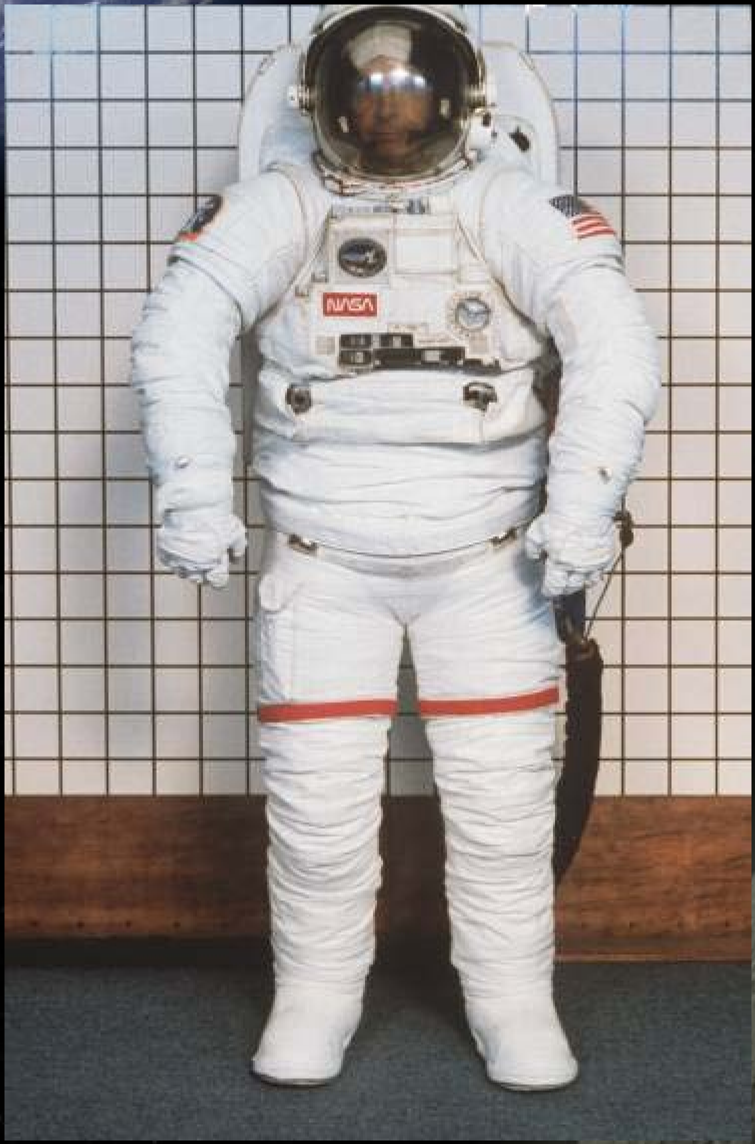
EVA Physiology, Systems & Performance (EPSP) Project

Mike Gernhardt

Overview

- Prebreathe Protocols
- Lunar Suit Testing & Development
- Lunar Electric Rover & Exploration Operations Concepts

Biomedical and Technological Challenges of EVA



- **Decompression** (denitrogenation required to work in low pressure suit (4.3 psi))
- **Thermoregulation** (-120°C to + 120°C)
- **Nutrition** (200 kcal/hr requirement)
- **Hydration** (1 liter/EVA)
- **Waste Management**
- **Radiation**
- **Micrometeoroids and Orbital Debris**
- **Suit Trauma**
- **Mobility/Dexterity:** current pressurized suits reduce mobility and dexterity
- **Visibility**

EPSP Project Overview

EVA Physiology, Systems & Performance

Integrated Decompression Stress Predictive Model

EVA Prebreathe Protocols & Physiology

EVA Biomedical Performance Reqmts. & Assessments

Adjunct Characterizations & Studies

EVA Prebreathe Protocol Testing

- Nucleation Mechanisms (NRA)
- Break-In Prebreathe (NRA)
- Saturation- Protocol I
- Prebreathe exercise saturation equivalent testing
- Variable pressure- Protocol II
- Intermittent recompression- Protocol III
- Variable Pressure- Protocol IV

:

- Final Saturation- Protocol X
- Model Validation Test
- Diluent gases
- N2 washout in µg

EVA Metabolic & Thermal Rates

- Suit metabolic cost vs. pressure & gravity
- AEVA Walk-back Test Augmentation
- EVA Task Metabolic profiles
- Ground-based EVA simulator development
- 14day Bed Rest study (w Muscle Disc.)

EVA Biomechanics & CG control

- EVA Task Analyses
- Optimum Suit/PLSS cg Study
- Reconfigurable PLSS cg rig development & testing (1/6g. 3/8g, NBL, NEEMO
- Suited contact forces/frequencies in 1/6 & 3/8g

Biomed Sensors & Control Algorithms

- Biomedical Sensors Requirements Definition
- Integrated Biomedical Vest
- Consumable Control & Regulation Algorithms
- Decompression Control Algorithm
- DCS/VGE detection devices

DCS Treatment Modalities (Identify, reduce, treat)

- Real-time In-suit treatments
- Perfluorocarbon treatment (animal studies)
- Hyperbaric Chamber Trade Studies

Related Studies & Characterizations

- USN Decompression Stress vs. g-level
- Biochemical DCS countermeasures
- Literature review to characterize Hypoxia/O2 threat
- DCS End Point characterization
- Advanced suit physiology

Exploration DCS Risk Definition & Contingency Plan

- Define policy/mission success statistics
- Risk Definition Report

EVA Countermeasures (Suit Trauma, Fatigue, Performance, Radiation)

- Suit/Human Biomechanical Interactions and Countermeasures
- Mechanisms of fingernail damage

EVA Nutrition & Delivery Systems

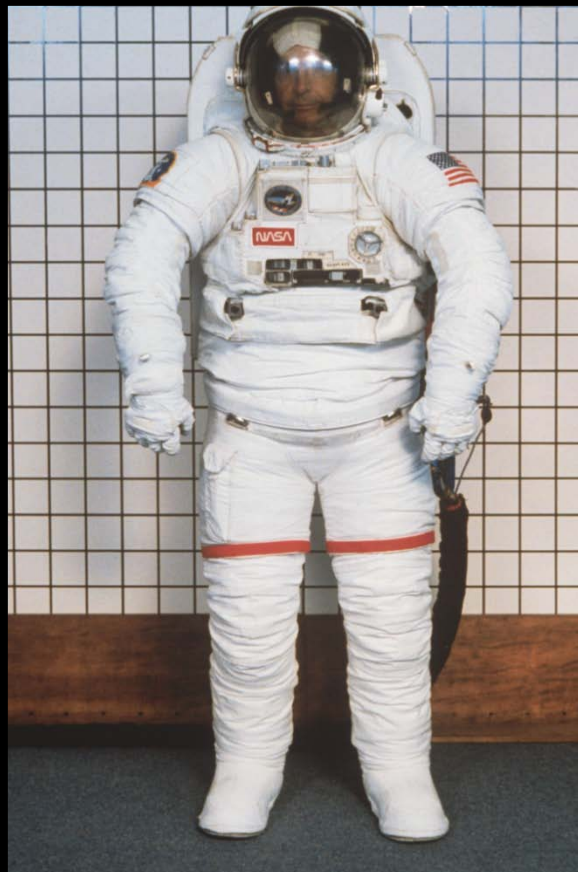
- Hydration & Nutrition Reqmts definition
- Integrated delivery systems
- Waste Mgmt

Work Efficiency Indices

- Task Efficiency Assessments
- Work Efficiency Assessments

Updated 7-18-06

EVA Suit Operates at 4.3 P.S.I



-Low pressure suit to Reduce the forces and Torques necessary to Work in vacuum

-Denitrogenation is necessary to prevent gas phase seperation that can lead to DCS

-From Boyles Law the pressure/volume response of a bubble increases at progressively lower pressures

-Lower suit pressures require increasingly more nitrogen elimination.

Why Bubbles Form

- Supersaturation (ΔP): a tendency or driving force for bubbles to form

$$\Delta P = \Sigma P_{tissue} - (P_{amb} + P_{mech})$$

  - ΣP_{gas} = sum of dissolved gas tensions & liquid vapor pressures
  - P_{abs} = absolute pressure
  - P_{mech} = “mechanical” supersaturation (surface tension, tissue elasticity decrease ΔP or mechanical tensile forces which can increase ΔP)

How Bubbles Form

- *De novo* nucleation - "from nothing"
  - ΔP = 1,300 atm with no dissolved gases
  - ΔP = 120-240 atm with dissolved gases
  - Impossible to have altitude DCS without "Gas nuclei"
- "Gas nuclei" - pre-existing gas cavities, or generation from localized muscoskelatal stresses or other mechanisms
  - ΔP < 1 atm
    - Diving: 12 hours at 12 fsw (ΔP = 0.4 atm)
    - Altitude exposure: 12,000 feet (ΔP = 0.4 atm)
    - Gibbs Free energy calculations suggest that bubble nuclei of 2-3 microns must exist, or form normally during decompression.

"Tribonucleation"

- Mechanical supersaturation

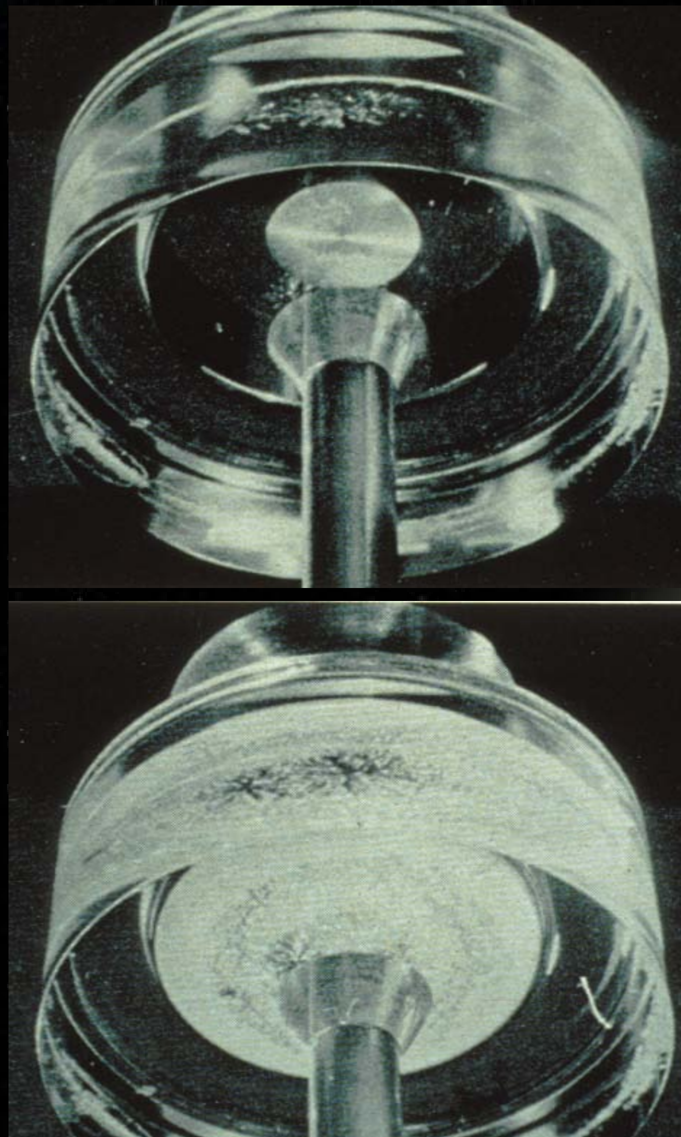
  $\Delta P = P_{gas} - P_{a} - P_{mech}$

  $\Delta P_{mech} \sim -1{,}000$ atm

  – *de novo* nucleation
- Viscous adhesion
  – Seperation of surfaces immersed in a viscous fluid can generate large tensile forces. (Function of the seperation velocity and the viscosity of the fluid)
  – opposite to mechanism of lubrication
  – cavitation on machinery
  – "vacuum phenomena" in joints

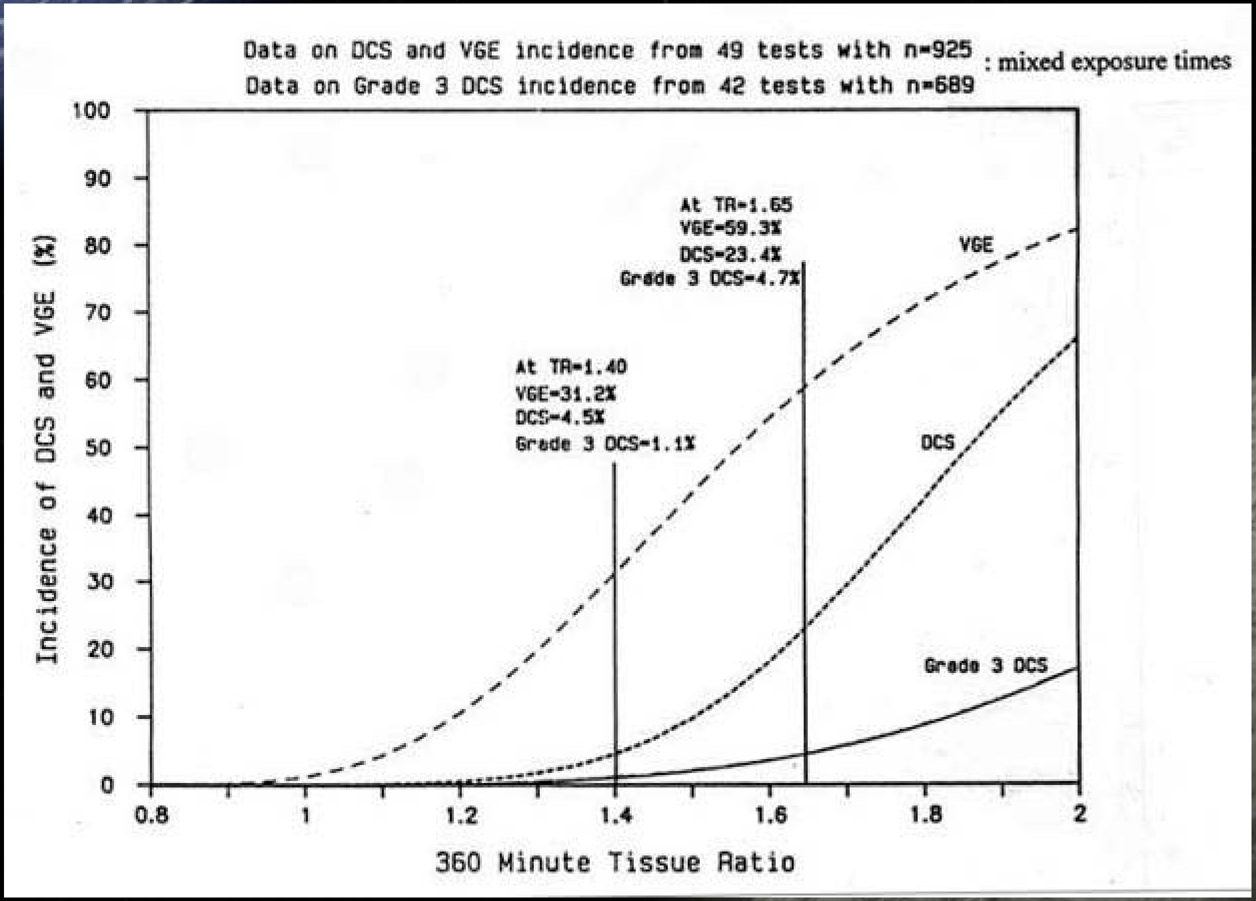
Viscous Adhesion

- Cottrell (1964)



- **Liquid fractures when surfaces separate too fast for viscous liquid to flow into gap**
- **Fracture is due to negative pressures approaching 1,000 atm**
- **Muscle contractions, tendons contraction/relaxation, cyclic loading from walking -potentially can generate negative pressures resulting in the constant formation of bubble nuclei- (dynamic equilibrium, with nuclei constantly forming and resolving under the driving force of surface tension)**

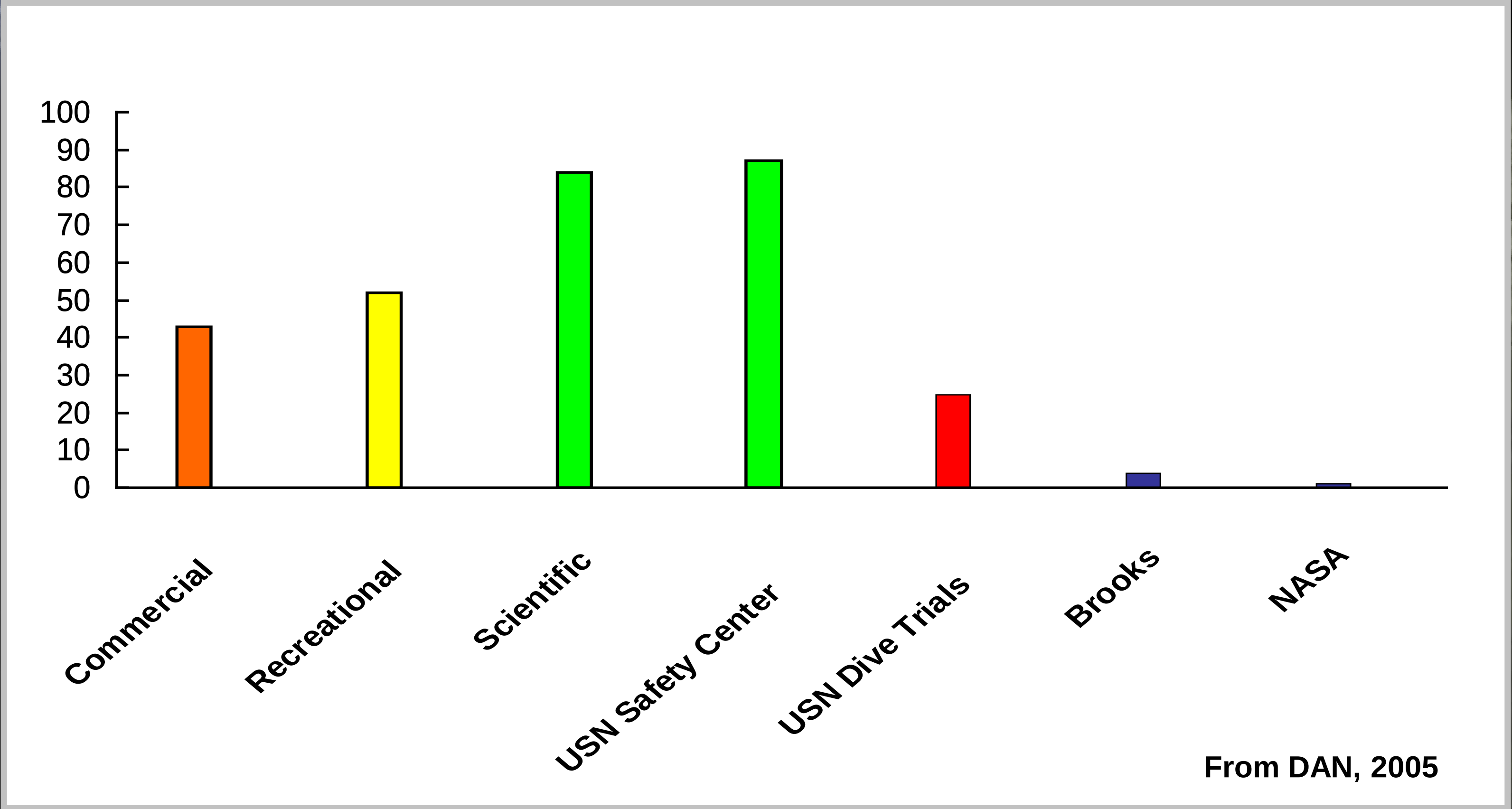
Shuttle Pre-breathe Ground Studies



Two Pre-breathe protocols approved for flight operation

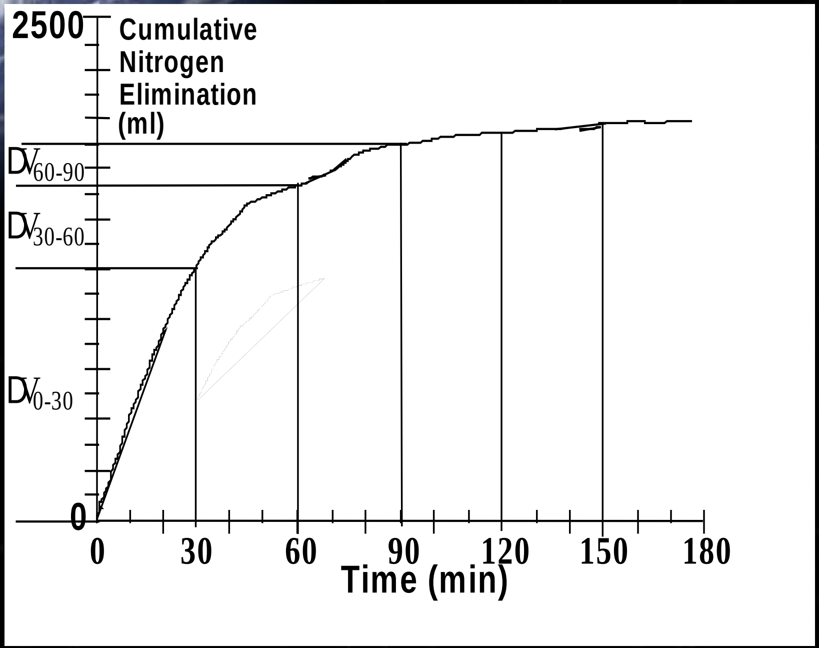
- **4 hour in-suit resting oxygen pre-breathe**
- **12 hr 10.2 psi staged decompression procedure**
- **R value (tissue tension (360)/suit pressure)= 1.65**

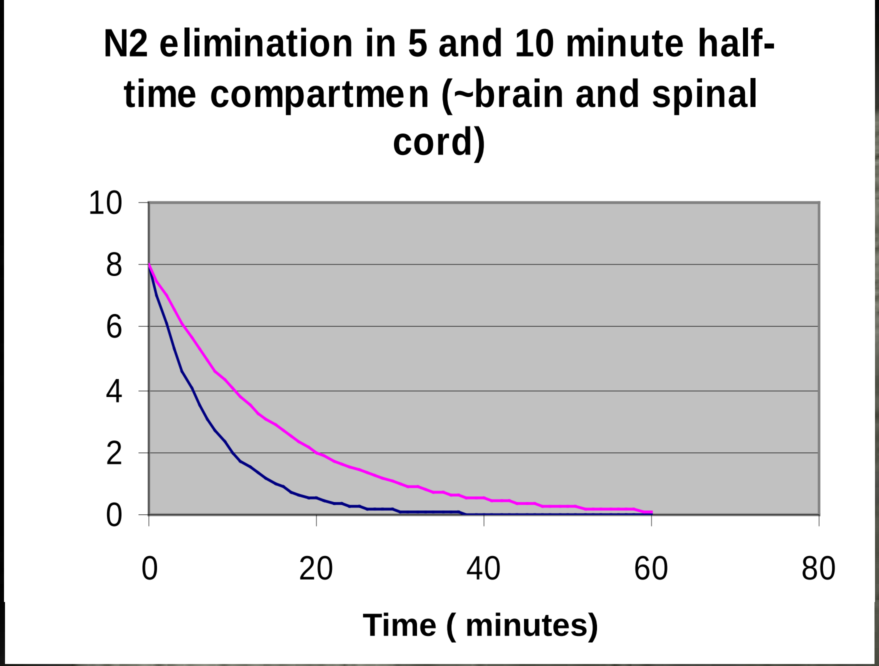
Type II DCS – Percentage of All DCS vs. Diving Methods



- Character of Altitude DCS Different from Diving DCS
- Undersaturated Neurological Tissues
- "Softer Bubbles" Metabolic Gases

Altitude DCS - Nitrogen Elimination during Oxygen Prebreathe

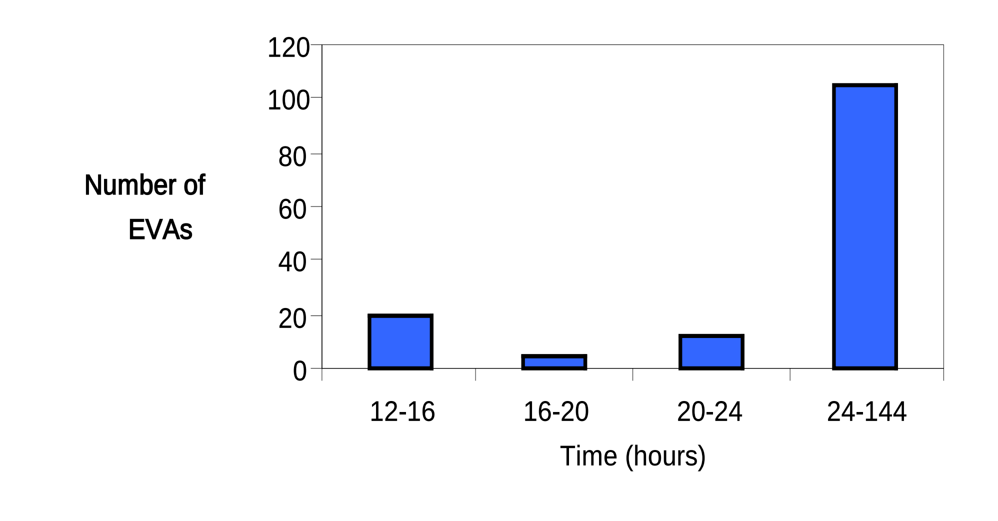




- Over 50% of nitrogen eliminated in first 30 minutes
- Brain, spinal cord Halftime ~ 5-10 minutes, muscle and skin halftimes
    - 15-25 minutes at resting conditions
- Resting prebreathe reaches point of diminishing return for reducing pain only DCS
- Type II DCS incidence higher on “Zero Prebreathe”

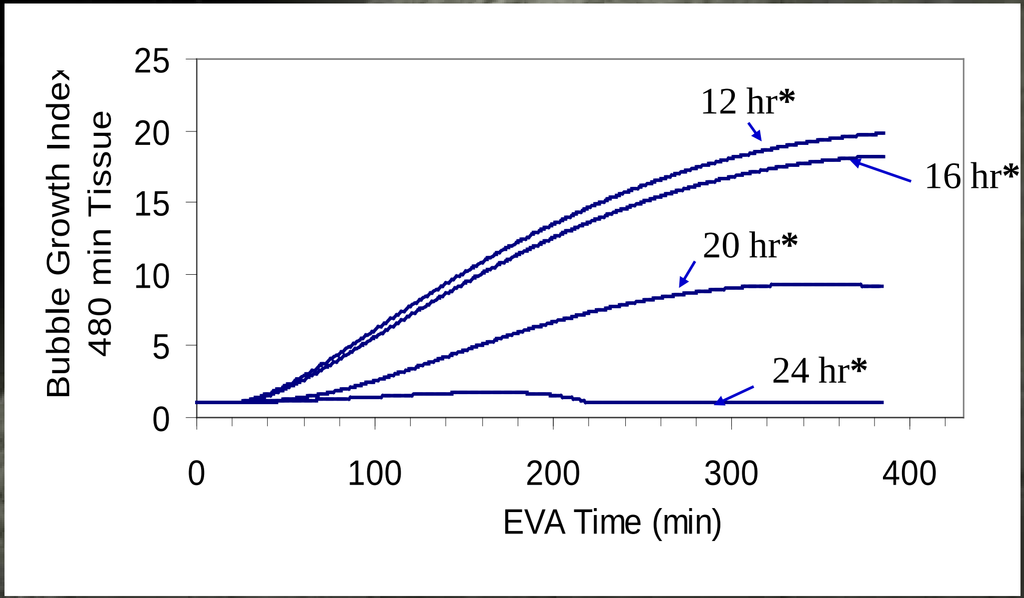
Gerth, W.A., R.D. Vann, N.E. Leatherman, and M.D. Feezor. 1987. Effects of microgravity on tissue perfusion and the efficacy of astronaut denitrogenation for EVA. Aviat. Space Environ. Med. 58(9, Suppl.): A100-105

Flight Experience Shuttle 10.2 psi Staged Protocol – Zero DCS



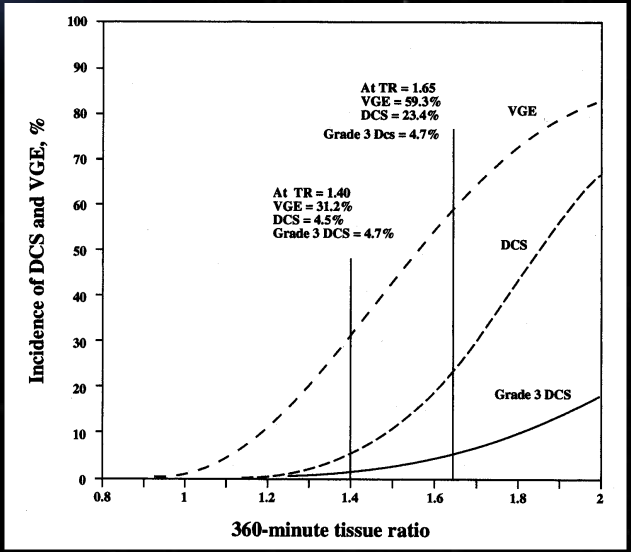
Time at 10.2 psi prior to shuttle EVA

Theoretical Tissue Bubble growth as a function of 10.2 exposure time



Defining and Controlling Risk in Operational Research Programs – Example of Prebreathe Reduction Program (PRP)

Background



Shuttle Prebreathe Ground Trials (~ 25% DCS, ~ 5% symptoms that would terminate an EVA.) Acceptable Risk?

- 4 hour prebreathe

- 10.2 psi staged protocol

- 146 EVAs exposures with no reports of DCS

ISS Overnight Campout

Limitations

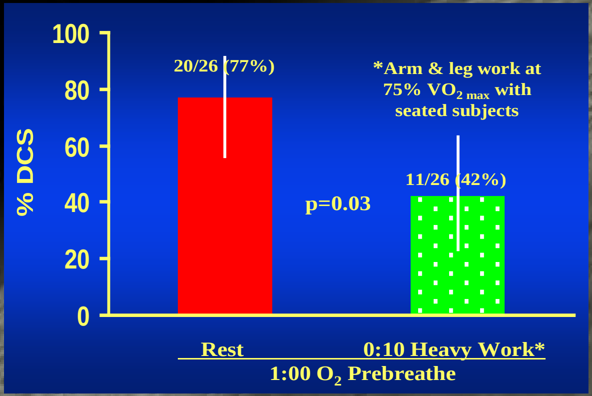
•Timeline, back to back EVAs,

•02 usage,ISS 02 concentration

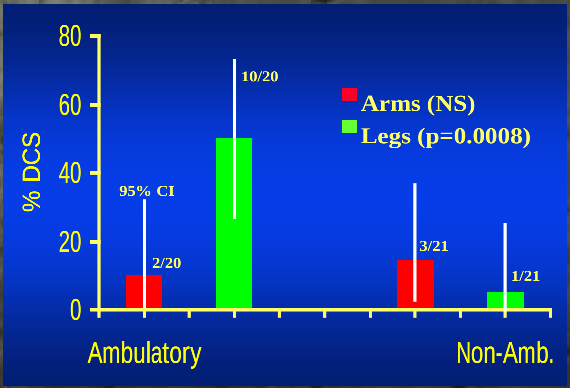
•crew isolation and comfort

Enabling Counter Measure Research

(NASA TRL 3/4)



USAF prebreathe exercise



Duke, NASA micro-gravity simulation (non ambulation)

Enabling Research

Air Force Research Laboratory

Brooks AFB, Texas

Dual-Cycle Ergometer used for Exercise-Enhanced Prebreathe

10 minutes 75% V02peak, 88% lower body, 12% upper body

ORIGINAL RESEARCH

Exercise-Enhanced Preoxygenation Increases Protection From Decompression Sickness

JAMES T. WEBB, M.S., Ph.D., MICHELE D. FISCHER, B.S., CRISTINE L. HEAPS, B.S., M.A., and ANDREW A. PILMANIS, M.S., Ph.D.

WEBB JT, FISCHER MD, HEAPS CL, PILMANIS AA. *Exercise-enhanced preoxygenation increases protection from decompression sickness.* Aviat Space Environ Med 1996; 67:618–24.

Introduction: Prevention of decompression sickness (DCS) during exposure to altitude equivalents of 30,000 ft (9144 m) requires extensive denitrogenation. In preparation for extravehicular activity (EVA), present NASA policy is to denitrogenate using a 10.2 psia staged decompression of the entire shuttle for at least 12 h, including 100 min of preoxygenation (breathing 100% oxygen at 14.7 psia prior to decompression), before decompression to the 4.3 psia (30,000 ft; 9144 m) suit pressure. This staged decompression provides the same or better protection from DCS as a 3.5- or 4-h preoxygenation used on earlier Shuttle EVA's. For high altitude reconnaissance flights at similar cockpit altitudes, a 1-h preoxygenation is currently required. ***Methods:*** We have investigated the use of a 1-h and a 15-min preoxygenation period, each beginning with 10 min of dual-cycle ergometry performed at 75% of each subject's peak oxygen consumption ($\dot{V}O_{2peak}$) to enhance preoxygenation efficiency by increasing perfusion and ventilation. Male subjects accomplished a 1-h preoxygenation with exercise, a 15-min preoxygenation with exercise, or a 1-h resting preoxygenation before exposure to 4.3 psia for 4 h while performing light to moderate exercise. ***Results:*** Incidence of DCS following the 1-h preoxygenation with exercise (42%; n = 26) was significantly less than that following the 1-h resting preoxygenation (77%; n = 26). Incidence and onset of DCS following the 15-min preoxygenation with exercise (64%; n = 22) was not significantly different from the incidence following the 1-h resting control. ***Conclusion:*** Preoxygenation with exercise has been shown to provide significantly improved DCS protection when compared with resting preoxygenation.

EXPOSURE TO THE ALTITUDE equivalent of 30,000 ft (4.3 psia; 9144 m) during extravehicular activity (EVA) or high altitude reconnaissance flight involves a risk of decompression sickness (DCS) (18,21). Formation and growth of gas emboli are believed to have a central role in the clinical manifestations of DCS. Venous gas emboli (VGE) and tissue gas emboli are formed due to tissue supersaturation with nitrogen following decompression from ground level.

Denitrogenation is the process of removing nitrogen from the tissues by inspiring gas with a lower partial pressure of nitrogen than contained in the body fluids and tissues. Denitrogenation reduces the potential for nitrogen supersaturation and subsequent gas emboli formation during the decompression. Breathing 100% oxygen prior to decompression (preoxygenation or prebreathing) is a common method of denitrogenating to reduce the risk of DCS (26). Improvement in denitrogenation efficiency would have application in both the space program and high altitude aviation.

Denitrogenation before extravehicular activity (EVA): Prior to EVA from the Space Shuttle's 14.7 psia environment (160 mm Hg PO_2), a staged decompression is the primary method of denitrogenation (21) because it has been shown to provide protection comparable to a 4-h preoxygenation at 14.7 psia. The staged decompression procedure begins with 1 h of preoxygenation at 14.7 psia, followed by decompression of the entire Shuttle to 10.2 psia for at least 12 h while the crew breathes 26% oxygen (137 mm Hg PO_2; equivalent to breathing atmospheric air at about 4200 ft; 1280 m), and then an additional 40-min period of breathing 100% oxygen at 10.2 psia before decompression to 4.3 psia. The staged decompression results in a 360-min theoretical tissue ratio (TR) of nitrogen (Final Tissue pN_2/Absolute Ambient Pressure) that is close to the TR resulting from a 4-h preoxygenation (1.70 vs 1.60; 8). However, the staged method also results in engineering problems such as reduced instrument cooling capacity due to lower air density. Time-efficient preoxygenation techniques allowing decompression directly from 14.7–4.3 psia while providing protection comparable to staged decompression would be preferable.

Preoxygenation before high altitude flight: A 1-h preoxygenation is presently required prior to most high-altitude flights. Surveys of the high altitude reconnaissance community (both active and retired) have revealed that over 60% had experienced DCS and that 4.2% of the flights involved symptoms; many with neurologic involvement (5). An improvement in the preoxygenation procedure could increase pilot safety and enhance operational efficiency and responsiveness.

From KRUG Life Sciences Inc. (J. T. Webb, M. D. Fischer, and C. L. Heaps); and High Altitude Protection Research, Armstrong Laboratory (A. A. Pilmanis), AL/CFTS, 2504 Gillingham Drive, Suite 25, Brooks AFB, TX.

This manuscript was received for review in April 1995. It was revised in September and December 1995, and was accepted for publication in December 1995.

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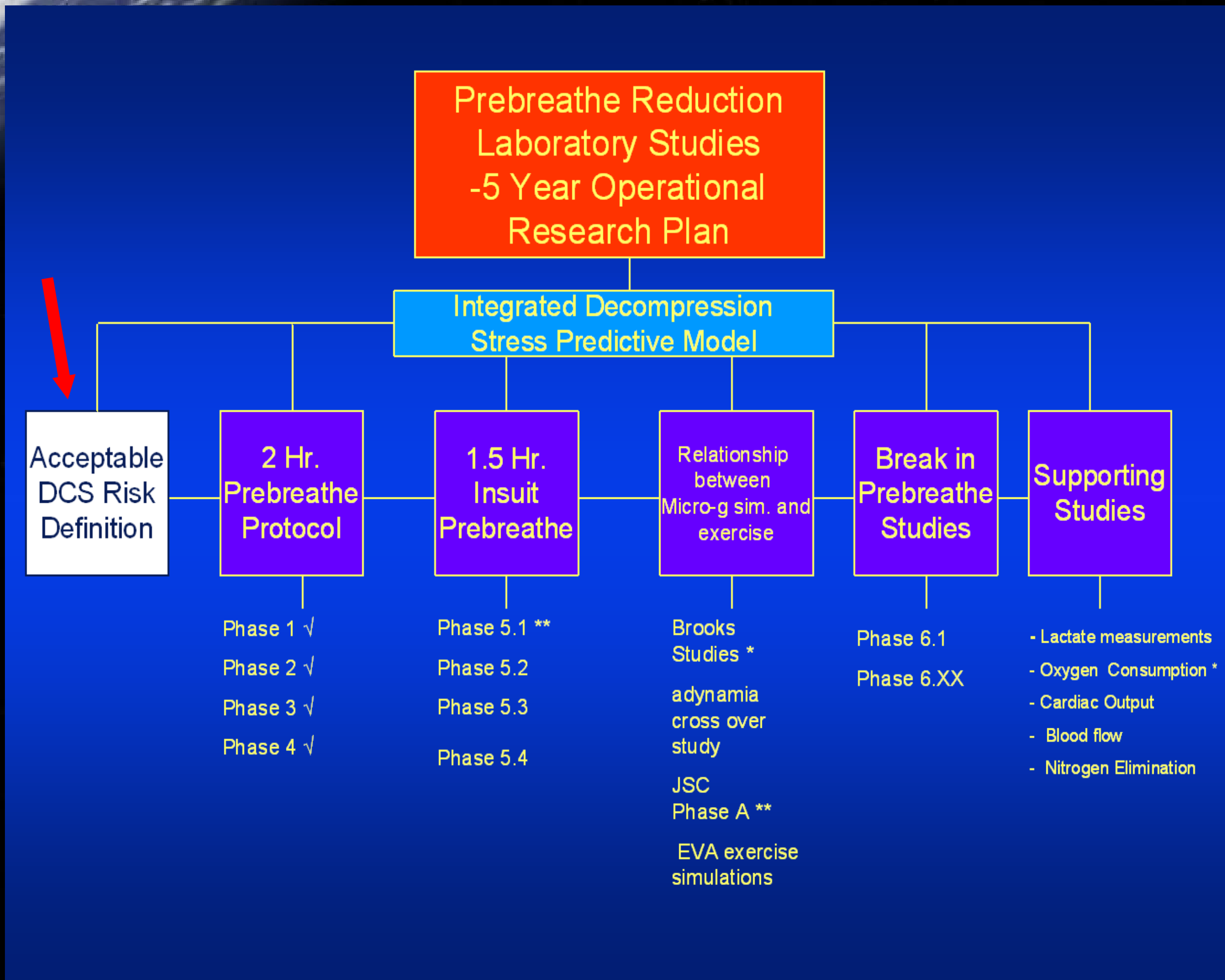
Prebreathe Reduction Program



- Start by defining acceptable DCS risk for ISS mission and developing accept/reject limits for countermeasure trials
- Early development focused on delivering acceptable/effective counter measure
- Later development focused on increased efficiency and improved scientific understanding of counter measure mechanisms

Accept: DCS $\leq$ 15% and Grade IV VGE $\leq$ 20% , @ 95% C.I

Reject: DCS $\geq$ 15% or Grade IV VGE $\geq$ 20% , @ 70% C.I

Multi-Center Study: NASA, Duke, DCIEM, Hermann UT

Exercise 10 mins @ 75% $V02_{peak}$
And/or light exercise (160-253 Kcal/hr)

2hr oxygen prebreathe

Micro-gravity simulation
(non-ambulation)

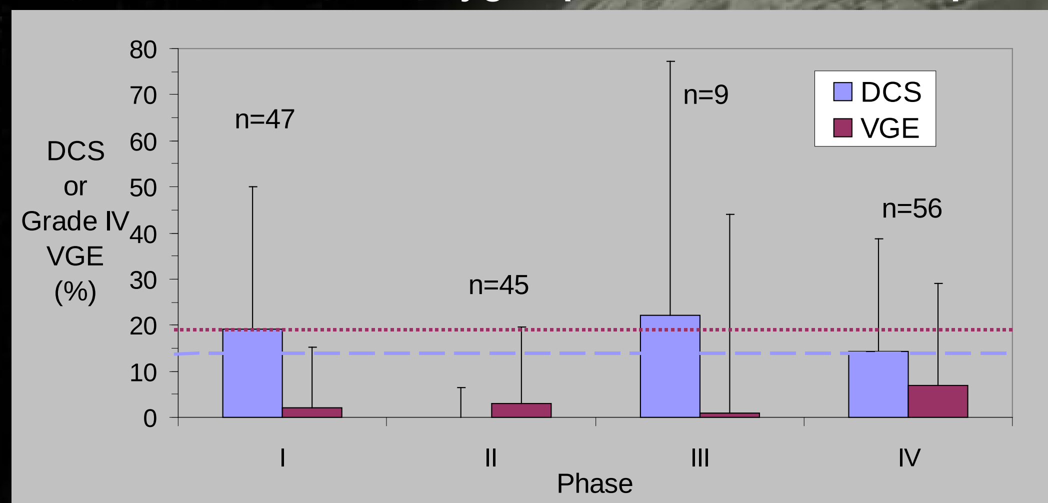
Simulated EVA exposure at
4.3 psi 4 hrs

Use of “Suit Simulator” for
EVA Exercise

Prebreathe Trials

Phase	Prebreathe protocol		4 hr EVA Simulation	DCS
Phase I	Rest	10 min 75% $VO_{2\ peak}$	4 hr EVA Simulation	19%
Phase II	Rest	10 min 75% $VO_{2\ peak}$; 40 min Light Activity		0%
Phase III	Rest	40 min Light Activity		22%
Phase IV	Rest	95 min Light Activity		14%

PRP Phase I-IV 2 hr oxygen prebreathe exercise protocols



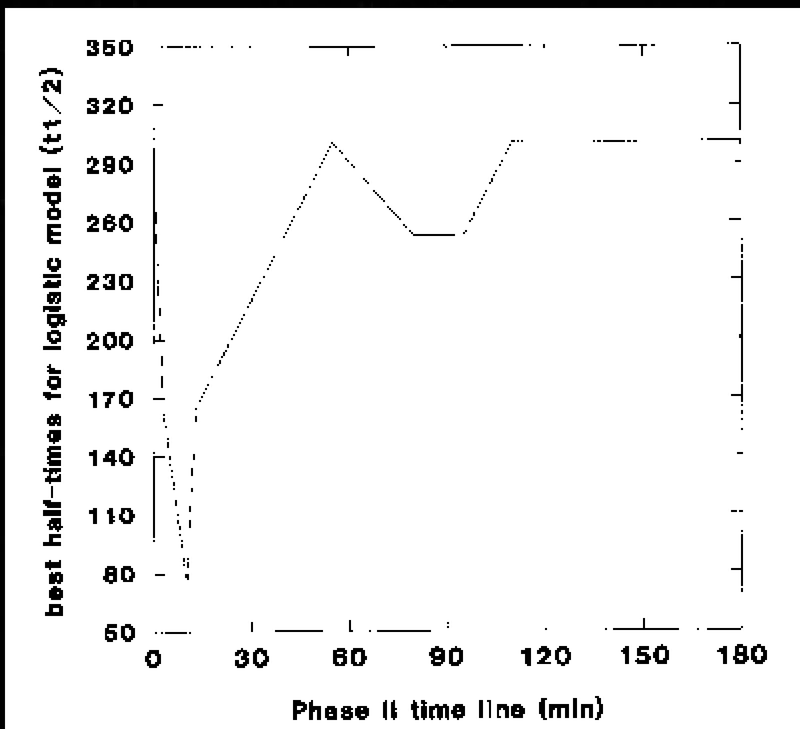
- **High intensity exercise (75% peak oxygen consumption [$VO_{2\ peak}$])**
- **Low intensity activity (5.8 $mL \cdot kg^{-1} \cdot min^{-1}$ VO_2)**
- **Neither High or low intensity exercise was acceptable**
- **Coupling High with low intensity exercise was acceptable**

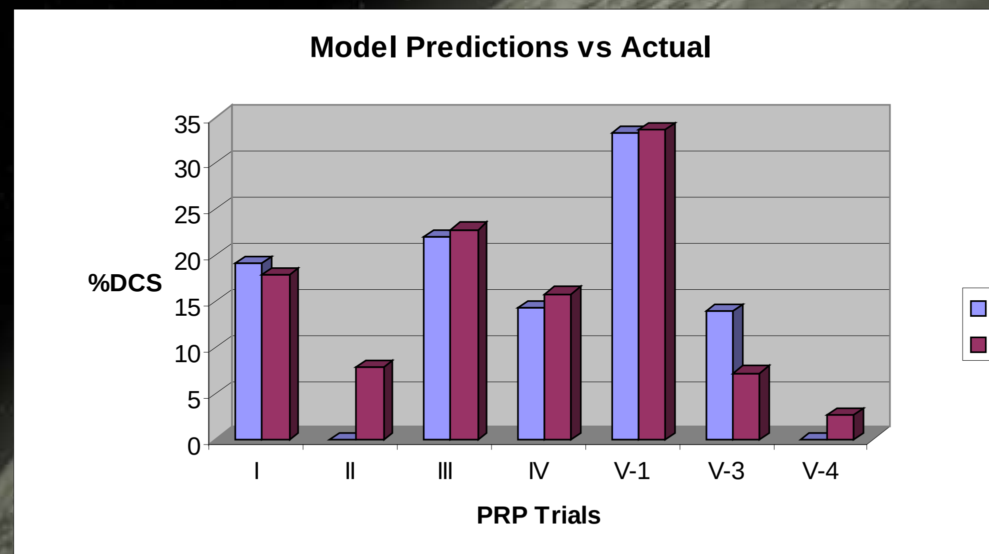
DCS and Grade IV VGE observations (shown with 95% upper confidence limit bars dashed lines indicating accept levels for DCS and VGE incidences)

Exercise and Inert Gas Kinetics

$$P1N2 = P0 + (1 - \exp - k1t) * (Pa - P0),$$

$$k1 = [(1 / \exp(-\lambda * mL*kg-1*min-1)) / 519.37].$$





Hosmer-Lemshow Goodness of fit statistic = 2.188 with 5 degrees of freedom, p = 0.82 (significance > .05)

Exercise Prebreathe Protocol: Experience to Date

- Overview- The exercise prebreathe protocol has been used successfully on 34 EVAs from the International Space Station (ISS)- no DCS
  - Five Shuttle assembly flights and two increment EVAs
    - Starting in July 2001
  - These assembly missions would have been difficult or impossible to execute as base-lined, without the protocol

A United States Airlock: Doorway to Space

U.S. “Quest” Airlock

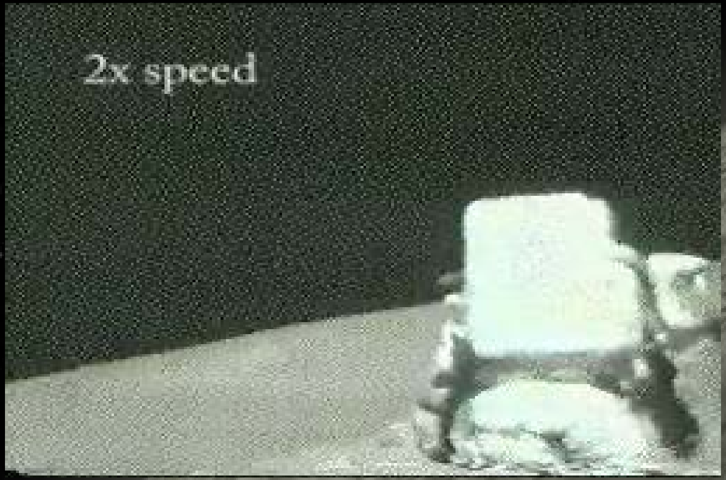
ISS Campout

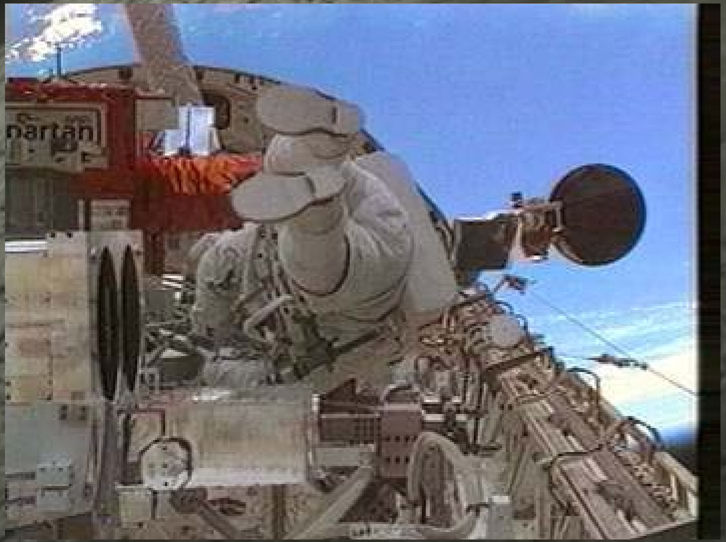
- 60 mins prebreathe prior to 8hrs 40 mins at 10.2 psi, 26.5% O2 during sleep
- Wake up, don O2 masks, repress airlock to 14.7 psi
- 70 minute hygiene break (on O2 mask)
- Return to 10.2 psi, 26.5% O2 for 60 mins for breakfast and suit donning
- Repress in suit to 14.7 psi 100% O2
- 50 minute in-suit prebreathe

59 pairs of spacewalkers have used the Campout protocol

The Challenge of Moving Past Apollo

- Apollo was a remarkable human achievement
- Fewer than 20 EVAs, maximum of three per mission
- Constellation Program, up to 2000 EVAs over the 10 year Lunar program
- Limited mobility, dexterity, center of gravity and other features of the suit required significant crew compensation to accomplish the objectives. It would not be feasible to perform the constellation EVAs using Apollo vintage designs
- The vision is to develop an EVA system that is low overhead and results in close to (or better than) one g shirt sleeve performance i.e. “ A suit that is a pleasure to work in, one that you would want to go out and explore in on your day off”
- Lunar EVA will be very different from earth orbit EVA – a significant change in design and operational philosophies will be required to optimize suited human performance in lunar gravity

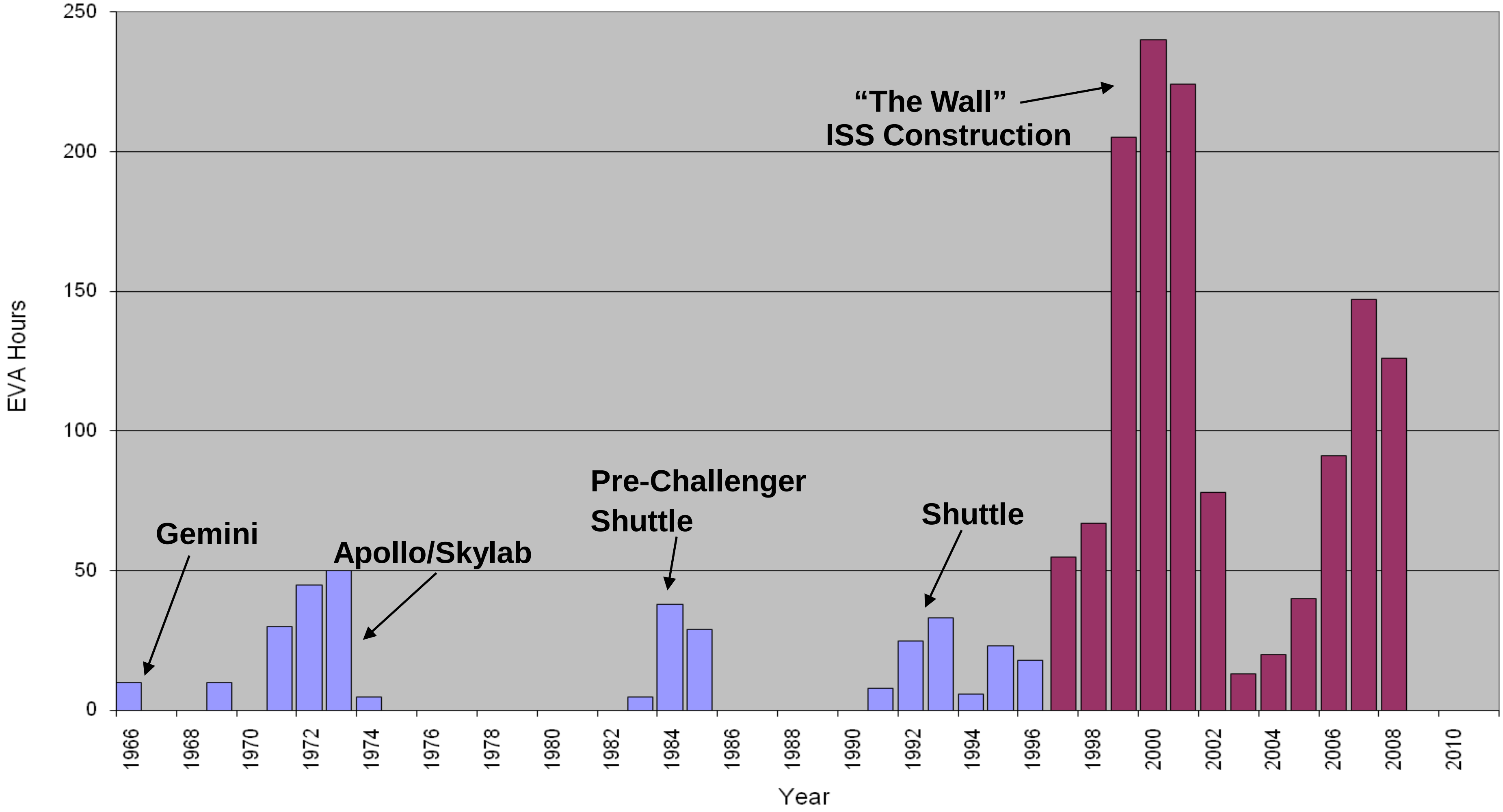




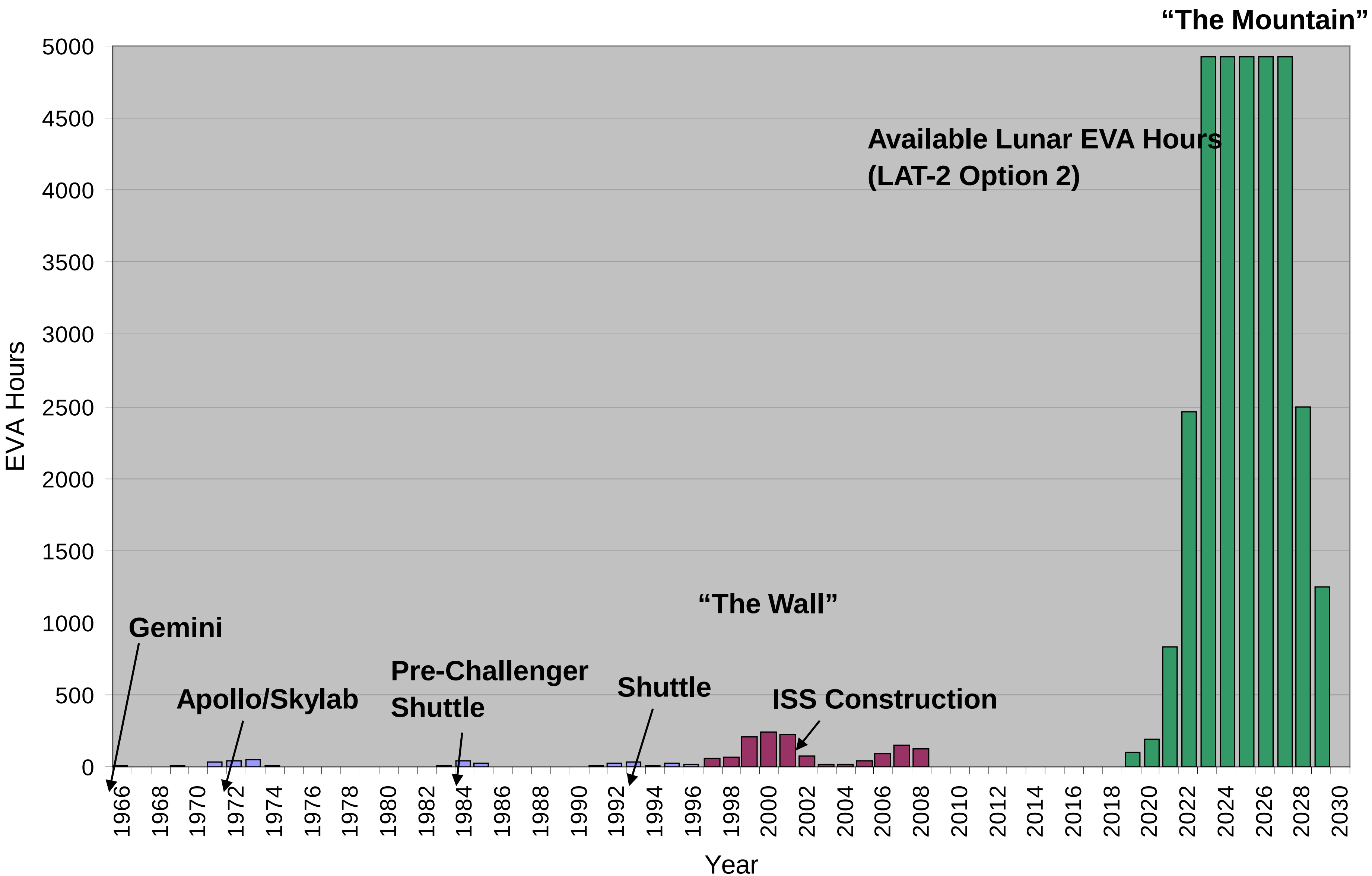
Challenges for EVA on the Moon

- **Dealing with risk and consequences of a significant Solar Particle Event (SPE)**
- **Long duration missions with three 8hr EVAs per person per week**
  - Apollo suits were used no more than 3 times
  - Individual crewmembers might perform up to 76 EVAs in a 6-month mission
  - Suit-induced trauma currently occurs with even minimal EVA time
- **With Apollo style un-pressurized rover (UPR), exploration range is limited by EVA sortie time and 10 km walkback constraint**
  - Science community input that optimal scientific return within this range could be accomplished within ~ 30 days of EVA
  - Two UPRs could extend exploration range up to 15-20 km (crew-day limited)
- **Apollo highlighted the importance of dust control for future long duration missions**
- **Increased Decompression Sickness (DCS) risk and prebreathe requirements associated with 8 psi 32% O_2 cabin pressure versus Apollo with 5 psi 100% O_2**
- **The high frequency EVA associated with the projected lunar architectures will require significant increases in EVA work efficiency (EVA prep time/EVA time)**

"The Wall of EVA"



"The Mountain of EVA"



EVA Walkback Test – Objectives & Products

- Energy -velocity tests vs. gravity level - Earth, Lunar and Mars
- Transition speeds
- 10 Km walk back
- Metabolic Costs
- Ground reaction forces and time series motion analysis
- Skin and core temperatures, EKG, Cooper Harper, RPE

Primary Objective:

- Collect biomedical and human performance data and produce a crew consensus regarding the feasibility of performing a suited lunar 10 km ‘Walk back’.

Products:

- Understanding of biomedical & performance limitations of the suit compared to weight matched unsuited controls
- Data to estimate consumables usage for input to suit and portable life support system (PLSS) design
- Metabolic & ground reaction force data to allow development of an EVA simulator to be used on future prebreathe protocol verification tests
- Assessments of cardiovascular & resistance exercise associated with partial gravity EVA to be used in planning appropriate Exploration countermeasures.

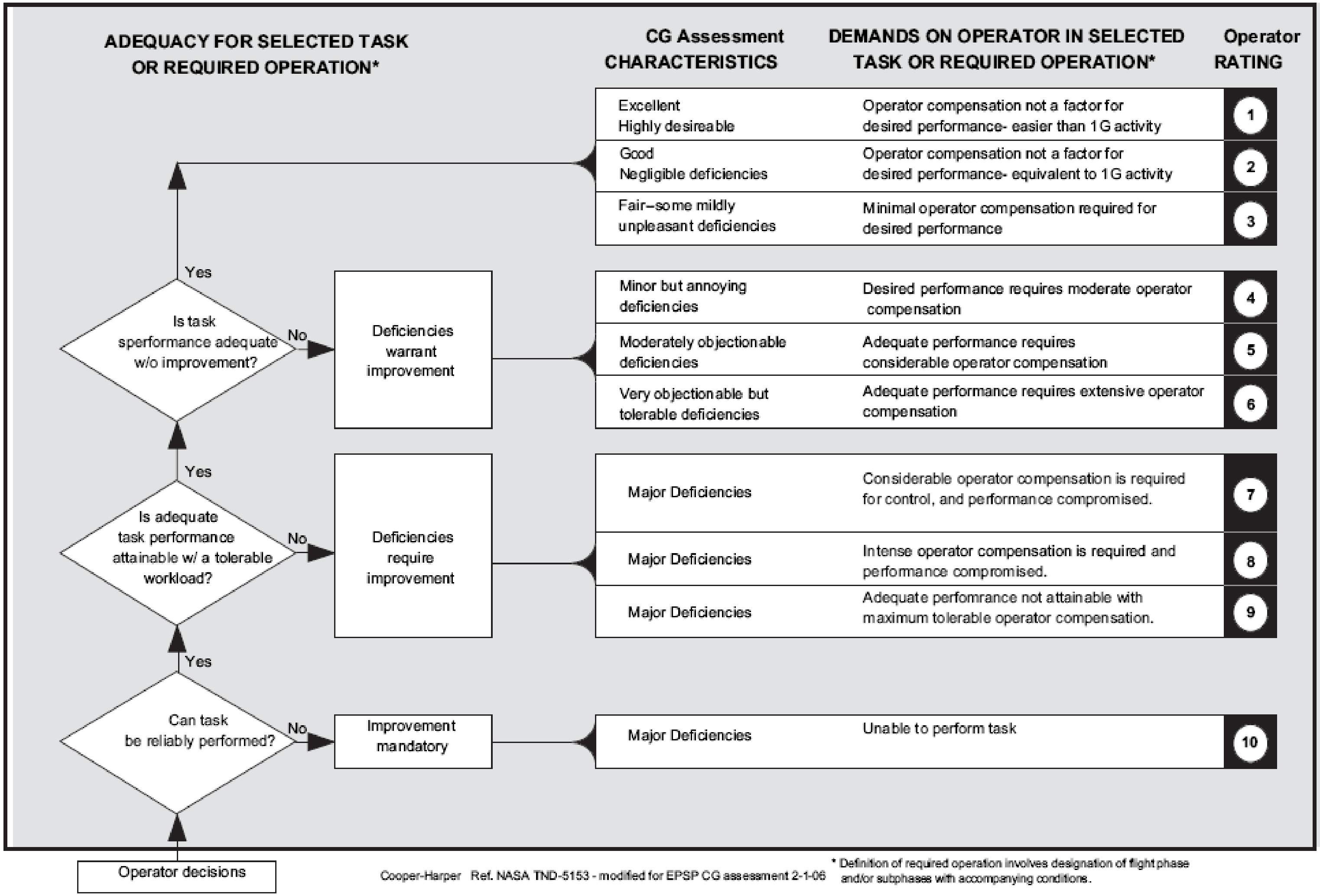
EVA Walkback Test – Subjects

- **NASA crewmembers**
  - **n = 6**
  - **Typically members of the EVA Branch**
- **Good fit with MKIII EVA Suit**
- **All males**
  - Females were not excluded, but were not included either due to inadequate suit fit or unavailability
- **Current Air Force Class III physical**

	Mean SD	Range
Age (yrs)	46.8 4.3	40 - 51
Height (cm)	180.3 5.0	175 -188
Body Mass (kg)	81.4 7.8	71.2 - 89.4
VO_2pk ($ml \bullet kg^{-1} \bullet min^{-1}$)	48.7 5.7	40.8 - 55.6

Subjective Measurements

Gravity Compensation Performance Scale



Cooper-Harper Ref. NASA TND-5153 - modified for EPSP CG assessment 2-1-06

* Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.

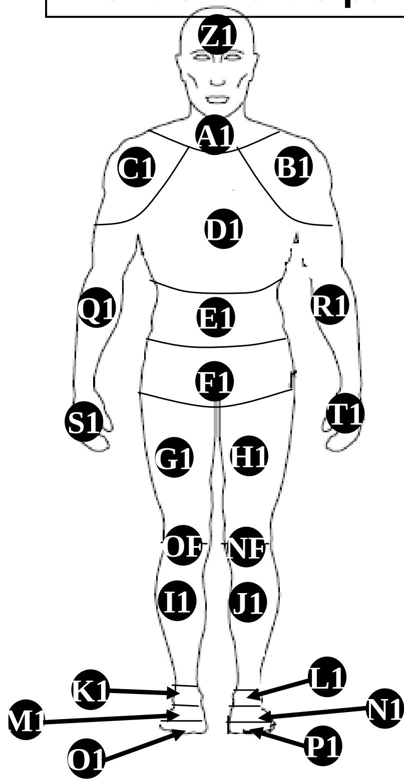
Subjective Measurements (continued)

RPE

6	No exertion at all
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

Discomfort

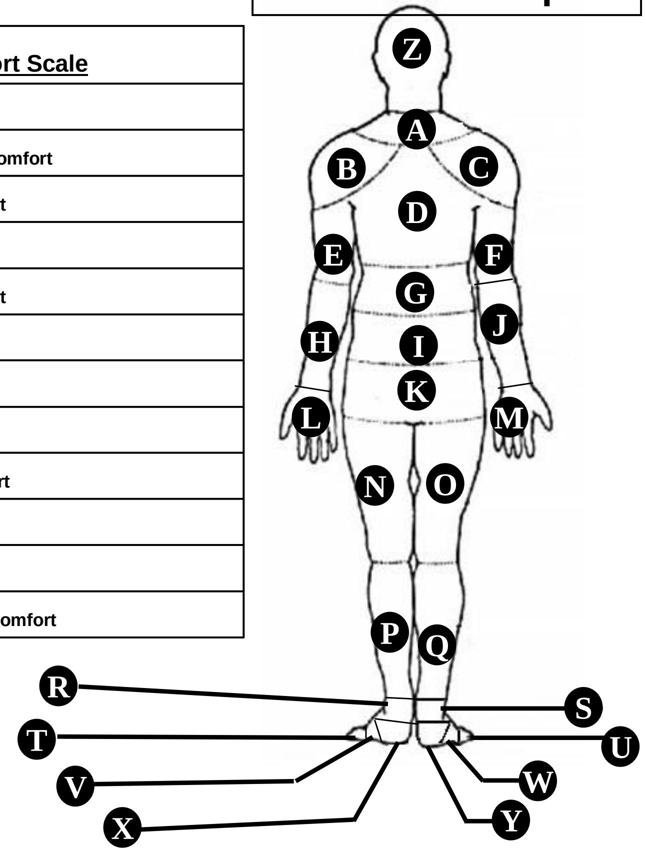
Front of Participant



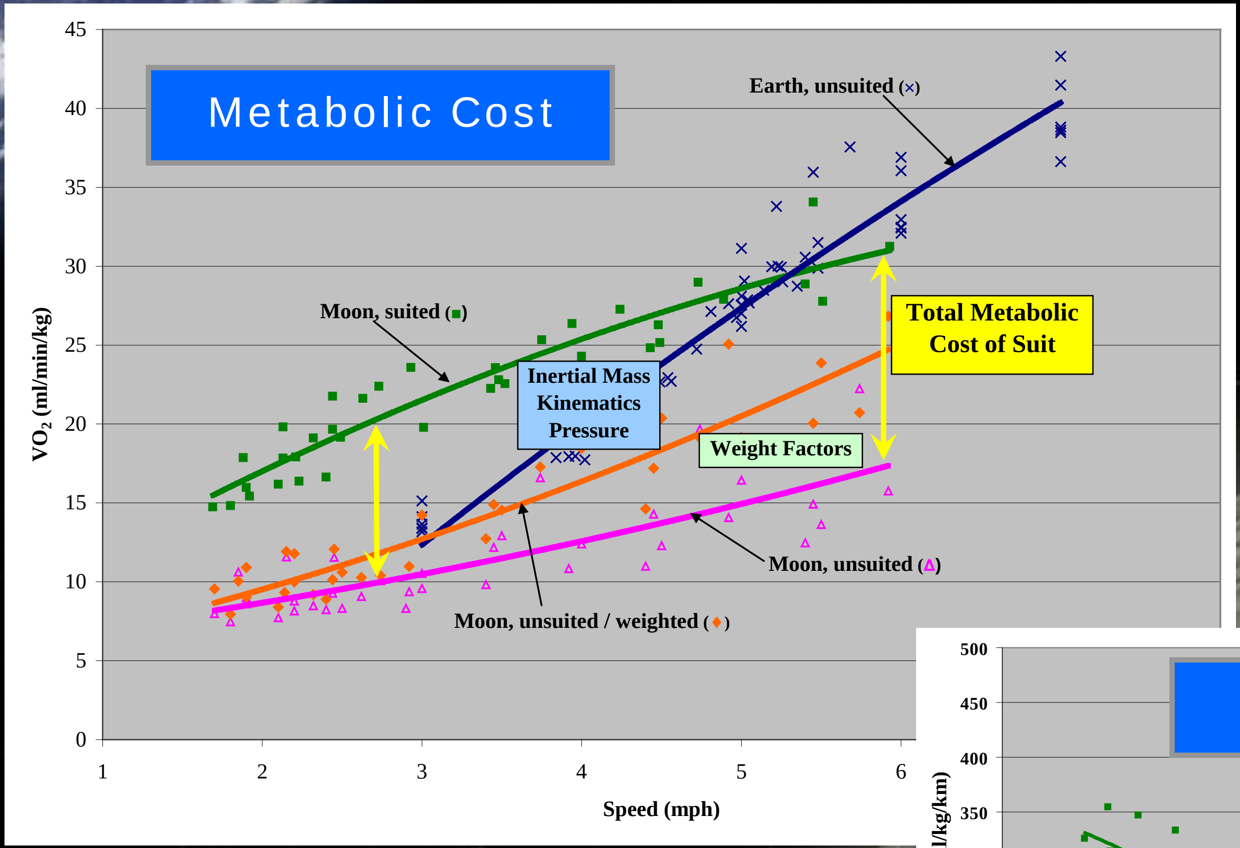
Discomfort Scale

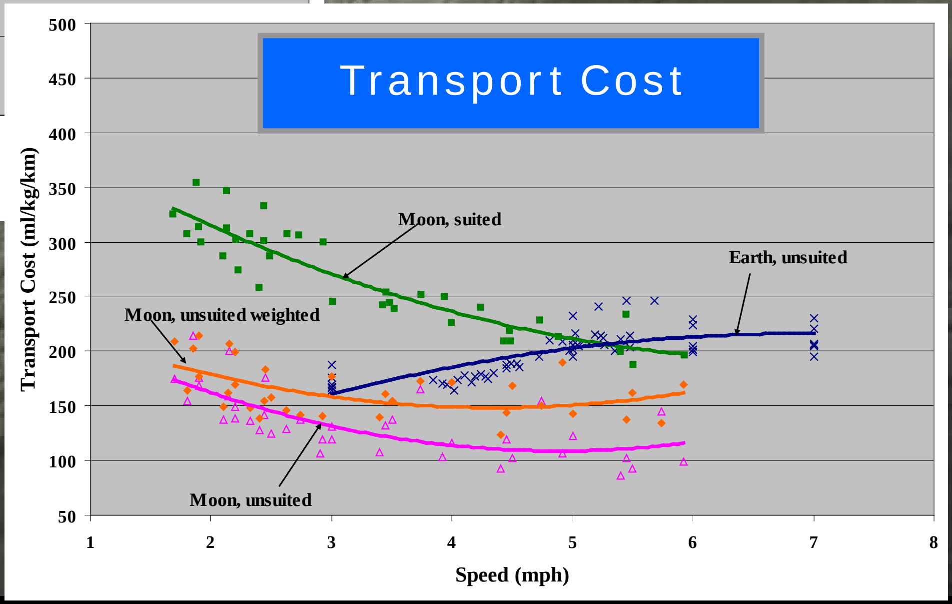
0	Nothing at All
0.5	Extremely Low Discomfort
1	Very Low Discomfort
2	Low Discomfort
3	Moderate Discomfort
4	
5	High Discomfort
6	
7	Very High Discomfort
8	
9	
10	Extremely High Discomfort

Back of Participant



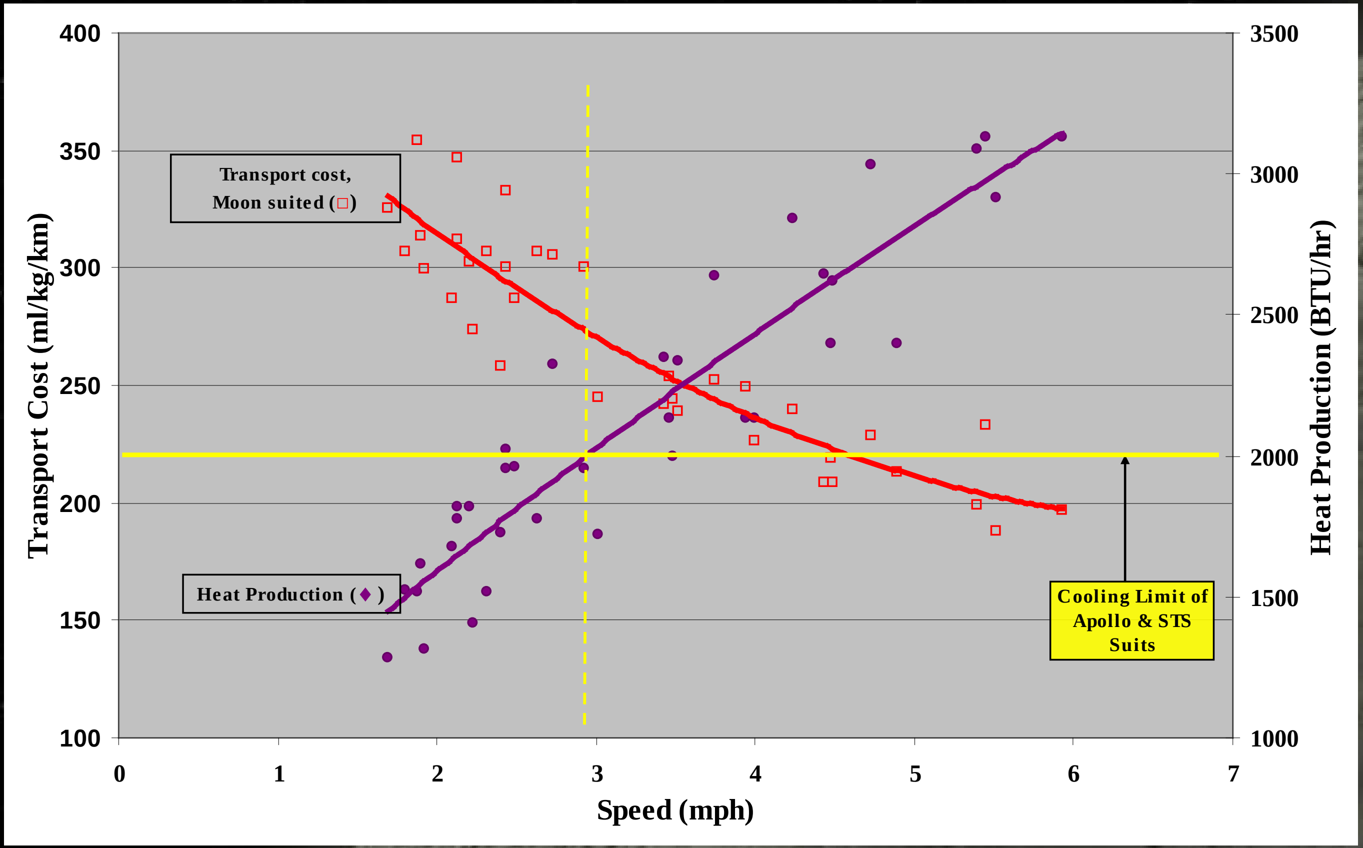
Energy-Velocity Series Results - Moon



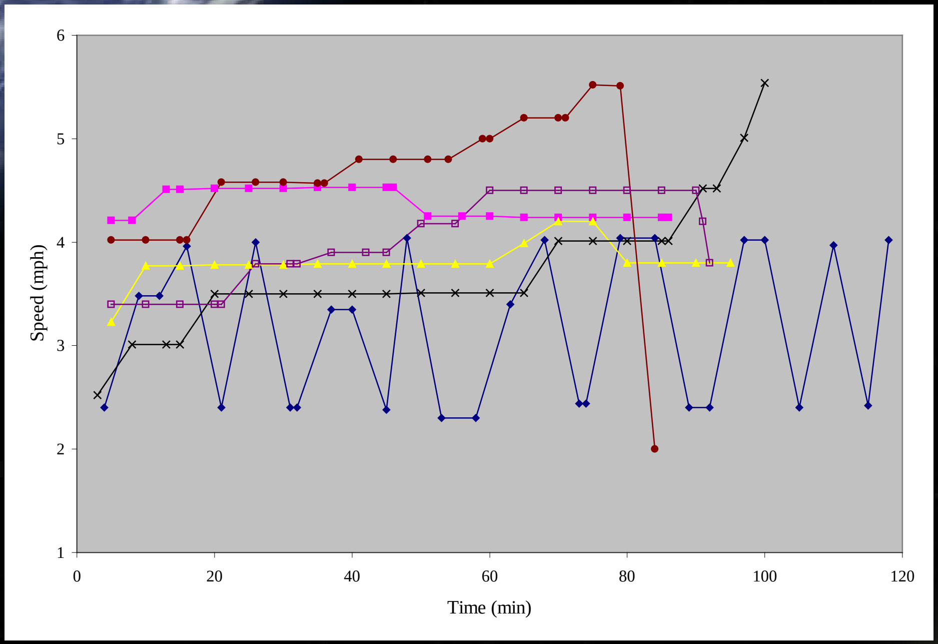


Implications for Walkback

1. Faster speeds provide improved efficiency, but require higher per-minute metabolic cost
2. Cooling may be a limiting factor



10 km Walkback Summary



10 km Walkback Summary Data (averaged across entire 10 km unless noted)		
	MEAN	SD
Avg walkback velocity (mph)	3.9	0.5
Time to complete 10 km (min)	95.8	13
Avg %VO_2pk	50.8%	6.1%
Avg met rate (BTU/hr)	2374	303.9
Max. 15-min-avg met rate (BTU/hr)	*2617*	*315*
Total energy expenditure (kcal)	944.2	70.5
RPE	11.8	1.6
Cooper-Harper	3.5	1.4
Water used for drinking (oz)	~24-32	N/A
Planning / PLSS Sizing Data	**Walkback**	**Apollo**
O_2 Usage	0.4 lbs/hr	0.15 lbs/hr
BTU average	2374 BTU/hr	933 BTU/hr
Cooling water	3.1 lbs/hr	0.98 lbs/hr
Energy expenditure	599 kcal/hr	233 kcal/hr

Haughton Mars Project Walkback Test

Haughton Mars Project (HMP) 10 km Radial Distance Walkback Test

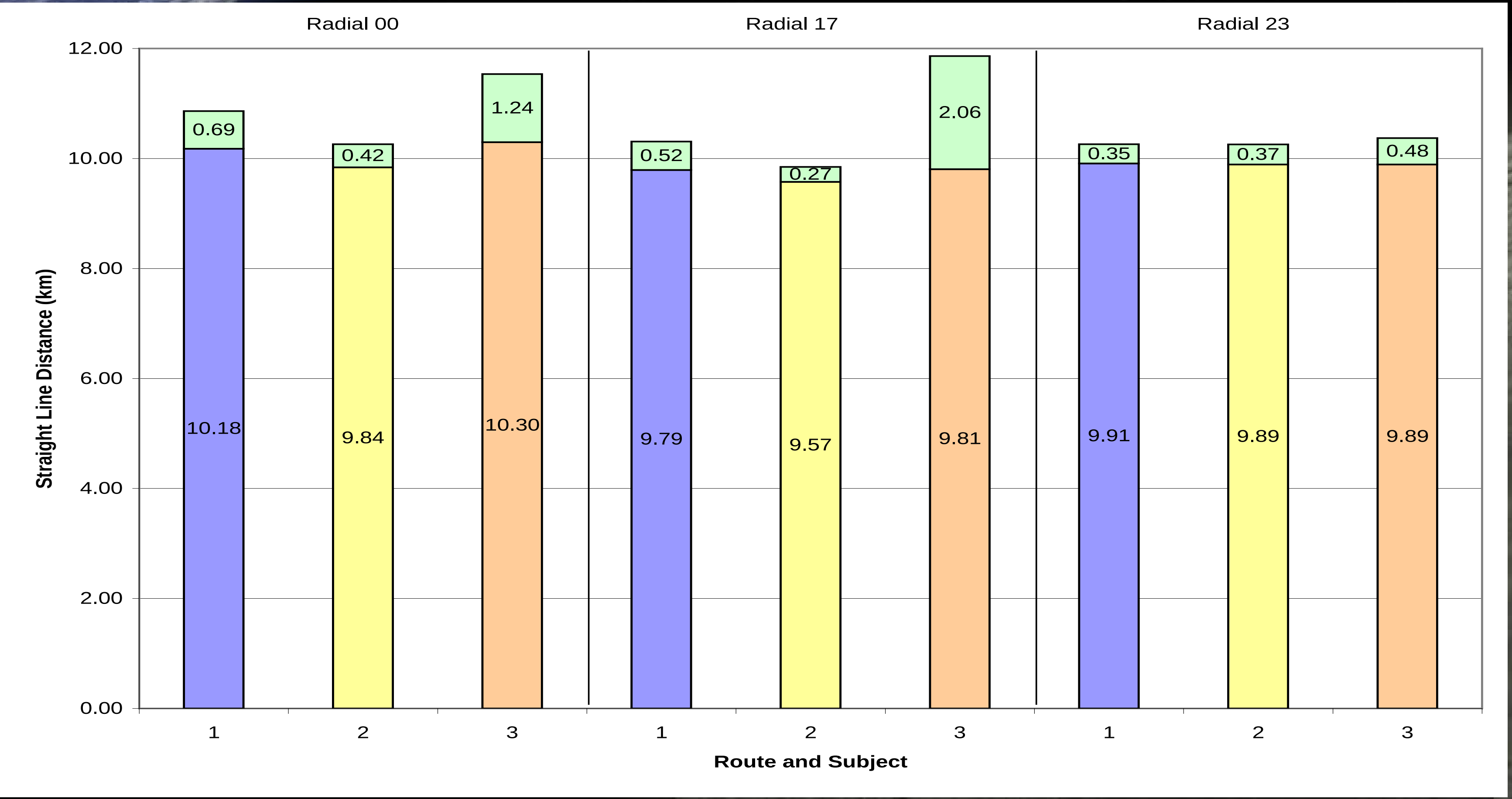
- To evaluate how terrain, regolith and navigation through landscape similar to the lunar surface affect a crewmembers' ability to complete a 10km walk
- To determine an EVA environment correction factor derived from the comparison of data collected on Partial Gravity System (EWT & Integrated Suit Test 1) with HMP data

HMP Walkback Test - Test Protocols

- **Haughton Mars Project (HMP) Walkback**
  - **10 km “as the crow flies”**
  - **GPS navigation**
  - **Rapid but sustainable pace**
    - **<85% predicted max HR**
  - **No time limit or route limitations**
  - **3 separate routes**
- **Matched Treadmill Control**
  - **Speed/grade/distance matched to HMP Walkback**
- **Level Treadmill Control**

HMP Walkback Test - Route Selection

HMP Walkback Test Results



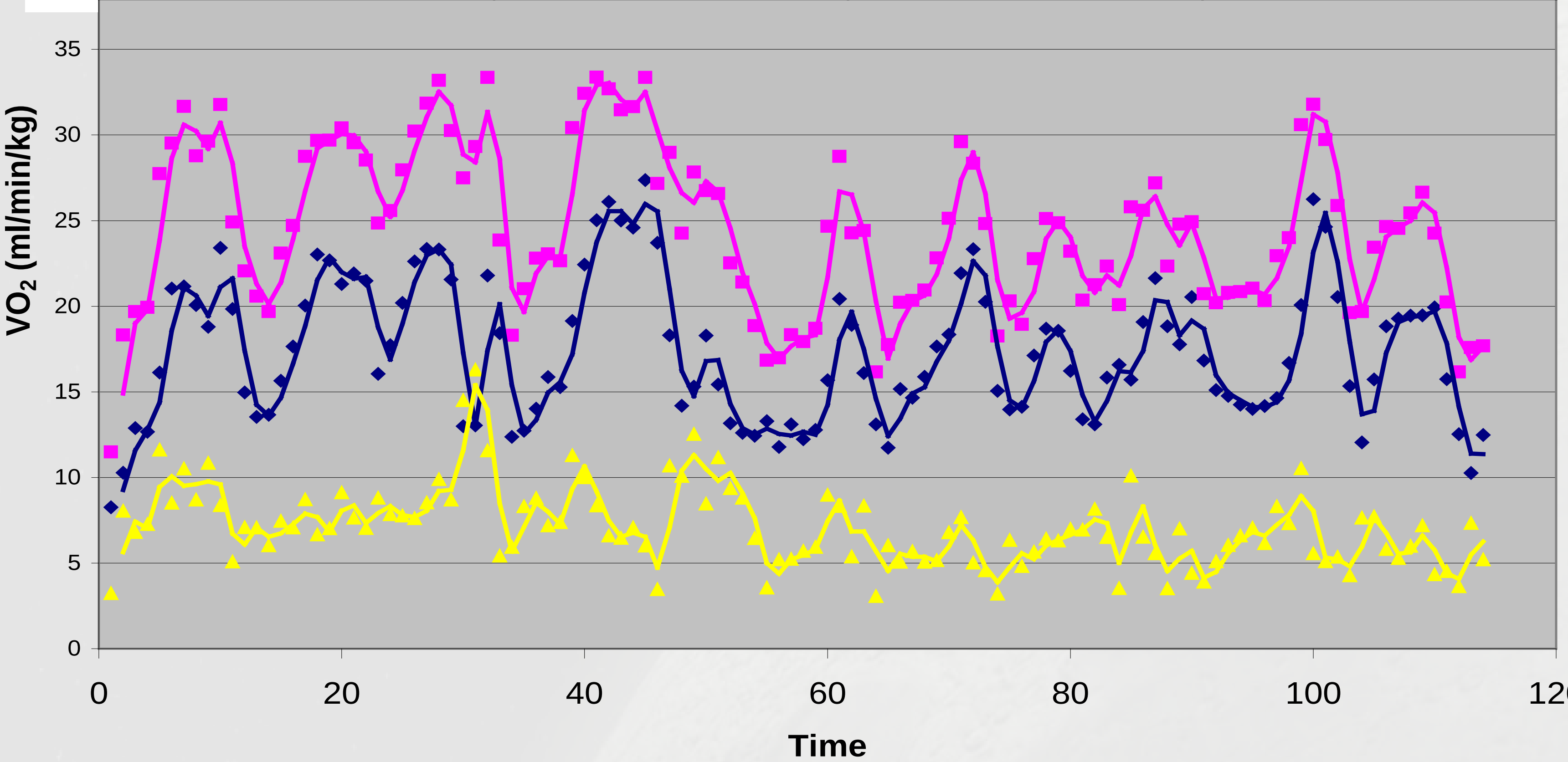
- Average time 126.5 ± 28.7 min (mean ± SD)……..[96 min for EWT]
- Average VO_2 27.8 ± 5.1 $mL \cdot kg^{-1} \cdot min^{-1}$…………………[24.8 for EWT]
- Straight line distance 9.91 ± 0.22 km
- Actual distance was 10.61 ± 0.61 km (7% increase)

HMP Walkback Speed/Grade Matched Control Trial

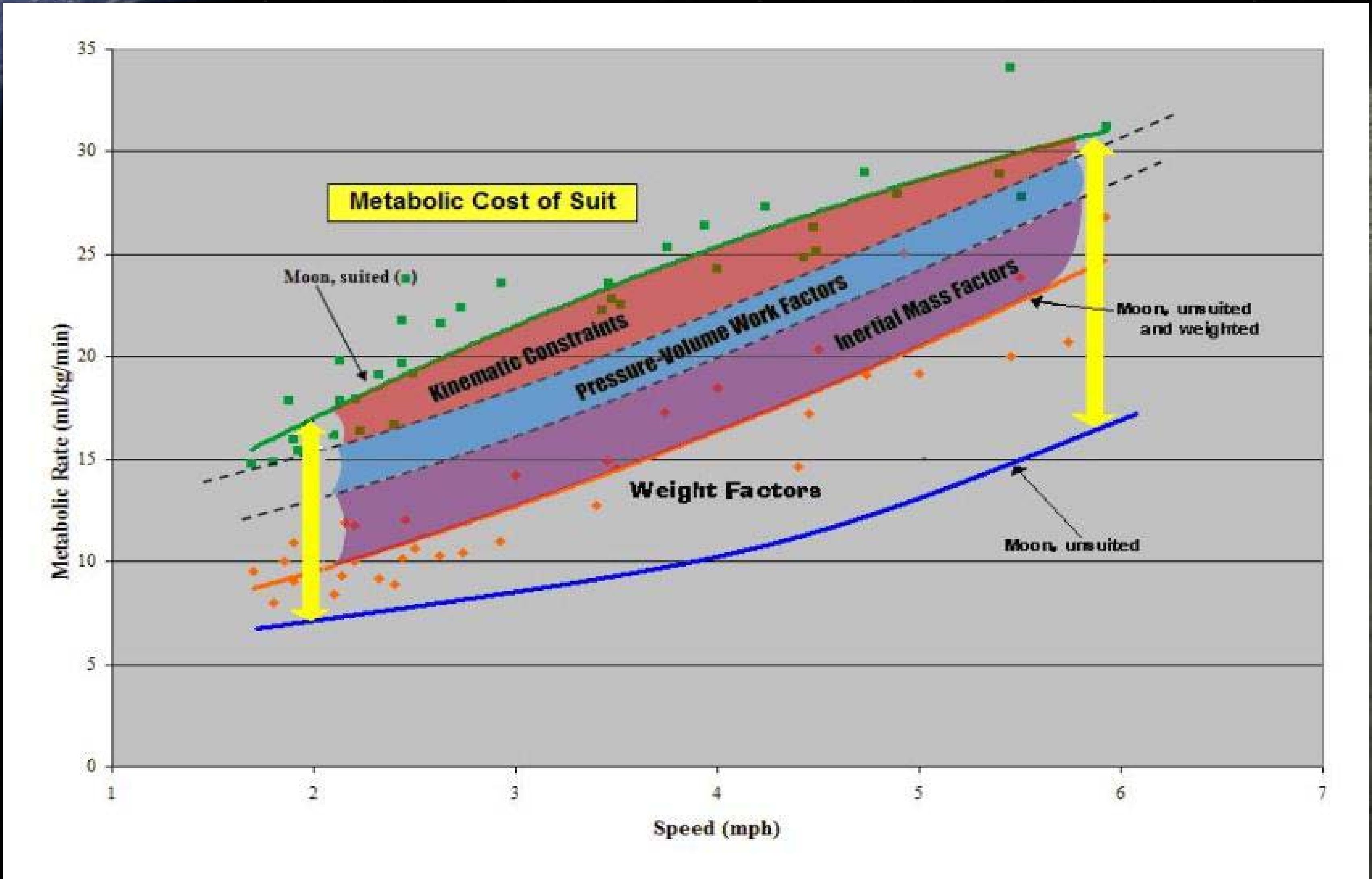
- Speed/grade matched to the best 1-min average from field
- Speed/grade adjusted manually every minute
- Clothing and boots similar to field trials
- Weighted vest used to account for weight differences
- -10 to 30 available
  - Within this band > 98% of time

HMP Walkback Test Results: Field vs. Matched Control

Summary (n=3)	HMP	JSC	ΔVO_2
Avg VO_2 ($mL \cdot kg^{-1} \cdot min^{-1}$)	26.9 6.4	17.1 ± 4.9	9.8 3.8



Suit Test One- Ambulation in a Planetary Suit
Understanding the breakdown of the total metabolic cost of the suit



Integrated Suit Test 1 Test Conditions

Suited (MKIII)

Varied Weight (29.6 kPa, 121 kg inertial mass)

63 kg	121 kg	186 kg	247 kg	308 kg

Varied Pressure (121 kg suit weight and inertial mass)

6.9 kPa (1.0 psi)	20.7 kPa (3.0 psi)	29.6 kPa (4.3 psi)	34.5 kPa (5.0 psi)	44.8 kPa (6.5 psi)

Shirt-Sleeve (Harness)

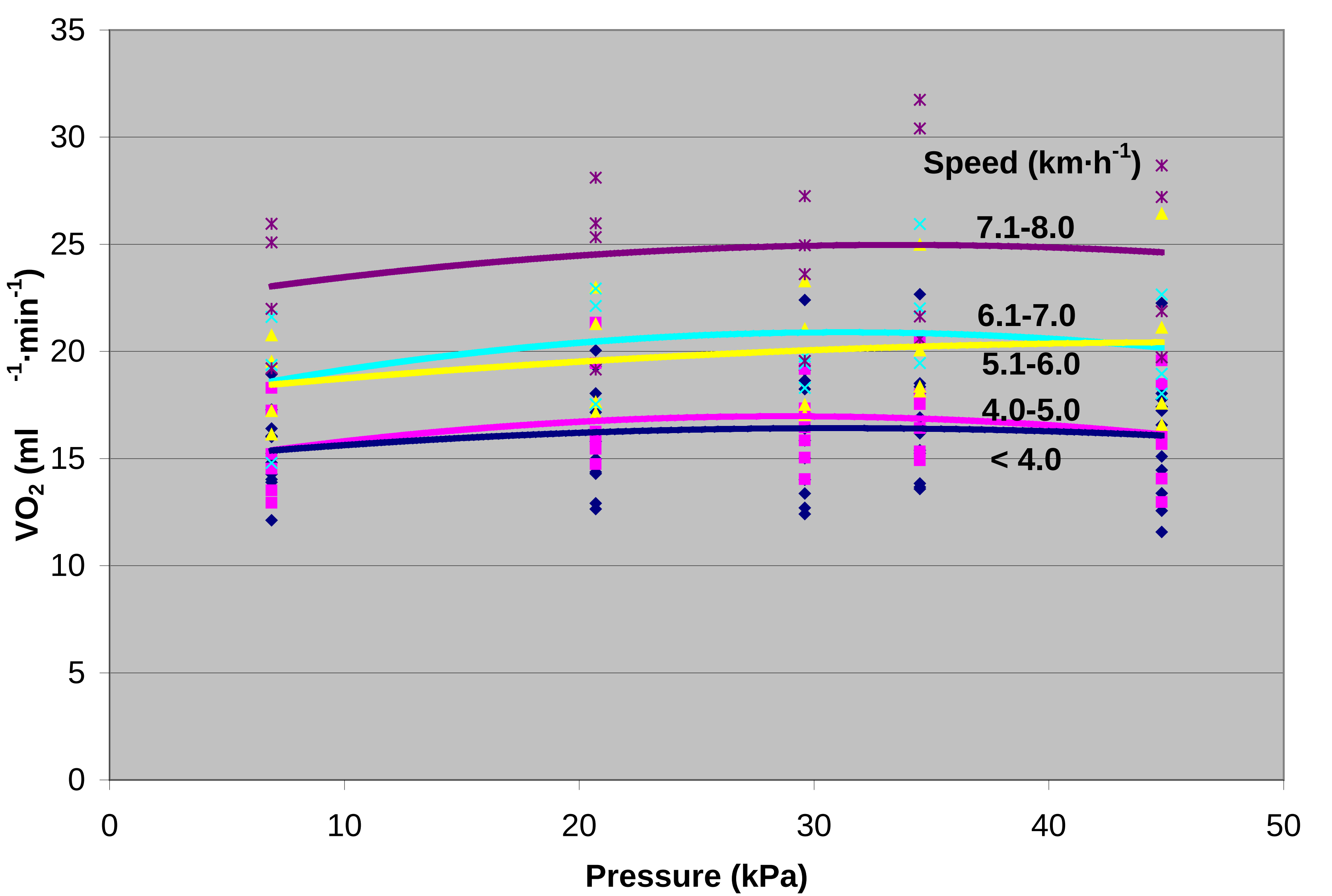
Varied Weight (weight-matched to suited configuration)

121 kg	247 kg	308 kg

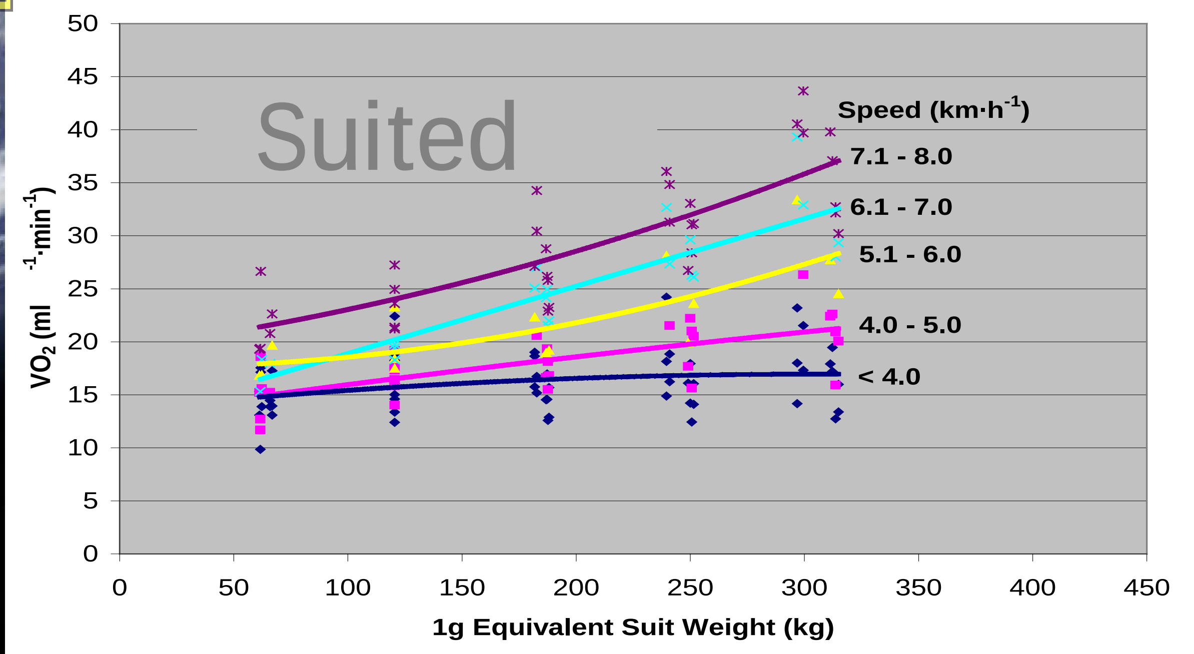
Varied Inertial Mass (weight-matched @ 121 kg)

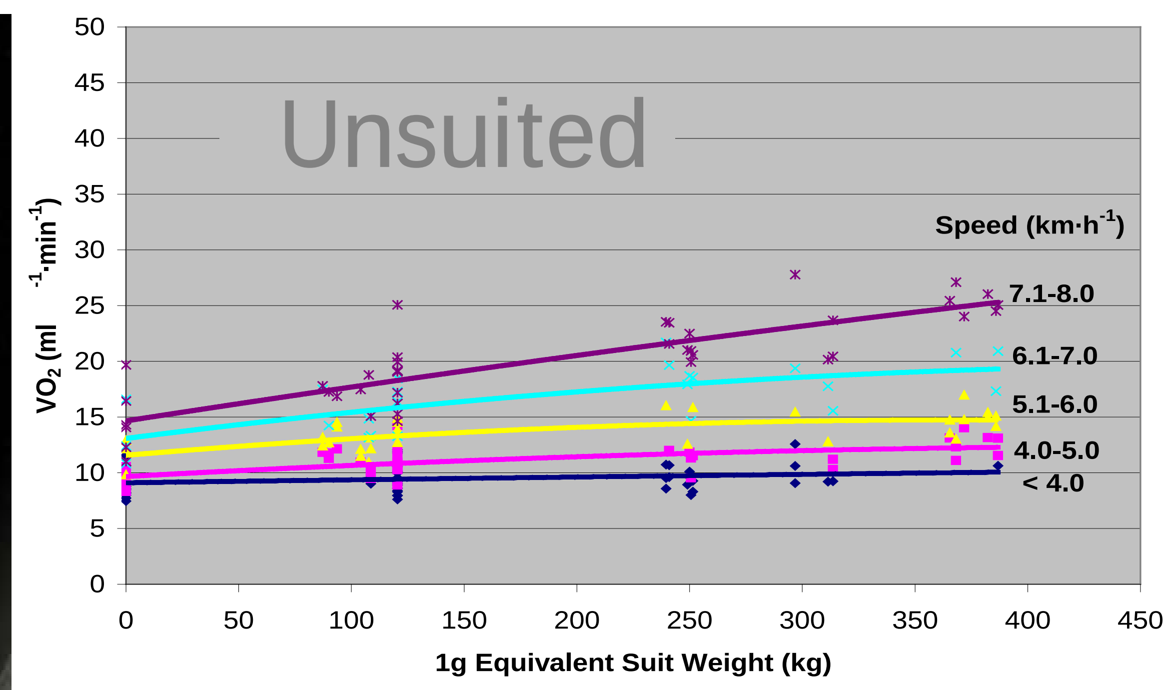
+ 0 kg	+ 11.4 kg	+ 22.7 kg	+ 34.1 kg

Suit Pressure



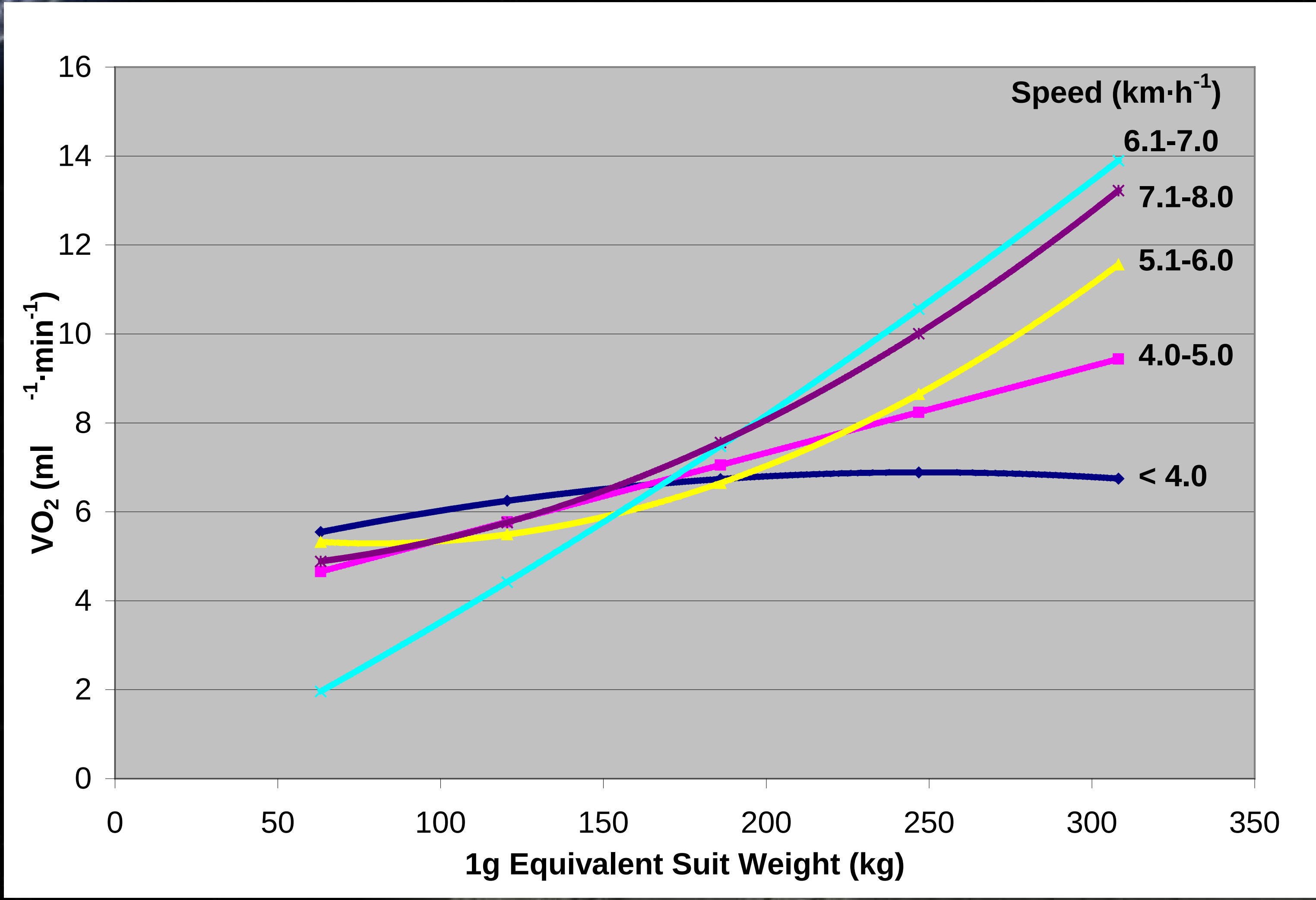
Metabolic Cost



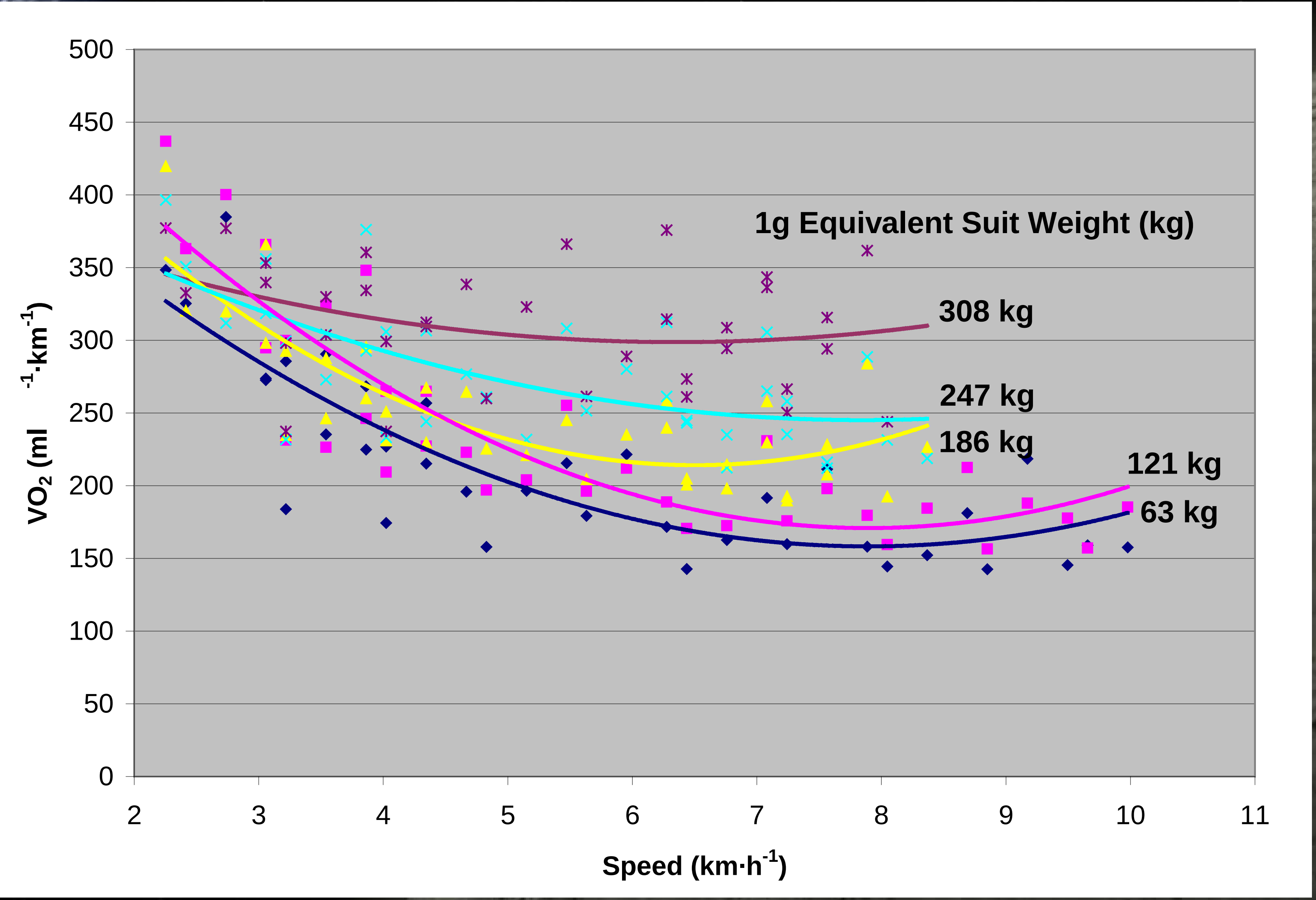


Operational significance =3.5 ml·kg-1·min-1

Metabolic Cost of the Suit Not Related to Weight (Suit – Shirtsleeve for Weight Matched Condition)



Suited Transport Cost



Predicted Effect Algorithm

- Preliminary linear regression model
  - Uses the following combination of variables to predict normalized metabolic rates during locomotion in the MKIII EVA suit:

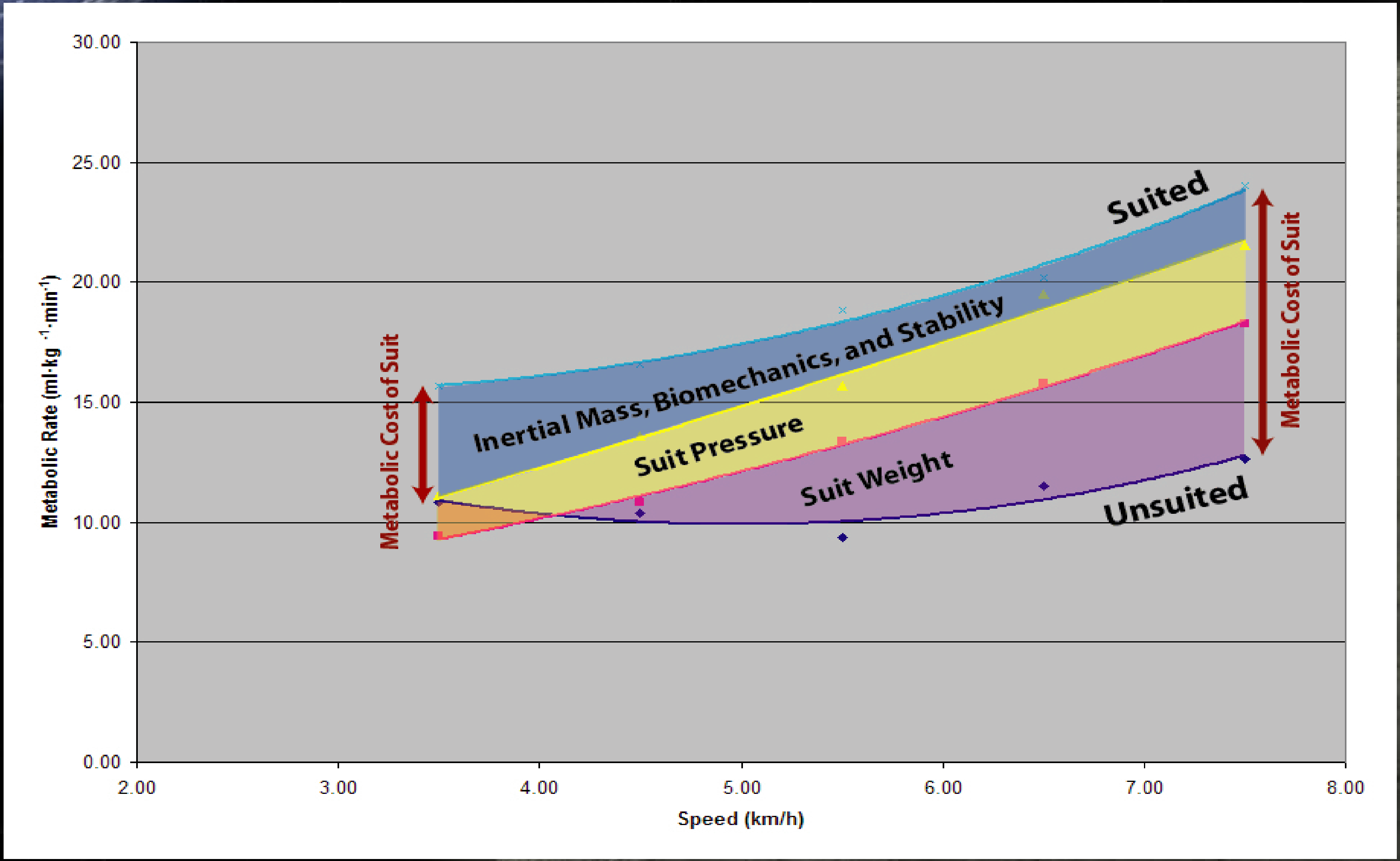
$$MR = b0 + b1 \cdot (Vlocomotion \times Wtotal) + b2 \cdot Mbody + b3 \cdot (Wtotal \times Lleg) + b4 \cdot Psuit$$

where

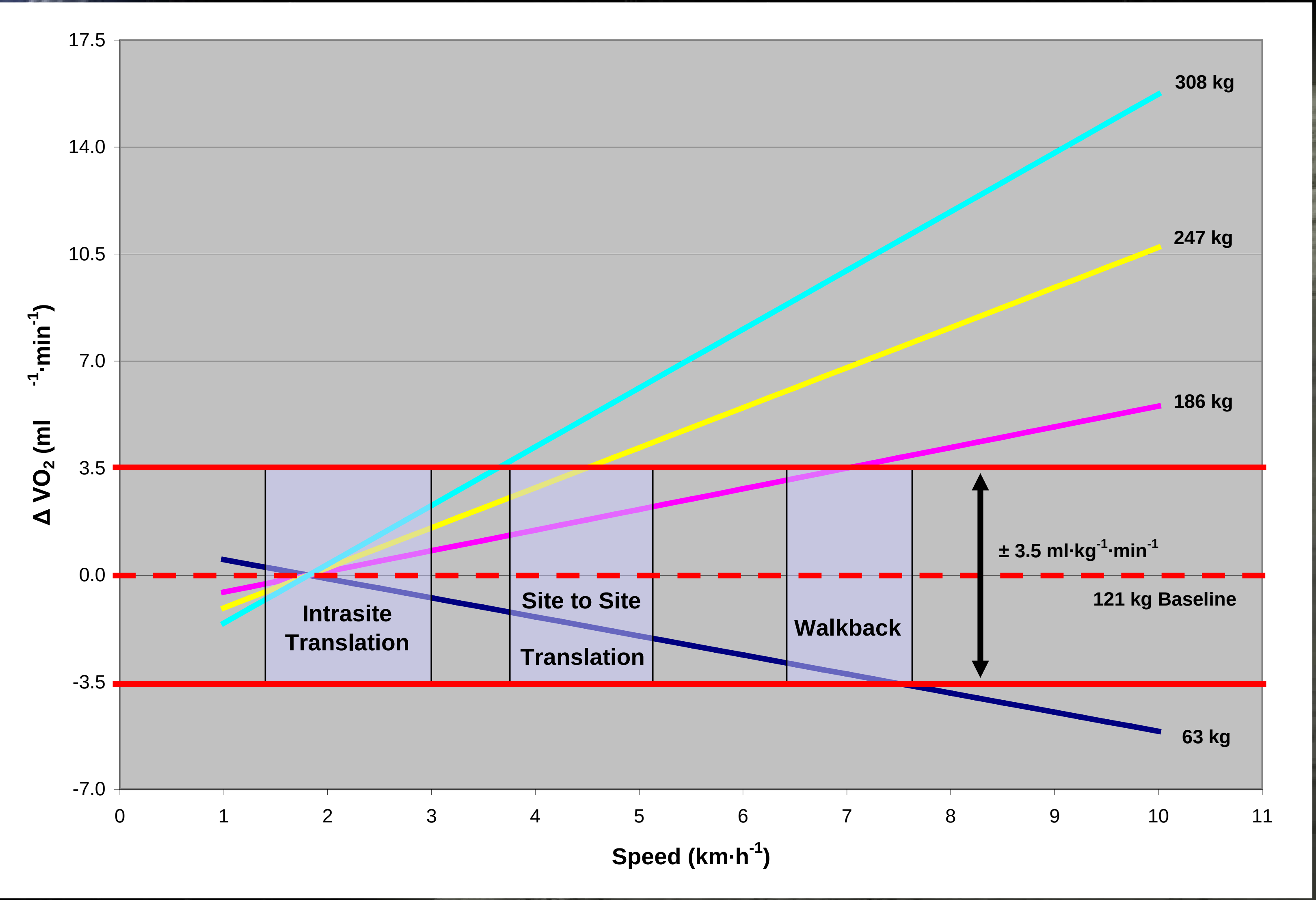
MR	= metabolic rate expressed as normalized VO2 (ml ·kg-1·min-1)
Vlocomotion	= locomotion speed (km/h)
Wtotal	= total weight of EVA suit plus astronaut (N)
Mbody	= body mass of unsuited astronaut (kg)
Lleg	= leg length of astronaut (cm)
Psuit	= suit pressure (kPa)

  - (R^2) = 0.846
  - Root mean square error = 2.52 $ml \cdot kg^{-1} \cdot min^{-1}$ (< 3.5 $ml \cdot kg^{-1} \cdot min^{-1}$)

Model for Metabolic Cost of MKIII Suit



*Predicted effect of suit weight on metabolic rate (operational concepts)



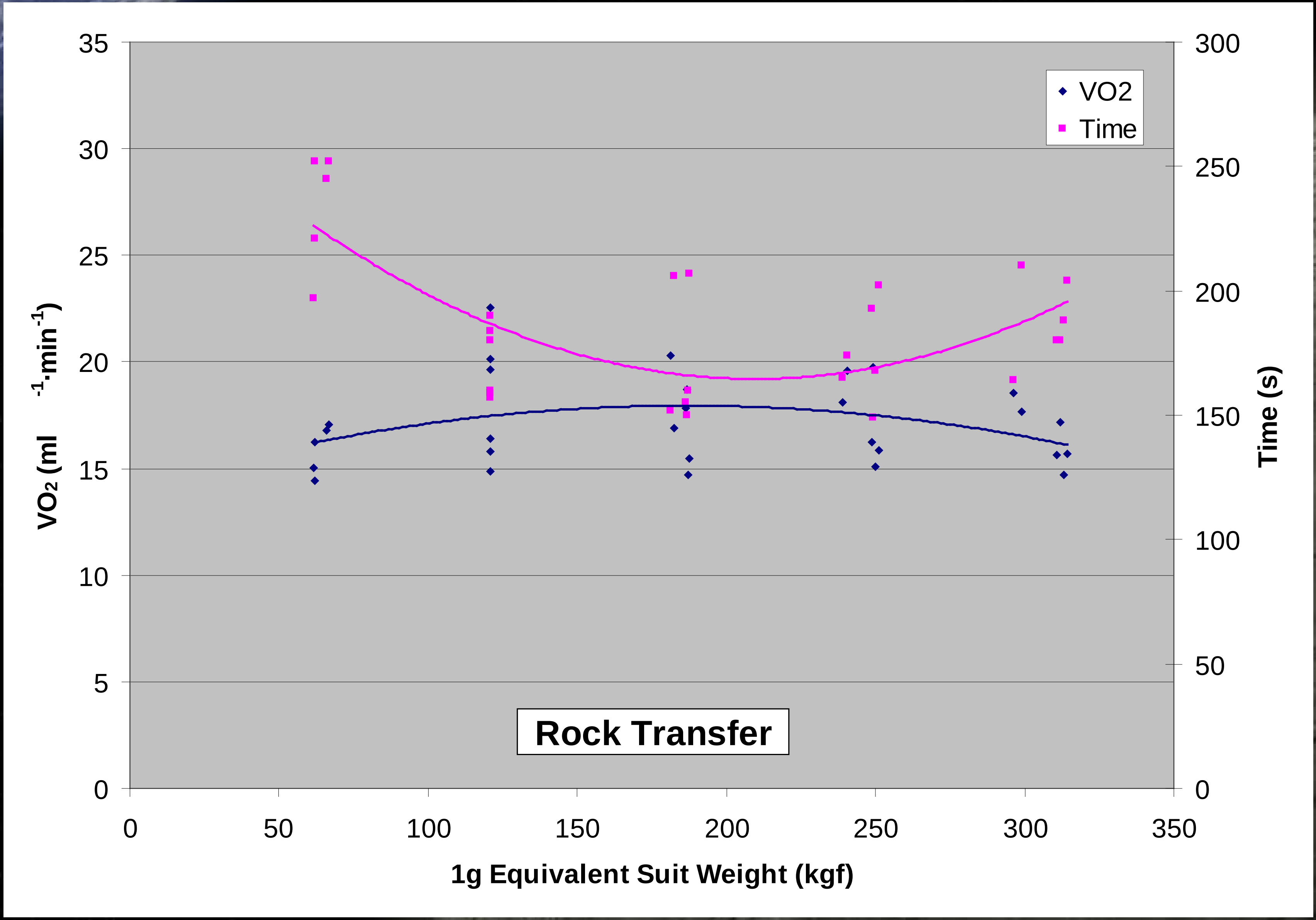
Integrated Suit Test 2 – Exploration Tasks

- Varied Suit Weight
  - 63, 121, 185, 246, 308 kg
  - Constant suit mass (121 kg)
  - Constant suit pressure (29.6 kPa)
  - Matched shirt-sleeve controls at 63, 121 and 185 kg
- Varied Pressure
  - 6.7, 20.7, 29.6 kPa
  - Constant suit mass/weight (121 kg)
- Varied Inertial Mass (shirt-sleeve)
  - Constant weight
  - 25, 50, 75 lbs added mass
- Waist-locked
  - Compared to standard MKIII configuration
  - 121 kg suit mass/weight, 29.6 kPa

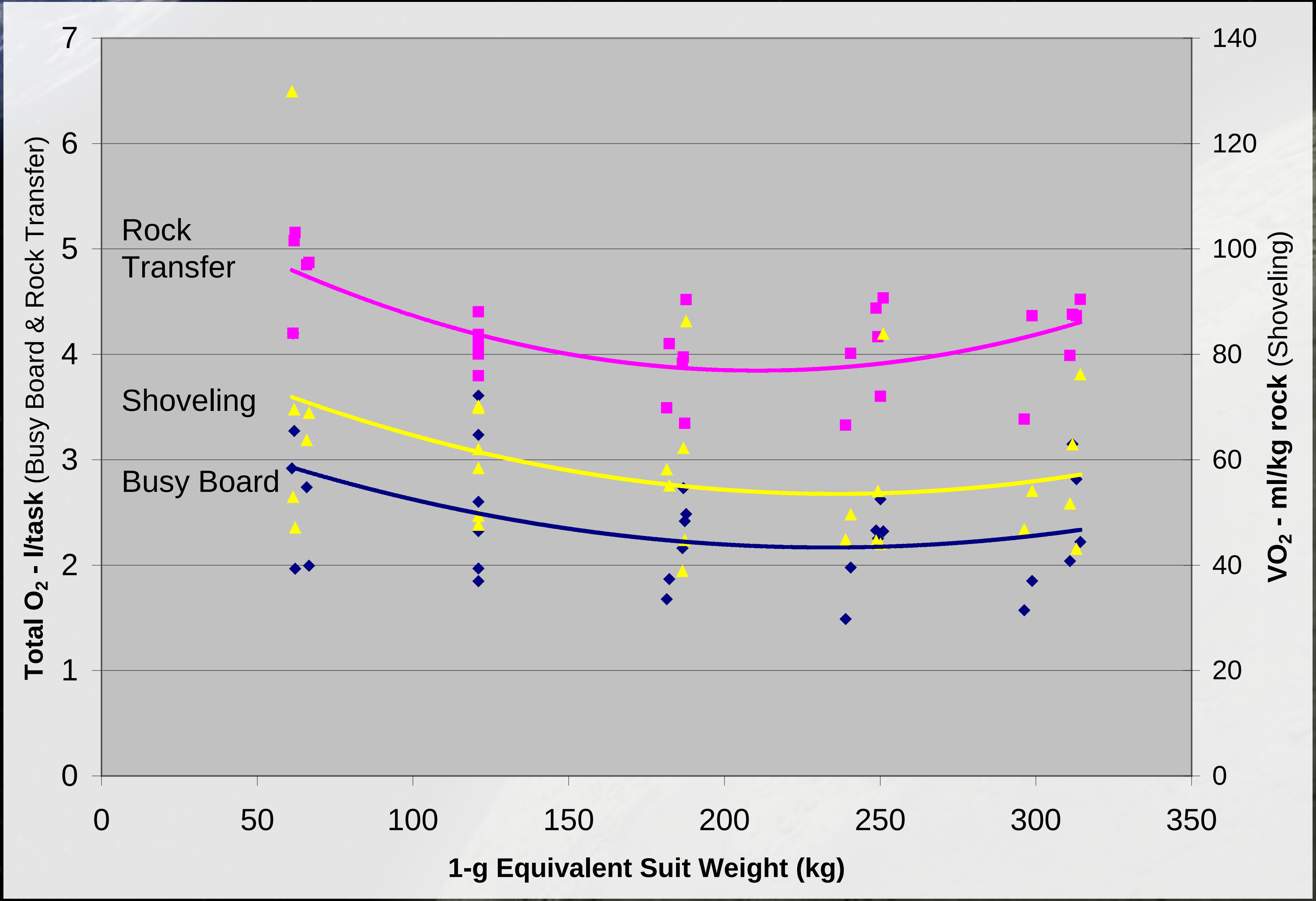
Integrated Suit Test 2 - Protocols and Data Collection

- Shoveling, rock transfer, busy board
  - Metabolic Rate (VO_2)
  - Modified Cooper-Harper (CH)
  - Rating of Perceived Exertion (RPE)
  - Time series motion analysis
  - Foot force contact vectors
- Rock pickup, kneel and recover, hammering, ladder setup
  - CH
- Incline Treadmill Walking (10,20,30% at slowest walking speed)
  - VO_2
  - CH, RPE
  - Time series motion/foot force contact vectors

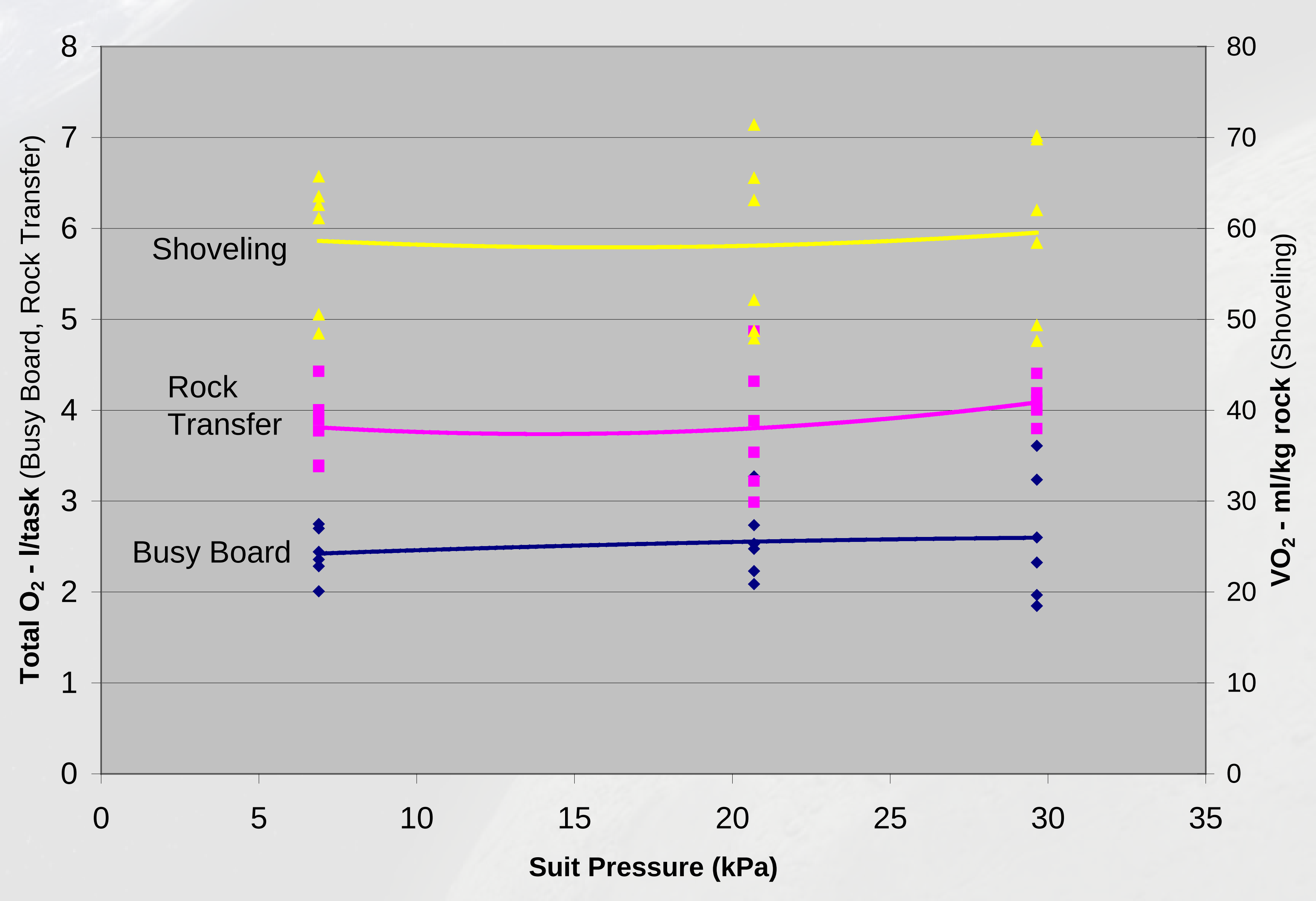
Metabolic Rate and Time to Completion



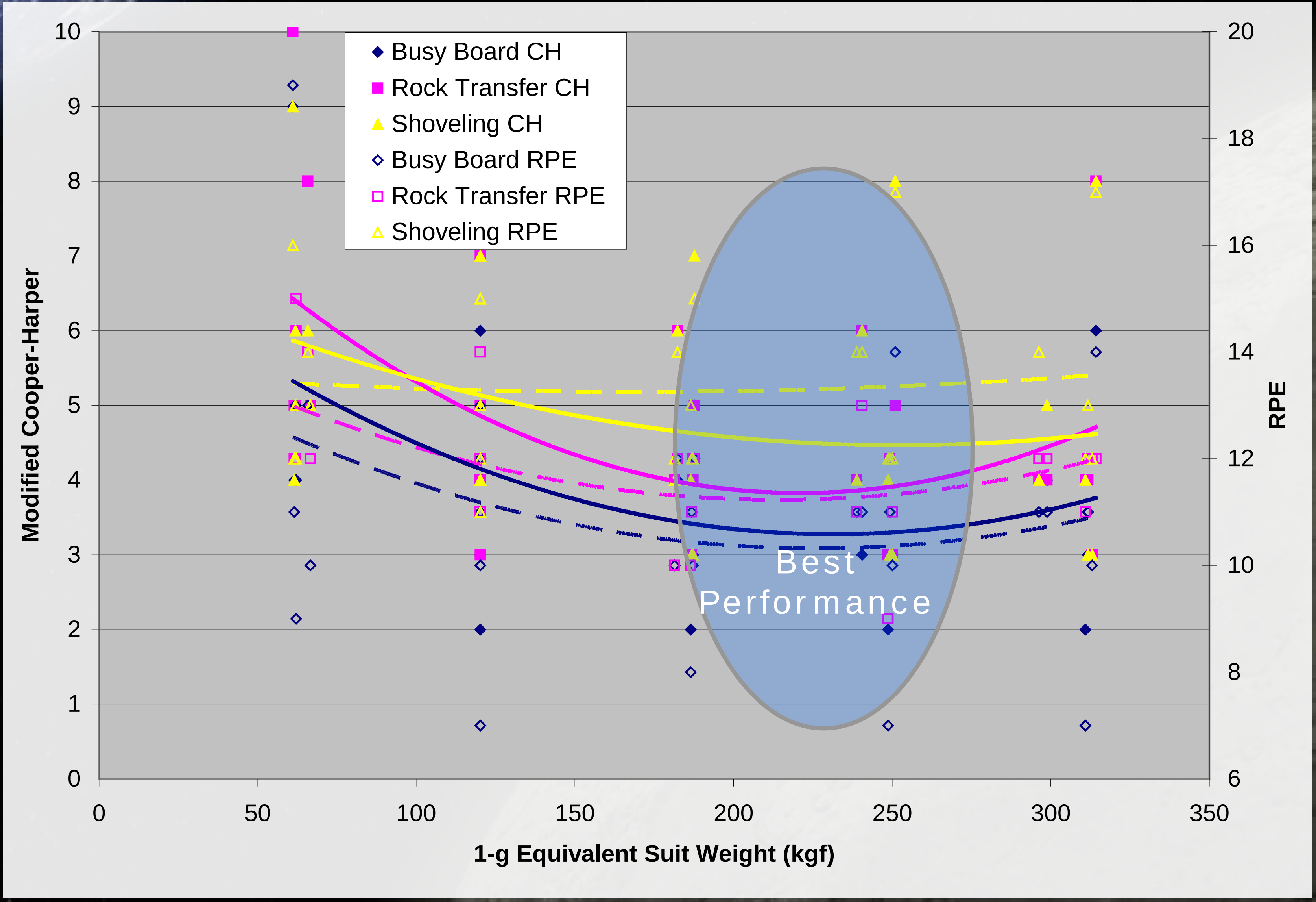
Exploration Task Metabolic Cost – Varied Weight



Exploration Task Metabolic Costs – Varied Pressure

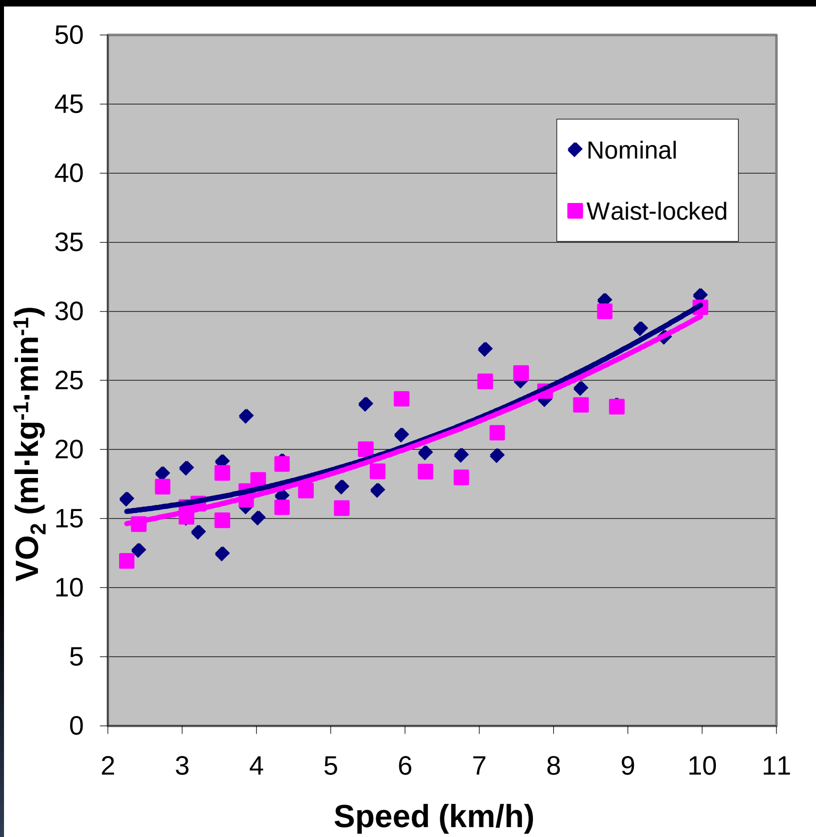


Exploration Task Subjective Ratings

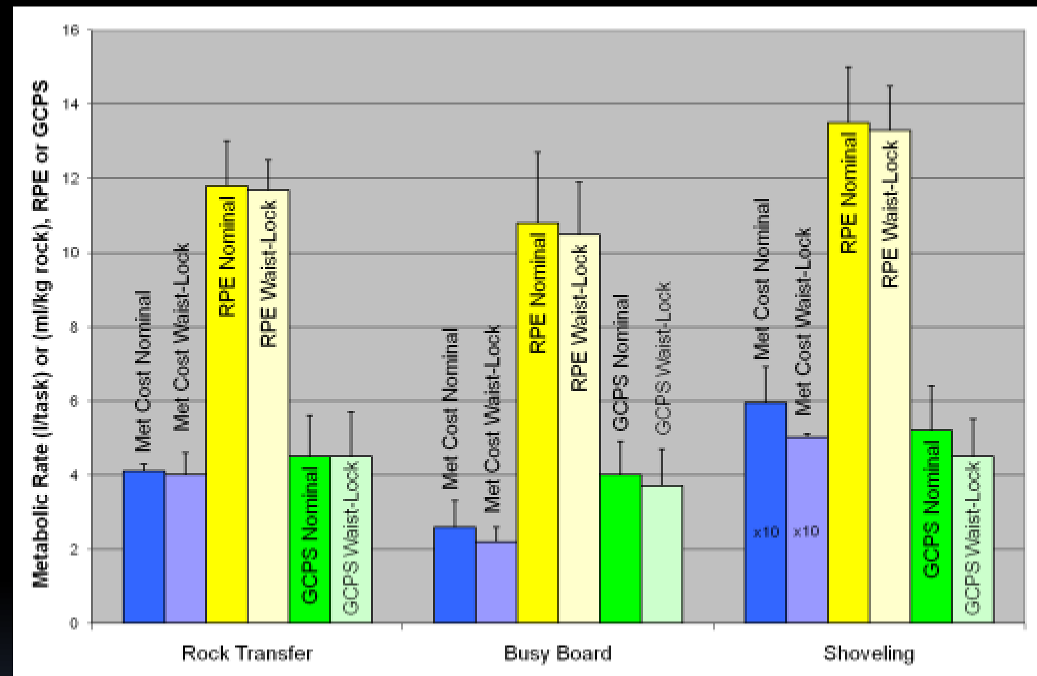


Locking MKIII Waist Bearing (POGO)

Ambulation

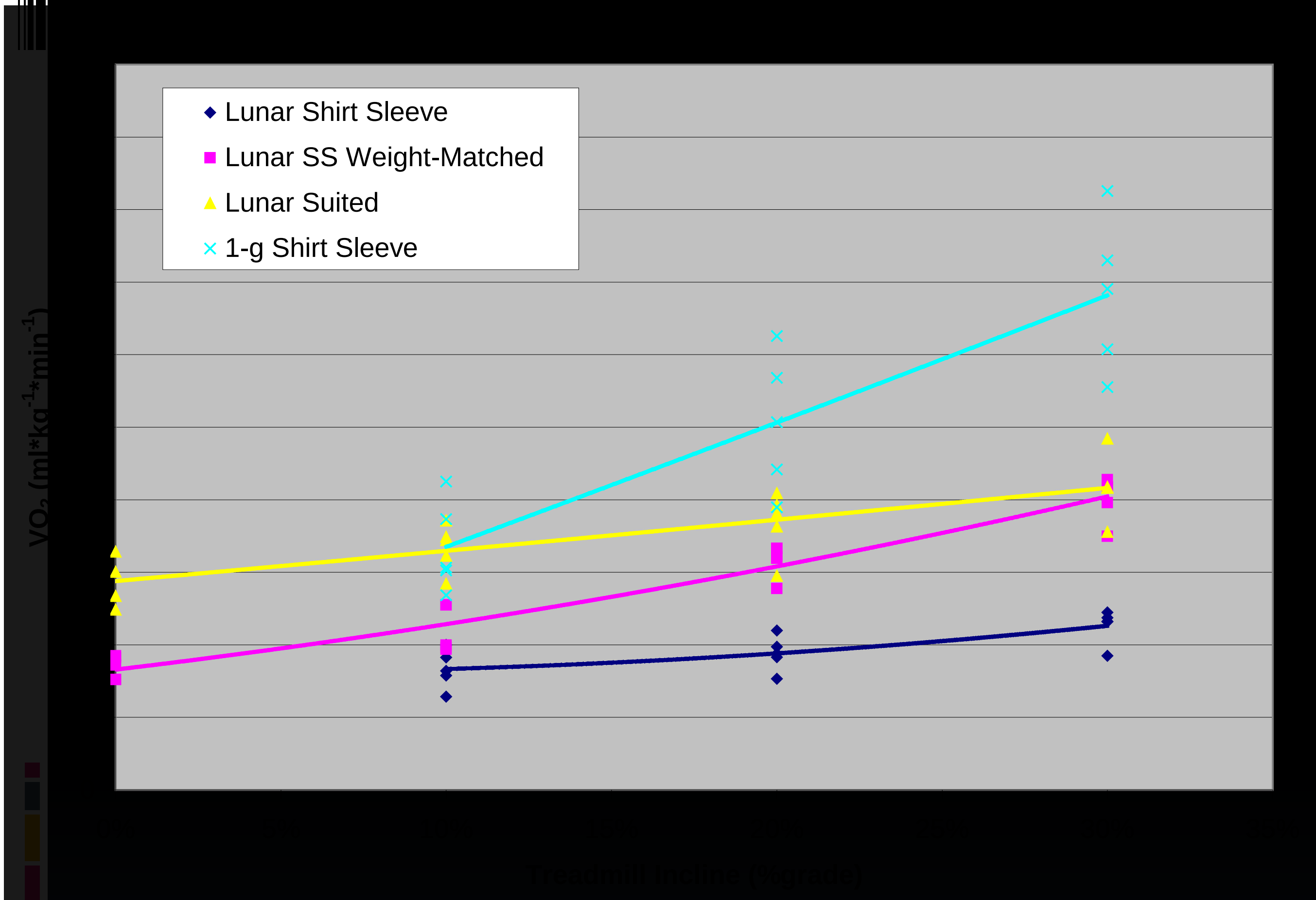


Exploration Tasks



- Little to no difference between conditions for metabolic rate and subjective ratings
- Note that waist-locked condition was always done last and familiarization over the trial may account for part of the lack of difference
- Mode of locomotion (hop, lope, run) greatly affected biomechanics measurements and limited direct comparison

Inclined Walking Results

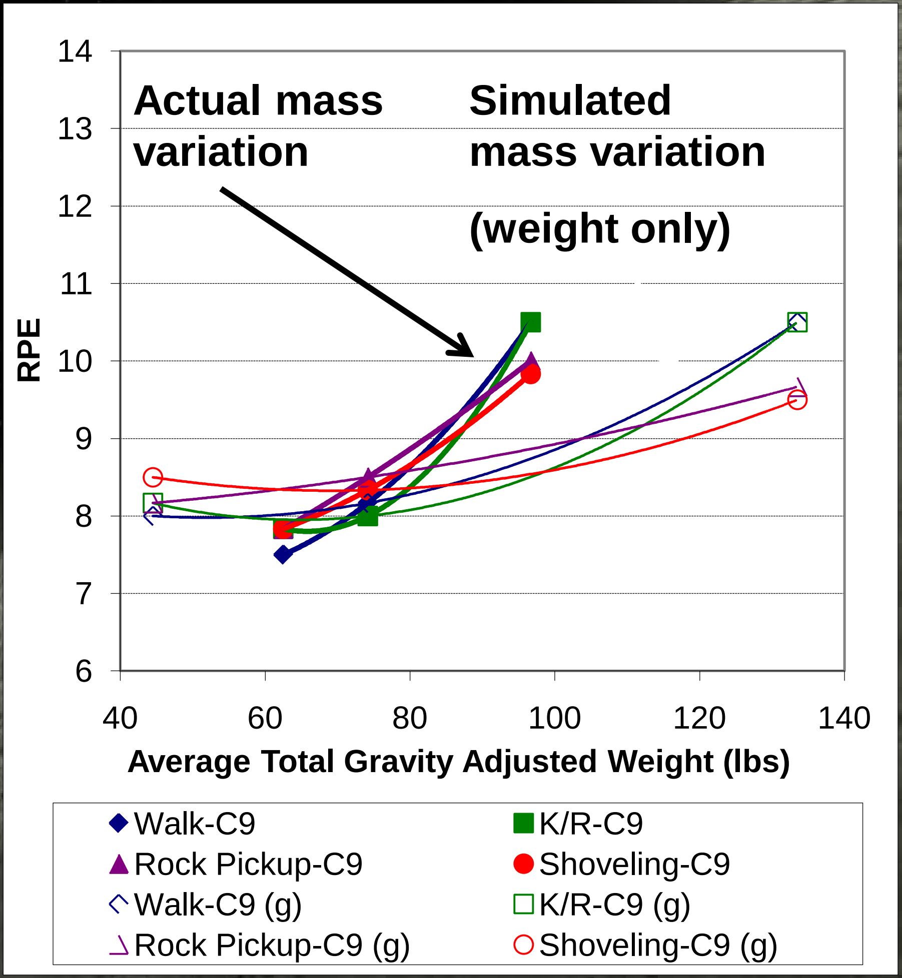


- Lowest walking speed used (1.4 – 2.2 mph)
- 3 min per grade

- Metabolic cost of weight increased with grade
- Metabolic costs unrelated to weight decrease with grade
  - Indicates energy recovery from suit

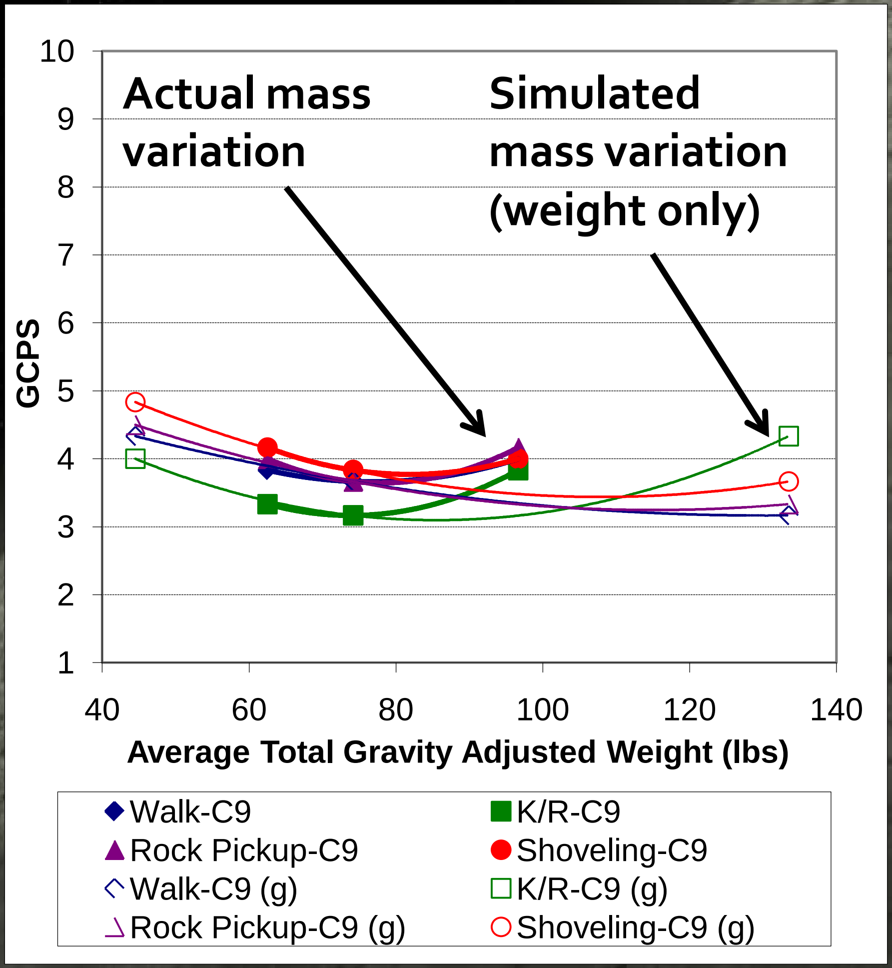
Δ Weight vs. Δ Mass Results (C-9)

- RPE results indicate that simulating mass by changing weight alone does not accurately reflect the RPE changes seen with an increase in actual mass
  - Trends more similar when simulating lower masses
  - Simulating small mass changes (5-10 lb TGAW) may not affect RPE significantly



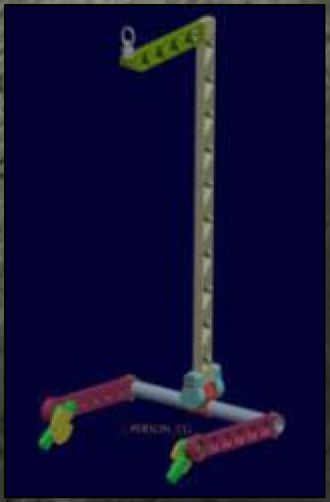
Δ Weight vs. Δ Mass Results (C-9)

- GCPS results indicate that simulating mass by changing weight alone does not accurately reflect the GCPS changes seen with an increase in actual mass
  - Trends are quite similar when simulating lower masses
  - Simulating small mass changes (5-10 lb TGAW) may not affect GCPS significantly



Gimbal Development

- Decreased moment of inertia
  - Less mass away from subject
  - Compact design
  - Big improvement in yaw axis
    - Example – with current gimbal, lower body movement is predominant [1]
  - Initial calculations indicate new design may have only 10-15% of the moments of inertia of current gimbal
- Decreased mass
  - Current gimbal assembly > 40 kg
  - New designs may be as low as 10 kg
- To be designed to work with other suits
- Same gimbal design will support both suited and unsuited testing

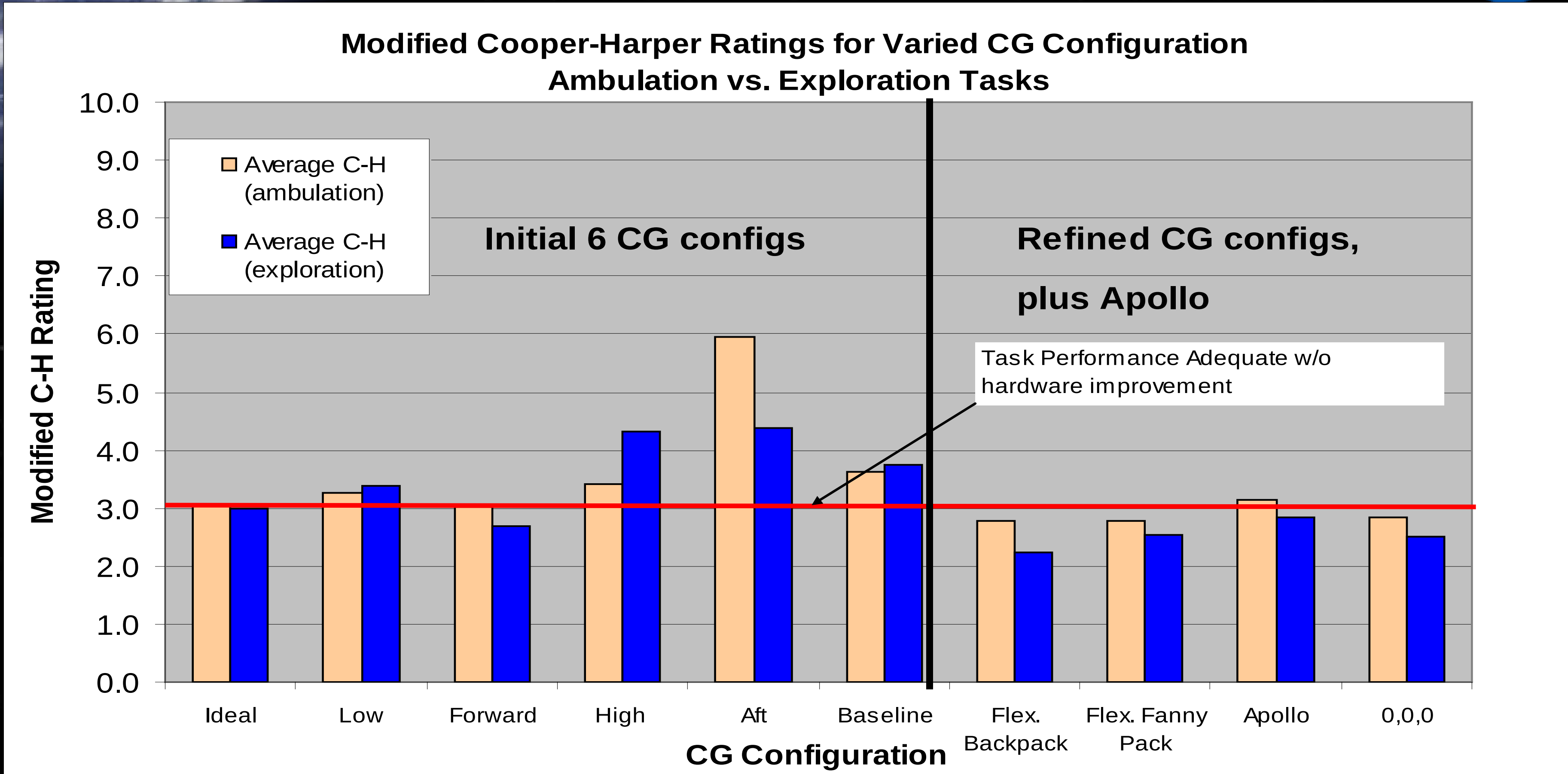


or

Center of Gravity (CG) Studies

- CG Study Objective
  - To understand the impact of a varied CG on human performance in lunar gravity
  - Divers weighed out to Apollo weight suit (60 pound suit, 135 pound backpack)
  - Six different c.g locations (high, low, forward, aft, baseline backpack (high and aft), ideal)

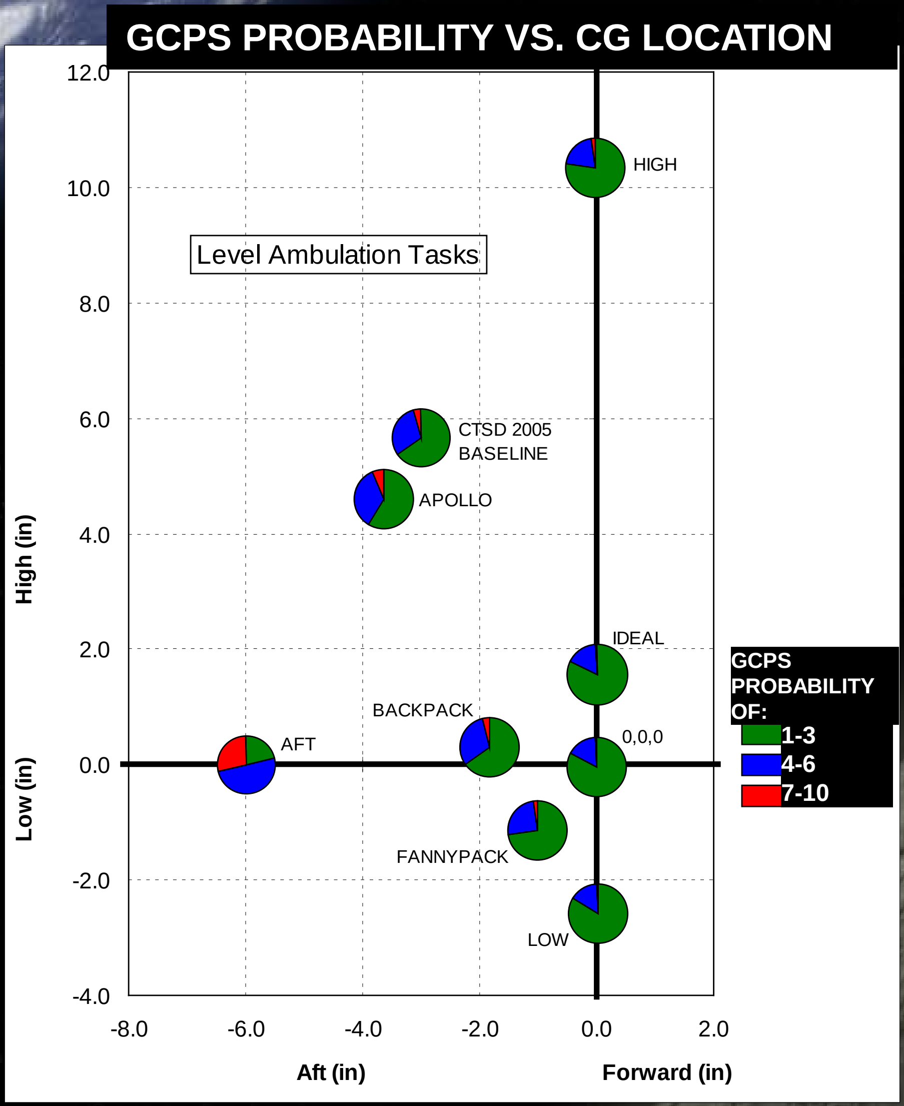
Underwater CG Study Results (continued)

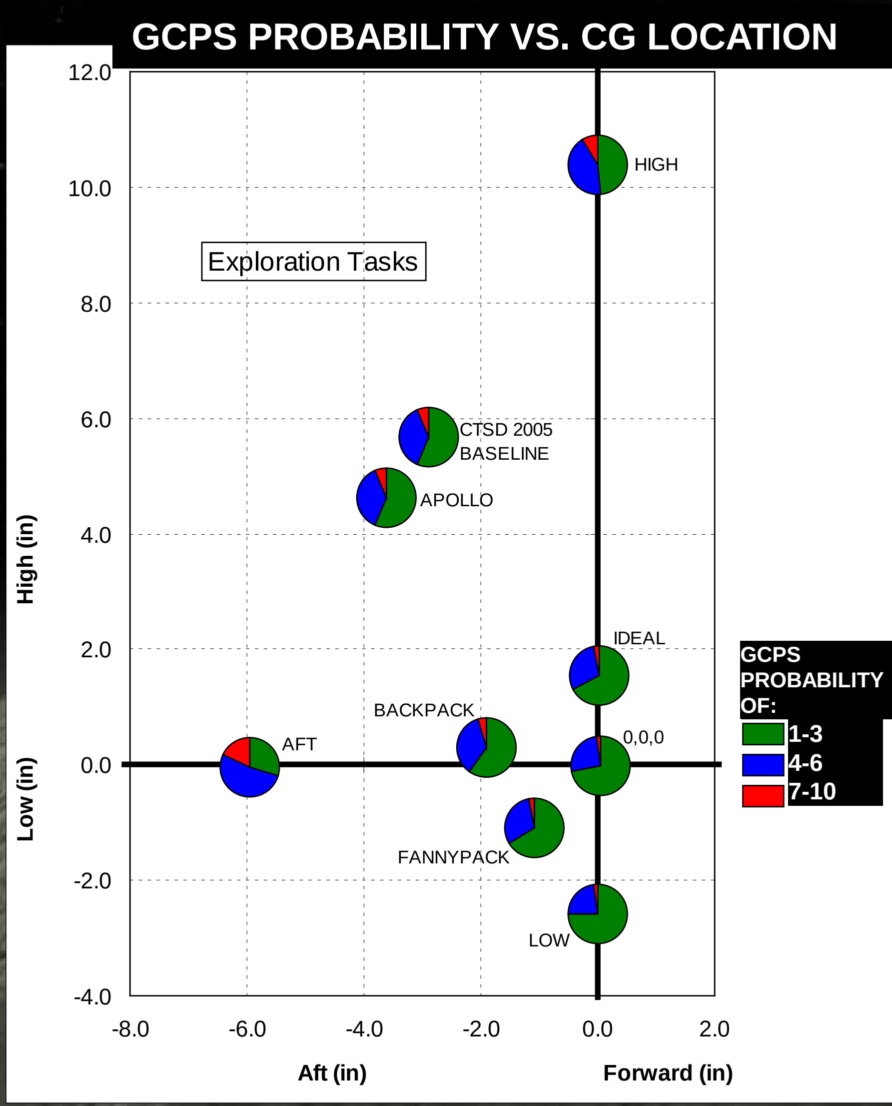


Rank Order (Best to Worst)

Ambulation	*Exploration Tasks*	*Incline*	*Decline*
• Forward	• Forward	• Forward	• Forward
• Ideal	• Ideal	• Ideal	• Ideal
• Low	• Low	• Low	• Low
• High	• Baseline	• High	• Baseline
• Baseline	• High	• Baseline	• High
• Aft	• Aft	• Aft	• Aft

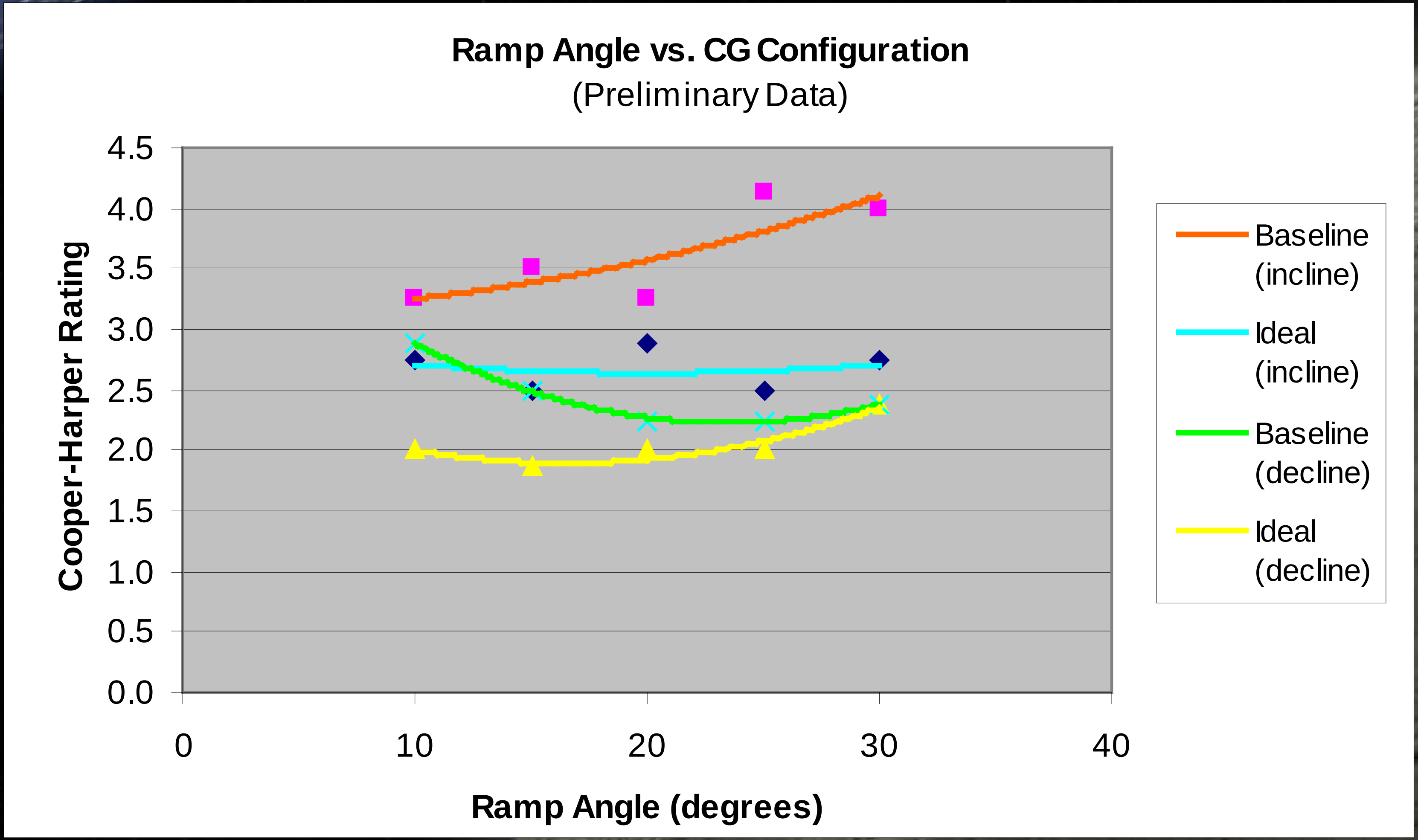
Δ CG Results





s from EPSP underwater CG studies indicate

Underwater CG Study Results (continued)

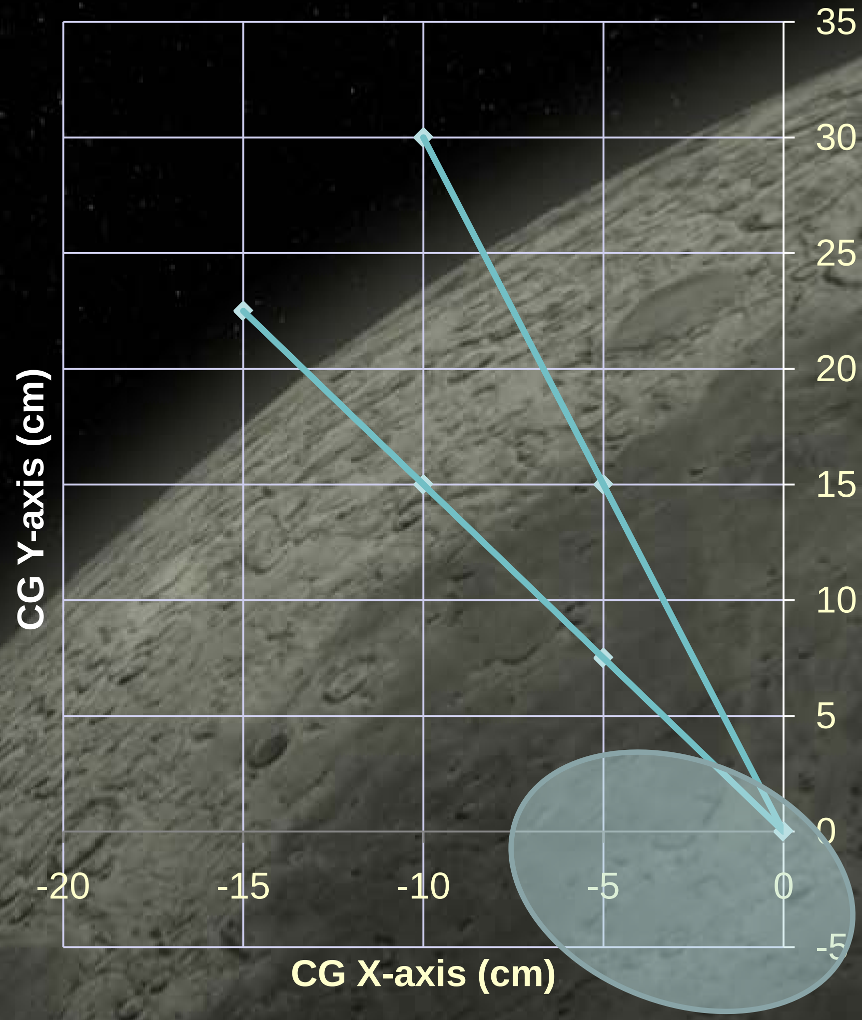


Ideal – (0.08 cm x, 0.4 cm z)

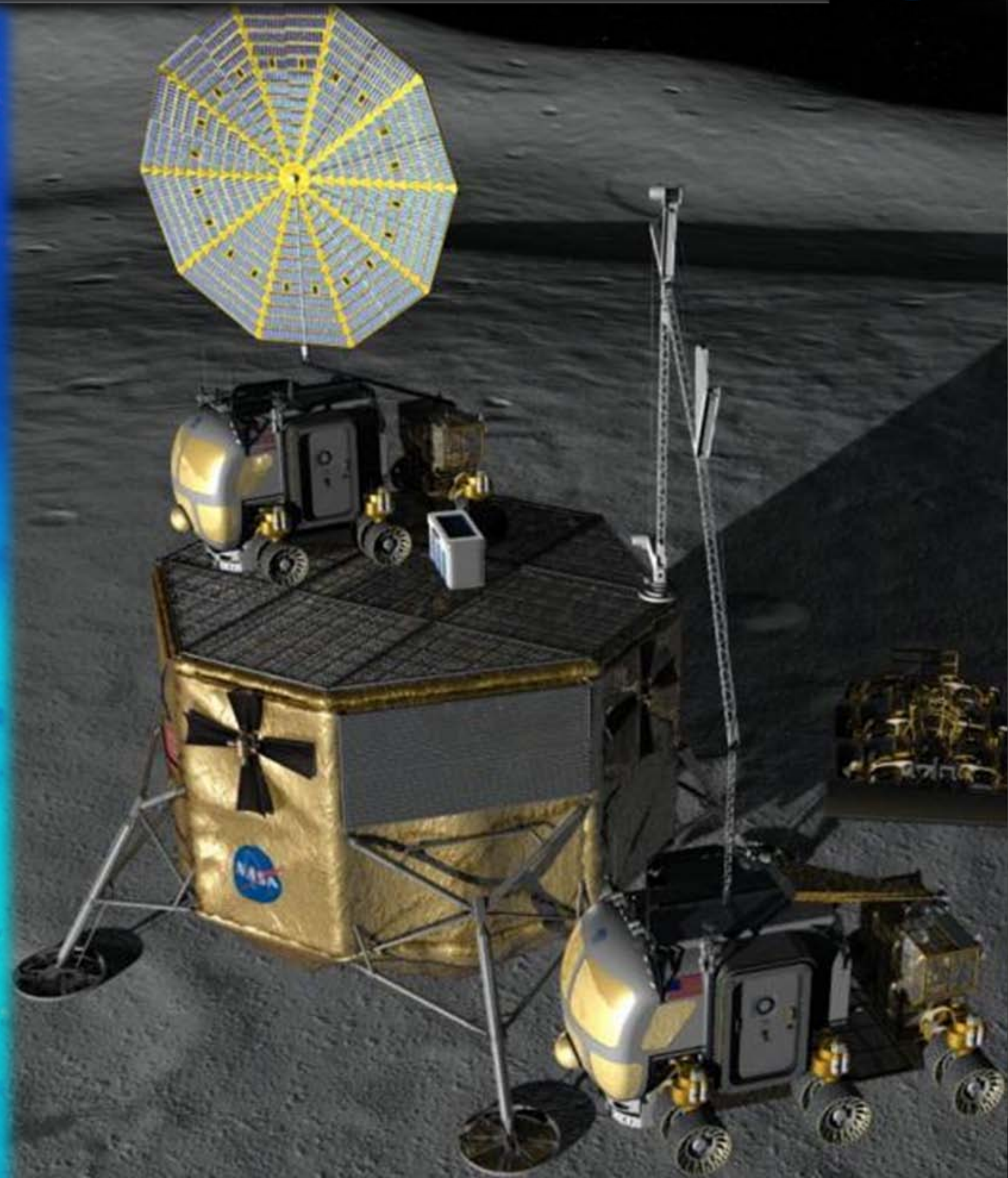
Baseline – (-7.6cm x, 14.4 cm z)

CG Target

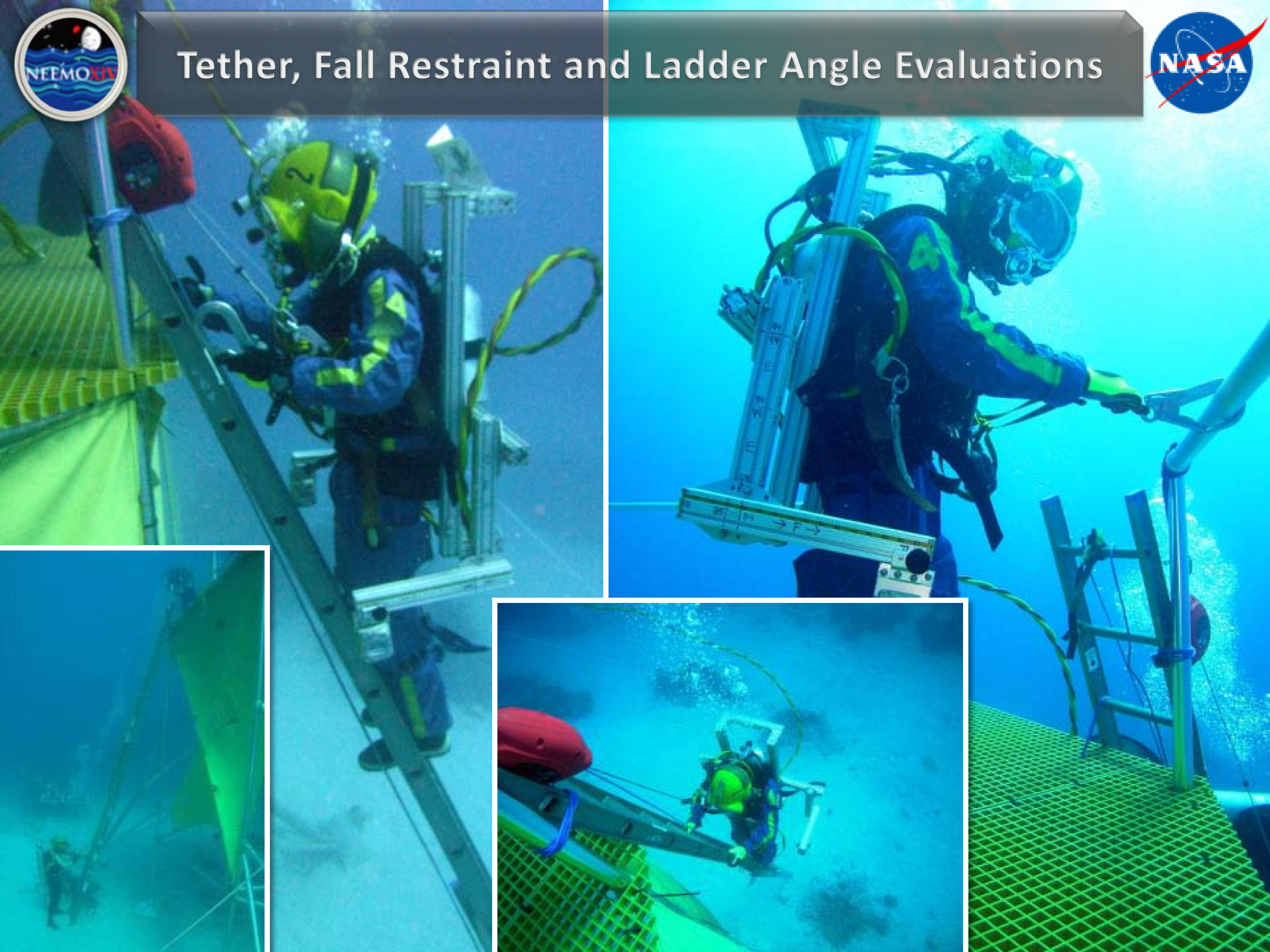
- NEEMO data indicates that 0,0 is the ideal target
- Parabolic data indicates that if the CG moves aft, it must also move high
  - For each 1 cm aft, raise the CG by 1.5 - 3 cm
- Consider both
  - 182.9-cm, 81.6-kg male (72-in, 180-lb)
  - 163-cm, 65-kg female (64-in, 143-lb)



LER Offload from Lander Deck using Davit

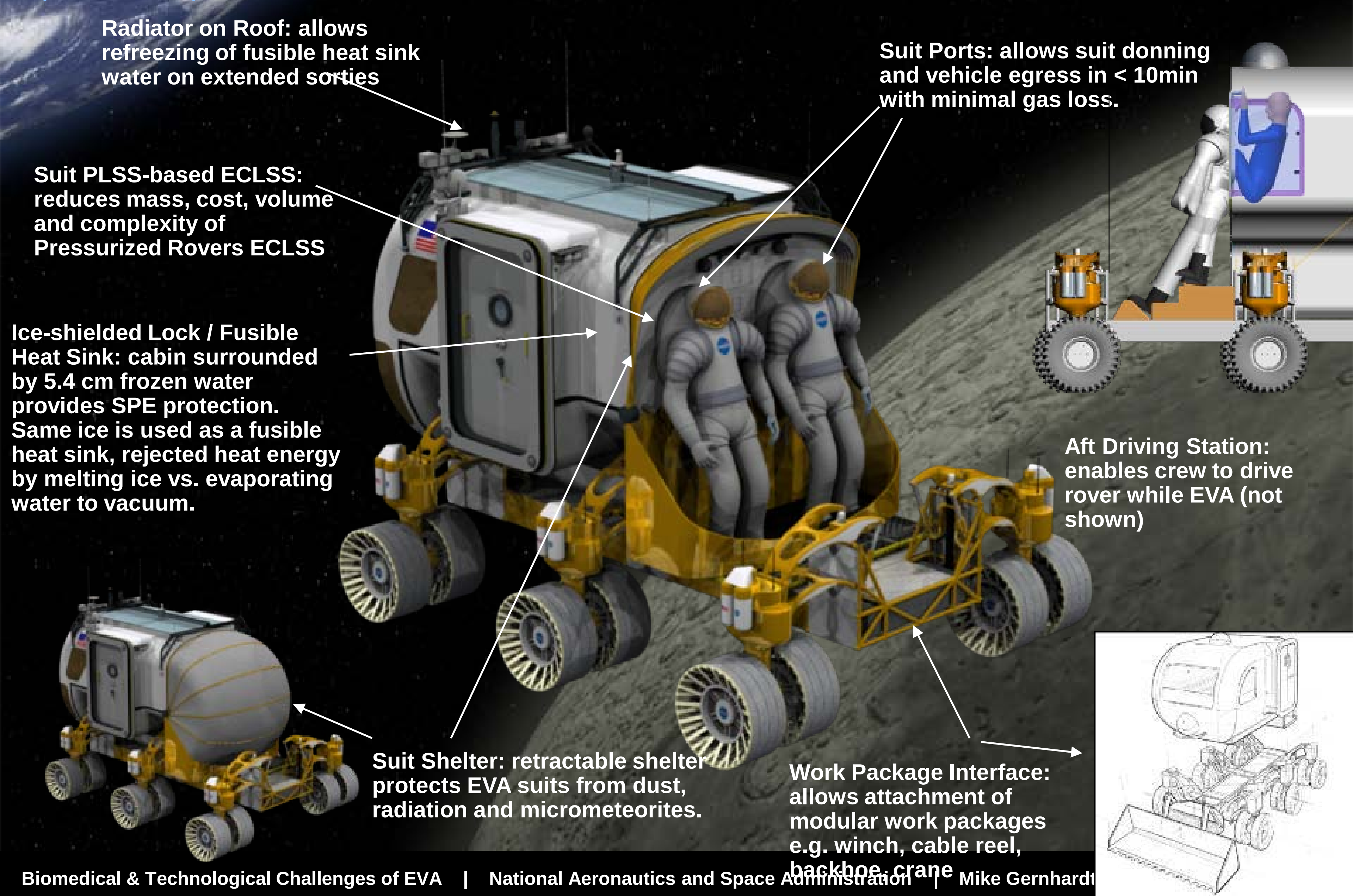


Tether, Fall Restraint and Ladder Angle Evaluations

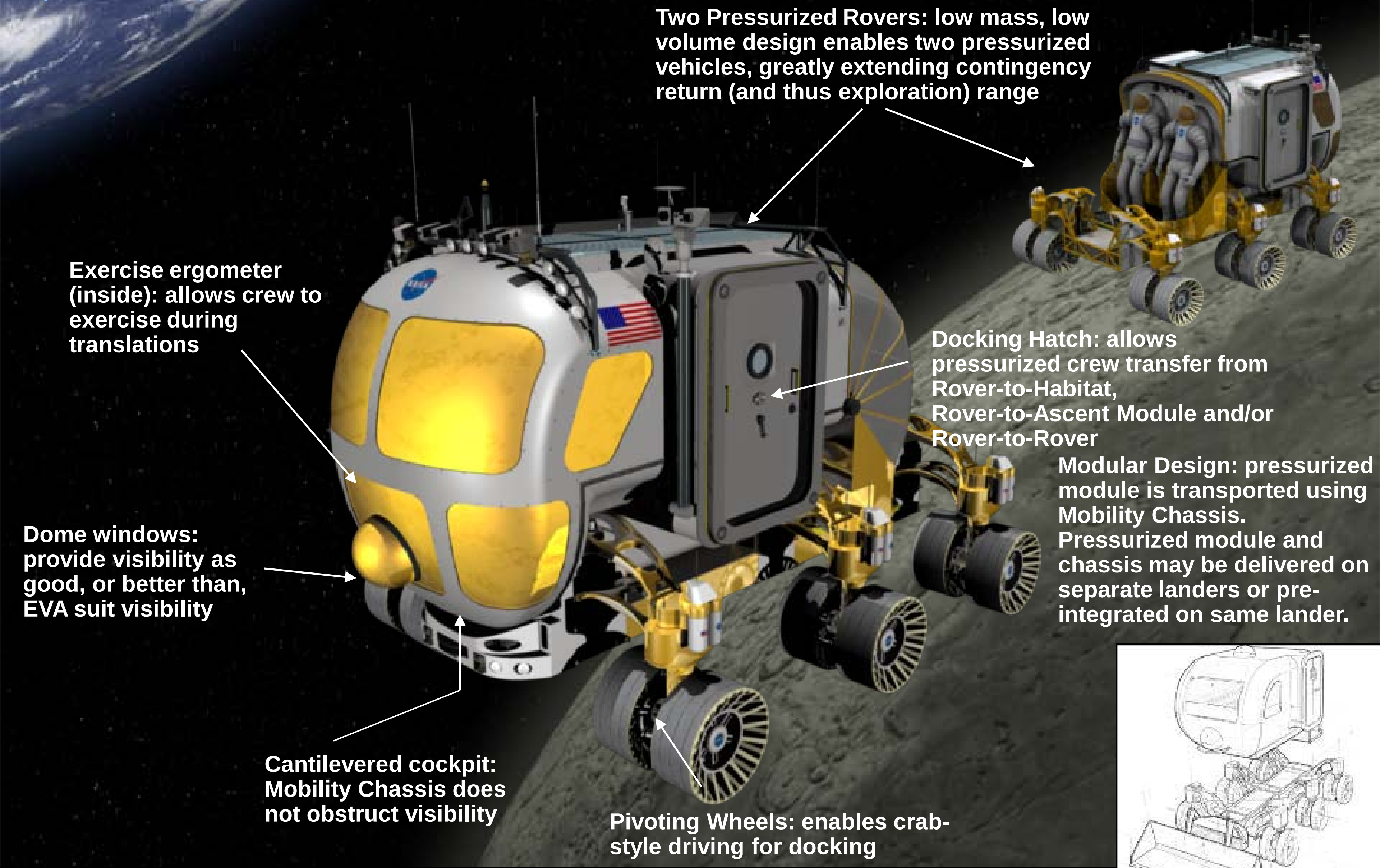


Incapacitated Crewmember Transfer into LER via Suit Port

Lunar Electric Rover Design Features
(Slide 1 of 2)



Lunar Electric Rover Design Features
(Slide 2 of 2)



An Accelerated, Highly Mobile, Flexible Architecture:
Moving Emphatically Beyond Apollo from the First Mission

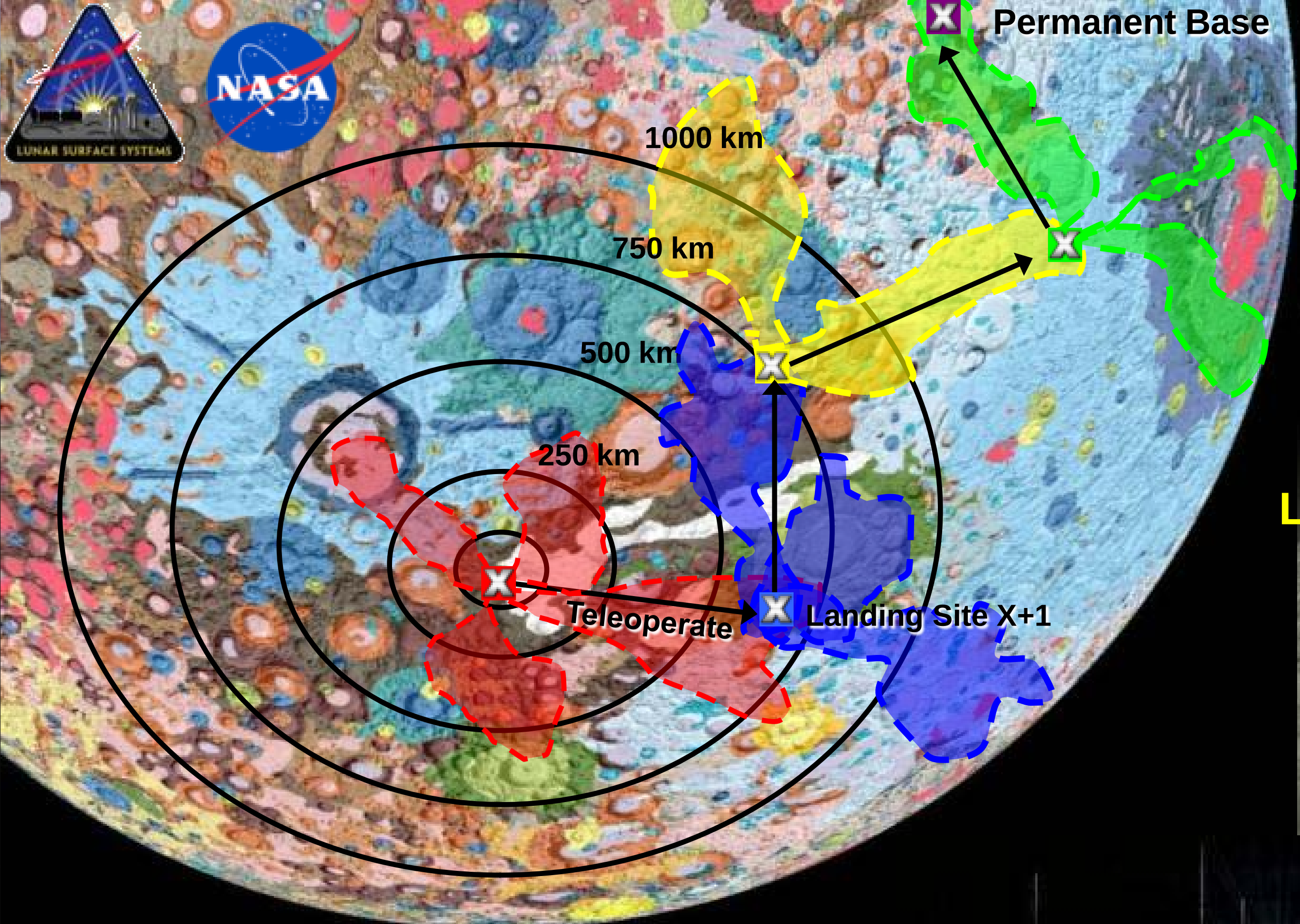
Phase 1: 2 LERs, 2 PUPs, 1 Davit or LSMS, 28 days Logistics
- Enables 4-person missions up to 28 days at polar locations
- Exploration range from poles ~ 100-200km
- LERs return to Lander to resupply after 14 days (no initial need for mobile logistics vehicle)

Optional Phase 2: Deliver chassis with additional energy storage
- Enables 14-28 day LER missions at non-polar locations
- Approx 700 KWh for un-crewed vehicles to survive lunar night

Optional Phase 3: Deliver additional pressurized volume (preferably with mobility) and ISRU
- Enables extended stay missions (60+ days)
- *Options include i) additional LERs, ii) pressurized rover(s) provided by commercial or international partners, iii) NASA-provided habitats / Logistics Modules.*

➤ Many Opportunities for Commercial and/or Industrial Partners

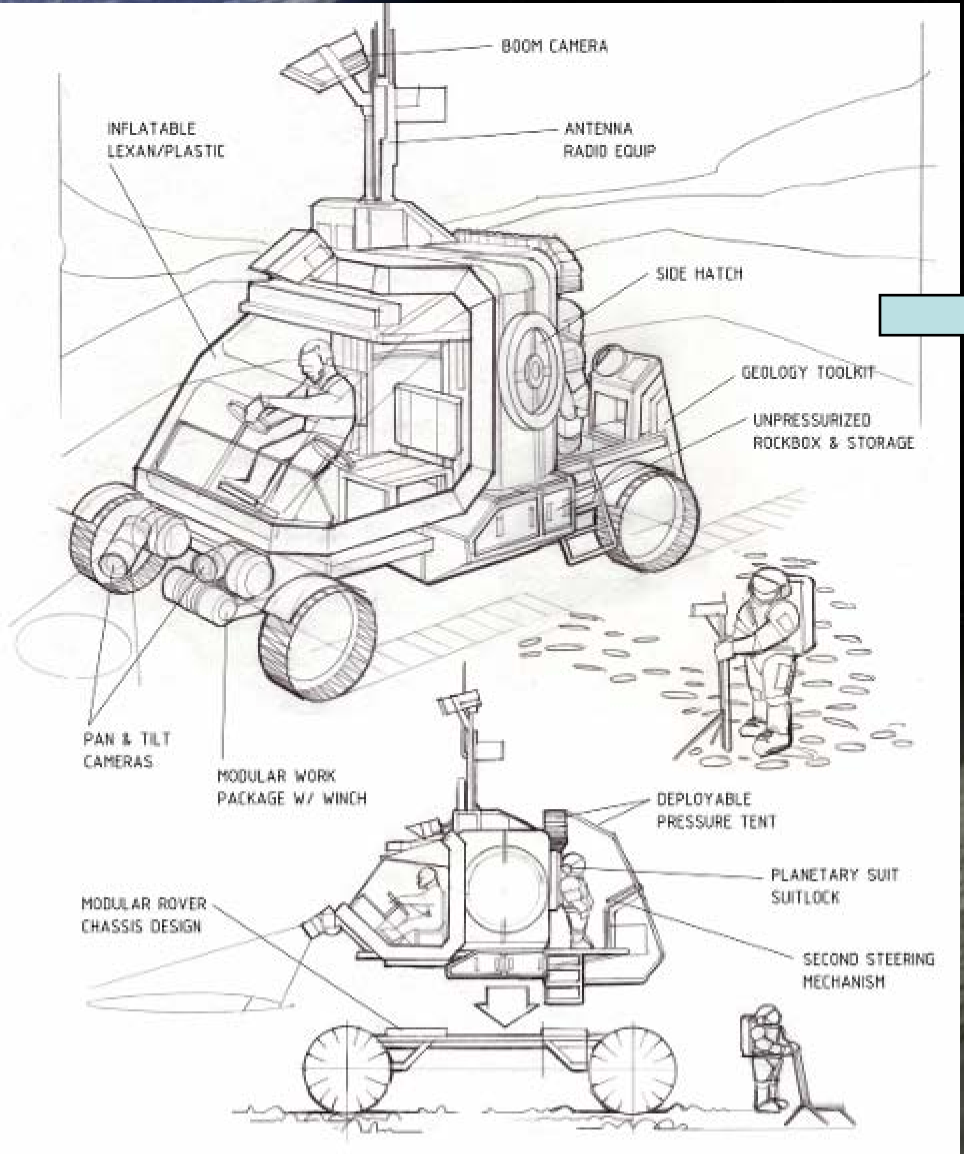
Leap Frog Exploration



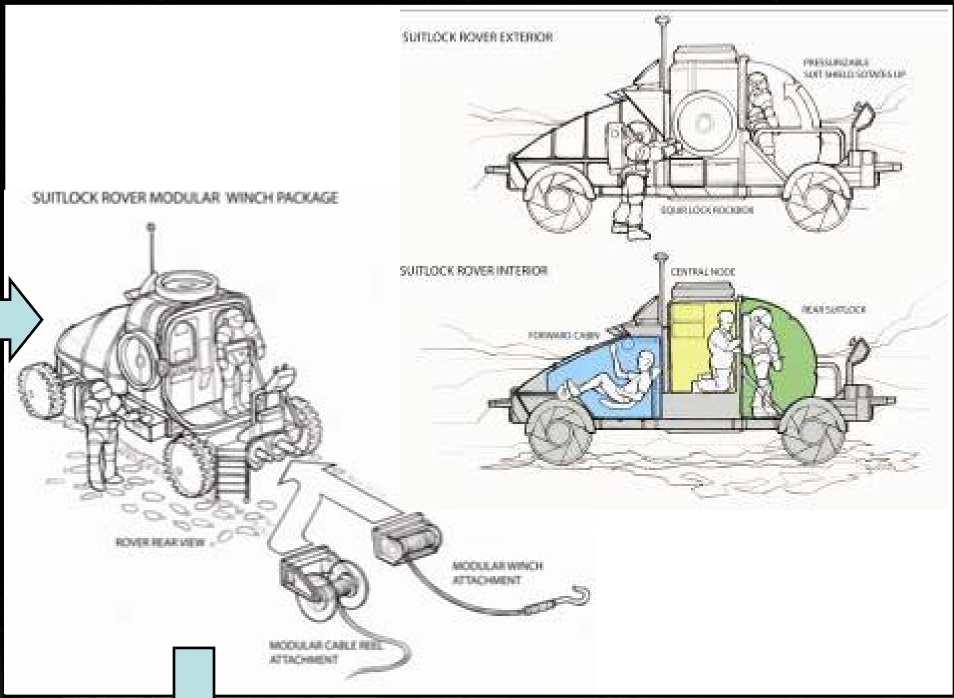
Relative Age	
Yellow = Copernican System	Youngest
Green = Eratosthenian System	
Blue/Red = Imbrian System/mare materials	
Orange/Tan = Nectarian System	
Brown = Pre-Nectarian System	Oldest

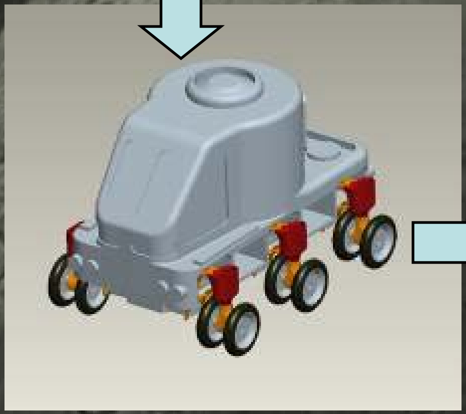
by John Gruener (LSS)

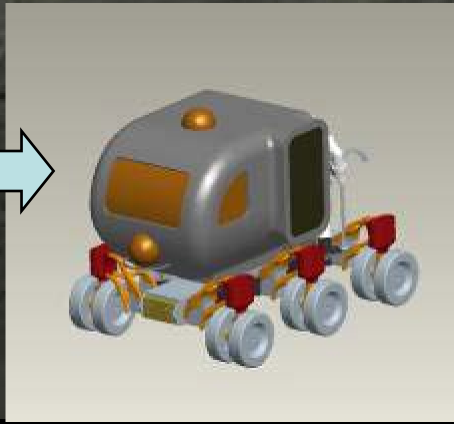
Lunar Electric Rover Design Evolution



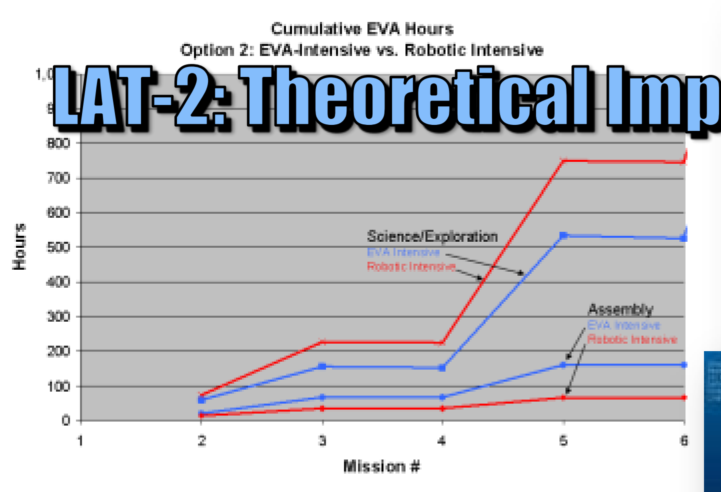
Original Concept

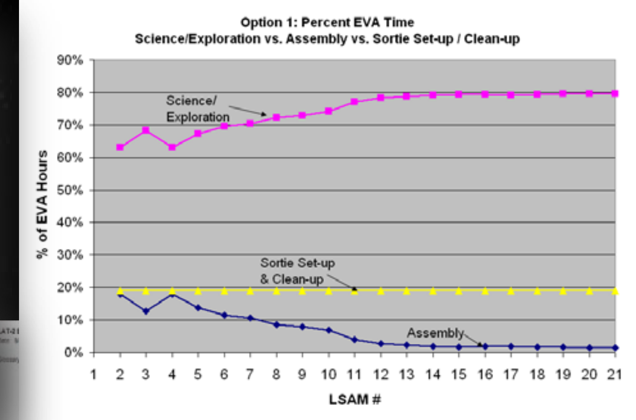


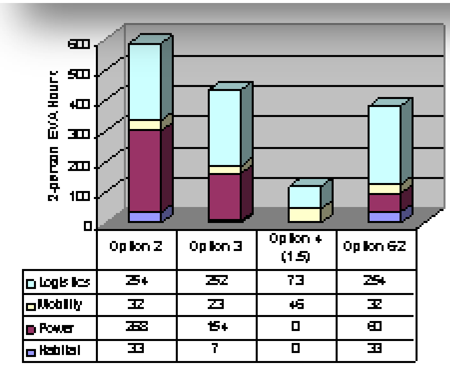


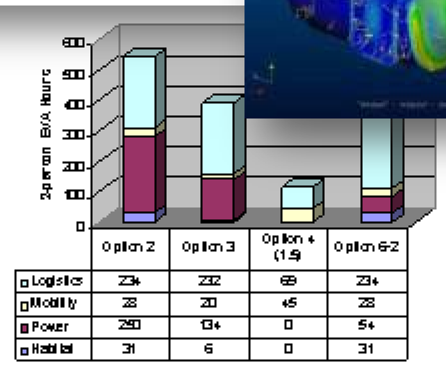


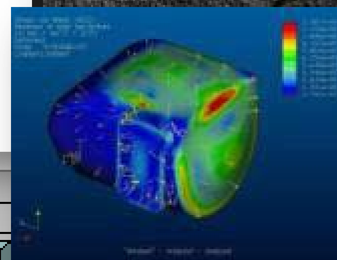
LAT-2: Theoretical Implications of LERs

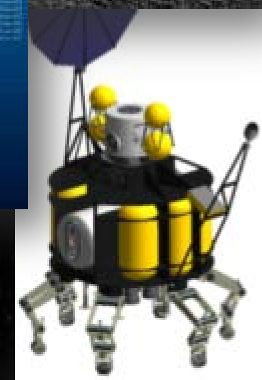


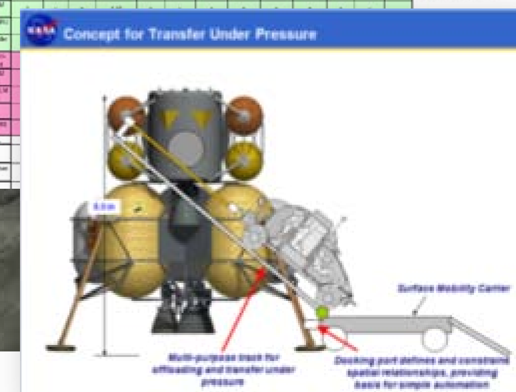


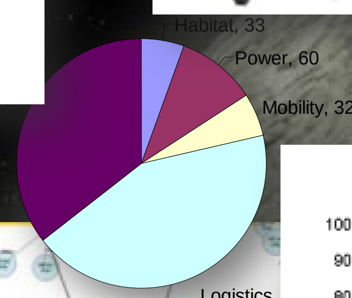


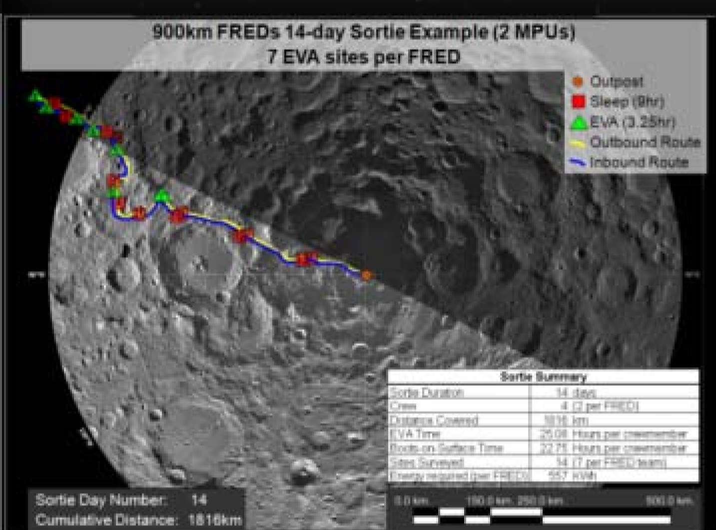


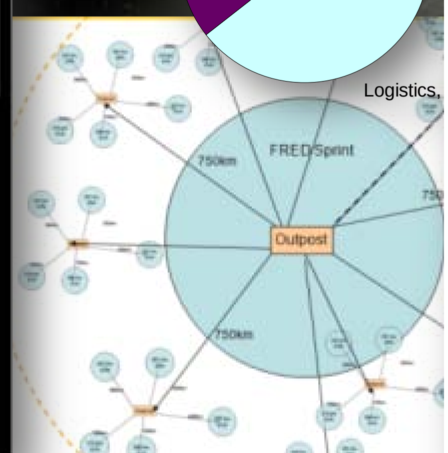


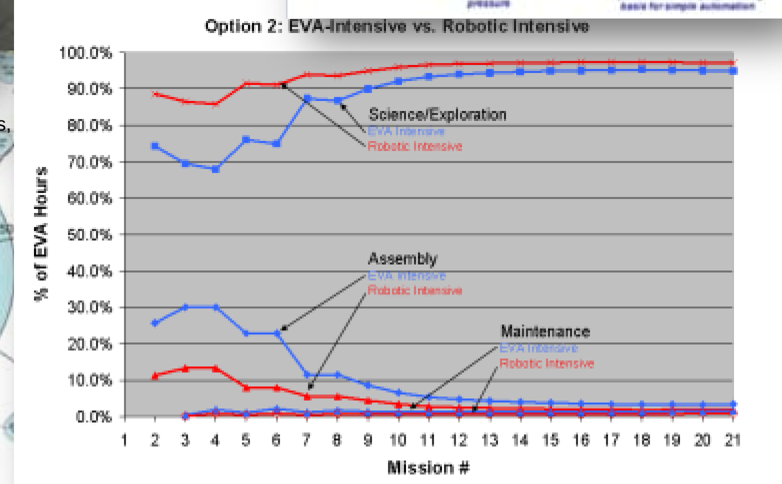












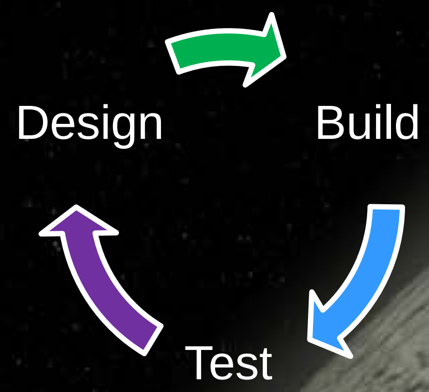
The Need to Answer Key Questions

- **Despite extensive analysis of the LER concept during LAT2, widely diverging opinions remained as to the efficacy of the concept e.g.:**
  - Human factors of suit ports
  - Viability of making scientific observations from inside the LER
  - The ops concept of SPR versus UPR exploration
  - How long crew could live and function in the LER
- **The cycle of debating these issues and conducting increasingly detailed theoretical analyses could have lasted years and still be ongoing**

It was clear that we needed to break out of the normal development process, and start a new process the focused on an iterative evolutionary Design – Build – Test – Refine approach

A New Process is Needed

Design-build-test conducted iteratively with increasing knowledge of the lunar environment will result in an end-product that optimizes safety and performance



Begin with a clear vision of what the vehicle will do and what it won't do

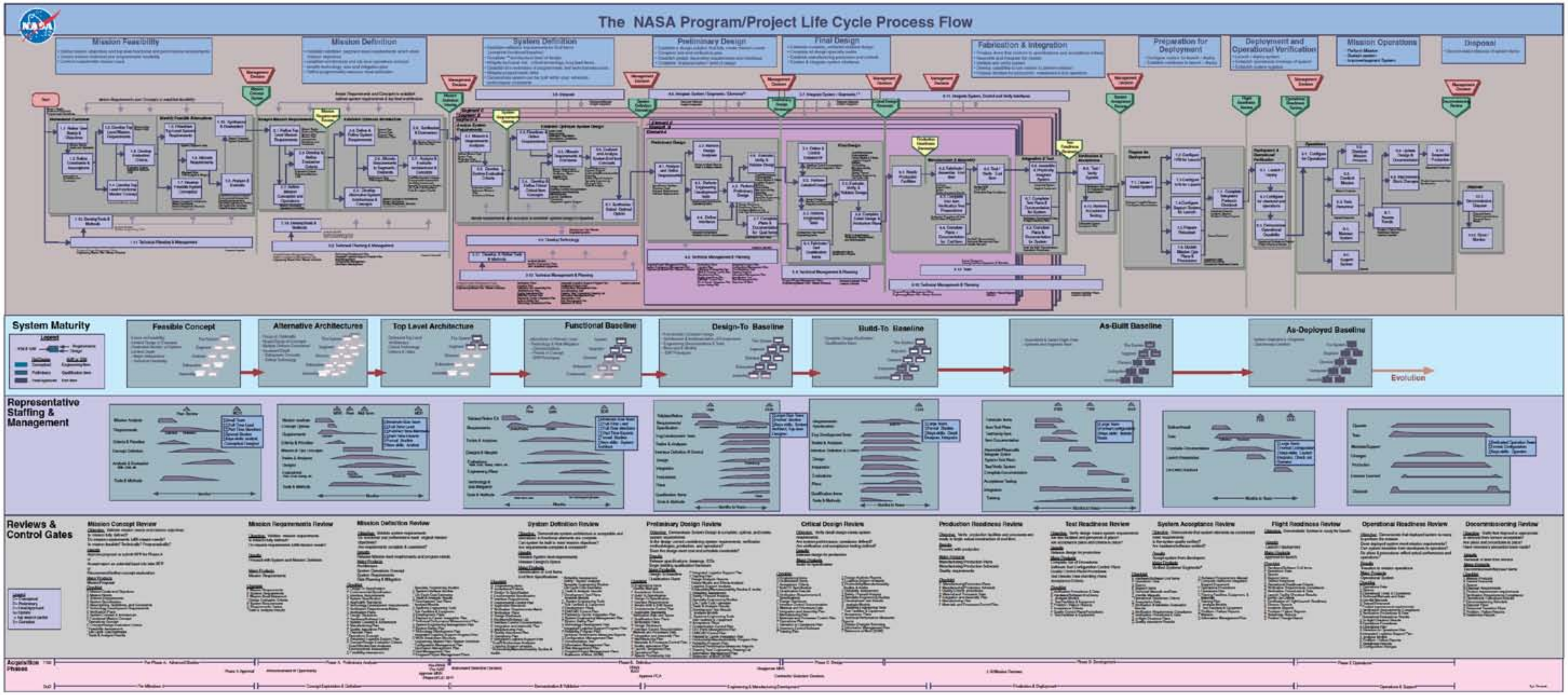
By PDR we will know exactly what we want and how we're going to operate it

Gen I	Gen II	Gen III	Flight
Functional Requirements	Expanded Functional Requirements	Preliminary Design Requirements	Flight Design Requirements

The Vision:
Generation 1 LER Initial Functional Requirements

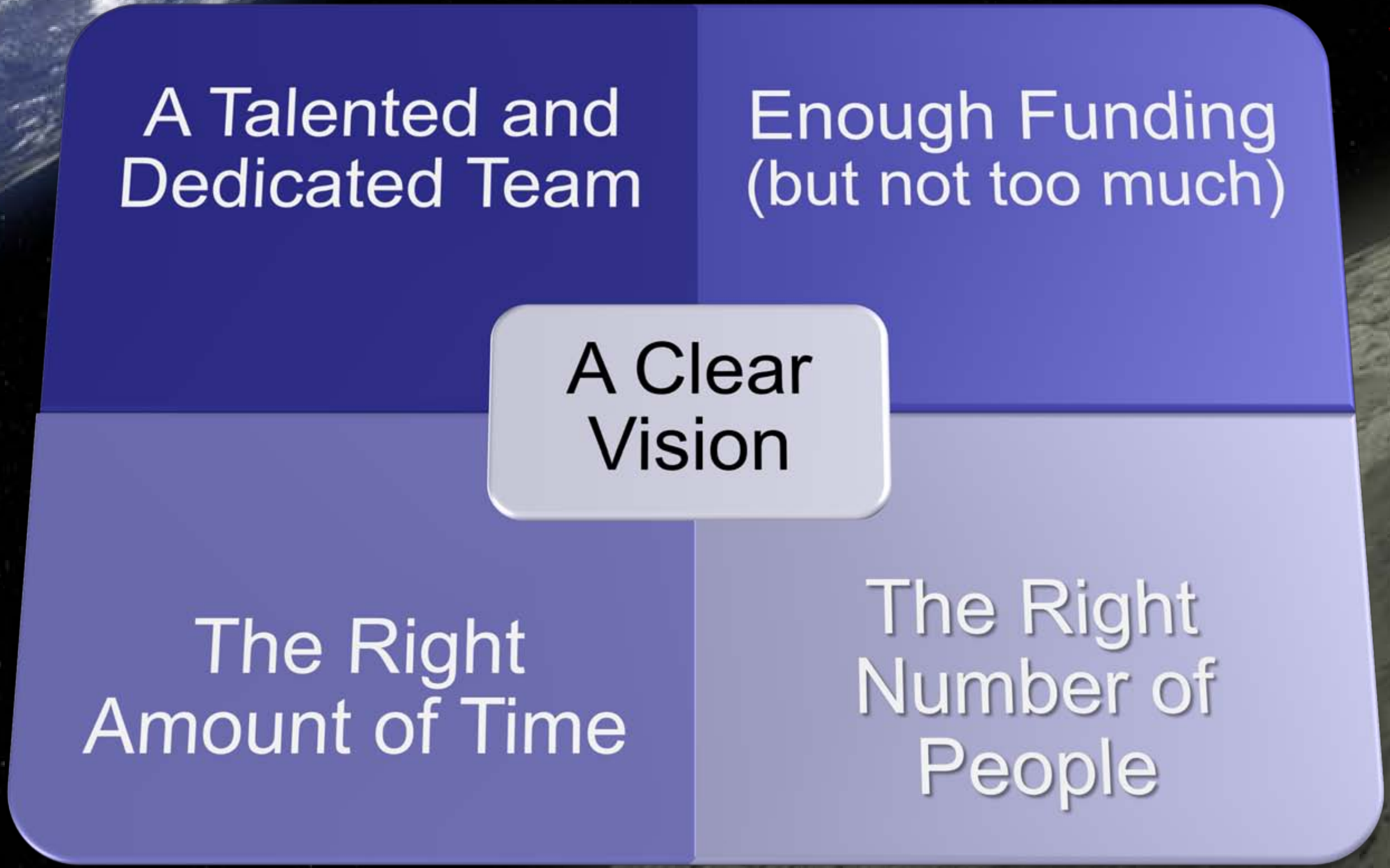
- Power-up and Check-out including suit/PLSS power up and check-out: ≤1hr
- Mate/de-mate from Hab/Lander: ≤ 10mins and ≤ 0.03kg gas losses
- Nominal velocity: 10kph
- Driving naked-eye visibility should be comparable to walking in suit i.e. eyes at same level, similar Field-of-View
  - Augmented by multi-spectral cameras/instruments
- Visual accessibility to geological targets comparable to EVA observations i.e. naked eyes ≤ 1m of targets
  - Possibility of magnification optics providing superior capability than EVA observations
- Suit don and Egress/Egress
  - ≤ 10mins
  - ≤ 0.03kg gas losses per person
  - ≥ 2 independent methods of ingress/egress
- Vehicle Mass (not incl. mobility chassis) ≤ 2400kg
- Habitable volume: ~10 m^3
- 12 2-person EVA hours at 200km range on batteries and nominal consumable load
- Ability to augment power and consumables range and duration to achieve ≥ 1000km
- PLSS recharge time ≤ 30mins
- Crewmembers ≤ 20mins from ice-shielded lock SPE protection (incl. translation to Small Pressurized Rovers and ingress)
- Heat and humidity rejection provided by airflow through ice-shielded lock and condensing heat exchanger

The NASA Project Life Cycle



The typical NASA project management approach works well if you know exactly what you want to build and how you want to operate it with a high level of fidelity before you begin the process

Otherwise, cost , schedule and content will be compromised.



History has shown that the NASA Team is at its best when it has a clear problem to solve and not too much time to solve it

→Lets recognize this and make it work for us in our new lunar developments

Lunar Electric Rover

FY08 Lunar Electric Rover Team

- Johnson Space Center
    - EC, ER, SF, SK, CB
- Langley Research Center
- Ames Research Center
- Glenn Research Center

Important Attributes of the LER Team

- Multi-center, multi-divisional, multi-disciplinary and highly integrated
- Sharp focus
- Capable of assimilating information and issues and making informed decisions, quickly and inexpensively


XIV
BLACK POINT 2009
Exploration Analogs &
Mission Development
DRATS 14 Day Excursion

DRATS 2009: Primary Hypotheses

1. The habitability and human factors of the LER vehicle during a 14-day mission will be acceptable as assessed by established human factors metrics.

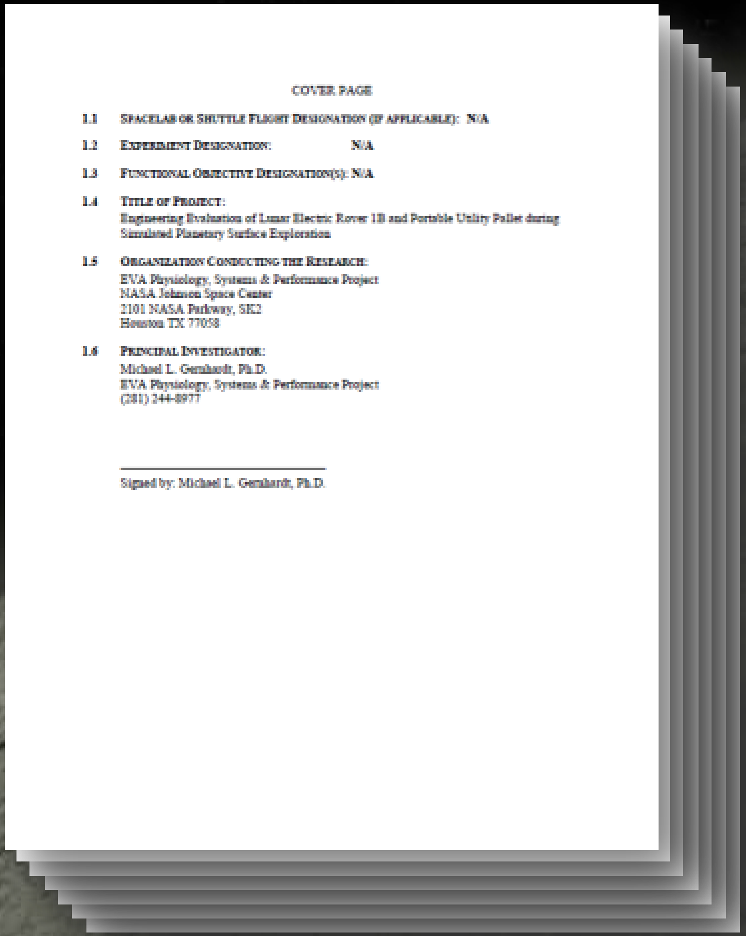
2. Crew productivity during LER mission tasks (EVA and IVA science operations and vehicle maintenance tasks) will not significantly vary among two different communications scenarios:
   - Continuous real-time comm. (baseline)
   - Limited comm. (66% coverage, 34% no coverage – based on single highly-elliptical south pole coverage relay satellite)

Secondary Test Objective:

- Assess the ability to navigate to predefined targets under different levels of navigational uncertainty (± 50m, 100m)

Protocol and Hypothesis Testing

- Practically significant Accept-Reject criteria for specific metrics were prospectively defined for the testing of all study hypotheses
  - 10% difference in time, range and productivity metrics
  - Categorical difference in subjective human factors metrics
  - Acceptability Rating of 1-4 (scale below)



COVER PAGE

1.1 SPACELAB OR SHUTTLE FLIGHT DESIGNATION (IF APPLICABLE): N/A

1.2 EXPERIMENT DESIGNATION: N/A

1.3 FUNCTIONAL OBJECTIVE DESIGNATION(S): N/A

1.4 TITLE OF PROJECT:
Engineering Evaluation of Lunar Electric Rover 1B and Portable Utility Pallet during Simulated Planetary Surface Exploration

1.5 ORGANIZATION CONDUCTING THE RESEARCH:
EVA Physiology, Systems & Performance Project
NASA Johnson Space Center
2101 NASA Parkway, SK2
Houston TX 77058

1.6 PRINCIPAL INVESTIGATOR:
Michael L. Gernhardt, Ph.D.
EVA Physiology, Systems & Performance Project
(281) 244-8977

Signed by: Michael L. Gernhardt, Ph.D.

Acceptability Rating Scale

Totally Acceptable		Acceptable		Borderline		Unacceptable		Totally Unacceptable	
No improvements necessary		Minor improvements desired		Improvements warranted		Improvements required		Major improvements required	
1	2	3	4	5	6	7	8	9	10

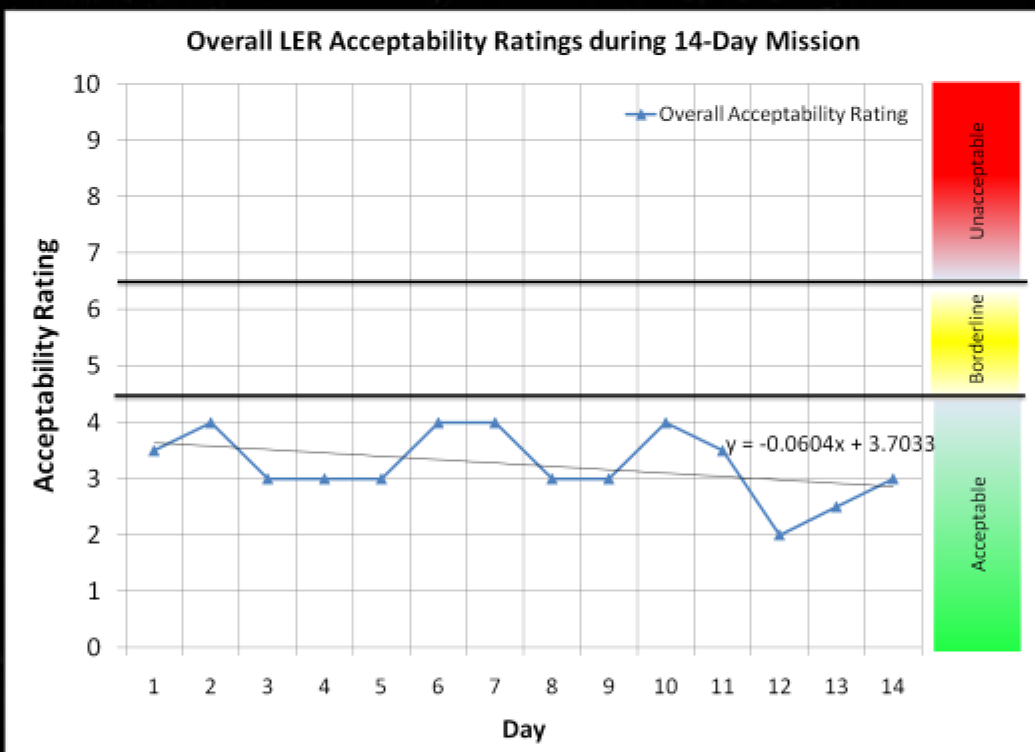
Video: Driving, Bubble Viewing & Suit Ports

Video: Food Preparation

Video: Exercise

Hypothesis 1: The habitability and human factors of the LER vehicle during a 14-day mission will be acceptable as assessed by established human factors metrics.

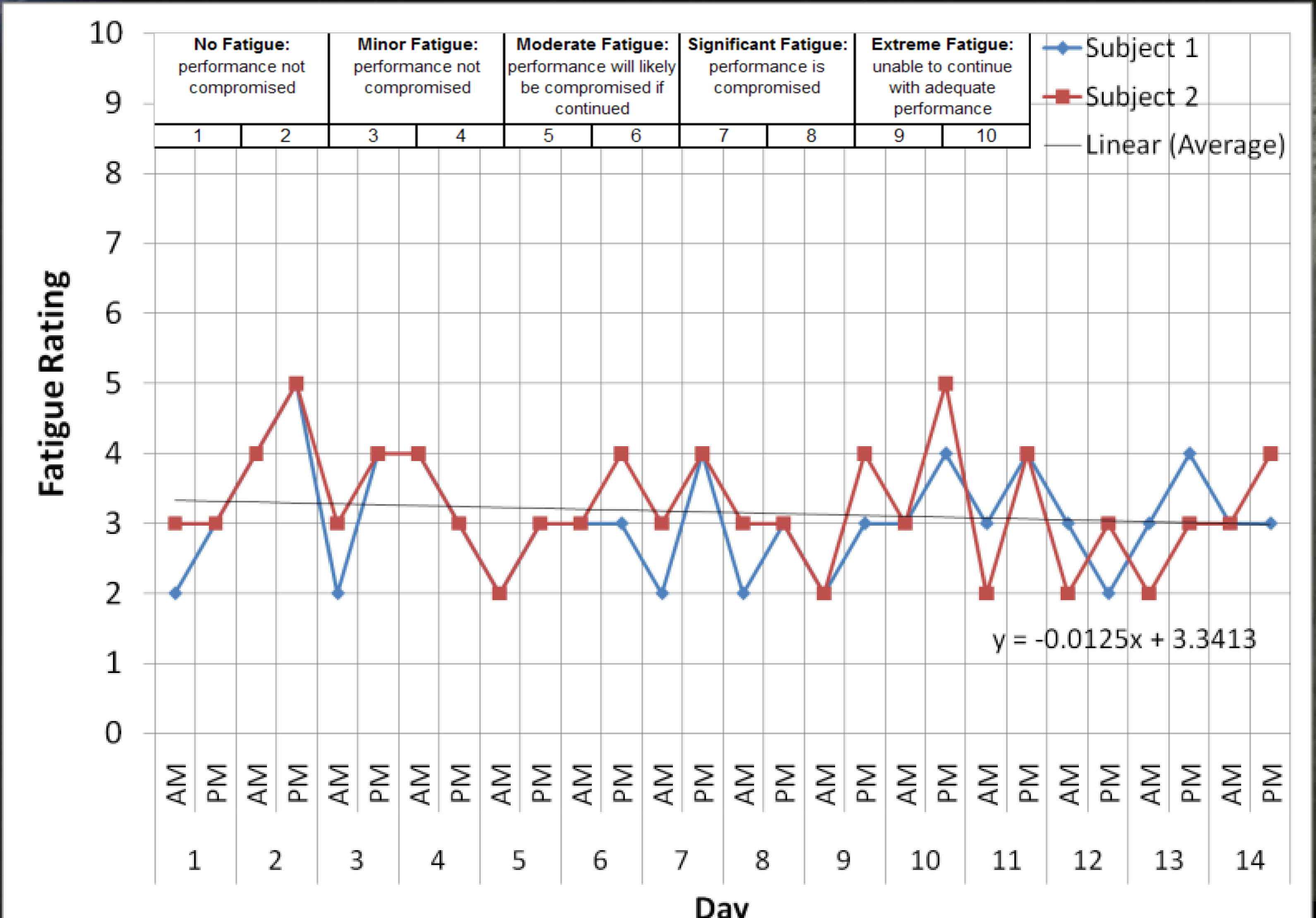
Data Collection: 14-day LER mission completed with no violations of Habitability Assessment Rules. Overall Vehicle Acceptability Ratings collected daily from 2 subjects. Acceptability Ratings also collected for individual elements of the LER (e.g. sleep stations, seats, displays & Controls, etc).



Results: All Overall Vehicle Acceptability Ratings were within the Acceptable Range. Results for individual aspects of LER habitability are currently being analyzed.

➔ HYPOTHESIS ACCEPTED

Hypothesis 1: The habitability and human factors of the LER vehicle during a 14-day mission will be acceptable as assessed by established human factors metrics.



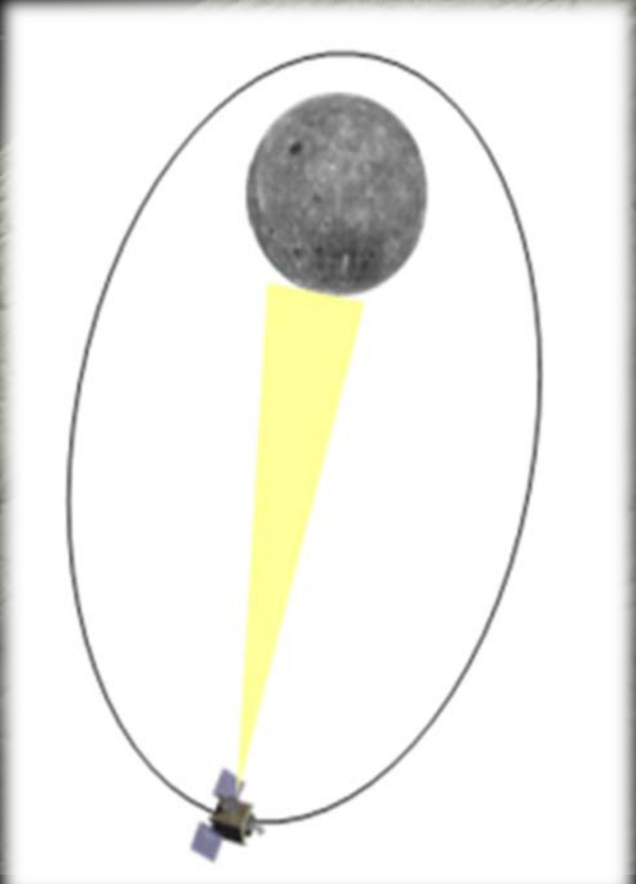
Hypothesis 2: Crew productivity during LER mission tasks (EVA and IVA science operations and vehicle maintenance tasks) will not significantly vary among different communications scenarios:

- Continuous real-time comm. (baseline)
- Limited comm. (66% coverage, 34% no coverage – based on single highly-elliptical south pole coverage relay satellite)

Data Collection: EVA productivity data collected throughout the 14-day mission.

Unintentional comm. dropout affected portions of several traverse days.

<u>Where Data Quality ratings were affected by unintentional comm. dropout the scores were not used.</u>

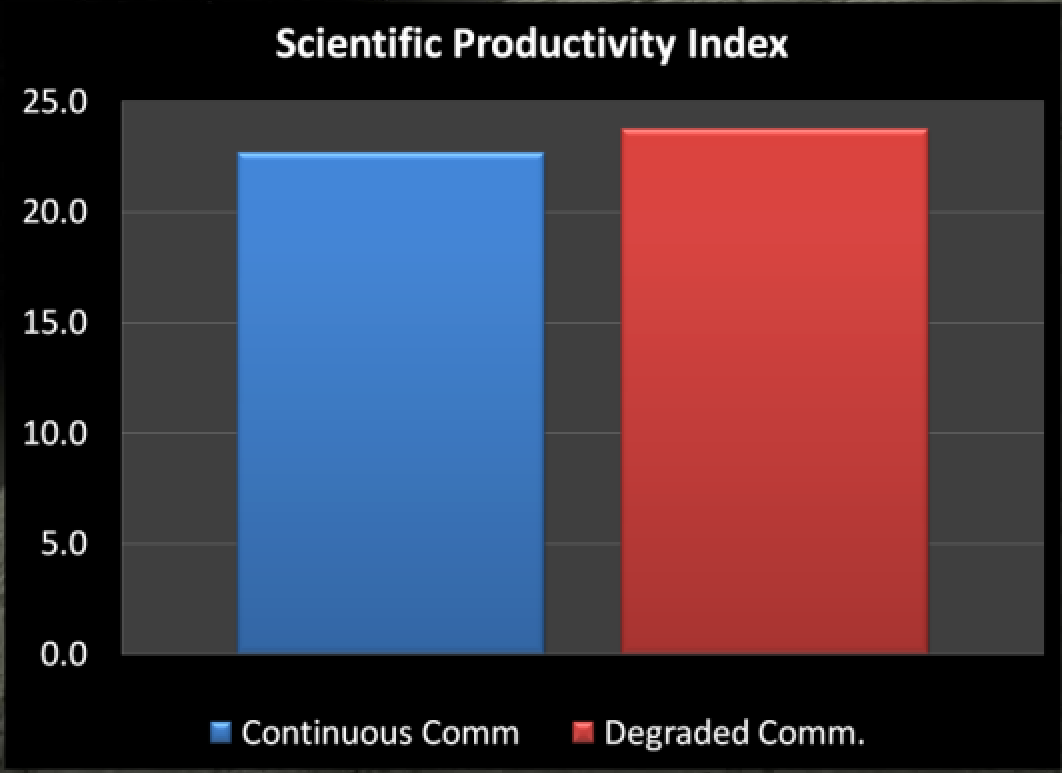


Hypothesis 2: Crew productivity during LER mission tasks (EVA and IVA science operations and vehicle maintenance tasks) will not significantly vary among different communications scenarios:

- Continuous real-time comm. (baseline)
- Limited comm. (66% coverage, 34% no coverage – based on single highly-elliptical south pole coverage relay satellite)

Results: The Scientific Productivity Index was marginally greater during the degraded comm scenario but the difference (4.8%) did not meet the prospectively defined level of practical significance (10%).

➔ HYPOTHESIS ACCEPTED



Test Objective 1: Assess the ability to navigate to predefined targets under different levels of navigational uncertainty (± 50m, 100m)

Data Collection: A series of six targets were identified and a traverse plan created using an annotated map and photographic references.

The crew then attempted to reach the exact target locations using the traverse plan, photographs and vehicle position data with an rms error of 50m or 100m.

Results: All targets were reached successfully by the crew with minimal difficulty.

LER Consumables and Logistics

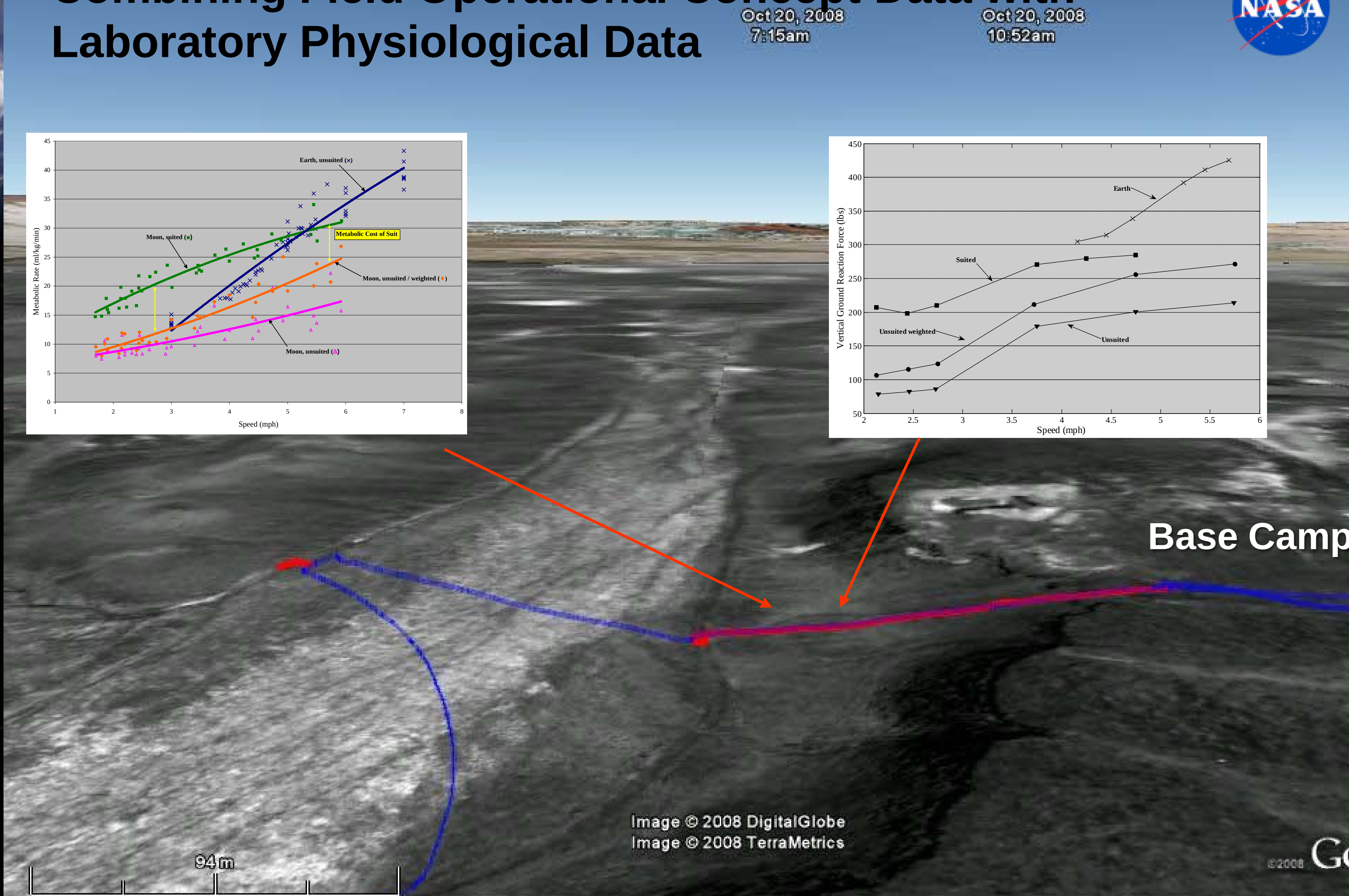
	DRATS '09	LSS Baseline	DRATS-modified Baseline
	kg per person per day		
Water, Food Prep	0.57	0.5	0.86
Water, EVA	0.86	1.71	0.86
Water, Laundry	0	0	0
Water, Hygiene	0.12	0.4	0.12
Water, Flush	0	0.5	0
Food / Packaging	0.47	2.06	0.71
Clothing	0.69	0.46	0.08
Misc. Crew Consumables	0.34	0.64	0.34
IVA O2	0.88	0.88	0.88
EVA O2	0.15	0.3	0.15
N2	0.06	0.06	0.06
Water, Drinking	*7.9**	*2*	*2*
	4.14	**7.51**	**4.05**

* DRATS drinking water consumption very high due to A/C failure, heavy suits in 1g and summer desert weather. HSIR specifies 2L per person per day.

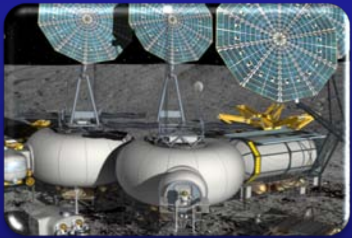
- 50% reduction in EVA hours will reduce cooling water, drinking water and O_2 consumption (due to higher met rates during EVA)
- Significant savings in food possible by reducing packaging waste
- Silver-impregnated clothing may reduce clothing mass
  - DRATS-modified baseline based on actual clothing used versus clothing manifested

Mass Savings of 46% plus tankage and packaging may be achievable

Combining Field Operational Concept Data with Laboratory Physiological Data

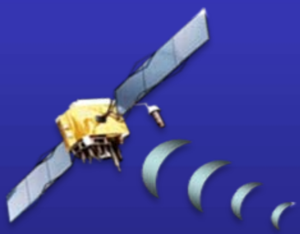


What This Means for the Exploration Architectures



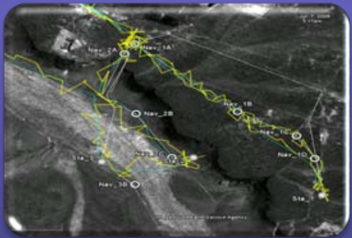
Habitats

- Dedicated habitats or large pressurized rovers probably unnecessary for stays of 14-28 days



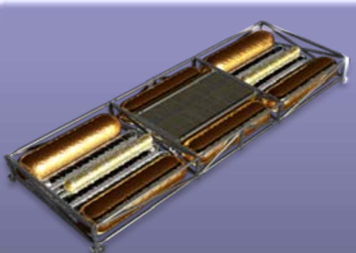
Communications and Ground Support

- DRATS results suggest continuous real-time comms and ground support will not significantly improve productivity
  - Significant cost and infrastructure savings



Navigation

- Desert RATS demonstrated the ability to return to specific rocks using GNC system with only 100m accuracy
  - Expensive, high accuracy GNC is probably unnecessary



Logistics

- Potential savings of 30-50% versus current campaign assumptions

Accelerated, Highly Mobile, Flexible: Moving Emphatically Beyond Apollo from the First Mission

- 1 x Cargo Lander
  - 2 x LERs
  - 2 x PUPs
  - 1 x Simple Off-loading davit
  - 14-28 days logistics delivered with each 4-person crew

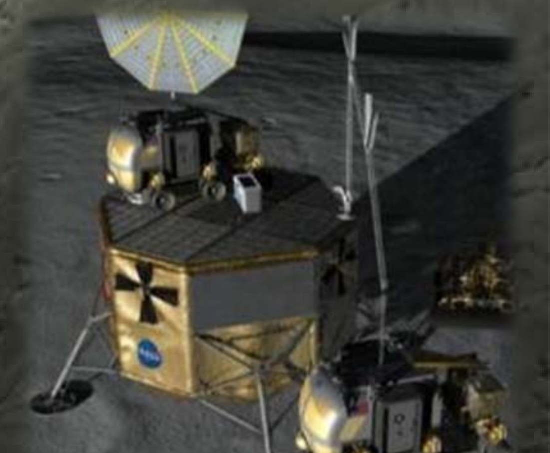
14-28 day Mission Capability +
"Leap-Frog" Exploration Capability +
Hundreds of kilometers exploration range

LER and Desert RATS testing indicates that complex and expensive comm., nav., power, habitation and unloading infrastructure is not required for this initial capability

International and commercial partners can augment the architecture with additional robotics, logistics and possibly additional cargo landers

Simple, exciting, capable, affordable, with "shallow roots"

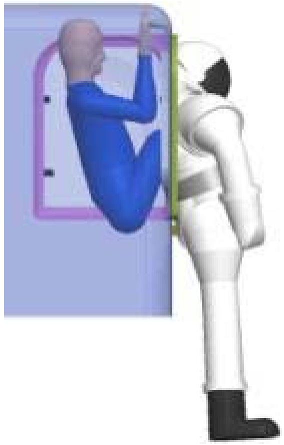
- This architecture can be the driver to get the heavy lift capability needed to execute the flexible exploration strategy ***without tying us to the moon***
- By 2021 we could have a lunar program that takes America emphatically beyond Apollo while still preserving the possibility of other concurrent human exploration programs

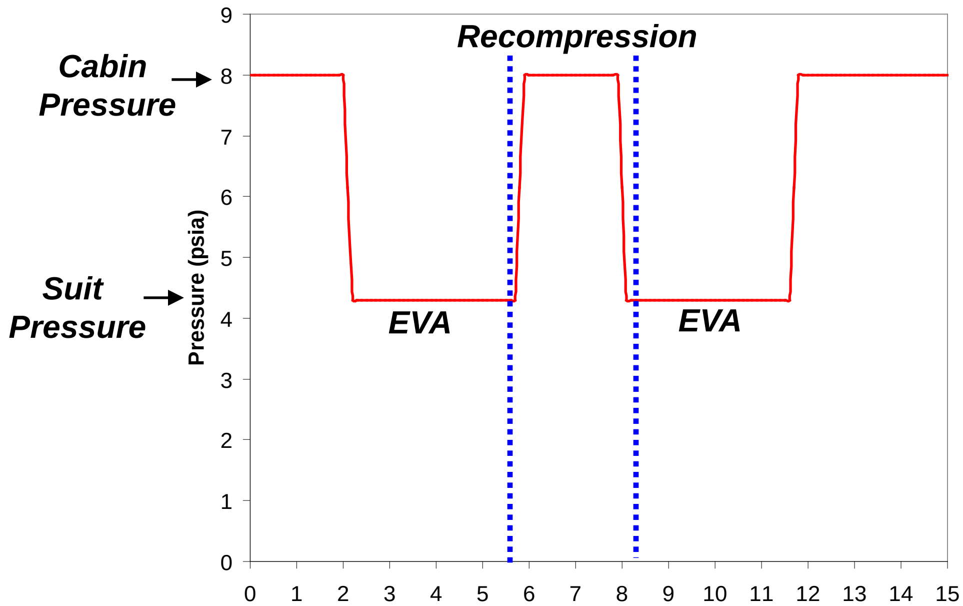


Lets pick the date 2018 and go execute

Intermittent Recompression - Background

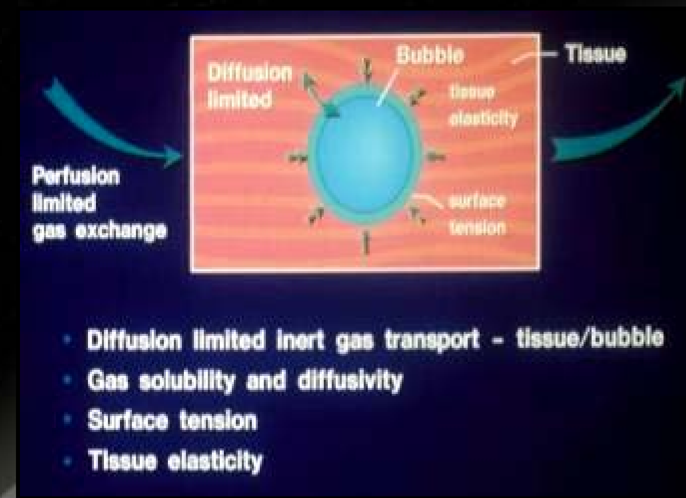
- **Current plans for lunar surface exploration include Small Pressurized Rovers (SPRs) that are quickly ingressed and egressed with minimal loss of consumables**
- **This capability enables crew members to perform multiple short extravehicular activities (EVAs) at different locations in a single day versus a single 8-hr EVA**
- **Previous modeling work and empirical human and animal data indicate that the intermittent recompressions may reduce decompression stress**





Tissue Bubble Dynamics Model (TBDM)- Provides Significant Prediction and Fit of Diving and Altitude DCS Data

- 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

...tion of a Decompression Stress Index Based on Tissue Bubble Dynamics, Ph.D dissertation, University of

Intermittent Recompression - Background

- Intermittent recompression during saturation decompression was previously proposed as a method for decreasing decompression stress and time ***(Gernhardt,1988)***
  - Gas bubbles respond to changes in hydrostatic pressure on a time scale much faster than the tissues
- Intermittent recompression (IR) has been shown to decrease decompression stress in humans and animals ***(Pilmanis et al. 2002, Møllerløkken et al. 2007)***

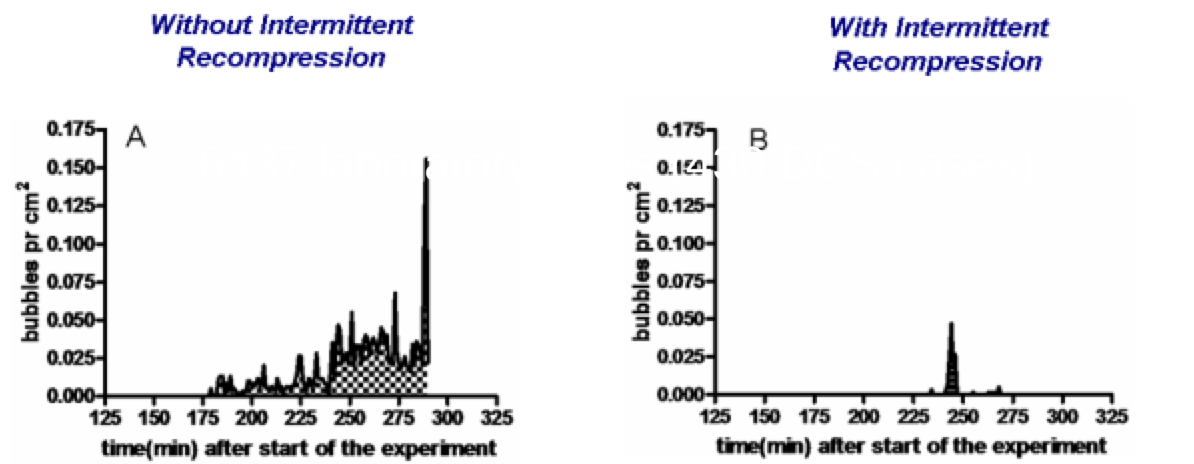


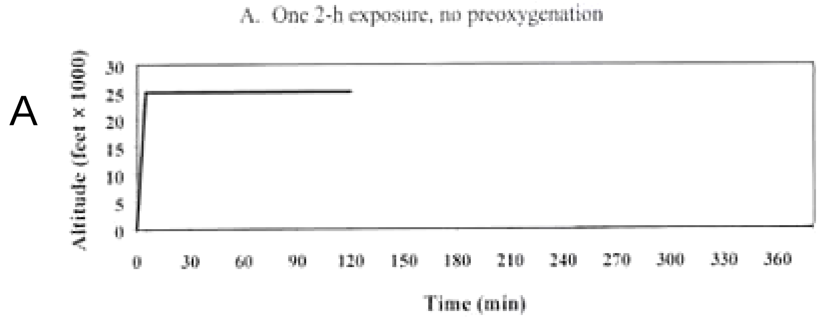
Fig. 10. Two groups of six pigs were compressed to 121 FSW with 90 minutes bottom time and were then decompressed following one of two decompression procedures; either with a 5-min 12 FSW recompression at the end of the three last decompression stops (experimental group), or without such recompression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

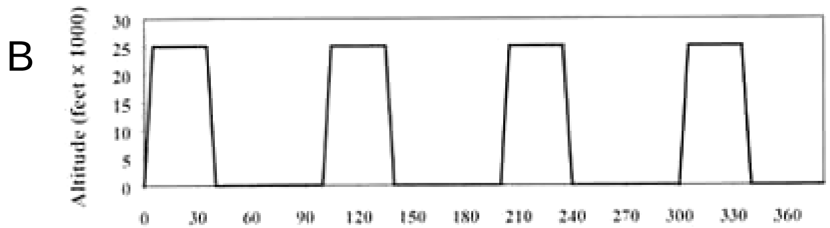
Gernhardt, M.L. Mathematical modeling of tissue bubble dynamics during decompression. *Advances in Underwater Technology, Ocean Science and Offshore Engineering, Volume 14: Submersible Technology. Society for Underwater Technology,* 1988.

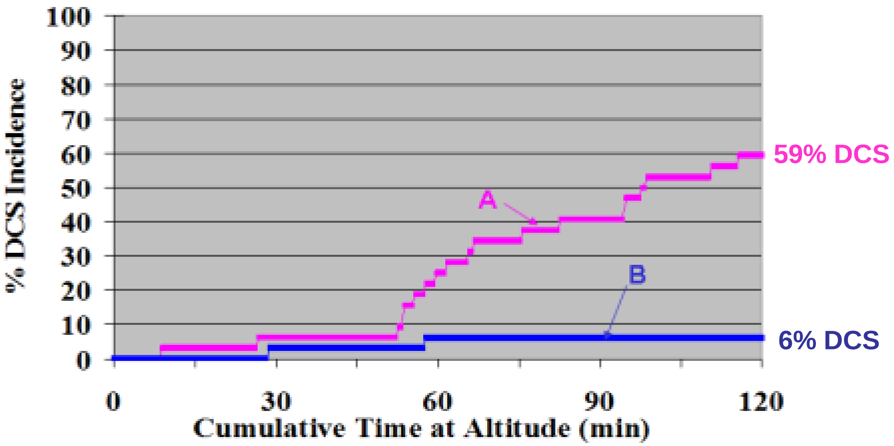
Pilmanis A.A., Webb J.T., Kannan N., Balldin U. The effect of repeated altitude exposures on the incidence of decompression sickness. Aviat Space Environ Med; 73: 525-531, 2002.

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.

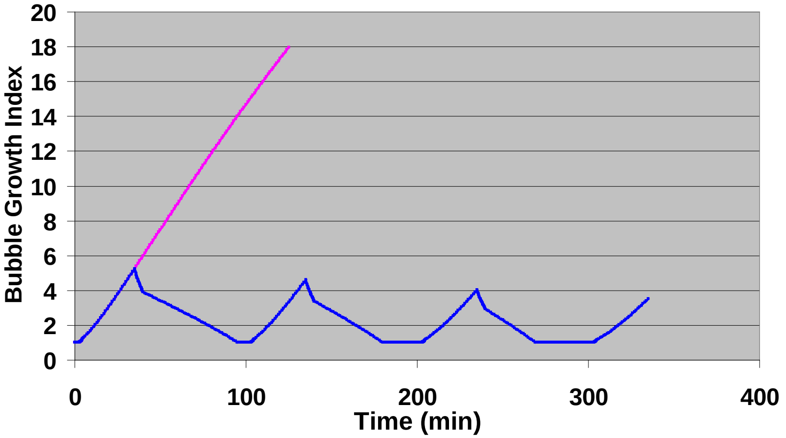
Discussion







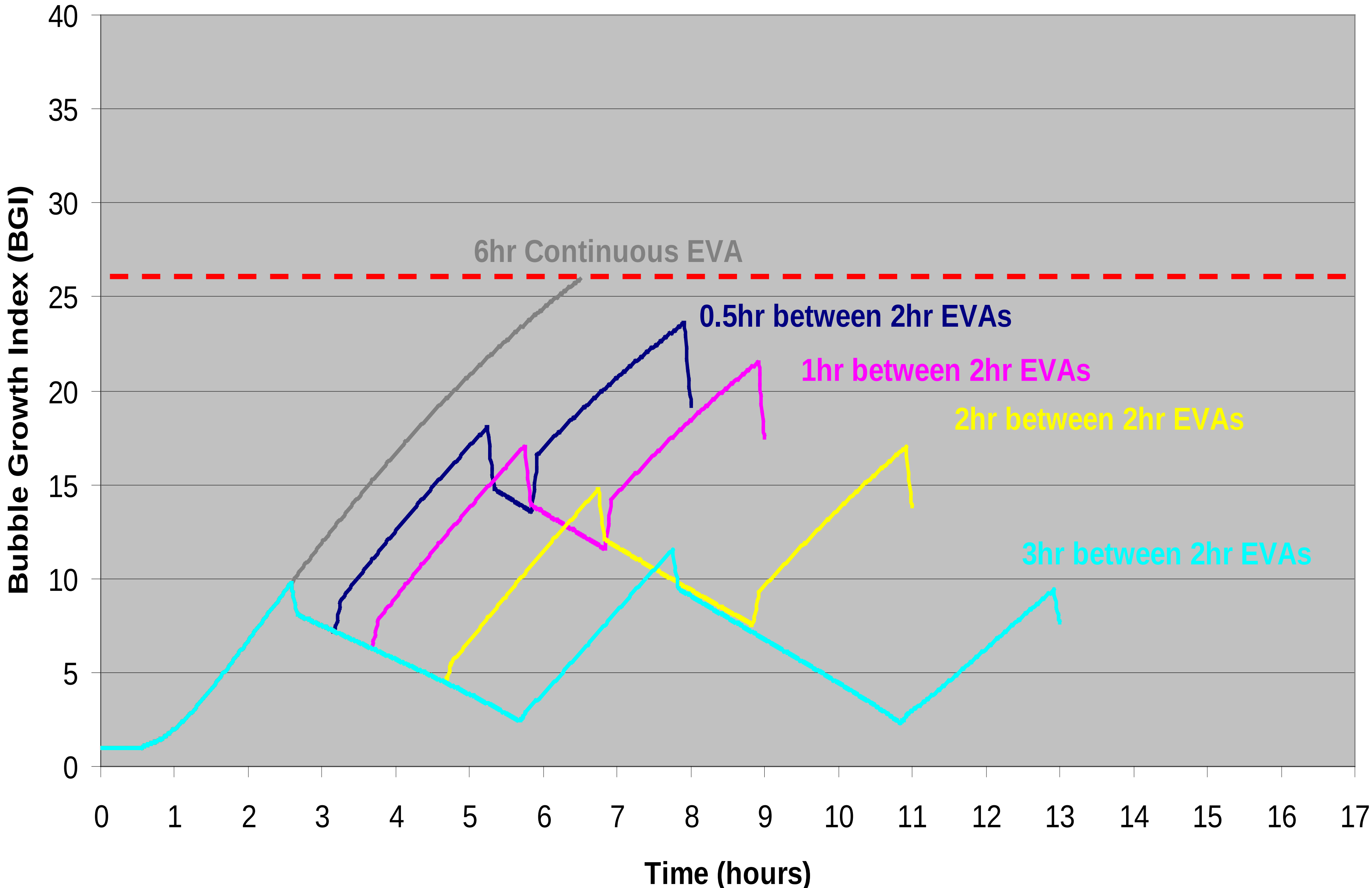
DCS Incidence

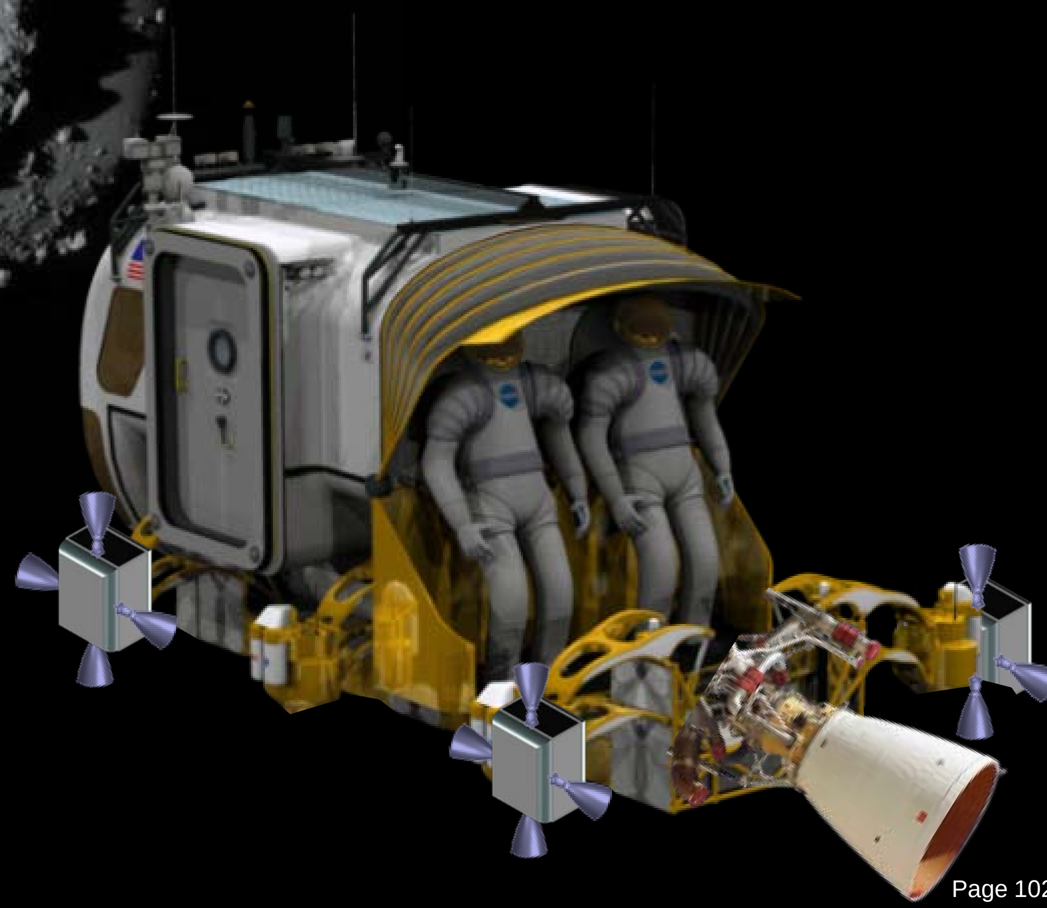


TBDM Predictions

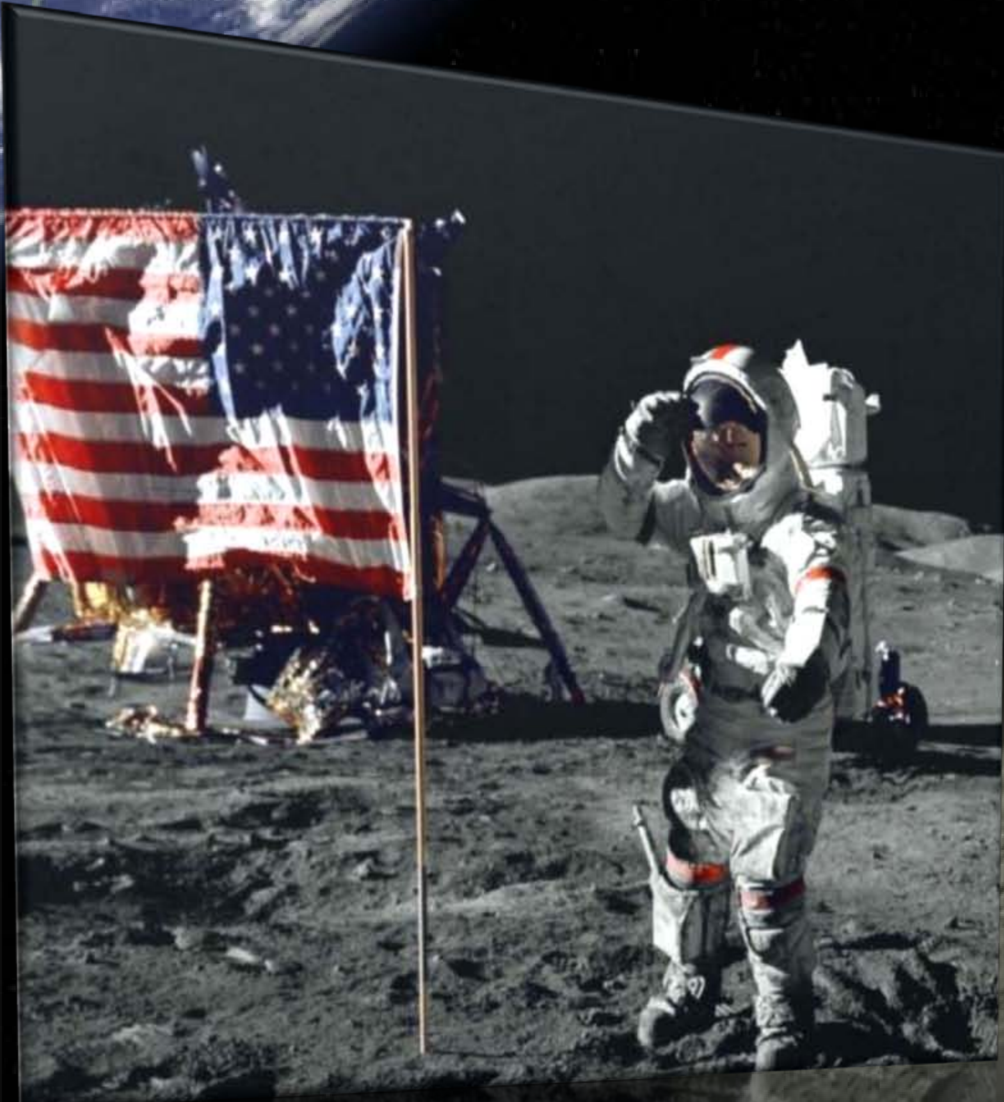
Pilmanis A.A., Webb J.T., Kannan N., Balldin U. The effect of repeated altitude exposures on the incidence of decompression sickness. Aviat Space Environ Med; 73: 525-531, 2002.

Intermittent Recompression - 3 x 2hr EVA at 4.3 psi





What this Means to America



Leadership

- Cements America's leadership in space and technology with a program that is exciting, high value and relatively low cost

Inspiration & Education

- Inspires a new generation of American engineers and scientists

Industrial Innovation / Green Energy

- Strengthens the US Energy and Automobile Industries through the collaborative development of solar array and high-performance battery technologies

Opportunity

- Provides other new opportunities for collaboration with industry and international partners

Floating Through the Terminator in the Sea Space Continuum