JSC/EC5 U.S. Spacesuit Knowledge Capture (KC) Series Synopsis

All KC events will be approved for public using NASA Form 1676.

This synopsis provides information about the Knowledge Capture event below.

Topic: Implications of Operational Pressure

Date: February 14, 2008 **Time:** unknown **Location:** JSC/B5S/R3102

DAA 1676 Form #: 29767

This is a link to all lecture material and video: \\js-ea-fs-01\pd01\EC\Knowledge-Capture\FY08 Knowledge Capture\20080214 R.Lee Operational Pressure\For 1676 Review & Public Release

*A copy of the video will be provided to NASA Center for AeroSpace Information (CASI) via the Agency's Large File Transfer (LFT), or by DVD using the USPS when the DAA 1676 review is complete.

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For 1676 review use Synopsis Lee Implications of Operational Pressure 2-14-2008.pdf

Presenter: G. Ryan Lee

Synopsis: The Constellation Spacesuit Element (CSSE) was required to support crew survival (CS); launch, entry, and abort (LEA) scenarios; zero gravity (0-g) extravehicular activity (EVA) (both unscheduled and contingency); and planetary EVA. Operation of the CSSE in all of these capacities required a pressure garment subsystem (PGS) that would operate efficiently through various pressure profiles. The PGS team initiated a study to determine the appropriate operational pressure profile of the CSSE and how this selection would affect the design of the CSSE PGS. This study included an extensive review of historical PGS operational pressure selection and the operational effects of those pressures, the presentation of four possible pressure paradigm options for use by the CSSE, the risks and design impacts of these options, and the down-selected pressure option.

Biography: Ryan Lee has been a senior design engineer working for ESCG as part of the PGS team for CSSE. Before this position, Lee spent three years as an advanced spacesuit design engineer with ILC Dover, working on both advanced planetary spacesuits and enhanced designs for the EMU. He also worked two years with Barrios Technology, supporting MOD as an EMU systems trainer and an EVA flight controller.

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Implications of Operational Pressure on CSSE PGS Design

Ryan Lee
CSSE Pressure Garment

14 February 2008

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):

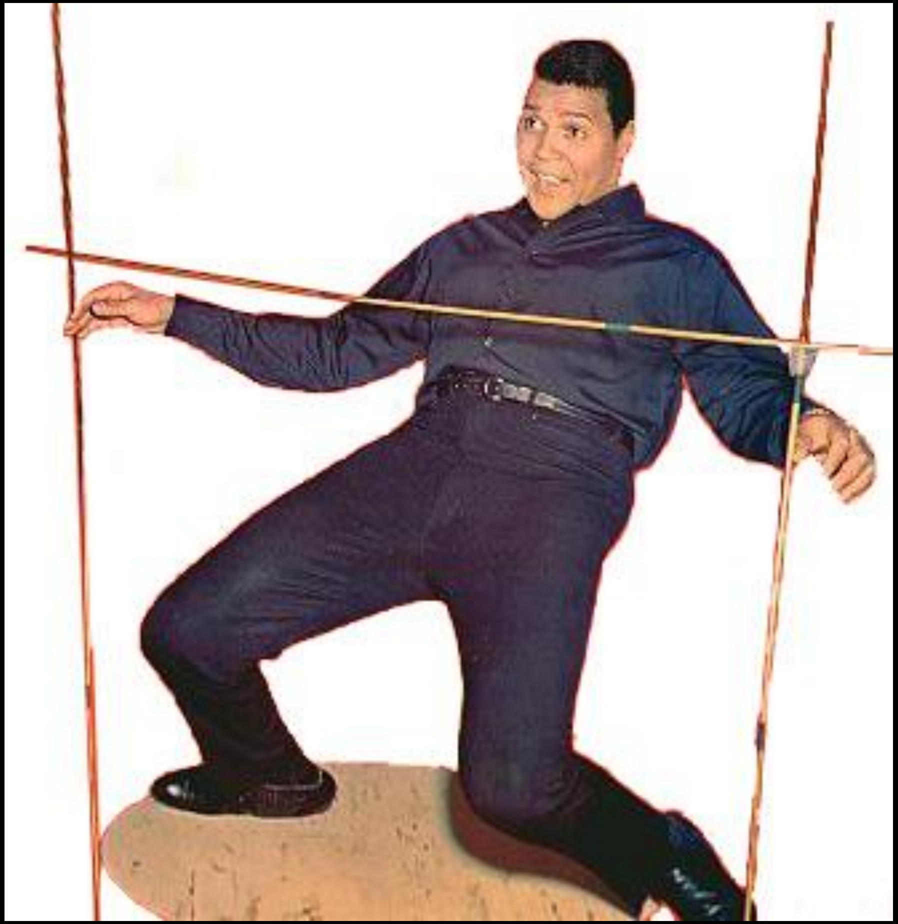
$$\sigma \; \alpha \; p$$

- 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?



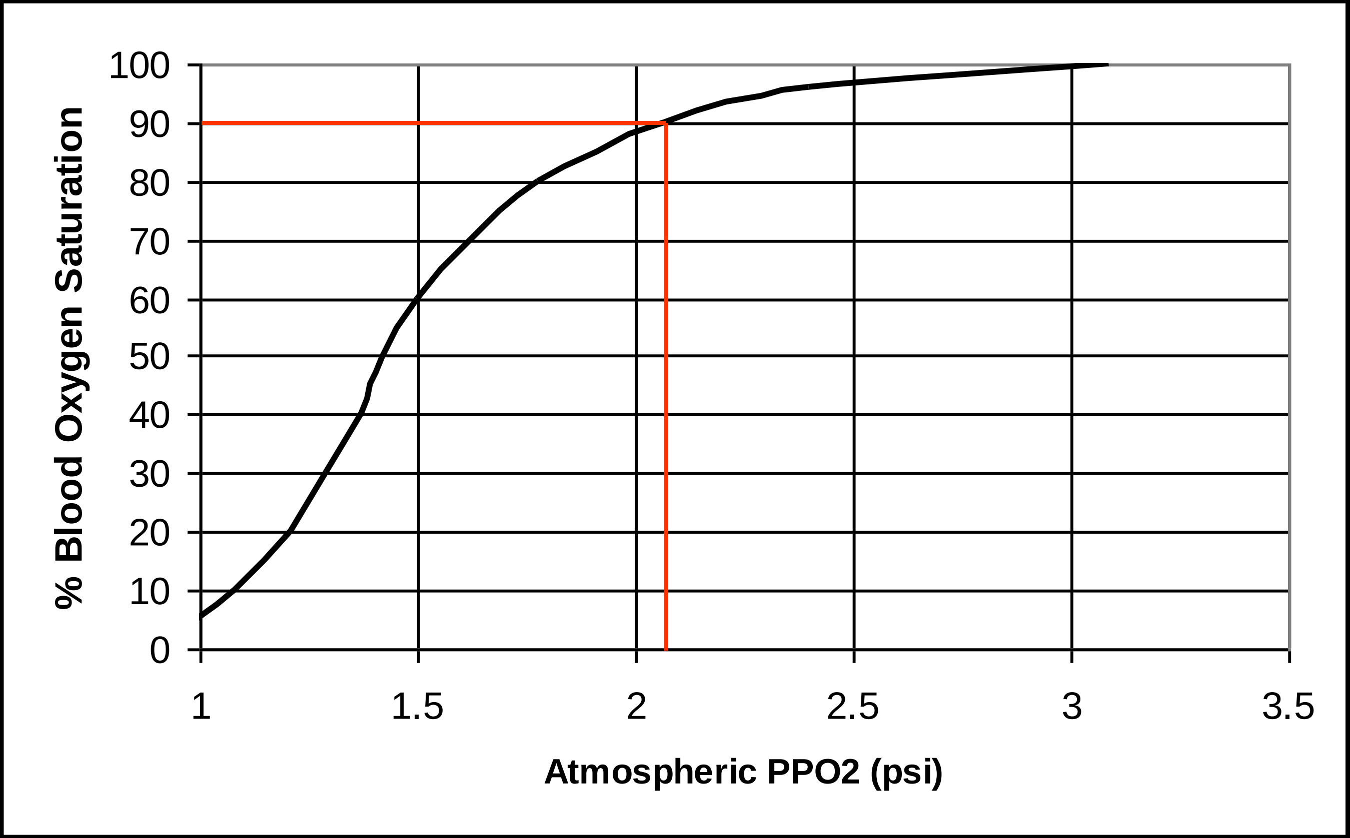
- Lower bound of design space, highest suit mobility

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)

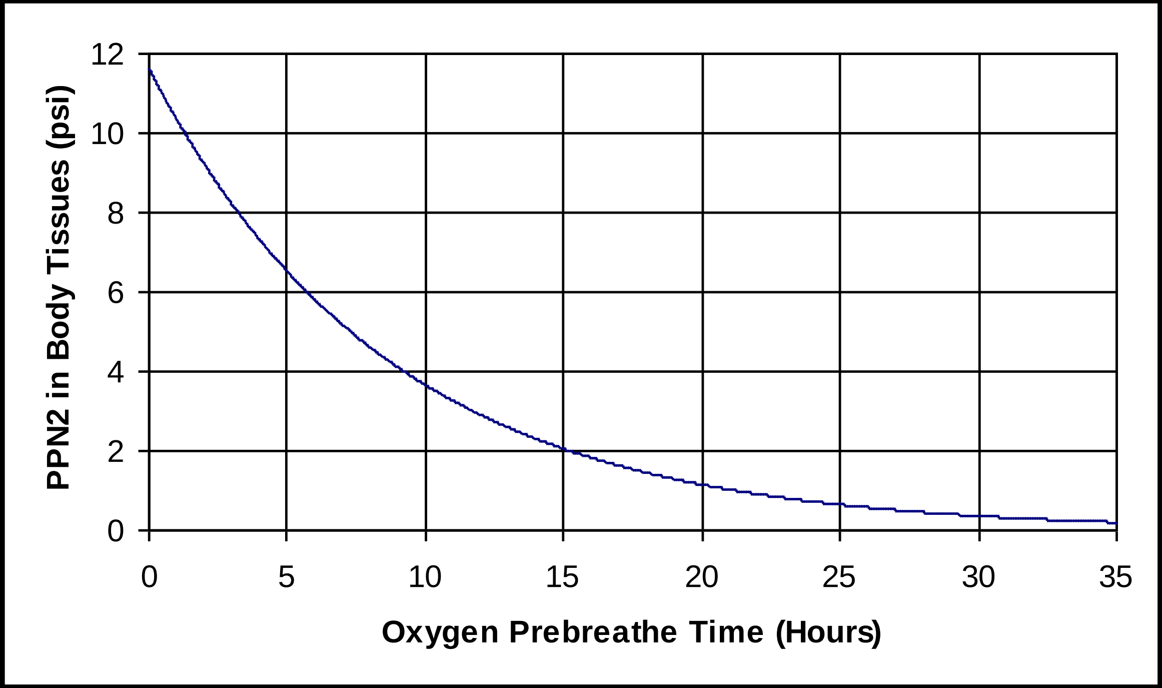
PPN_2 Body (Psi)	P_{Suit} (Psi)	R-value	1g Risk of Minor Symptoms
11.6	11.6	1	None
11.6	9.7	1.2	<2%
11.6	8.3	1.4	~5%
11.6	7.3	1.6	~20%
11.6	6.4	1.8	~45%
11.6	4.3	2.7	Huge

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

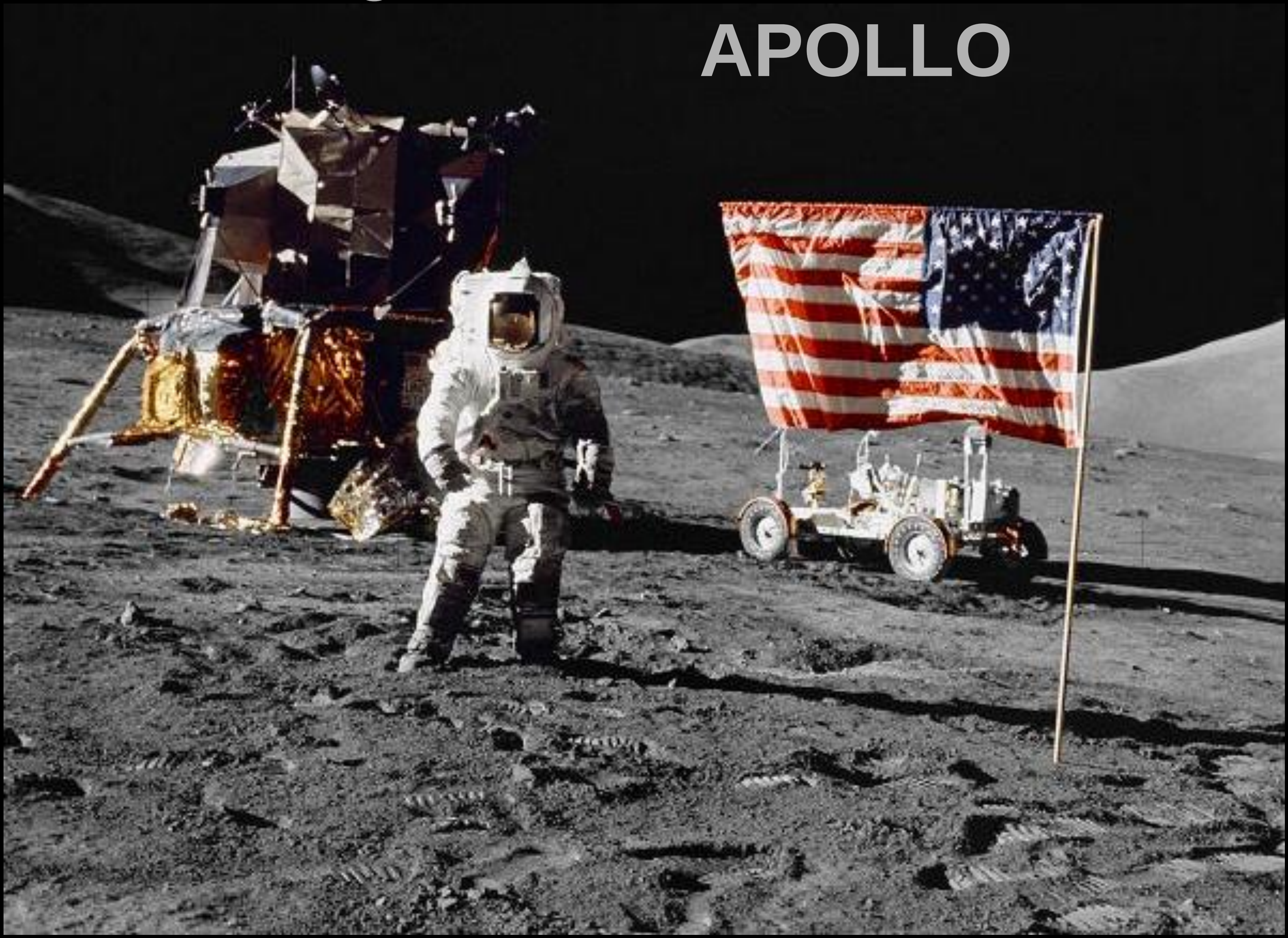
The Pressure Selection Problem

- 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

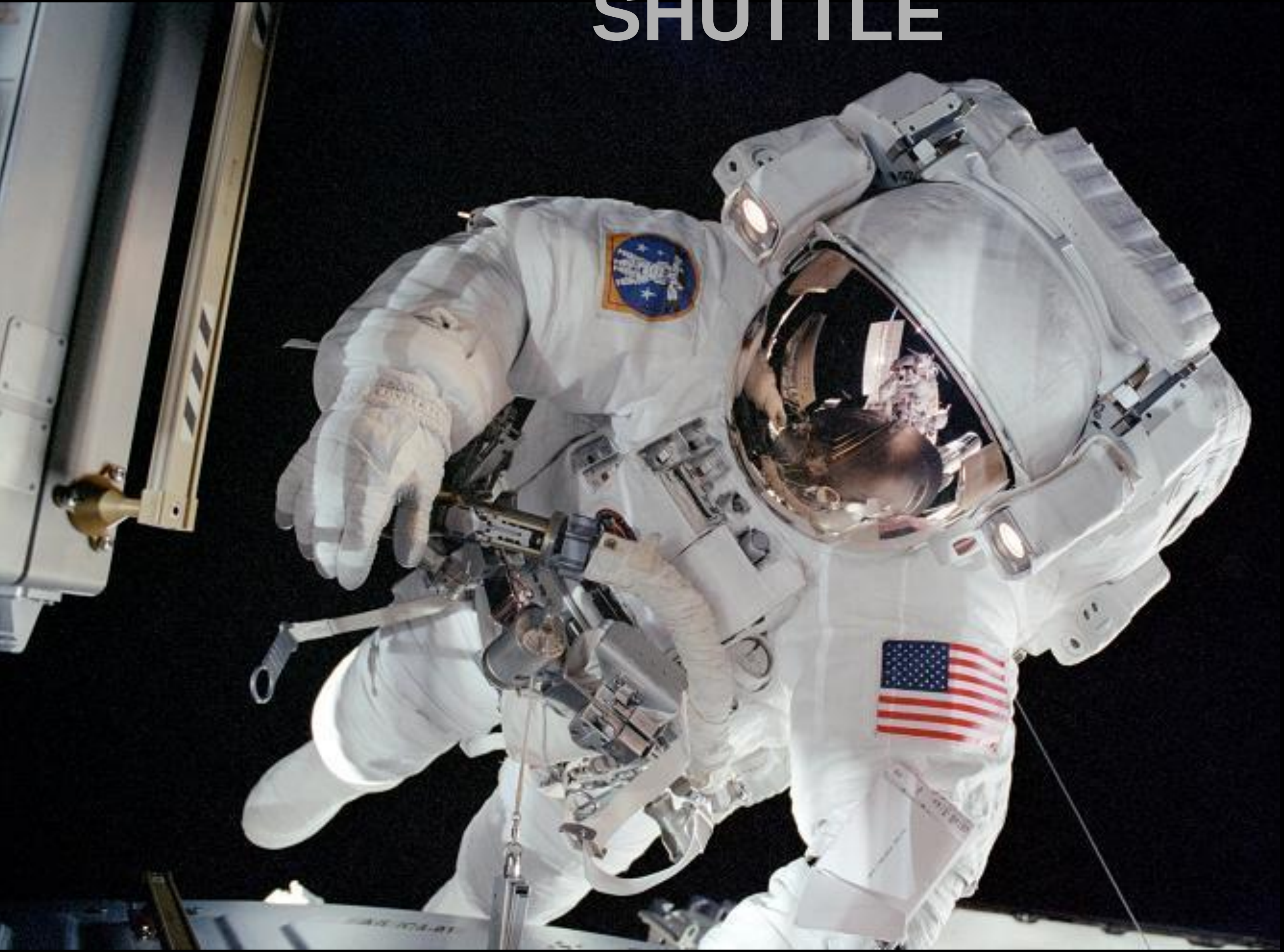
Solving the Pressure Problem:



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

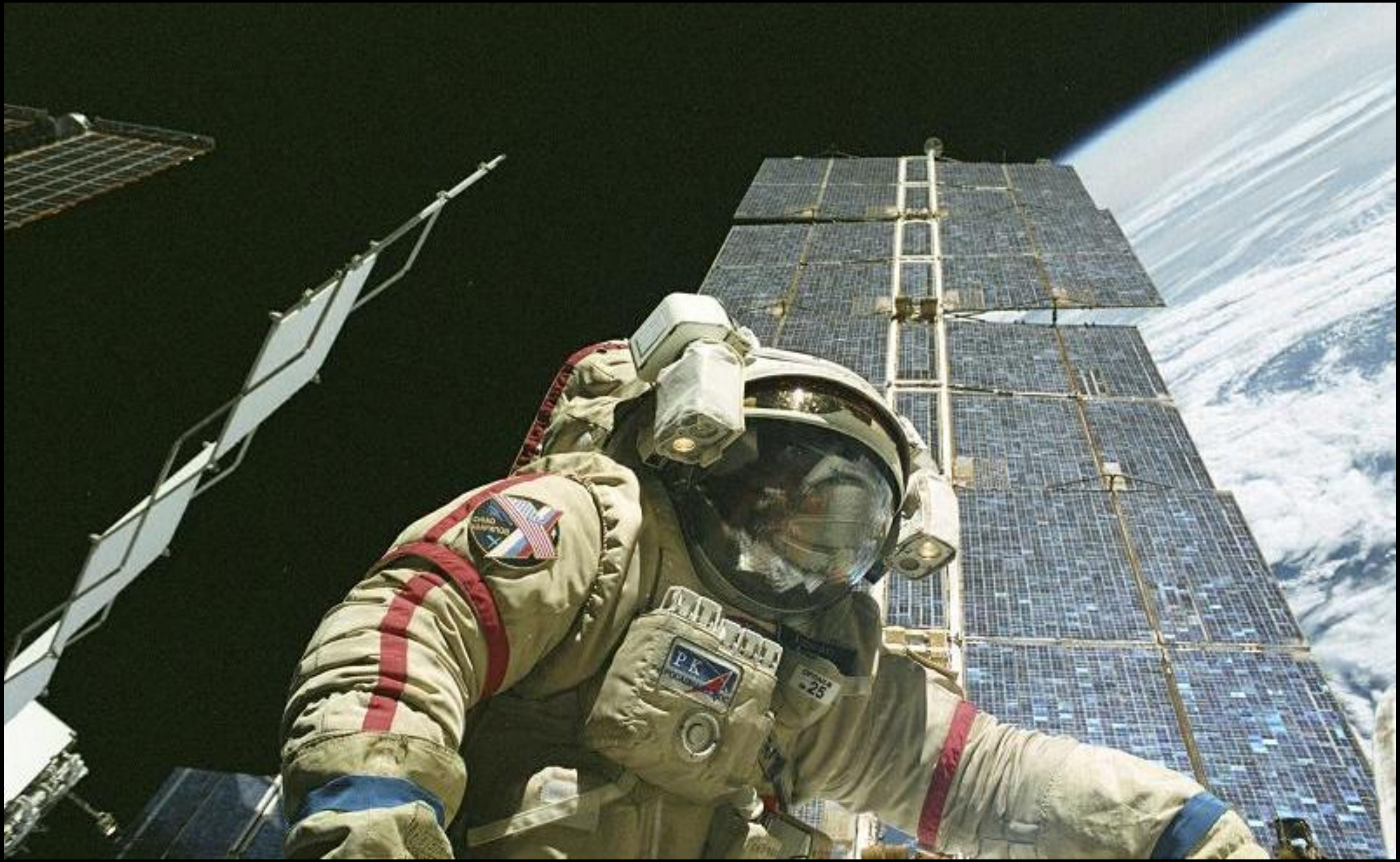
U.S. Pressure Selection – Shuttle

- 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

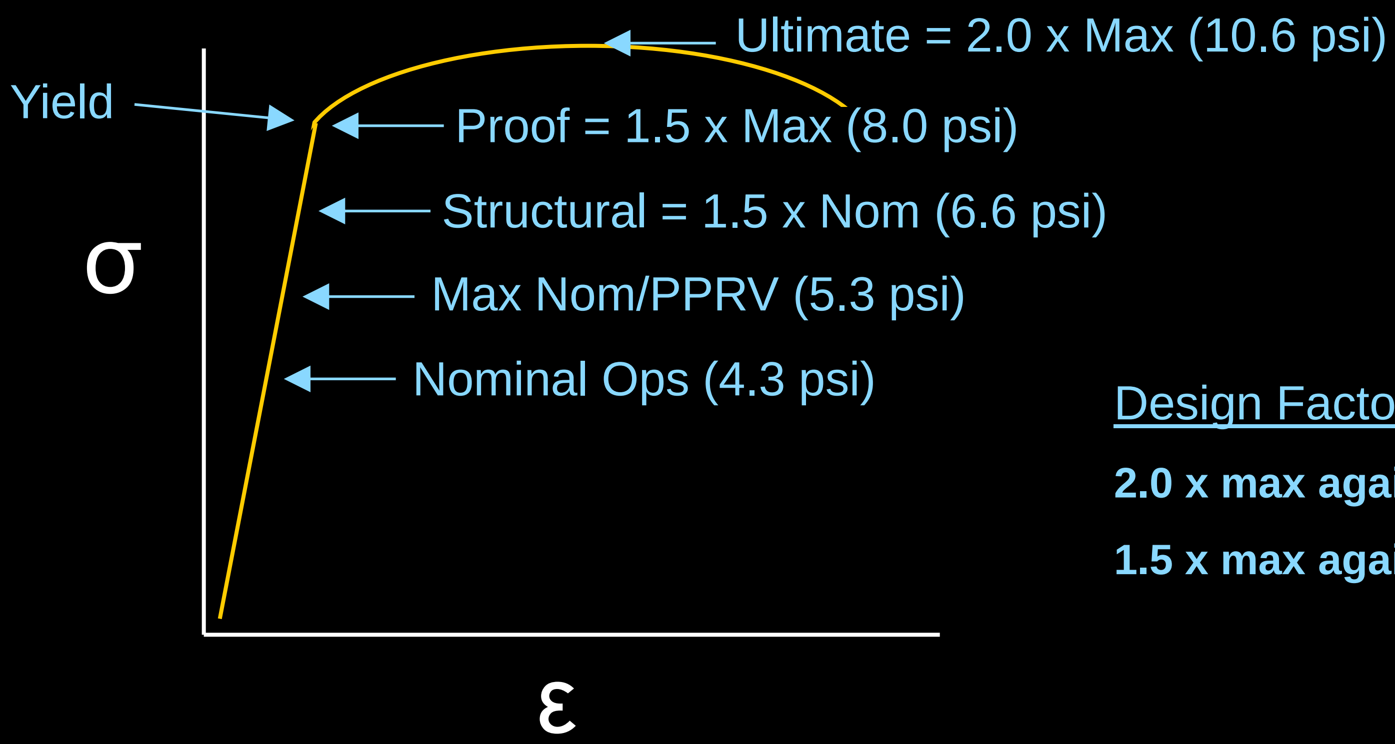
- For Nominal Operations:

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

NASA