4.3 4.3	6.6 6.6 6.6	5.3 5.3 5.3	8.0 8.0 8.0	40 min to R=1.6 0 min to R=1.27 20 min to R=1.23

- Selection of Single Pressure
  - Raises 0-g EVA prebreathe time to 40 min
  - 0-g EVA currently not a nominal CSSE task

CSSE PGS Loading Considerations

- Pressure Selection will also affect PGS design loads
- PGS loading includes two types of loads
  - Pressure induced, or ‘plug’ loads
  - Man induced, or ‘man’ loads
- Plug load
  - Based on suit geometry
  - Loads are easily predicted

CSSE PGS Loading Considerations

- Man loading occurs both internal and external to the suit
- Internal loads are called ‘isometric’ loads
  - EMU is certified to an isometric man load equivalent to 95th percentile isometric strength with a specified negative sizing delta
- External loads are also referred to as ‘satellite’ man loads
  - Satellite/man loads are a product of reacting large mass inertial loads while restrained in a foot restraint
  - Currently, satellite/man loads do not apply to the CSSE operational paradigm

CSSE PGS Loading Considerations

- Sample EMU Load Limits (Taken from EMU S/AD)

	Pressure (psig)	Plug Load (lb)	Max Man Load (lb)*	Load Limit (lb)
Upper Arm Axial – Per Restraint Line	4.3	122	163**	285
	8.0	227	45	272
Lower Arm Axial – Per Restraint Line	4.3	55	163**	218
	8.0	103	45	148
Waist Axial – Per Restraint Line	4.3	394	507**	901
	8.0	735	158	893
Leg Outboard Axial – per Restraint Line	4.3	104	470**	574
	8.0	189	79	268

*Max man load at 8.0 psi is for an inactive crewmember at max BTA
**Max man load is satellite/man load

CSSE PGS Loading Considerations

- Load Limit Comparison Using Isometric Man Loads

	Pressure (psig)	Plug Load (lb)	Isometric Man Load (lb)*	Load Limit (lb)	EMU Load Limit (lb)
Upper Arm Axial – Per Restraint Line	4.3	122	134	256	285
	6.6	187	134	321	
	8.0	227	134	361	
Lower Arm Axial – Per Restraint Line	4.3	55	134	189	218
	6.6	84	134	218	
	8.0	103	134	237	
Waist Axial – Per Restraint Line	4.3	394	351	745	901
	6.6	605	351	956	
	8.0	735	351	1086	
Leg – per Restraint Line	4.3	102	240	342	574
	6.6	157	240	397	
	8.0	189	240	429	

* Isometric loads taken from EMU S/ADs

CSSE PGS Loading Considerations

- Pressure selection also effects operational life
- Ops Con will dictate the operational life limits of the PGS
- Certified EMU Operational Life:

	Time (Yrs.)	Pressurized Hours at 4.3 psig	Pressure Cycles at 4.3 psig	Pressure Cycles at 5.3 psig	Pressure Cycles at 6.6 psig
Hard Upper Torso – (Fiberglass)	15	458	194	74	32
Arm Assembly –	10	458	194	74	32
Gloves –	8	229	97	37	16
Lower Torso Assembly –	10	458	194	74	32

Summary

- Nominal PGS pressure selection range:
  - Low End: 4.3 psi
    - Physiologically ~2.5 psi is low end
    - For 20 minute lunar prebreathe 4.0 psi is low end
    - 4.3 psi driven by 8.0 psi emergency prebreathe requirement
  - High End: 4.5 psi
    - Considering 20 minute prebreathe from 10.2 psi cabin
    - For zero prebreathe from 10.2 psi cabin 4.7 is high end
    - Assumes no EVA from 14.7 psi
- For nominal operations 4.3 psi chosen
  - Optimal suit usability characteristics
  - Zero lunar prebreathe, 40 min 0-g prebreathe

Summary

- For contingency operations:
  - 6.6 psi maximum for DCS treatment
    - Equivalent to suit ‘structural’ pressure
    - Can continue nominal operation after treatment w/o engineering evaluation
    - May require reduced man load certification (equivalent to EMU incapacitated crewmember load)
  - 8.0 psi minimum for emergency prebreathe
    - For instantaneous cabin depress from 14.7 psi
    - May require reduced man load certification

Summary

- Loading Considerations:
  - Isometric loads will be a major driving force in the PGS Design
  - Satellite man loads will not apply
    - Need to determine if any other external loading does apply
  - If full isometric loads must be considered at contingency pressures the design load limit will be higher than current satellite man loads in many cases
  - Reduced man load schemes need to be considered for contingency operations