Space Suit Inspired CO$_2$: Development of standard test methods and exposure requirements

EVA Technology Workshop 2017

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KBRwyle/NASA JSC SK
• NASA seeks a validated, standardized methodology for measuring the inspired carbon dioxide gas (CO$_2$) in spacesuits to verify that ventilation designs maintain safe levels of CO$_2$ during suited operations.

• Recent work has aimed to define a validated, standardized methodology for measuring inspired CO$_2$ in pressurized spacesuits.
  – Characterize measurement methods and setup
  – Define a standard analysis method for quantification of inspired CO$_2$
  – Characterize intra-subject and inter-subject variability
  – Validate methods during human-in-the-loop (HITL) testing of CO$_2$ washout in the extravehicular mobility unit (EMU) spacesuit

• The importance of a validated, standardized methodology is presented within the context of a proposed roadmap for the development of an evidence-based CO$_2$ exposure standard for suited astronauts.
Current CO₂ Standard

- NASA STD 3001 Volume 2
  - Habitat focused
  - Recent findings have led to more conservative CO₂ habitat levels
  - These levels may not be applicable to short term exposures at 4.3psia, 95% O² experienced during EVA

**6.2.1.3 Carbon Dioxide Levels [V2 6004]**

CO₂ levels shall be limited to the values stated in the tables located in JSC 20584, Spacecraft Maximum Allowable Concentrations for Airborne Contaminants.

Rationale: Requirements are to define upper CO₂ limits; there is no minimum CO₂ level for human existence. Limits are to be defined for indefinite exposure but may also be defined for short durations outside of indefinite limits to protect for contingency conditions. Durations of CO₂ exposure above indefinite limits are to be based on expected performance and health decrements and the risks imposed by these decrements.

**Potential Exposure Duration**

<table>
<thead>
<tr>
<th>Duration</th>
<th>1 hr ppm</th>
<th>1 hr mg/m³</th>
<th>24 hr ppm</th>
<th>24 hr mg/m³</th>
<th>7 d ppm</th>
<th>7 d mg/m³</th>
<th>30 d ppm</th>
<th>30 d mg/m³</th>
<th>180 d ppm</th>
<th>180 d mg/m³</th>
<th>1000 d ppm</th>
<th>1000 d mg/m³</th>
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<tr>
<td></td>
<td>20000</td>
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<td>Hyperventilation</td>
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</table>
• Nominal Cabin CO$_2$ Standard
  – The system shall limit the time-weighted average 24-hour inspired ppCO$_2$ levels to no more than 2 mmHg.

• Off Nominal Cabin CO$_2$ Standard
  – The program shall limit the ppCO$_2$ in emergency and off-nominal situations to levels associated with an acceptable severity of symptoms.

• Suited CO$_2$ Standard
  – The program shall limit the inspired CO$_2$ partial pressure in spacesuits to levels associated with acceptable task performance, without cognitive impairment and without undue physiological stress.
• Industries that use respiratory protective equipment such as diving, firefighting, or aviation, typically require donning a mask that seals over the nose and mouth.
  – Provides a direct means of sampling inspired CO₂ from the small dead space volume inside the oral-nasal cup for human test standards.

• NIOSH and European standards employ breathing simulator-based methods to eliminate human breathing variability and provide unambiguous pass or fail results.
  – There are no commercially available breathing machines that will work in the spacesuit environment (head movement within helmet, no neck dam), and it is impractical to construct unique machines for various spacesuit designs.
  – In order to specify an inspired CO₂ requirement for spacesuits, human testing is required to quantify and understand the real variability that occurs in CO₂ washout due to factors such as breathing characteristics, fitness levels, face anthropometry, and head positioning and movement.
NASA CO₂ Washout Methods Development

Ongoing effort since Gemini EVAs demanded crewmembers operate at higher work rates.

1969

EMU/LES Tests (1980s – 1990s)

Sampling method assessments

2011-2015

Z2 Suit Testing

2016

EMU Suit Testing

2017
1. CO₂ sample probe (Nasal Cannula) worn by subject
2. Suit pass-through
3. Needle valve or Rotameter
4. CO₂ Sensor
• Developed a simulated breathing technique to determine effects of various portions of test set up on measured CO₂ data integrity.

• A manual valve is switched between 1% (inspired) and 4% (expired) CO₂ calibration gas.

• A vacuum pump draws gas to the sensor through a sample tube.

Table 1. Sample line lengths, diameters, and flow rates tested using calibration gas methodology. Flow rates (mL/min) are shown in each cell of the matrix.

<table>
<thead>
<tr>
<th>Line Length, m (ft)</th>
<th>Line Internal Diameter mm (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.61 (2)</td>
<td>1.6 (0.063) 1000 250, 500, 750, 1000 1000</td>
</tr>
<tr>
<td>3.0 (10)</td>
<td>2.4 (0.094) 1000 250, 500, 750, 1000 1000</td>
</tr>
<tr>
<td>6.1 (20)</td>
<td>3.2 (0.13) 1000 250, 500, 750, 1000 1000</td>
</tr>
<tr>
<td></td>
<td>4.8 (0.19) 1000 250, 500, 750, 1000 1000</td>
</tr>
</tbody>
</table>
Measurement error can result from such factors as low sample flow rates, or large sample tubing diameter.

These errors can compound upon one another to misrepresent the as measured inspired CO$_2$.

Test data used to define subsequent suit testing setup

- Conduct subsequent testing with the 1.6 mm (0.063 inch) diameter, 3.0 m (10 ft) length sample line at a flow rate of 1000 mL/min.
- Provides a practical length for future HITL testing while minimizing error due to mixing

Specific future configurations of fittings can be tested using the methodology described here to identify the associated measurement error.
Calculation of Inspired CO\textsubscript{2}

Comparison against industry standards for certification of CO\textsubscript{2} washout performance suggests that the whole inspiration cycle and not just the local end-expired minimum be considered.

**Average of minimum inspired**

**Time weighted average of inspired**
Example breath trace data

• Human in the loop testing is required in order to quantify the variability that occurs during suited operations which may impact washout.
  – Can include factors such as crewmember breathing characteristics, fitness levels, face anthropometry, and head positioning and movement.

• Deviations from a characteristic breath trace may not mean the inspiration trace is poor, but it is an indication of an unusual breath
  – Possibly caused by talking, swallowing, slurping spitting, nasal drainage, yawning, skip breathing, etc. which may carry over to the inspiration.

• Standard criteria have been defined to provide consistency to breath selection and data analysis
Defining Washout Test Subject Population

- A separate study was completed characterizing expired ventilation ($V_E$), tidal volume ($V_t$) and respiratory rate (RR) trends across increased metabolic rates by subject demographics using the VO$_2$peak tests of NASA crewmembers.

- Subjects with a higher absolute peak oxygen consumption (VO$_2$pk), will have a lower relative workload (% max effort) at the same absolute metabolic rates
  - Predicts better overall CO$_2$ washout as compared to lower fitness subjects due to ↓$V_E$, ↓RR ↑$V_t$

Astronauts met fitness for duty standard of >32.9 ml/min/kg but show great variability in absolute VO$_2$pk
Defining Washout Test Subject Population

- \( \leq 1500 \text{ BTU/hr} - V_E, V_t \text{ and RR are relatively stable across subjects} \)
- Driving cases for CO\(_2\) washout testing are typically higher workload targets (e.g. 1500 BTU/hr or greater) where differences between subjects begin to appear and selection is of greater importance
  - Low < 2.5 L/min (~3000 BTU/hr)
  - Avg 2.5-3.75 L/min (~3000-4500 BTU/hr)
  - High > 3.75 L/min (~4500 BTU/hr)
Characterization of EMU Washout

- Use the EMU as a test bed to refine the standard in-suit CO2 washout assessment methodology
  - Testing with mouth guard sample probe and nose clipped
  - Test additional in-suit sensors for monitoring CO2 in the bloodstream (transcutaneous pCO2 sensor)

- 21 Subject Test planned spanning a range of fitness levels

- Data will be used to validate in-suit sampling methodology and to inform requirements for in-suit CO2 exposure limits.
Defining Spacesuit Exposure Requirements

• Astronauts during EVA and IVA will rebreathe CO₂, particularly during periods of physical activity, since helmet CO₂ washout is never perfect.
  – In addition, any compromised suit ventilation and degradation of CO₂ removal capacity will also increase inspired PCO₂ partial pressure (PICO₂).

• We will analyze through literature review and test, human physiological, cognitive, and functional performance responses across a range of PCO₂ from 0 to 20 mmHg and metabolic rates from rest to 3000 BTU/hr

• Data-driven evidence will establish operational PCO₂ limits to maximize safety, health, and performance during suited operations.
Comparing Ground Testing and Flight Exposures

- A practical measure of iso-hypercapnic dose is the inspired partial pressure of CO$_2$: P$_i$CO$_2$.

- P$_i$CO$_2$ is not the same for each F$_i$CO$_2$ across the three pressure conditions.
  - Dilution of inspired CO$_2$ by water vapor at 47 mm Hg has a greater effect at lower absolute pressure.

<table>
<thead>
<tr>
<th>Ambient Reference</th>
<th>Ground Testing (19 psia)</th>
<th>Flight (4.3 psia)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F$_i$CO$_2$ as %</td>
<td>P$_i$CO$_2$ @ 760 mmHg</td>
<td>P$_i$CO$_2$ @ 982 mmHg</td>
</tr>
<tr>
<td>0.5</td>
<td>3.8</td>
<td>4.91</td>
</tr>
<tr>
<td>1.0</td>
<td>7.6</td>
<td>9.82</td>
</tr>
<tr>
<td>2.0</td>
<td>15.2</td>
<td>19.64</td>
</tr>
<tr>
<td>3.0</td>
<td>22.8</td>
<td>29.4</td>
</tr>
</tbody>
</table>

- Ground-based exposure testing will need to match F$_i$CO$_2$ to provide the same inspired CO$_2$ for data comparison.
Comparing Ground Testing and Flight Exposures

<table>
<thead>
<tr>
<th></th>
<th>Ground Test – 1G Standing 19 psia (982 mmHg) 21% oxygen</th>
<th>EVA - μG “free-falling” 4.3 psia (222 mmHg) 100% oxygen</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Goal</strong></td>
<td>( P_a \text{CO}_2 )</td>
<td>( P_a \text{CO}_2 )</td>
</tr>
<tr>
<td><strong>Approach</strong></td>
<td>( P_i \text{CO}_2 )</td>
<td>( P_i \text{CO}_2 )</td>
</tr>
<tr>
<td>( P_i \text{O}_2 )</td>
<td>196 mmHg</td>
<td>175 mmHg</td>
</tr>
<tr>
<td>( P_a \text{O}_2 )</td>
<td>145 mmHg</td>
<td>135 mmHg</td>
</tr>
<tr>
<td>( P_a \text{CO}_2 )</td>
<td>40 mmHg</td>
<td>40 mmHg</td>
</tr>
<tr>
<td>( P_a \text{H}_2\text{O} )</td>
<td>47 mmHg</td>
<td>47 mmHg</td>
</tr>
<tr>
<td>( P_a \text{N}_2 )</td>
<td>850 mmHg</td>
<td>0 mmHg</td>
</tr>
<tr>
<td><strong>Total pressure (( P_b ))</strong></td>
<td>982 mmHg</td>
<td>222 mmHg</td>
</tr>
<tr>
<td><strong>Gas density</strong></td>
<td>greater</td>
<td>lesser</td>
</tr>
</tbody>
</table>

Comparing Ground Testing and Flight Exposures

- This work with increasing CO₂ in the suit is analogous to recent work with normobaric and hypobaric hypoxia.
  - The same “isohypoxic dose” defined as P₁O₂ at sea level and at altitude does not result in identical hypoxia-mediated responses.
  - Better to define hypoxic equivalency based on equivalent arterial O₂ partial pressure (PaO₂).
  - PaO₂ changes in response to ventilatory drive whereas P₁O₂ is indifferent to ventilatory drive.

- Similar effects are expected when analyzing CO₂ exposure test and literature data.

- The likelihood is low, that a true difference in hypercapnic mediated responses is measureable under low dose exposures.

- Only when the isohypercapnic dose between two tests is high will you be able to distinguish if there is a true difference in the responses.
Space Suit Inspired CO2 Standard Development Plan
Version 1.1
Questions
Defining Spacesuit Exposure Requirements

• We build on a large body of previous work, for example:

  Effect of inspired $PCO_2$ up to 30 mm Hg on response of normal man to exercise

  STUART J. MENN, RICHARD D. SINCLAIR, AND B. E. WELCH
  Sealed Environment Branch, Environmental Systems Division, US Air Force School of Aerospace Medicine,
  Brooks Air Force Base, Texas 78235

• Subjects should tolerate our protocol and provide a variety of measurable responses.
  – Physiological differences are expected, but will these changes be at a level where functional significance will occur?
• An important goal is to quantify subject variability to hypercapnic dose superimposed on exercise.
• Addition of neurocognitive and EVA – LEA functional tasks is new and exciting work.
Proposed Metrics of Interest

• Physiological measurements:
  – Metabolic variables: VO$_2$, VCO$_2$, RER
  – Respiratory variables: V$_E$, RR, V$_t$
  – Heart rate

• CO$_2$ status
  – Transcutaneous arterial blood CO$_2$ tension (T$_C$P$_a$CO$_2$)
  – End tidal PCO$_2$
  – Inspired CO$_2$ dose

• Neurocognitive measurements using COTS software or Cognition
  – Reaction time
  – Memory
  – Executive function
  – Attention

• Subjective measurements
  – RPE
  – CO$_2$ Symptoms

• EVA and LEA functional task performance
Potential CO₂ Exposure Study Design

- Repeated measures design with balanced test order
- 20 subjects - each subject completes all 5 test conditions
  - PCO₂ of 0, 5, 10, 15, or 20 mmHg
- Subjects reflect the range of astronaut physical characteristics
  - Age, gender, fitness
  - Consideration for 1-Carbon Polymorphism?

<table>
<thead>
<tr>
<th>Timeline</th>
<th>Stage</th>
<th>Metabolic</th>
<th>NeuroCog</th>
<th>Subjective</th>
<th>TcPaCO₂</th>
<th>P&lt;sub&gt;ET&lt;/sub&gt;CO₂</th>
<th>P&lt;sub&gt;F&lt;/sub&gt;CO₂</th>
<th>Task Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 min</td>
<td>Rest</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>15 min</td>
<td>LEA Functional</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>30 min</td>
<td>1000 BTU/hr</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>15 min</td>
<td>EVA Functional</td>
<td>x</td>
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<td>30 min?</td>
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<td></td>
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<tr>
<td>30 min</td>
<td>Rest</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>
K-bottle test gases: 0, 5, 10, 15, 20 mmHg PCO$_2$

Exhaust

Metabolic cart (Parvomedics)

Metabolic data + $T_cP_aCO_2$

End tidal PCO$_2$

Heart rate

Ergometer (Lode Excalibur)

Douglas Bag (200 L)

Neurocognitive data

EVA – LEA functional task data

CO$_2$ symptoms and Borg RPE scale data

Metabolic data + $T_cP_aCO_2$

End tidal PCO$_2$

Heart rate
Proposed roadmap to develop evidence-based CO2 exposure requirements for suited astronauts.

<table>
<thead>
<tr>
<th>Objective</th>
<th>Activity</th>
<th>Complete</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Review existing methodologies for CO2 washout measurement</td>
<td>Perform literature search in analogous and related fields</td>
<td>2016</td>
</tr>
<tr>
<td>2. Characterize sources of variability associated with spacesuit CO2 washout measurement equipment and methods</td>
<td>Perform unmanned test to explore variations in CO2 sampling hardware to determine critical effects</td>
<td>2016</td>
</tr>
<tr>
<td>3. Determine sample probe type</td>
<td>Perform uns suited human testing to explore sample probe types and positions</td>
<td>2017</td>
</tr>
<tr>
<td>4. Characterize intra- and inter-subject variability related to washout testing</td>
<td>Perform uns suited and suited human testing to explore variability due to respiratory variability</td>
<td>2017</td>
</tr>
<tr>
<td>5. Quantify inspired CO2 in existing spacesuits using developed methodology</td>
<td>Perform suited human testing in existing spacesuits to determine inspired CO2</td>
<td>2017</td>
</tr>
<tr>
<td>6. Correlate ambient CO2 levels used in research to actual inspired CO2 levels to allow comparison of suited exposure to existing research data on CO2 effects</td>
<td>Perform chamber testing with uns suited subjects while measuring ambient and inspired CO2 levels</td>
<td>2018</td>
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<tr>
<td>7. Collect data for EVA-like durations, metabolic rates, and tasks that are missing from existing research data</td>
<td>Perform human testing of functional performance at different levels of inspired CO2</td>
<td>2018</td>
</tr>
<tr>
<td>8. Acquire inspired CO2 data from ISS crew to allow comparison of crew levels to research data on CO2 effects</td>
<td>Use or supplement existing equipment and methodology to measure ISS crew inspired CO2 levels</td>
<td>2019</td>
</tr>
<tr>
<td>9. Develop evidence-based CO2 exposure requirement for crew in spacesuits</td>
<td>Combine data from steps 1 through 8 to develop standards</td>
<td>2019</td>
</tr>
</tbody>
</table>
• Bullet
  – Sub Bullet
    • Sub sub bullets
    • No less than 18 pt font!
    • Think about those in back of the room
  – Sub Bullet