Characterization of Variability Sources Associated with Measuring Inspired Carbon Dioxide in Spacesuits

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Background

- **Adequate elimination of CO_2 produced by respiration is an essential requirement for spacesuits.**
  - Exposure to excessive levels of carbon dioxide (CO_2) can lead to hypercapnia.

- **Washout refers to the ability of a suit's ventilation design to remove CO_2 from the helmet environment.**

- **Previous studies indicate that the accuracy and reliability of inspired CO_2 measurements depends on many variables:**
  - Measurement equipment setup
  - Analysis methods used
  - Human subjects

Study Objectives

1. **Review existing methodologies for CO_2 washout measurement and analysis.**

2. **Characterize sources of variability associated with spacesuit CO_2 washout measurement equipment and methods.**

3. **Define a methodology that minimizes measurement error for use with future human testing.**
   - Hardware configurations
   - Analysis methods

Existing Carbon Dioxide Washout Measurement Methods

- **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 CO_2 from the small dead space volume inside the oral-nasal cup for human test standards

- **NIOSH and European standards also employ breathing simulator based methods to limit variability in human breathing both intra- and inter- wearers**
  - Impractical for suited testing
  - Human testing is important to quantify the real variability that occurs in CO_2 washout due to factors such as breathing characteristics, fitness levels, face anthropometry, and head positioning and movement.
  - During the developmental stages of spacesuit design before designs have been finalized it is not practical to construct unique manikins for each design iteration

NASA CO_2 Washout Methods Development

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

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Fig. 2. Carbon dioxide monitoring in space suit research.

- **Subjects breathe through a small mouthpiece**
- **Inspired CO2 calculated from minimum inspired value**

NASA CO_2 Washout Methods Development

Recent NASA testing has evaluated different methods of affixing sampling lines to the person

- These investigations span multiple suits, both EVA prototype and Launch/Entry/Abort (LEA)

- Several iterations on the oral-nasal mask design were evaluated
  - Potential for the mask to alter the nominal air flow path inside the helmet
  - Dead space volume inside the mask may affect measurement

- None were able to provide repeatable measurement of respiratory data

- Unacceptable human factors
  - Test subject comfort
  - Ability to use a Valsalva device for pressure equalization

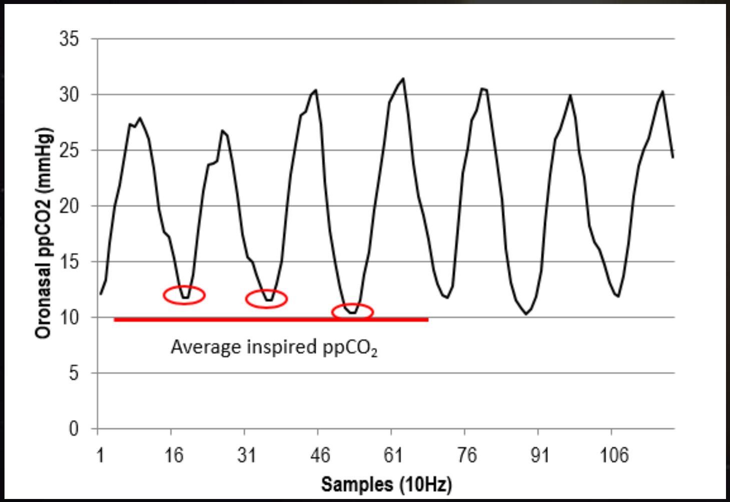
NASA CO_2 Washout Methods Development

Variability of results using masks and a desire to improve human factors aspects of the sampling system led us to use a nasal cannula for in suit sampling.

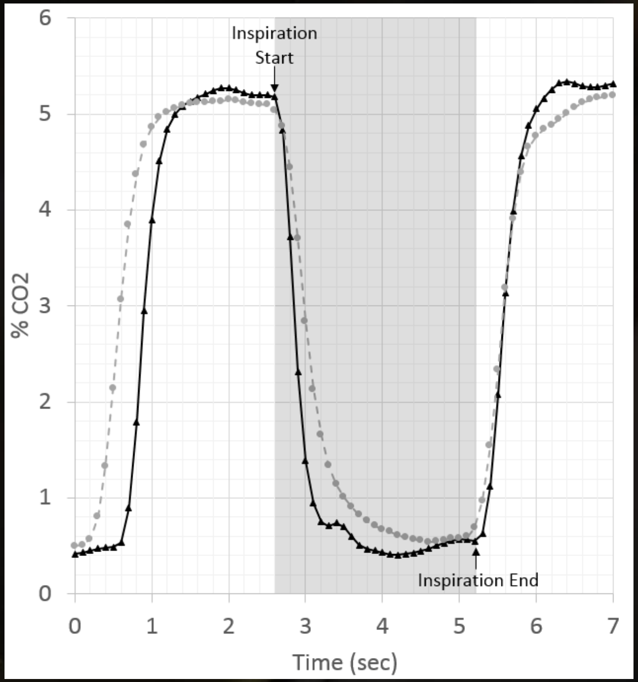
- Provides a low profile sampling line that is placed directly in the nasal cavity
- Reduces dead space
- Prevents interference with nominal flow paths of the suit.
- Possible concerns related to breathing style (nose vs nose\mouth)
  - Potentially resolved through standardizing sampling methodology

Calculation of Inspired CO_2

Comparison against industry standards for certification of CO_2 washout performance suggests that the whole inspiration cycle and not just the local end-expired minimum be considered



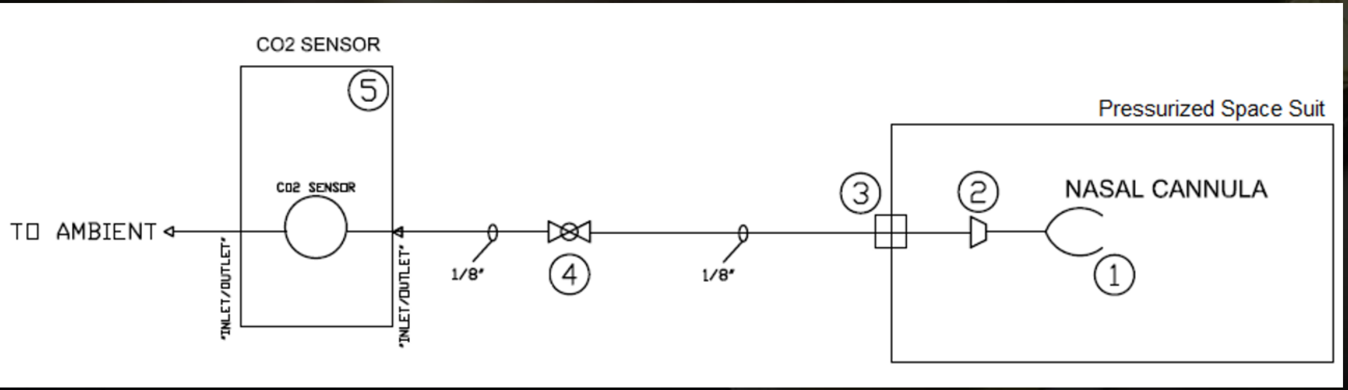
Average of minimum inspired



Time weighted average of inspired

Typical Spacesuit Testing Equipment Configuration

1. Nasal Cannula worn by subject
2. Cannula tubing reducer
3. Suit pass-through
4. Needle valve or Rotameter
5. CO2 Sensor

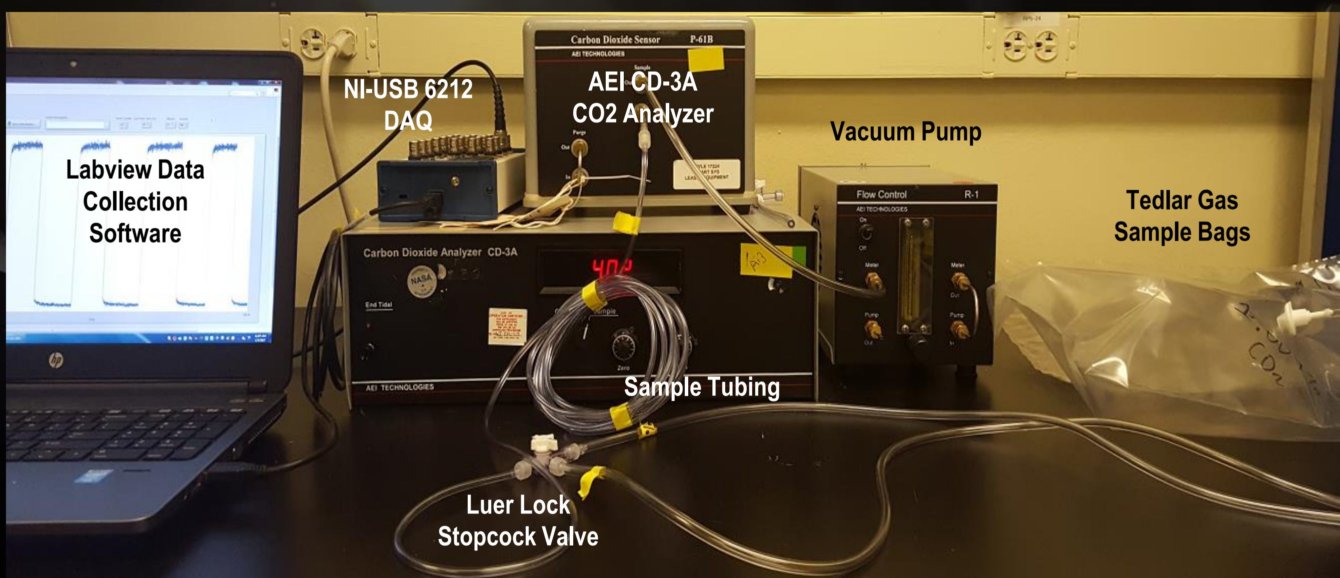


Simulated Breathing Gas Testing Technique

- A manual valve is switched between 1% (inspired) and 4% (expired) CO_2 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.

		Line Length, m (ft)		
		0.61 (2)	3.0 (10)	6.1 (20)
Line Internal Diameter mm (in)	1.6 (0.063)	1000	250, 500, 750, 1000	1000
	2.4 (0.094)	1000	250, 500, 750, 1000	1000
	3.2 (0.13)	1000	250, 500, 750, 1000	1000
	4.8 (0.19)	1000	250, 500, 750, 1000	1000



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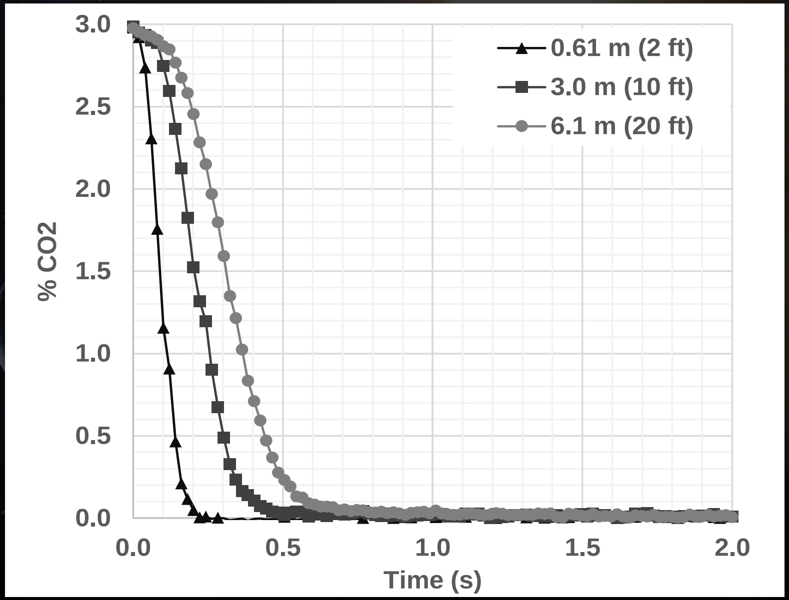
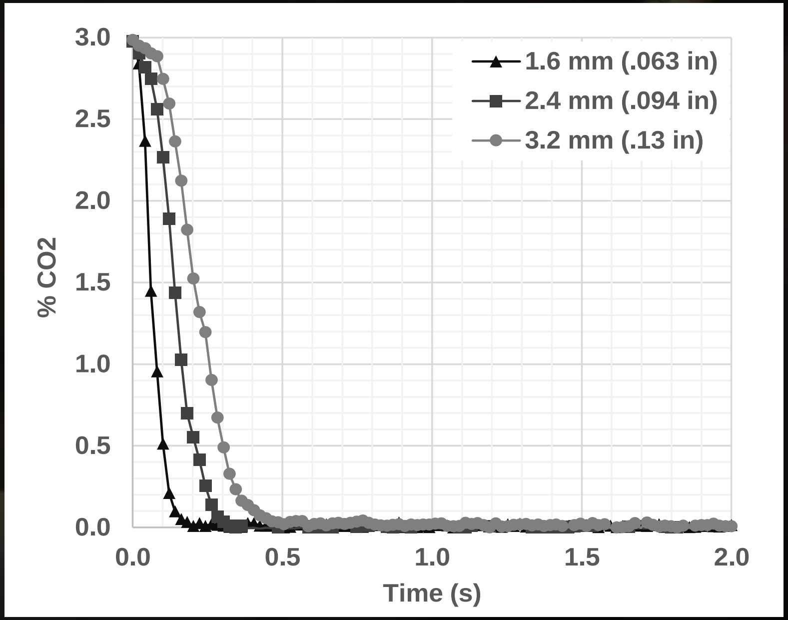
Sample Line Length and Inner diameter

- All data collected were normalized to 0% CO_2 as a baseline by subtracting the 1% calibration gas from all data points.
- CO_2 concentrations are known and subtracted from all data
- Values of inspired CO_2 greater than zero represent inherent error due to the testing methodology.





Data integrity decreases as line length and inner diameter increases for a constant sample rate of 1000 mL/min.

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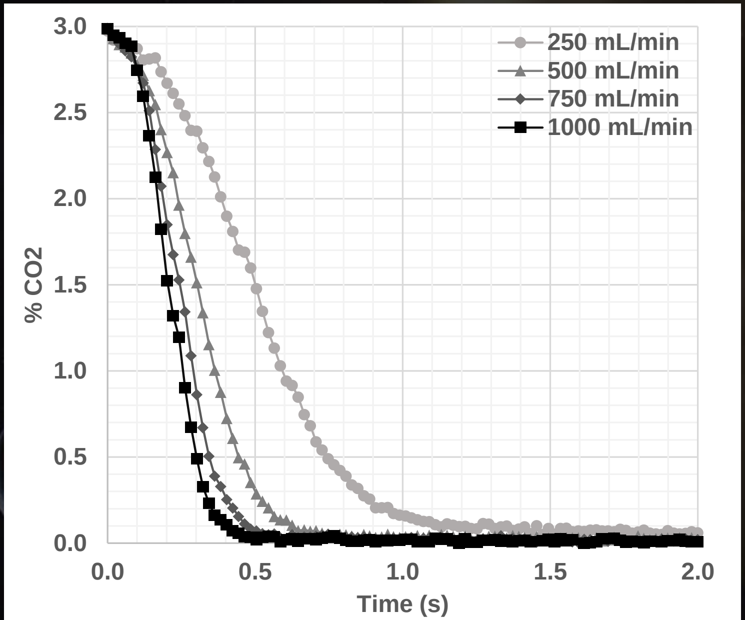
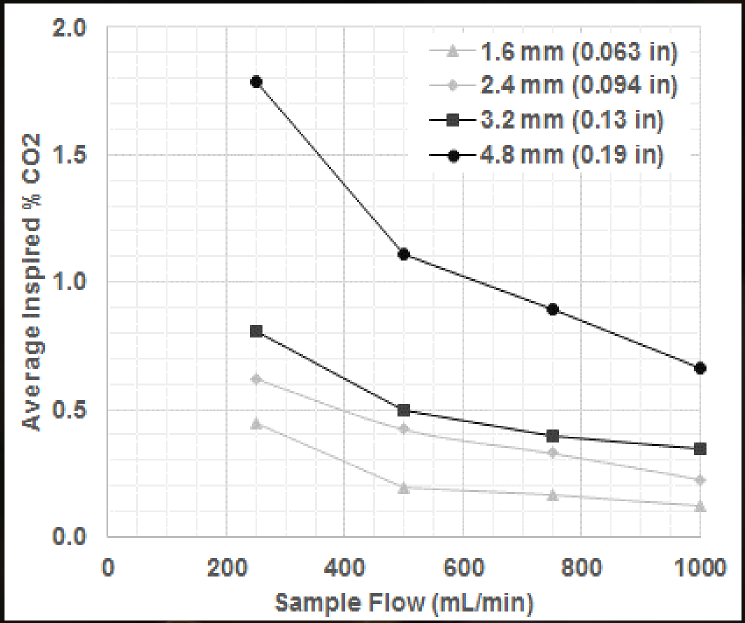
Sampling Flow Rate

- **Data integrity decreases as flow rate decreases**



Decreased data integrity as flow rate decreases for a constant line length (3.0 m) and diameter (3.2 mm).

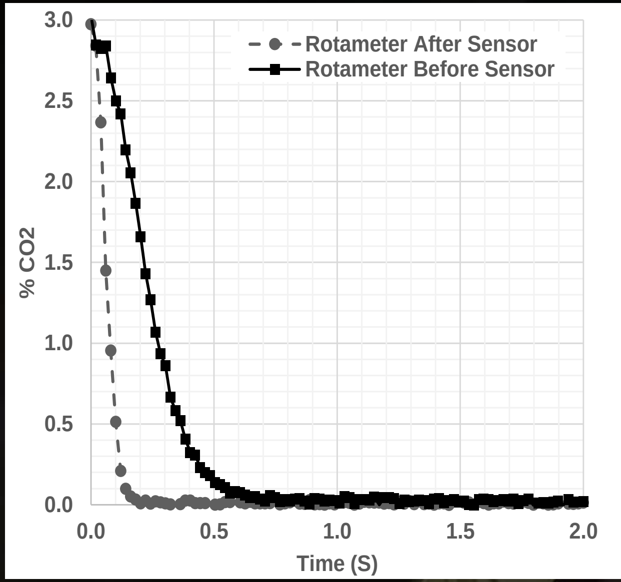


Inspired $\%CO_2$ based on measurements of different sample flow rates and sample line diameters with 3.0 m long sample tube time was assumed.

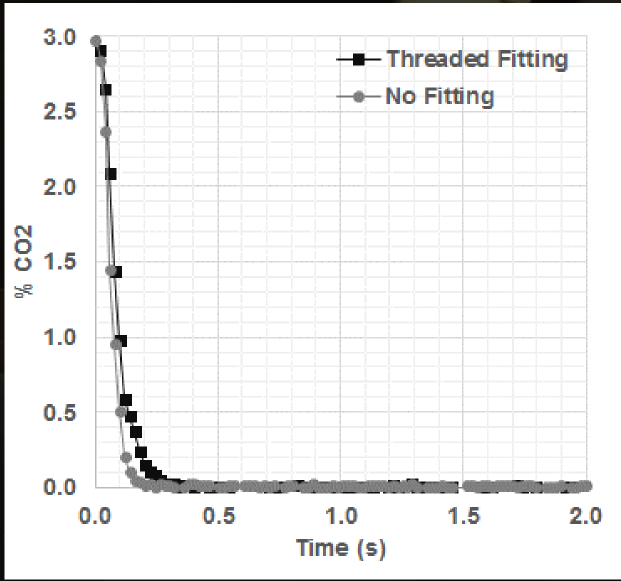
Rotameter Location and Passthrough Fittings

A rotameter has previously been positioned prior to the sensor to provide the proper flow rate from the cannula to the sensor external to the suit.

- Spacesuits are typically operated at approximately 29.6 to 56.5 kPa (4.3 to 8.3 psi) above ambient
- The pre-sensor rotameter had a time-weighted inspired ppCO2 level of 0.38% CO2, compared with the post-sensor rotameter which had a time-weighted inspired ppCO2 level of 0.12% CO2, assuming a 2 second inspiration.



Threaded fittings or similar pass-throughs are needed to accommodate cannula sample line in the suit



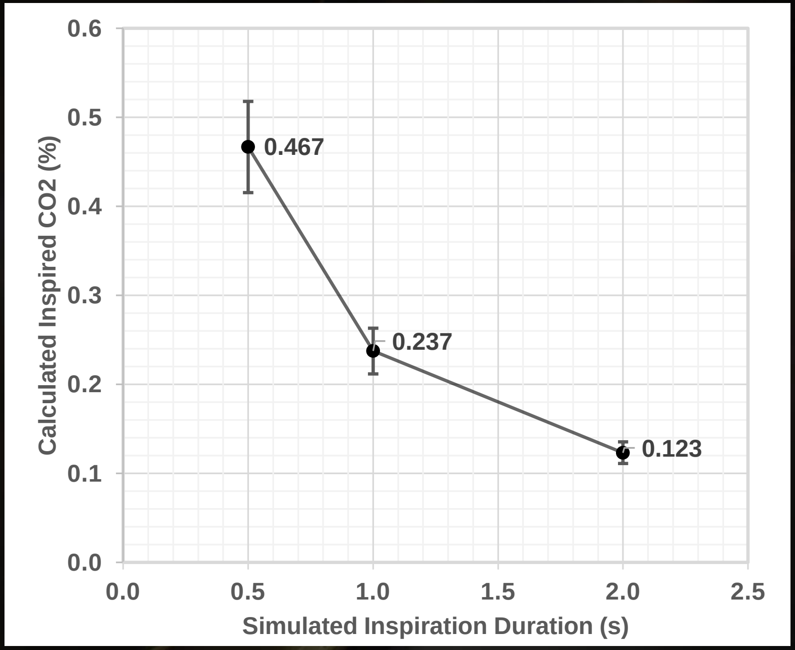
Accounting for impact of inspiration duration

- The shorter the duration of an inspiration, the larger the effect of the methodology error when a time-weighted average is calculated

- A single error value may not be applicable to all HITL test conditions.

- An option to account for this variability is to match human and methodology error inspiration durations when calculating inspired CO_2 levels.

- Human inspiration duration is available from the recorded data, and the same duration would be applied to the error calculation.



CO_2 Washout Sampling Methodology Recommendations

- **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.

- **Position rotameter after the CO_2 analyzer**

- **Specific future configurations of fittings can be tested using the methodology described here to identify the associated measurement error.**

- **Consider adjusting inspired CO2 calculation to match subject breathing variability**

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Proposed roadmap to develop evidence-based CO_2 exposure requirements for suited astronauts.

Objective	Activity	Complete
1. Review existing methodologies for CO_2 washout measurement	Perform literature search in analogous and related fields	2016
2. Characterize sources of variability associated with spacesuit CO_2 washout measurement equipment and methods	Perform unmanned test to explore variations in CO_2 sampling hardware to determine critical effects	2016
3. Determine sample probe type	Perform unsuited human testing to explore sample probe types and positions	2017
4. Characterize intra- and inter-subject variability related to washout testing	Perform unsuited and suited human testing to explore variability due to respiratory variability	2017
5. Quantify inspired CO_2 in existing spacesuits using developed methodology	Perform suited human testing in existing spacesuits to determine inspired CO_2	2017
6. Correlate ambient CO_2 levels used in research to actual inspired CO_2 levels to allow comparison of suited exposure to existing research data on CO_2 effects	Perform chamber testing with unsuited subjects while measuring ambient and inspired CO_2 levels	2018
7. Collect data for EVA-like durations, metabolic rates, and tasks that are missing from existing research data	Perform human testing of functional performance at different levels of inspired CO_2	2018
8. Acquire inspired CO_2 data from ISS crew to allow comparison of crew levels to research data on CO_2 effects	Use or supplement existing equipment and methodology to measure ISS crew inspired CO_2 levels	2019
9. Develop evidence-based CO_2 exposure requirement for crew in spacesuits	Combine data from steps 1 through 8 to develop standards	2019

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Backup

Potential method for In-suit sampling at pressure

May be possible to avoid this problem if an open T port is used before the sensor and the rotameter is placed after the sensor during suited testing