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**
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 separation that can lead to DCS.

- From Boyle’s 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 ($\Delta P$): a tendency or driving force for bubbles to form

\[
\Delta P = \sum P_{\text{tissue}} - (P_{\text{amb}} + P_{\text{mech}})
\]

- $\sum P_{\text{gas}} = $ sum of dissolved gas tensions & liquid vapor pressures
- $P_{\text{abs}} = $ absolute pressure
- $P_{\text{mech}} = $ “mechanical” supersaturation (surface tension, tissue elasticity decrease $\Delta P$ or mechanical tensile forces which can increase $\Delta P$)
How Bubbles Form

• **De novo** nucleation - “from nothing”
  - $\Delta P = 1,300$ atm with no dissolved gases
  - $\Delta P = 120-240$ 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
  - $\Delta P < 1$ atm
    - **Diving**: 12 hours at 12 fsw ($\Delta P = 0.4$ atm)
    - **Altitude exposure**: 12,000 feet ($\Delta P = 0.4$ atm)
    - Gibbs Free energy calculations suggest that bubble nuclei of 2-3 microns must exist, or form normally during decompression.
“Tribonucleation”

- **Mechanical supersaturation**
  \[ \Delta P = P_{\text{gas}} - P_a - P_{\text{mech}} \]
  \[ \Delta P_{\text{mech}} \sim -1,000 \text{ atm} \]
  - *de novo* nucleation

- **Viscous adhesion**
  - Separation of surfaces immersed in a viscous fluid can generate large tensile forces. (Function of the separation 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
• 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”

Flight Experience Shuttle 10.2 psi Staged Protocol – Zero DCS

Theoretical Tissue Bubble growth as a function of 10.2 exposure time

Time at 10.2 psi prior to shuttle EVA
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**

- Timeline, back to back EVAs,
- O2 usage, ISS O2 concentration
- Crew isolation and comfort

**Enabling Counter Measure Research**

- **USAF prebreathe exercise**
  - **Background**
    - **Ambulatory Non-Amb.**
      - **% DCS**
      - **Arms (NS)**
      - **Legs (p=0.0008)**
  - **Duke, NASA micro-gravity simulation (non ambulation)**
    - **% DCS**
      - **Arms (NS)**
      - **Legs (p=0.0008)**

( NASA TRL 3/4)
Enabling Research

Air Force Research Laboratory
Brooks AFB, Texas

Dual-Cycle Ergometer used for Exercise-Enhanced Prebreathe

10 minutes 75% VO2peak, 88% lower body, 12% upper body

Exercise-Enhanced Preoxygenation Increases Protection From Decompression Sickness

JAMES T. WERB, M.S., PH.D., MICHELE D. FICHER, B.S., CRISTINE L. HAPIS, B.S., M.A., AND ANDREW A. PLAMANN, M.S., PH.D.

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). 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.

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

Desitrogenation before extravehicular activity (EVA): Prior to EVA from the Space Shuttle's 14.7 psia environment (160 mm Hg PO2), a staged decompression is the primary method of desitrogenation (21) because it has been shown to provide protection comparable to a 6-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 1.2 h while the crew breathes 28% oxygen (117 mm Hg PO2, 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 300-min theoretical tissue ratio (TR) of nitrogen (Final Tissue NTR/Absolute Ambient Pressure) that is close to the TR resulting from a 6-h preoxygenation (1.70 vs 1.60). 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 4.3-1.3 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 42% 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.

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 countermeasure
- Later development focused on increased efficiency and improved scientific understanding of countermeasure mechanisms

Accept: DCS ≤ 15% and Grade IV VGE ≤ 20% , @ 95% C.l
Reject: DCS > 15% or Grade IV VGE > 20% , @ 70% C.l
Multi-Center Study: NASA, Duke, DCIEM, Hermann UT

Exercise 10 mins @ 75% $V_{O2 \text{peak}}$
And/or light exercise (160-253 Kcal/hr)

2hr oxygen prebreathe

Simulated EVA exposure at 4.3 psi 4 hrs

Use of “Suit Simulator” for EVA Exercise

Micro-gravity simulation (non-ambulation)
Prebreathe Trials

- High intensity exercise (75% peak oxygen consumption [VO₂ peak])
- Low intensity activity (5.8 mL·kg⁻¹·min⁻¹ VO₂)
- Neither High or low intensity exercise was acceptable
- Coupling High with low intensity exercise was acceptable

**Phase I**
- Rest
- 10 min
- 4 hr
- DCS 19%

**Phase II**
- Rest
- 75% VO₂ peak
- 40 min
- EVA 0%

**Phase III**
- Rest
- Light Activity
- Simulation 22%

**Phase IV**
- Rest
- 95 min Light Activity
- Simulation 14%

**PRP Phase I-IV 2 hr oxygen prebreathe exercise protocols**

- High intensity exercise (75% peak oxygen consumption [VO₂ peak])
- Low intensity activity (5.8 mL·kg⁻¹·min⁻¹ VO₂)
- 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

\[ P1N2 = P0 + (1 - \exp(-k1t)) \times (Pa - P0), \]

\[ k1 = \left(\frac{1}{\exp(-\lambda \times mL*kg^{-1}*min^{-1})}\right) / 519.37. \]

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% O₂ cabin pressure versus Apollo with 5 psi 100% O₂
- 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”

ISS Construction

“The Wall”

Year

EVA Hours

Gemini
Apollo/Skylab
Pre-Challenger Shuttle
Shuttle

### Available Lunar EVA Hours (LAT-2 Option 2)

<table>
<thead>
<tr>
<th>Year</th>
<th>Gemini</th>
<th>Apollo/Skylab</th>
<th>Pre-Challenger</th>
<th>Shuttle</th>
<th>ISS Construction</th>
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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

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<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
<th>Range</th>
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<tbody>
<tr>
<td>Age (yrs)</td>
<td>46.8</td>
<td>4.3</td>
<td>40 - 51</td>
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<tr>
<td>Height (cm)</td>
<td>180.3</td>
<td>5.0</td>
<td>175 - 188</td>
</tr>
<tr>
<td>Body Mass (kg)</td>
<td>81.4</td>
<td>7.8</td>
<td>71.2 - 89.4</td>
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<tr>
<td>$\text{VO}_{2}\text{pk}$ (ml·kg$^{-1}$·min$^{-1}$)</td>
<td>48.7</td>
<td>5.7</td>
<td>40.8 - 55.6</td>
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Subjective Measurements

Gravity Compensation Performance Scale

Adequacy for selected task or required operation*

<table>
<thead>
<tr>
<th>CG Assessment Characteristics</th>
<th>Demands on operator in selected task or required operation*</th>
<th>Operator Rating</th>
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</thead>
<tbody>
<tr>
<td>Excellent Highly desirable</td>
<td>Operator compensation not a factor for desired performance- easier than 1G activity</td>
<td>1</td>
</tr>
<tr>
<td>Good Negligible deficiencies</td>
<td>Operator compensation not a factor for desired performance- equivalent to 1G activity</td>
<td>2</td>
</tr>
<tr>
<td>Fair-some mildly unpleasant deficiencies</td>
<td>Minimal operator compensation required for desired performance</td>
<td>3</td>
</tr>
<tr>
<td>Minor but annoying deficiencies</td>
<td>Desired performance requires moderate operator compensation</td>
<td>4</td>
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<tr>
<td>Moderately objectionable deficiencies</td>
<td>Adequate performance requires considerable operator compensation</td>
<td>5</td>
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<tr>
<td>Very objectionable but tolerable deficiencies</td>
<td>Adequate performance requires extensive operator compensation</td>
<td>6</td>
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<tr>
<td>Major Deficiencies</td>
<td>Considerable operator compensation is required for control, and performance compromised.</td>
<td>7</td>
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<tr>
<td>Major Deficiencies</td>
<td>Intense operator compensation is required and performance compromised.</td>
<td>8</td>
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<tr>
<td>Major Deficiencies</td>
<td>Adequate performance not attainable with maximum tolerable operator compensation.</td>
<td>9</td>
</tr>
<tr>
<td>Major Deficiencies</td>
<td>Unable to perform task</td>
<td>10</td>
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</table>

* Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.
Subjective Measurements (continued)

**RPE**

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<th>Description</th>
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<tr>
<td>7</td>
<td>Extremely light</td>
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<td>Very light</td>
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<td>9</td>
<td>Light</td>
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<tr>
<td>10</td>
<td>Somewhat hard</td>
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<td>11</td>
<td>Hard (heavy)</td>
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<tr>
<td>12</td>
<td>Very hard</td>
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<tr>
<td>13</td>
<td>Extremely hard</td>
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<tr>
<td>14</td>
<td>Maximal exertion</td>
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**Discomfort Scale**

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<tr>
<th>Discomfort Level</th>
<th>Description</th>
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<tbody>
<tr>
<td>0</td>
<td>Nothing at all</td>
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<tr>
<td>0.5</td>
<td>Extremely Low Discomfort</td>
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<tr>
<td>1</td>
<td>Very Low Discomfort</td>
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<td>2</td>
<td>Low Discomfort</td>
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<tr>
<td>10</td>
<td>Extremely High Discomfort</td>
</tr>
</tbody>
</table>

**Front of Participant**

**Back of Participant**
Energy-Velocity Series Results - Moon

**Metabolic Cost**

- **VO2 (ml/min/kg)**
- **Speed (mph)**
- **Moon, suited (●)**
- **Moon, unsuited (●)**
- **Moon, unsuited / weighted (●)**
- **Earth, unsuited (∞)**
- **Total Metabolic Cost of Suit**

**Inertial Mass Kinematics Pressure**

**Transport Cost**

- **Transport Cost (ml/kg/km)**
- **Speed (mph)**
- **Moon, suited**
- **Moon, unsuited**
- **Moon, unsuited weighted**
- **Earth, unsuited**
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)

<table>
<thead>
<tr>
<th></th>
<th>MEAN</th>
<th>SD</th>
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<tbody>
<tr>
<td>Avg walkback velocity (mph)</td>
<td>3.9</td>
<td>0.5</td>
</tr>
<tr>
<td>Time to complete 10 km (min)</td>
<td>95.8</td>
<td>13</td>
</tr>
<tr>
<td>Avg %VO2pk</td>
<td>50.8%</td>
<td>6.1%</td>
</tr>
<tr>
<td>Avg met rate (BTU/hr)</td>
<td>2374</td>
<td>303.9</td>
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<tr>
<td>Max. 15-min-avg met rate (BTU/hr)</td>
<td>2617</td>
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<td>Total energy expenditure (kcal)</td>
<td>944.2</td>
<td>70.5</td>
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<td>RPE</td>
<td>11.8</td>
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<td>Cooper-Harper</td>
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<td>Water used for drinking (oz)</td>
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#### Planning / PLSS Sizing Data

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<th>Walkback</th>
<th>Apollo</th>
</tr>
</thead>
<tbody>
<tr>
<td>O2 Usage</td>
<td>0.4 lbs/hr</td>
<td>0.15 lbs/hr</td>
</tr>
<tr>
<td>BTU average</td>
<td>2374 BTU/hr</td>
<td>933 BTU/hr</td>
</tr>
<tr>
<td>Cooling water</td>
<td>3.1 lbs/hr</td>
<td>0.98 lbs/hr</td>
</tr>
<tr>
<td>Energy expenditure</td>
<td>599 kcal/hr</td>
<td>233 kcal/hr</td>
</tr>
</tbody>
</table>
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

South Route
“Crater Climb Out”

Southwest Route
“Lunar Highlands”

North Route
“Mare”

Haughton Mars Project
EVA 10 Km Walkback
2007

- Subject Number 1
- Subject Number 2
- Subject Number 3
HMP Walkback Test Results

- Average time 126.5 ± 28.7 min (mean ± SD)...........[96 min for EWT]
- Average VO₂ 27.8 ± 5.1 mL·kg⁻¹·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

<table>
<thead>
<tr>
<th>Summary (n=3)</th>
<th>HMP</th>
<th>JSC</th>
<th>ΔVO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg VO₂ (mL·kg⁻¹·min⁻¹)</td>
<td>26.9</td>
<td>6.4</td>
<td>17.1 ± 4.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>9.8</td>
</tr>
</tbody>
</table>

![Graph showing VO₂ (mL/min/kg) over time for HMP and JSC, with ΔVO₂ between the two conditions.]
Suit Test One- Ambulation in a Planetary Suit
Understanding the breakdown of the total metabolic cost of the suit

![Graph showing metabolic cost of suit](image)
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

Pressure (kPa) vs. VO₂ (ml·min⁻¹) for different Speed (km·h⁻¹) levels:
- < 4.0
- 4.0-5.0
- 5.1-6.0
- 6.1-7.0
- 7.1-8.0

The graph illustrates the relationship between suit pressure and oxygen consumption (VO₂) at varying speeds during spacewalks.
Metabolic Cost

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

Suited

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

![Graph showing the relationship between speed (km·h⁻¹) and VO₂ (ml·km⁻¹) for different 1g equivalent suit weights (kg). The graph includes data points for 121 kg, 186 kg, 247 kg, and 308 kg. The x-axis represents speed in km·h⁻¹, ranging from 2 to 11. The y-axis represents VO₂ in ml·km⁻¹, ranging from 0 to 500.]
• Preliminary linear regression model
  – Uses the following combination of variables to predict normalized metabolic rates during locomotion in the MKIII EVA suit:

  \[ MR = b0 + b1 \cdot (V_{\text{locomotion}} \times W_{\text{total}}) + b2 \cdot M_{\text{body}} + b3 \cdot (W_{\text{total}} \times L_{\text{leg}}) + b4 \cdot P_{\text{suit}} \]

  where

  - \( MR \) = metabolic rate expressed as normalized VO2 (ml \( \cdot \) kg\(^{-1} \) \( \cdot \) min\(^{-1} \))
  - \( V_{\text{locomotion}} \) = locomotion speed (km/h)
  - \( W_{\text{total}} \) = total weight of EVA suit plus astronaut (N)
  - \( M_{\text{body}} \) = body mass of unsuited astronaut (kg)
  - \( L_{\text{leg}} \) = leg length of astronaut (cm)
  - \( P_{\text{suit}} \) = 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

The graph illustrates the metabolic rate (mL·kg⁻¹·min⁻¹) against speed (km/h) for suits in various conditions.

- **Suit Pressure**
- **Suit Weight**
- **Inertial Mass, Biomechanics, and Stability**
- **Suited**
- **Unsuited**

The graph shows how metabolic cost increases with speed and is affected by suit pressure, weight, and other factors.
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 (VO₂)
  - 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)
  - VO₂
  - CH, RPE
  - Time series motion/foot force contact vectors
Metabolic Rate and Time to Completion

![Graph showing VO2 and Time as functions of 1g Equivalent Suit Weight (kgf)]

- VO2 (ml · min⁻¹)
- Time (s)
- 1g Equivalent Suit Weight (kgf)

**Rock Transfer**
Exploration Task Metabolic Cost – Varied Weight

The graph illustrates the metabolic cost of different tasks under varied 1-g equivalent suit weight. The tasks include Rock Transfer, Shoveling, and Busy Board. The x-axis represents the 1-g Equivalent Suit Weight (kg), while the y-axis shows the Total O₂ l/task (Busy Board & Rock Transfer) and VO₂ - ml/kg rock (Shoveling). The data points and lines indicate the metabolic cost for each task at different weight levels.
Exploration Task Metabolic Costs – Varied Pressure

![Graph showing the relationship between suit pressure and metabolic costs for different tasks. The x-axis represents suit pressure (kPa) ranging from 0 to 35, and the y-axis represents total O₂ usage per task. The graph includes three tasks: Shoveling, Rock Transfer, and Busy Board, with distinct markers for each task at various suit pressures.]
Exploration Task Subjective Ratings

Modified Cooper-Harper vs. 1-g Equivalent Suit Weight (kgf)

- Busy Board CH
- Rock Transfer CH
- Shoveling CH
- Busy Board RPE
- Rock Transfer RPE
- Shoveling RPE

Best Performance
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

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

- Lowest walking speed used (1.4 – 2.2 mph)
- 3 min per grade
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
Weight vs. \( \Delta \) 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
    - 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
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)

Modified Cooper-Harper Ratings for Varied CG Configuration
Ambulation vs. Exploration Tasks

Initial 6 CG configs
Refined CG configs, plus Apollo

Task Performance Adequate w/o hardware improvement

Rank Order (Best to Worst)

Ambulation
- Forward
- Ideal
- Low
- High
- Baseline
- Aft

Exploration Tasks
- Forward
- Ideal
- Low
- Baseline
- High
- Aft

Incline
- Forward
- Ideal
- Low
- High
- Baseline
- Aft

Decline
- Forward
- Ideal
- Low
- Baseline
- High
- Aft
CG Results

Results from EPSP underwater CG studies indicate
Underwater CG Study Results (continued)

Ramp Angle vs. CG Configuration
(Preliminary Data)

Ideal – (0.08 cm x, 0.4 cm z)
Baseline – (-7.6 cm x, 14.4 cm z)
• 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

Suit Ports: allows suit donning and vehicle egress in < 10min with minimal gas loss.

Suit PLSS-based ECLSS: reduces mass, cost, volume and complexity of Pressurized Rovers ECLSS

Ice-shielded Lock / Fusible Heat Sink: cabin surrounded by 5.4 cm frozen water provides SPE protection. Same ice is used as a fusible heat sink, rejected heat energy by melting ice vs. evaporating water to vacuum.

Radiator on Roof: allows refreezing of fusible heat sink water on extended sorties

Aft Driving Station: enables crew to drive rover while EVA (not shown)

Suit Shelter: retractable shelter protects EVA suits from dust, radiation and micrometeorites.

Work Package Interface: allows attachment of modular work packages e.g. winch, cable reel, backhoe, crane
Lunar Electric Rover Design Features

(2 of 2)

- **Modular Design**: pressurized module is transported using Mobility Chassis. Pressurized module and chassis may be delivered on separate landers or pre-integrated on same lander.

- **Docking Hatch**: allows pressurized crew transfer from Rover-to-Habitat, Rover-to-Ascent Module and/or Rover-to-Rover.

- **Two Pressurized Rovers**: low mass, low volume design enables two pressurized vehicles, greatly extending contingency return (and thus exploration) range.

- **Dome windows**: provide visibility as good, or better than, EVA suit visibility.

- **Cantilevered cockpit**: Mobility Chassis does not obstruct visibility.

- **Exercise ergometer (inside)**: allows crew to exercise during translations.

- **Pivoting Wheels**: enables crab-style driving for docking.

- **Exercise**: ergometer allows crew to exercise during translations.
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
Lunar Electric Rover Design Evolution

Original Concept
LAT-2: Theoretical Implications of LERs

- Habitat, 33
- Power, 60
- Mobility, 32
- Logistics, 25
- Maintenance, 210

Cumulative EVA Hours

Option 1: Percent EVA Time
- Science/Exploration vs. Assembly vs. Sortie Setup/Cleanup

Option 2: EVA-Intensive vs. Robotic Intensive
- Outpost, 900km FREDs 14-day Sortie Example (2 MPUs)
- EVA sites per FRED
- Outpost, Sleep (9hr), EVA (3.25hr)
- Outbound Route, Inbound Route
- Sorting Day Number: 14, Cumulative Distance: 1816km
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.

Functional Requirements

Expanded Functional Requirements

Preliminary Design Requirements

Flight Design Requirements

Gen I

Gen II

Gen III

Flight
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 m³
- 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 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. Let's recognize this and make it work for us in our new lunar developments.
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
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)

Acceptability Rating Scale

<table>
<thead>
<tr>
<th>Totally Acceptable</th>
<th>Acceptable</th>
<th>Borderline</th>
<th>Unacceptable</th>
<th>Totally Unacceptable</th>
</tr>
</thead>
<tbody>
<tr>
<td>No improvements necessary</td>
<td>Minor improvements desired</td>
<td>Improvements warranted</td>
<td>Improvements required</td>
<td>Major improvements required</td>
</tr>
</tbody>
</table>

1  2  3  4  5  6  7  8  9  10
Video: Driving, Bubble Viewing & Suit Ports
Video: Food Preparation
Video: Exercise
Biomedical & Technological Challenges of EVA

National Aeronautics and Space Administration

Mike Gernhardt

NASA
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. Where Data Quality ratings were affected by unintentional comm. dropout the scores were not used.
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

<table>
<thead>
<tr>
<th></th>
<th>DRATS '09</th>
<th>LSS Baseline</th>
<th>DRATS-modified Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>kg per person per day</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Water, Food Prep</td>
<td>0.57</td>
<td>0.5</td>
<td>0.86</td>
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<tr>
<td>Water, EVA</td>
<td>0.86</td>
<td>1.71</td>
<td>0.86</td>
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<tr>
<td>Water, Laundry</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Water, Hygiene</td>
<td>0.12</td>
<td>0.4</td>
<td>0.12</td>
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<tr>
<td>Water, Flush</td>
<td>0</td>
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<td>0</td>
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<tr>
<td>Food / Packaging</td>
<td>0.47</td>
<td>2.06</td>
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<td>2</td>
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<tr>
<td></td>
<td><strong>4.14</strong></td>
<td><strong>7.51</strong></td>
<td><strong>4.05</strong></td>
</tr>
</tbody>
</table>

* 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 O₂ 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

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

\[
P_a - v t + \frac{4\gamma}{3r} + \frac{8}{3} \pi r^3 M
\]

- **Variables:**
  - \(t = \text{Time (sec)}\)
  - \(a = \text{Gas Solubility ((mL gas)/(mL tissue))}\)
  - \(D = \text{Diffusion Coefficient (cm^2/sec)}\)
  - \(h(r,t) = \text{Bubble Film Thickness (cm)}\)
  - \(P_a = \text{Initial Ambient Pressure (dyne/cm^2)}\)
  - \(v = \text{Ascent/Descent Rate (dyne/cm^2)}\)
  - \(\gamma = \text{Surface Tension (dyne/cm)}\)
  - \(M = \text{Tissue Modulus of Deformability (dyne/cm^2-cm^3)}\)
  - \(P_{\text{Total}} = \text{Total Inert Gas Tissue Tension (dyne/cm^2)}\)
  - \(P_{\text{metabolic}} = \text{Total Metabolic Gas Tissue Tension} \)
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)


**Discussion**

A. One 2-h exposure, no preoxygenation

B. Bubble Growth Index

![Chart A](image1.png)

![Chart B](image2.png)

Intermittent Recompression - 3 x 2hr EVA at 4.3 psi

- 6hr Continuous EVA
- 0.5hr between 2hr EVAs
- 1hr between 2hr EVAs
- 2hr between 2hr EVAs
- 3hr between 2hr EVAs
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