Validation of Inspired Carbon Dioxide Measurement Methods in the Extravehicular Mobility Unit Space Suit

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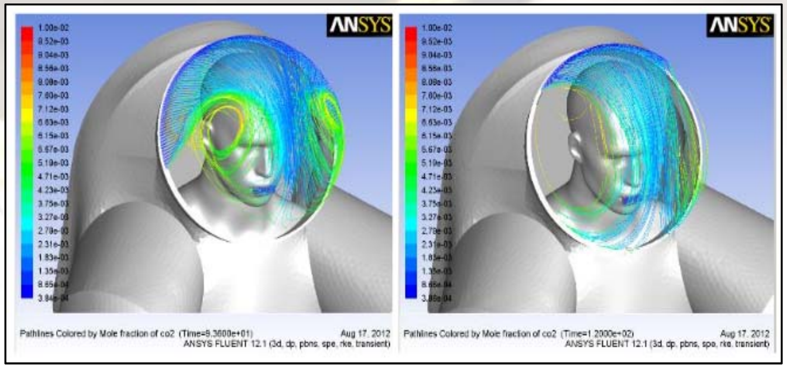
Introduction

- 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.

Specific Aims of this Effort

- Define a validated, standardized methodology for measuring and quantifying inspired CO_2 in pressurized spacesuits.
- Characterize intra-subject and inter-subject variability during human-in-the-loop (HITL) testing of CO_2 washout in the extravehicular mobility unit (EMU) spacesuit.
- Provide a dataset of inspired CO2, taken from the longest active EVA space suit, to build inspired CO2 exposure requirements for spacesuit operators.



NASA CO_2 Washout Methods Development Summary

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

1969

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

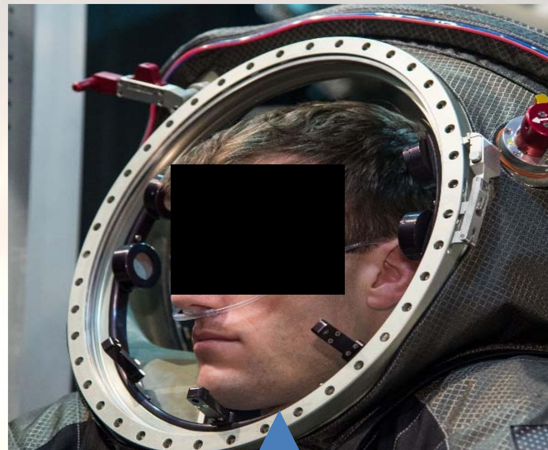
EMU/LES Tests (1980s – 1990s)

Sampling method assessments

2011-2015

Z2 Suit Testing

2016

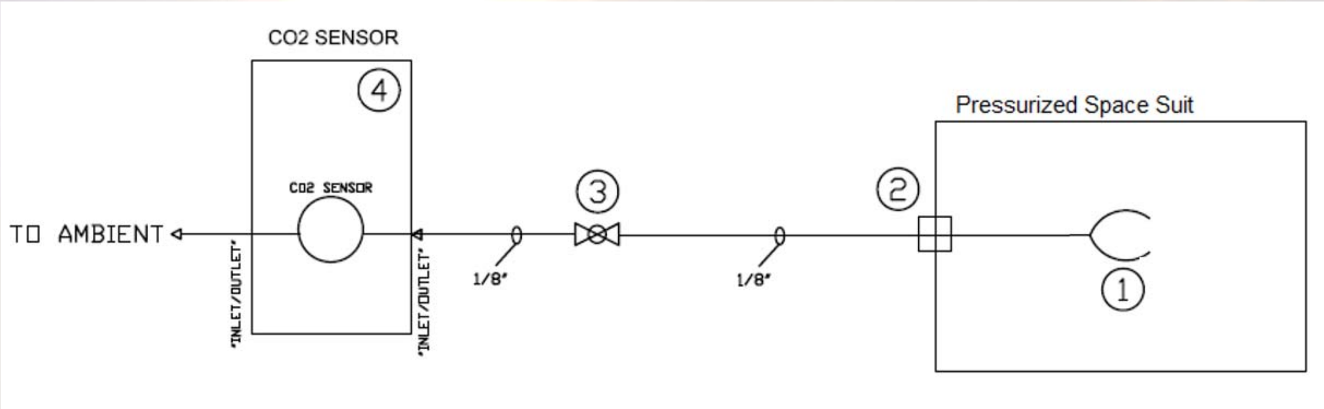


EMU Suit Testing

2017-2018

Quantifying Measurement Hardware Induced Data Uncertainty

- Typical Spacesuit Testing Equipment Configuration
  1. Some sort of CO_2 sample probe
  2. Suit pass-through
  3. Needle valve or Rotameter
  4. CO_2 Sensor



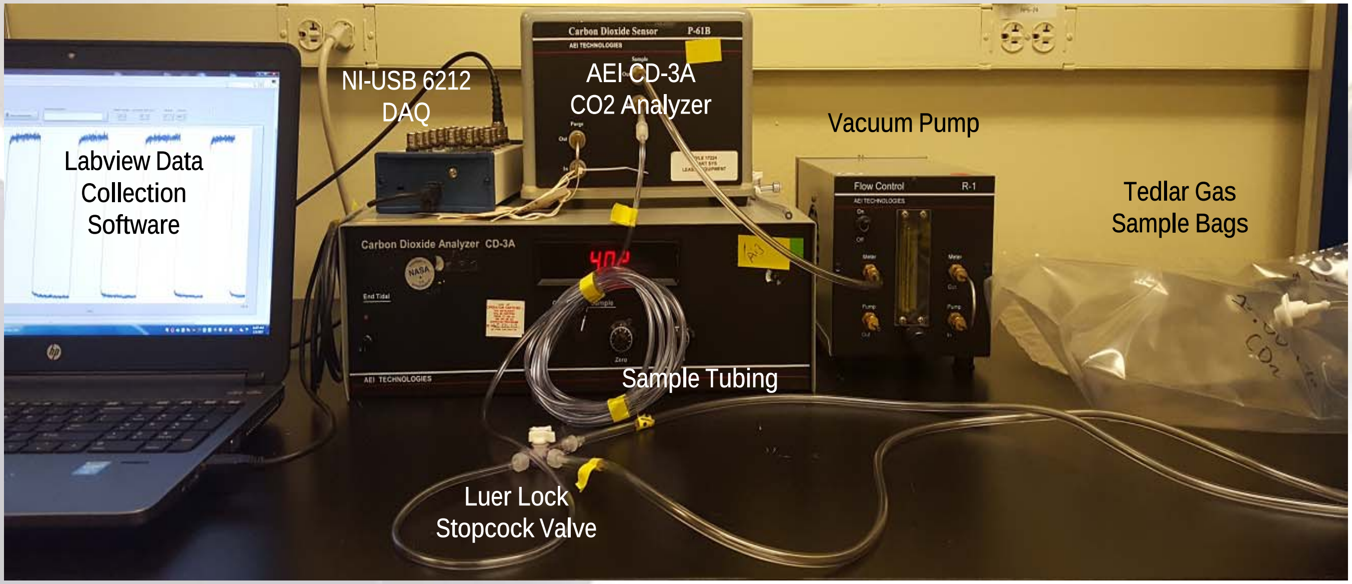
- Previous studies indicated that the accuracy and reliability of inspired CO_2 measurements depends on many variables:
  - Measurement equipment setup.
  - Analysis methods used.
  - Human subjects.

Measurement Equipment Characterization

- Developed a simulated breathing technique to determine effects of various portions of test set up on measured CO_2 data integrity.
- 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.

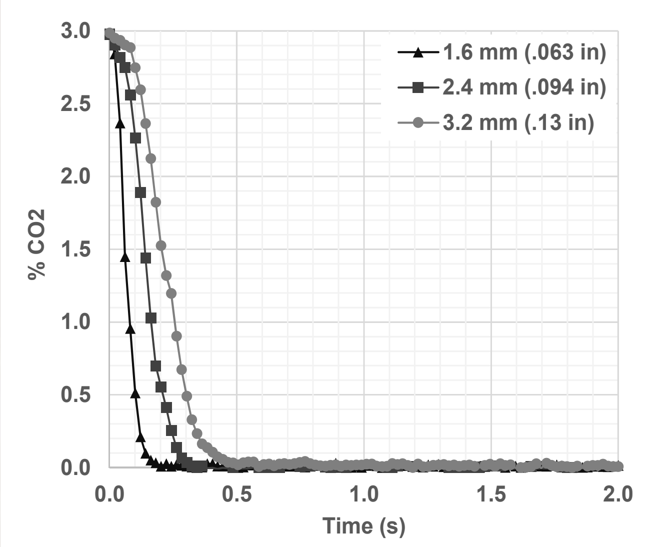
Table 1. Sample line lengths, diameters, and flow rates tested using calibration gas methodology. Flow rates (mL/min) are shown in each cell of the matrix.

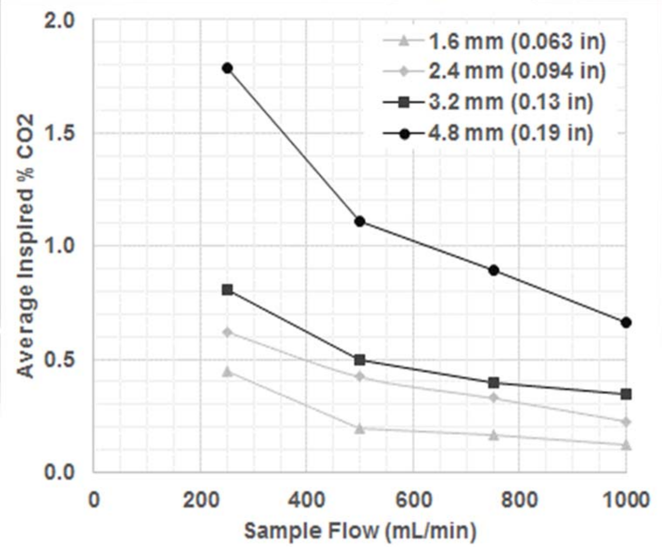
		Line Length, m (ft)		
		0.61 (2)	3.0 (10)	6.1 (20)
Line Internal Diameter mm (in)	1.6 (0.063)	1000	250, 500, 750, 1000	1000
	2.4 (0.094)	1000	250, 500, 750, 1000	1000
	3.2 (0.13)	1000	250, 500, 750, 1000	1000
	4.8 (0.19)	1000	250, 500, 750, 1000	1000



Measurement Equipment Characterization - Summary

- 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.





Sample probe selection criteria

Concerns related to breathing style when using the nasal cannula led to investigation of a new sample probe

The following criteria were used to define the requirements of the probe:

1. **Probe shall be placed close to the subject’s face to minimize interference with nominal ventilation flow paths.**
2. **Sample probe shall minimize measurement error resulting from breathing style.**
3. **Sample probe shall provide a consistent location from which samples are taken.**
4. **Sample probe design shall be readily available for suit designers and engineers to obtain and implement within any suit architecture.**

These criteria led to selection of a commercial off the shelf (COTS) mouth-guard with an open hole at the front in which the sample probe line is placed

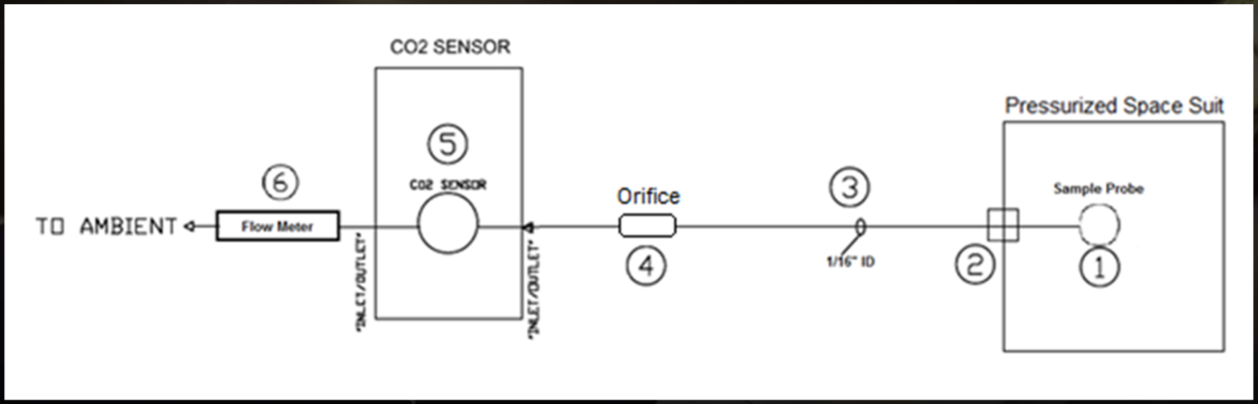
Down selecting an in-suit sampling system

- **Need to sample gas from within a suit operating at pressure to a CO_2 sensor operating at ambient conditions.**

- **Compared multiple different methods for flow control to CO_2 sensor:**
  1. Add bleed valve to dump excess flow to keep CO_2 sensor at ambient pressure
  2. Use flow controller upstream of CO_2 sensor
  3. Evaluate CO_2 washout at low suit pressure - use suit pressure to drive required flow rate to CO_2 sensor
  4. Add orifice upstream of CO_2 sensor
  5. Use a lot of line length between suit and CO_2 sensor to create necessary pressure drop between suit and CO_2 sensor
  6. Use smaller sample line ID to create necessary pressure drop
  7. Calibrate CO_2 sensor at different pressures

Down selected suit sampling configuration

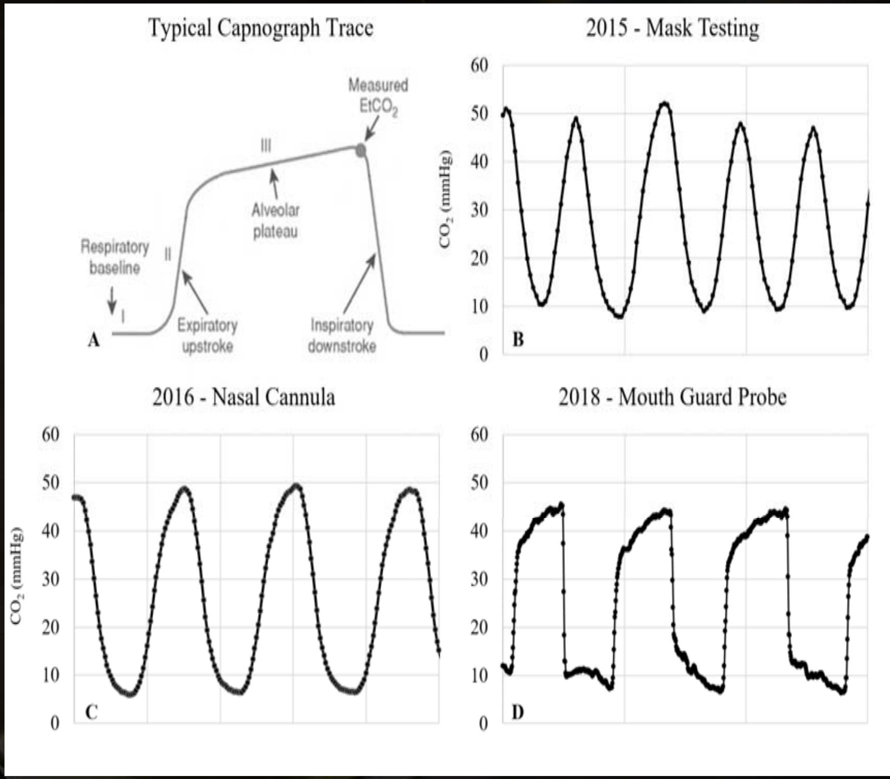
1. Mouth guard sample probe
2. RTV silicone potted suit pass-through hole
3. 10ft 1/16” ID tubing
4. Orifice sized to achieve 1000ml/min at sensor inlet
5. High sampling frequency (50Hz) CO2 sensor
6. Flow meter for verification of adequate sampling flow through system



Importance of minimizing hardware induced mixing effects

- The proposed methodology provided much higher resolution breath-by-breath data than any of the previous tests conducted in the last 10 years.
  - Breath trace quality relative to a more clinical standard (A) can be compared across sampling systems when considered as a total system (probe + downstream connections).

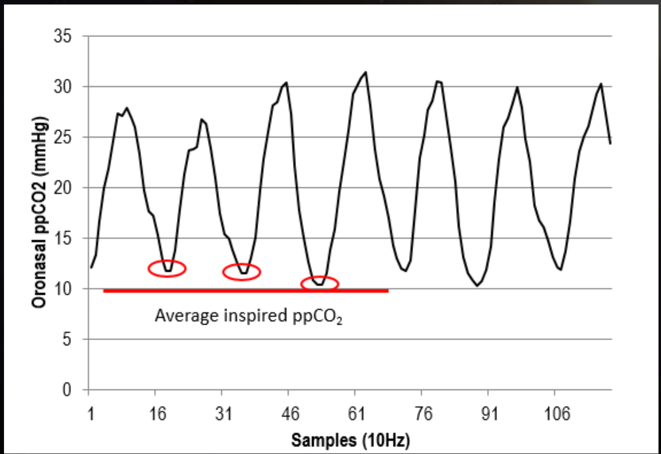
- In-suit sampled respiratory traces are most reflective of physiologic characteristics using the method proposed by this team while prior tests are indicative of sample mixing (more sinusoidal waveforms with less defined $EtCO_2$ and inspiration points) and would inaccurately reflect washout performance if used for calculation of inspired CO2

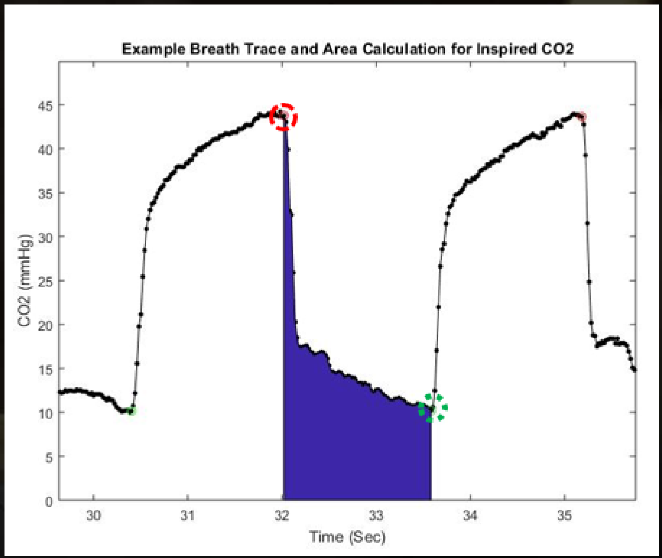


Calculation of Inspired CO_2

- Several prior studies calculated inspired CO_2 values by determining the minimum value reached during each inspiration phase and averaging all such points during the data collection period.
  - Only provides a simple and reasonable approximation of inspired CO_2 if the respiratory traces is a step decrease, representing a perfect and instantaneous washout of CO_2.
  - It is highly unlikely that outside of an environment that provides perfect washout (i.e. large open volume with high flow) that a step-wise function is seen in the breath trace data.

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.





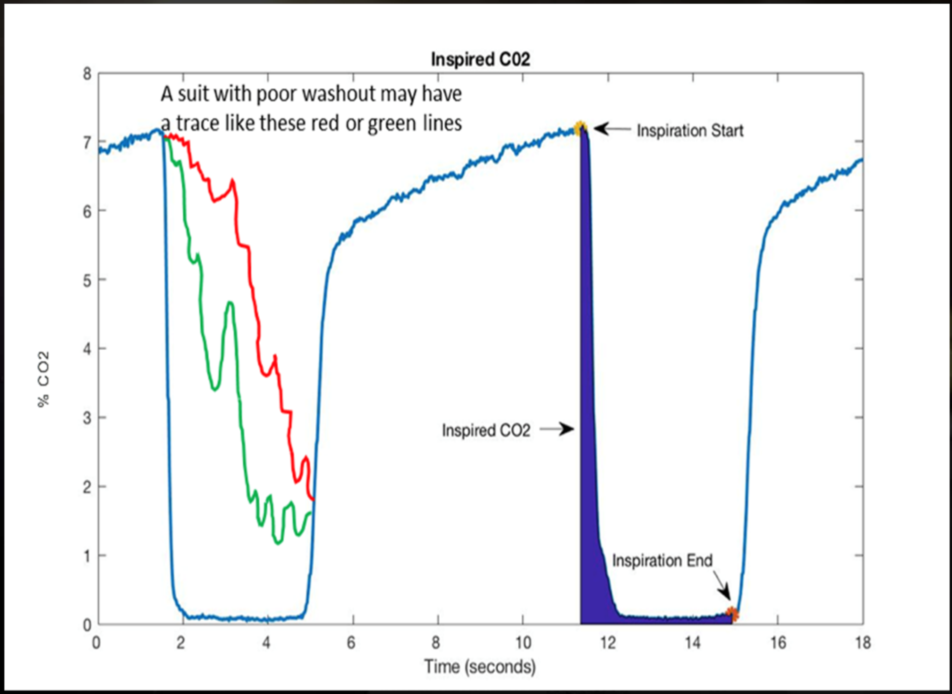
The concentration of CO_2 inhaled in this example would be 10.2 mmHg if the minimum value assumption was used, whereas the average total concentration over the entire course of inhalation is 15mmHg.

Breath Trace Analysis

- If the ventilation system mixes exhalations within the helmet rather than flushing them out of the helmet the first portion of the air inhaled by a suited subject will contain a portion of the previous exhalation, resulting in a sloped decrease instead of a step drop

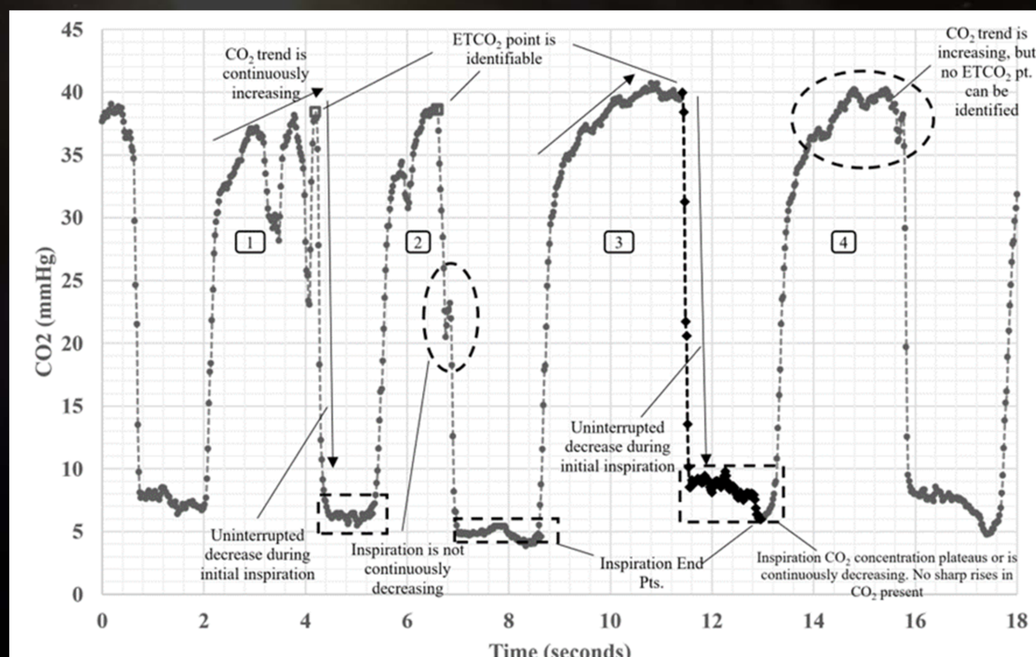
- In these cases, the minimum value does not reflect the total inspired CO_2 and the average inspired CO_2 should be calculated.

- Ideally a flow weighted averaged would be used, it is not possible at this time to collect flow weighted data from within the suit, a time weighted average provides a reasonable approximation and is compatible with other methods used across industry standard procedures in the United States and Europe.



Define the criteria for selecting acceptable breath traces

- Ensure that erroneous data resulting from unavoidable human in the loop induced errors (e.g., talking, swallowing, coughing, etc.) did not influence final reporting of inspired CO_2 values and suit washout performance.
  - While these "error" traces are still considered real data they are not representative of normal steady-state breathing and are deemed unacceptable when performing washout characterization.
- It also important to understand that the inhalation portion of the respiratory trace is the only component necessary for calculation of inspired CO_2 and washout performance.
  - Therefore it is possible to accept potentially noisy expiratory data if it has not interfered with the inspiration portion of the breath trace



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Accounting for Hardware Induced Uncertainty

- **Using data collected during benchtop characterization of hardware scaling of in-suit sampled data was possible to account for hardware induced mixing uncertainty.**

- **Benchtop assessment was a perfect washout test scenario, however we did not observe a perfect square wave when switching between the 2 gases (i.e. able to minimize not eliminate mixing effects)**
  - Calculated that 9 data points from start of switch to move from gas to gas 1 at sensor

- **These mixing effects will also be present to the same degree in our suit testing**

- **Therefore there is a portion of the in-suit sampled inspired calculation that we are uncertain of**
  - There is a maximum inspired average that includes all mixing effects in calculation
  - There is a potential minimum inspired average that does not include potential mixing effects in calculation

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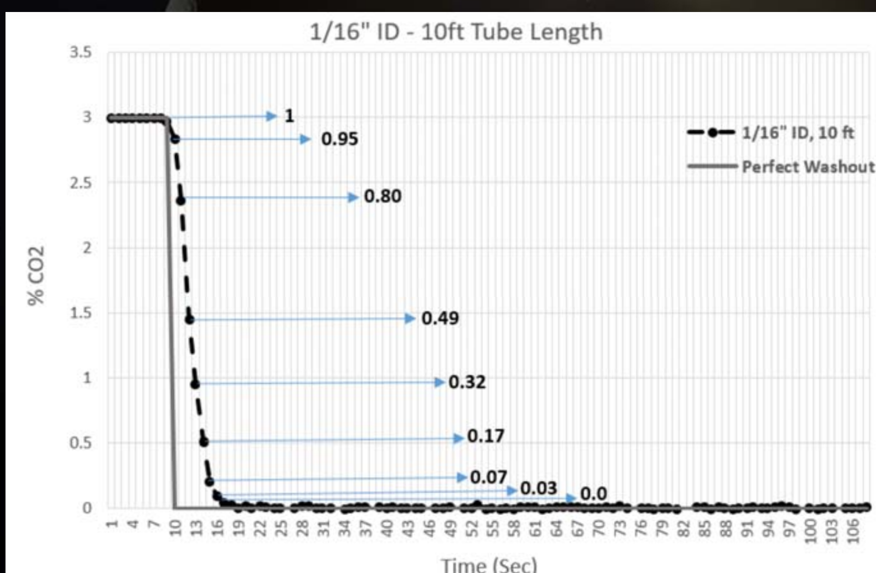
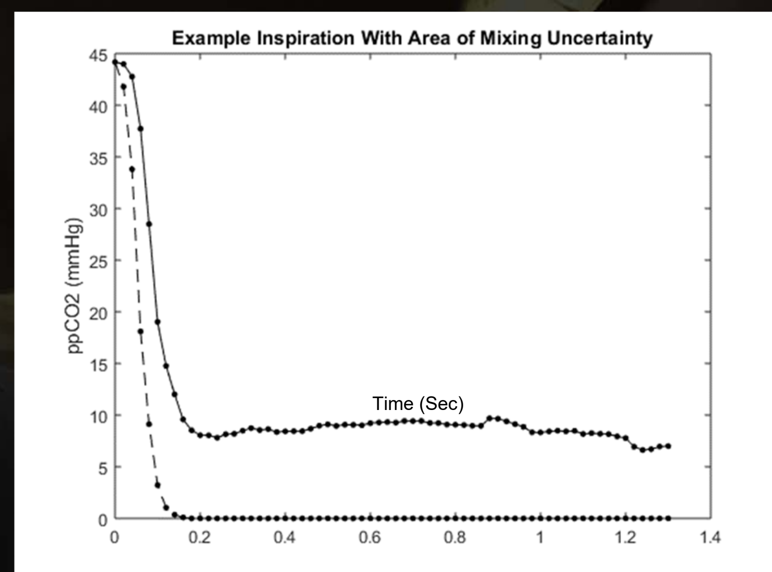
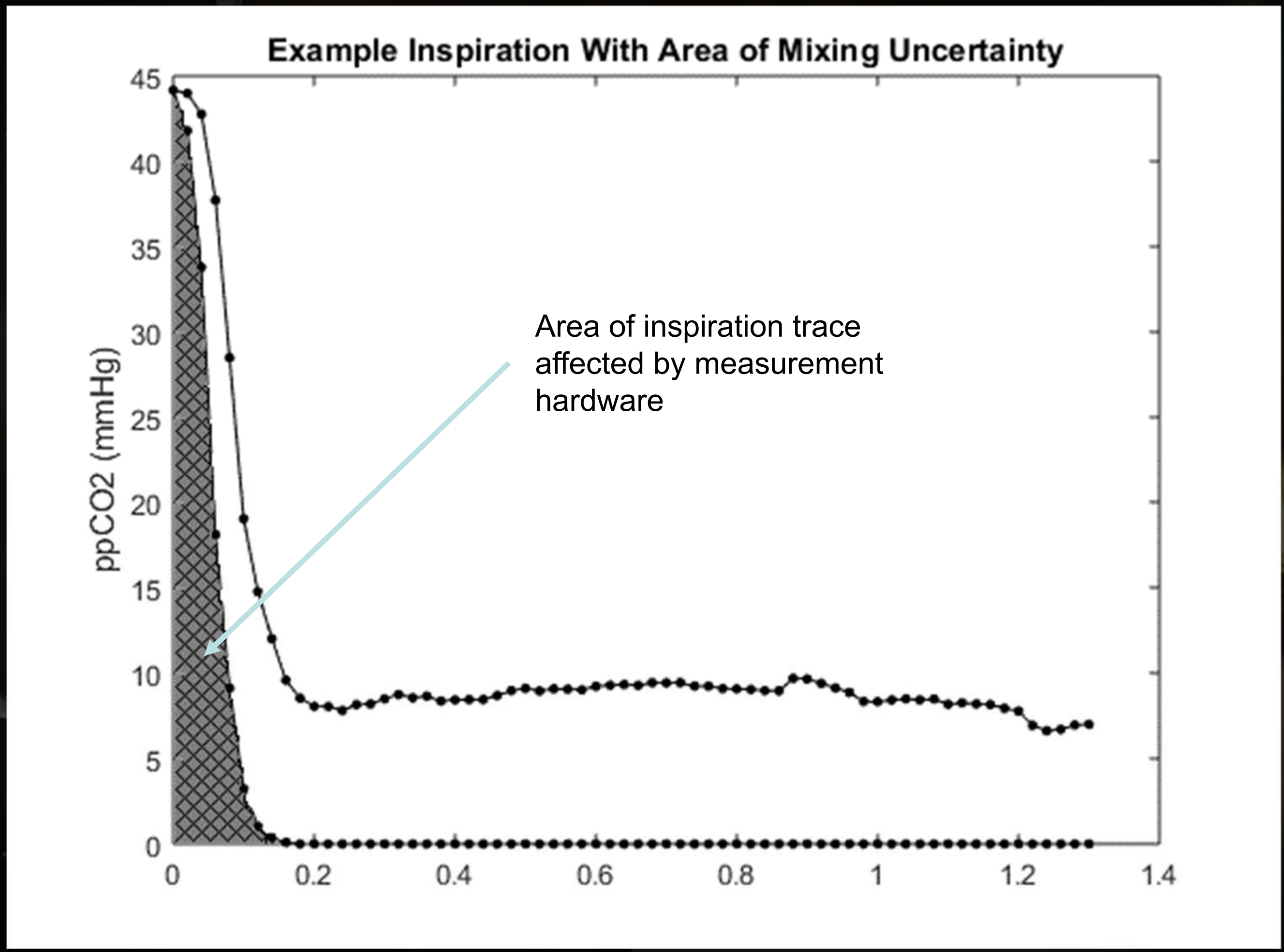
Scaling Inspired CO2 results

- **Each acceptable breath collected is scaled with these percent differences to identify the area of inspiration that is affected by hardware induced mixing effects**
- **If no mixing effects were present switching of benchtop valve from 3% to 0% would result in immediate drop in CO2 value measured**
  - The scale of the mixing can be found for each data point prior to measurement of 0% gas.
  - Each data point should report 0% in perfect washout case, the percent difference between gas 1 and gas 2 is the degree of uncertainty in the measurement
- **This inspired data is considered real, however it is not possible to definitively state what portion is attributable to the suit washout performance versus the sampling hardware**
  - This only serves to bound a potential minimum and maximum inspired CO2 value and both values are reported





Scaling Inspired CO2 results



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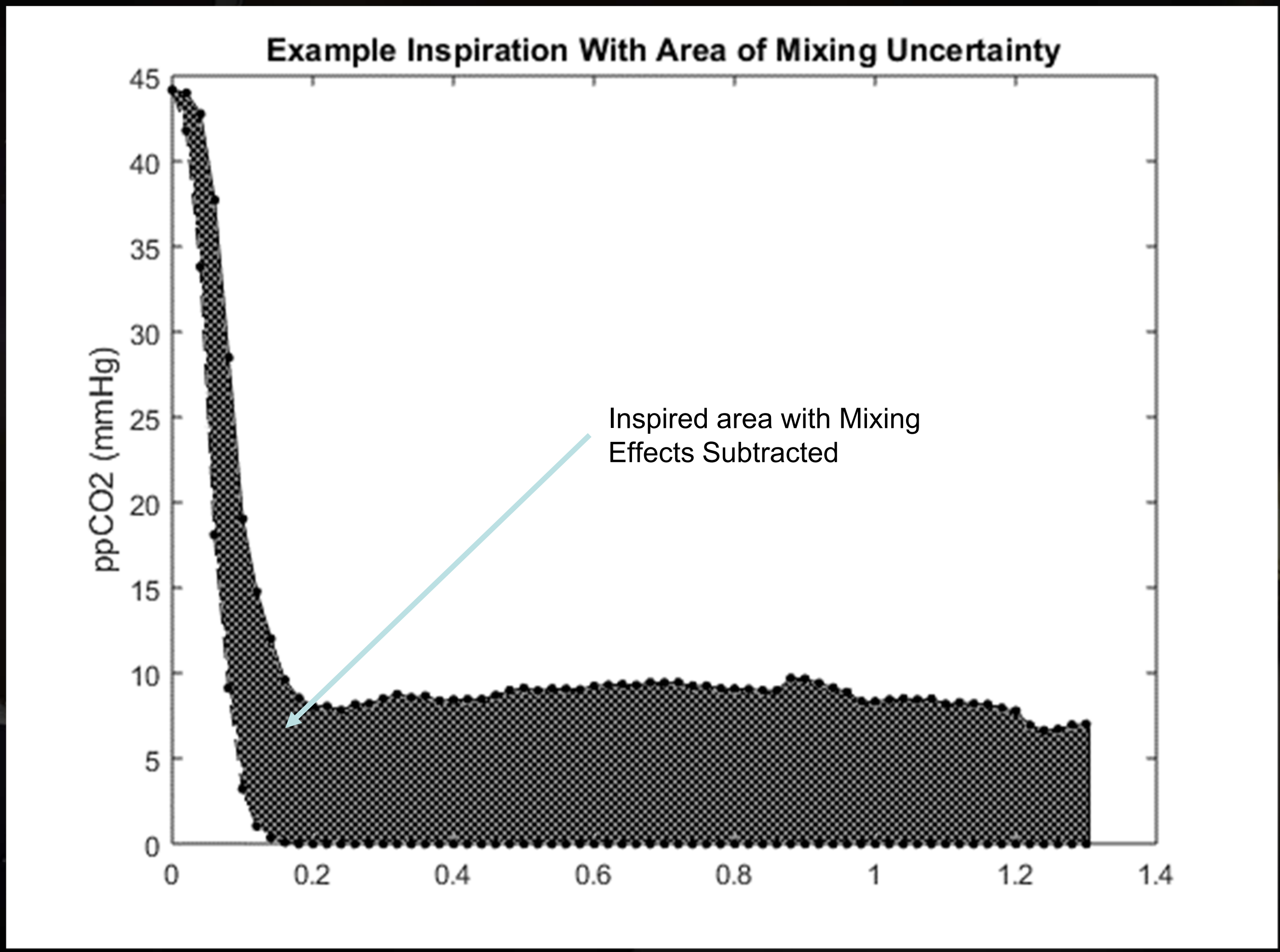
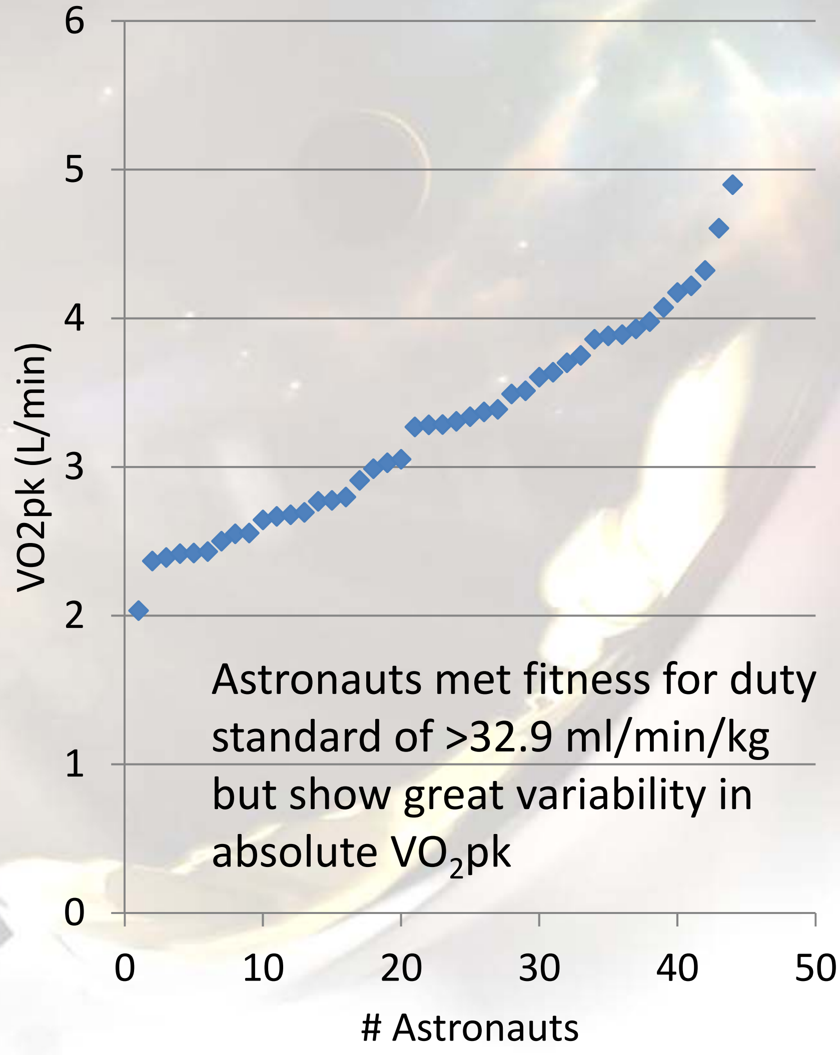


Defining Washout Test Subject Population

– 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_2peak tests of NASA crewmembers.

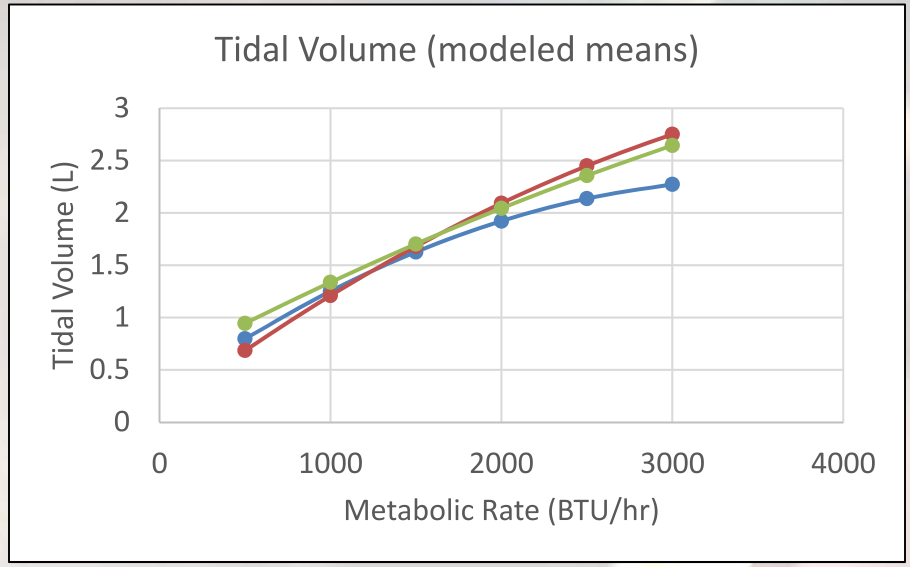
– Subjects with a higher absolute peak oxygen consumption (VO_2pk), will have a lower relative workload (% max effort) at the same absolute metabolic rates

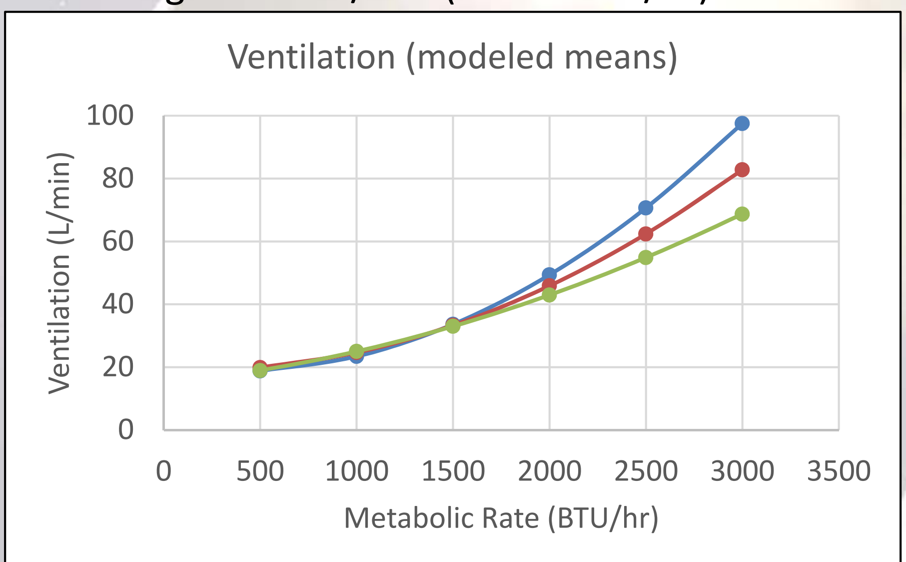
- Predicts better overall CO_2 washout as compared to lower fitness subjects due to ↓V_E, ↓RR ↑V_t

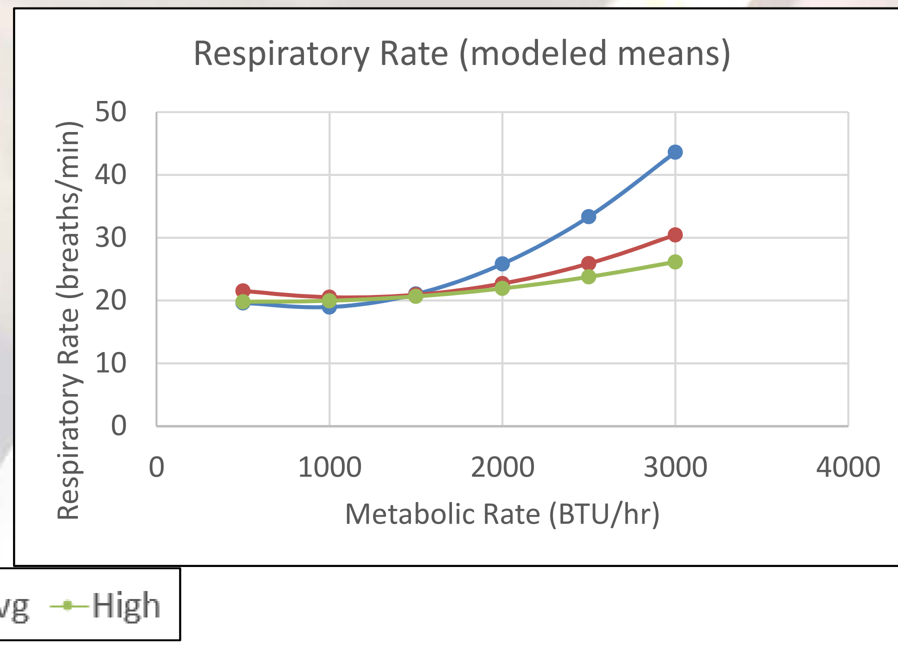


Defining Washout Test Subject Population

- ≤ 1500 BTU/hr - V_E, V_t 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)







EMU Test Series Specific Aims

1. Demonstrate a standardized CO_2 sampling methodology for spacesuit CO_2 washout testing.

2. Gather data across multiple subjects and workloads to develop a robust breath trace analysis methodology for calculation of inspired CO_2.

3. Identify the necessary subject population for conducting washout performance testing and confirm adequate data is achieved so that population demographics can be applied to subsequent CO_2 washout testing.

4. Gather in-suit data for comparison of inspired/expired CO_2 measurements with a $TcpCO_2$ monitor reading.

5. Collect data to characterize the EMU CO_2 washout performance.

EMU Washout Characterization

19 subjects were used to evaluate the washout performance of the EMU across a range of subject fitness levels.

Subjects performed two components in this study:

1. An unsuited (LCVG and TCU worn) characterization of respiratory performance at workloads of rest, 1000, and 2000 BTU/hr.;

2. A suited characterization of the EMU washout performance at workloads (generated via arm ergometer) of standing rest, 1000, 2000, and, if achievable by the subject, 3000 BTU/hr.

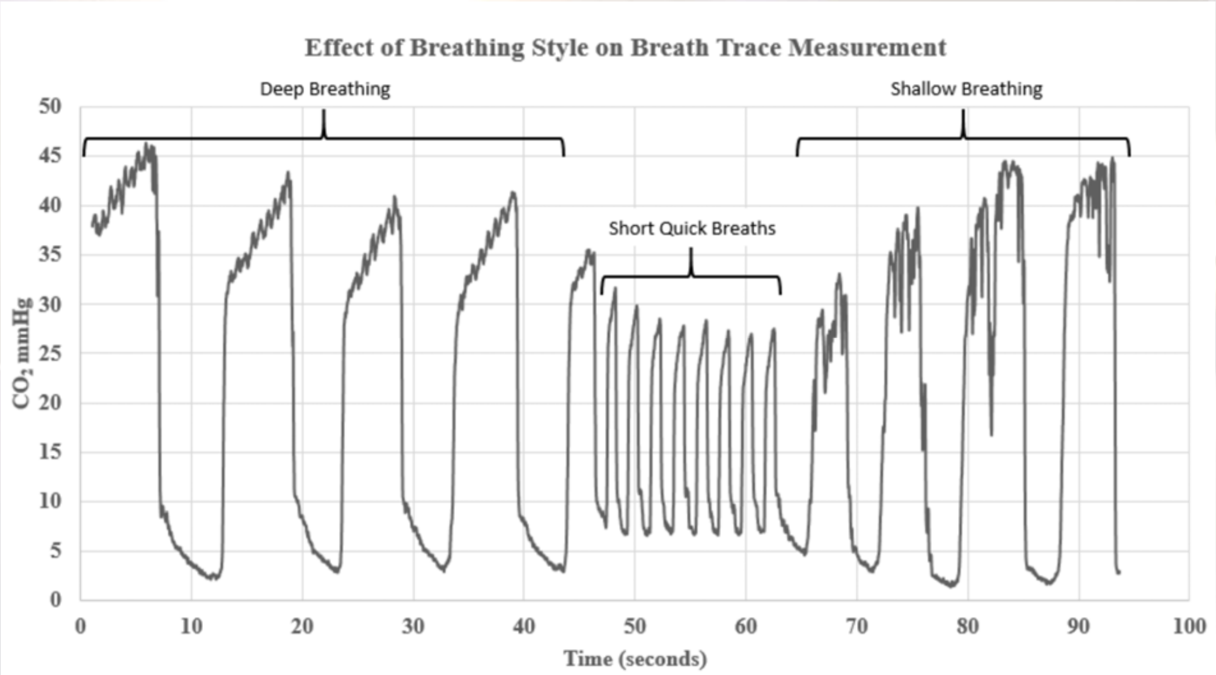
- Metabolic rate was calculated in real-time from the total CO_2 production measured at the air outlet from the suit

- This study also investigated incorporation of a $TcPCO_2$ sensor within the suit for transcutaneous gas monitoring of CO_2 levels

	Subject	Gender	VO_2pk (L/min)
≤ 2.5 L/min	1	F	1.4
	2	F	2.1
	3	F	2.2
	4	F	2.4
	5	F	2.4
	6	M	2.5
	7	F	2.5
2.5-3.75 L/min	8	F	2.6
	9	M	2.9
	10	M	3.0
	11	M	3.3
	12	M	3.4
	13	M	3.5
≥ 3.75 L/min	14	M	3.9
	15	M	4.0
	16	M	4.0
	17	M	4.1
	18	M	4.2
	19	M	4.2

Sample Probe Performance

- Overall, the sample probe provided acceptable data for most subjects
- A subject driven effect is present at lower metabolic rates, where some provided highly acceptable data after two minutes of data collection, and others resulted in high noise tracings that could not be used for inspired CO2 calculation.
  - Determined to be associated with lower breathing rate, flows, and velocity at lower metabolic rates.
  - Decision to collect for longer durations at lower metabolic rates to ensure adequate number of breath traces for analysis



Sample Probe Performance

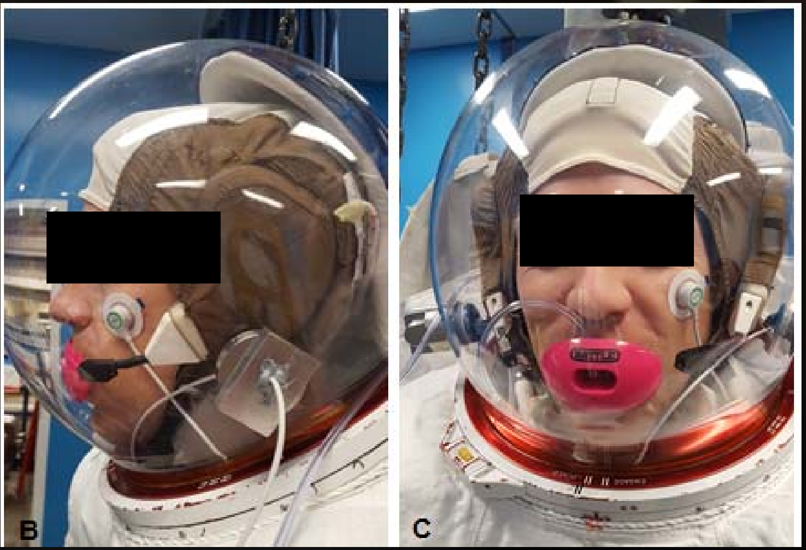
- The percent acceptable breaths given a specified level of sensitivity associated with acceptable variability within subjects.
- Breath to breath variability is most often greater than 1 mmHg, with around 80% acceptability rate if less than 2 mmHg is considered and 100% acceptable if less than 3 mmHg is used.
- Despite the higher variability in data quality at lower metabolic rates, the data collected using this probe and method still provided the highest resolution breath data to date

Target Metabolic Rate (BTU/hr)	Inspired CO_2 Variability (σ) Percent of Subjects (2 min Data Collection Period)		
	< 1 mmHg	< 2 mmHg	< 3mmHg
Resting	29%	79%	100%
1000	29%	79%	100%
2000	27%	89%	100%
3000	15%	77%	100%

TcpCO2 Sensor Integration and Results

- $TcpCO_2$ sensor probe was placed on the cheek.
  - Incorporation of the transcutaneous sensor into the suit environment proved feasible and subjects reported no discomfort or issue with wearing the sensor on their cheek during operation.

- Data were compared to the $EtCO_2$ values recorded by the sample probe to determine if there is any evidence for increasing blood $PaCO_2$ levels with increasing inspired CO_2 levels in the suit as metabolic rate increases.



Conclusions and Forward Work

- **Described implementation of a proposed standard method for measuring CO_2 washout in the spacesuit environment that can be applied to any spacesuit with minimal impact to nominal ventilation flow paths and suited operation.**
  - The sample probe type, hardware configuration, and test and analysis protocol demonstrate a measurement method for quantification of inspired CO_2 in the spacesuit helmet environment that minimizes hardware and sampling induced errors.

- **In the near-term, further analysis of this data will inform requirements development efforts for the future NASA spacesuit, and begin to provide evidence for development of exposure standards for suited EVA and IVA exposures as NASA prepares for future missions.**

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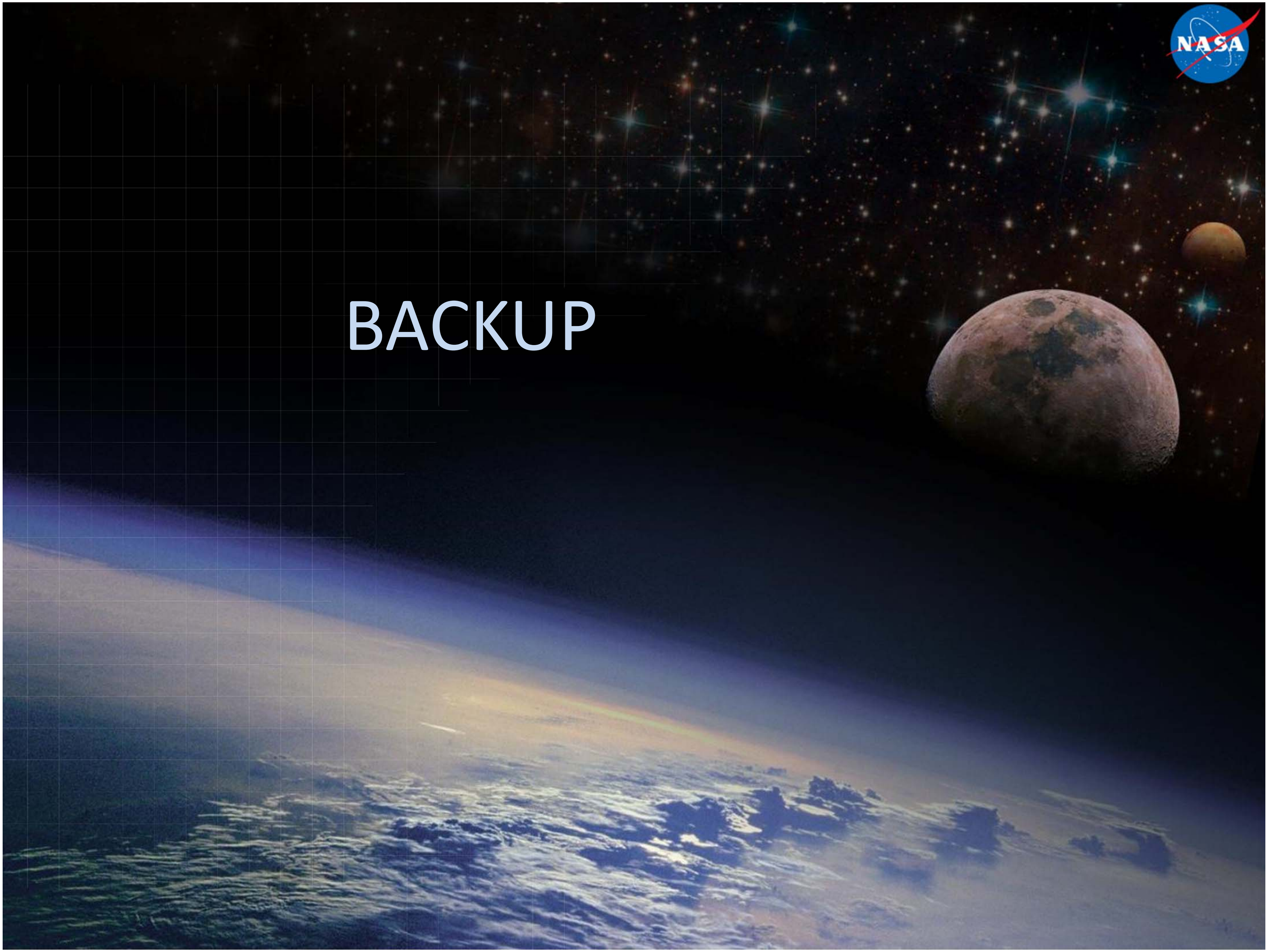
Questions

Additional Information:

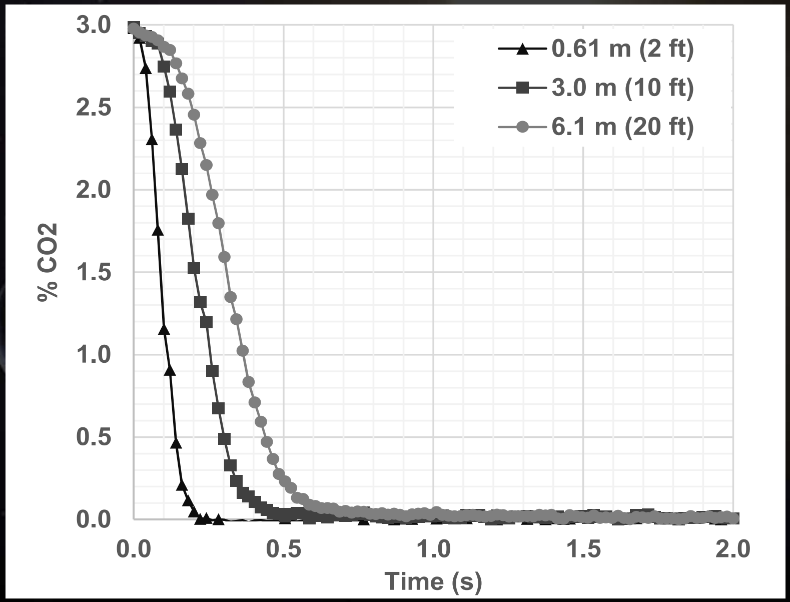
Bekdash, O.S., Norcross, J.R., Fricker, J., Young, M., Meginnis, I.M. and Abercromby, A.F., 2018, July. Validation of Inspired Carbon Dioxide Measurement Methods in the Extravehicular Mobility Unit Space Suit. 47th International Conference on Environmental Systems.

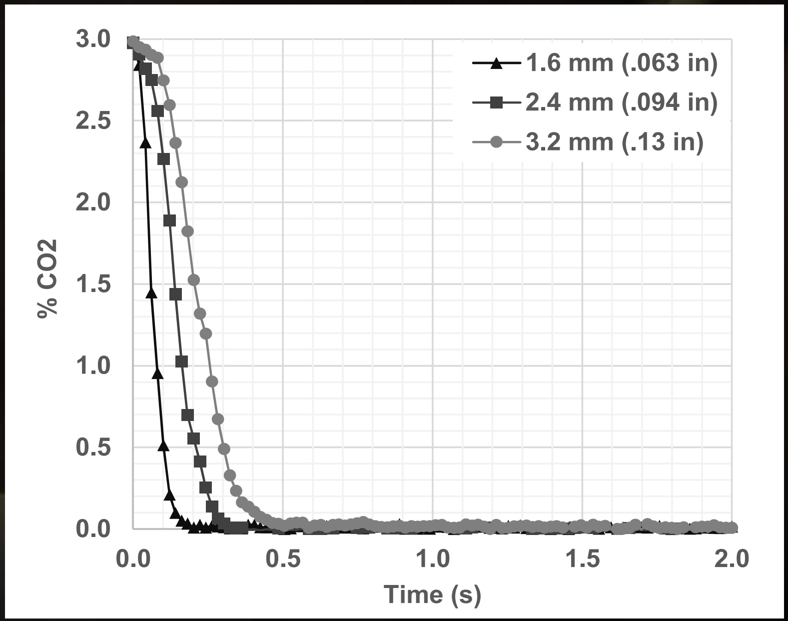
Bekdash, O.S., Norcross, J.R., Fricker, J., Meginnis, I.M. and Abercromby, A.F., 2017, March. Characterization of variability sources associated with measuring inspired CO2 in spacesuits. In Aerospace Conference, 2017 IEEE (pp. 1-15). IEEE.


BACKUP

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.

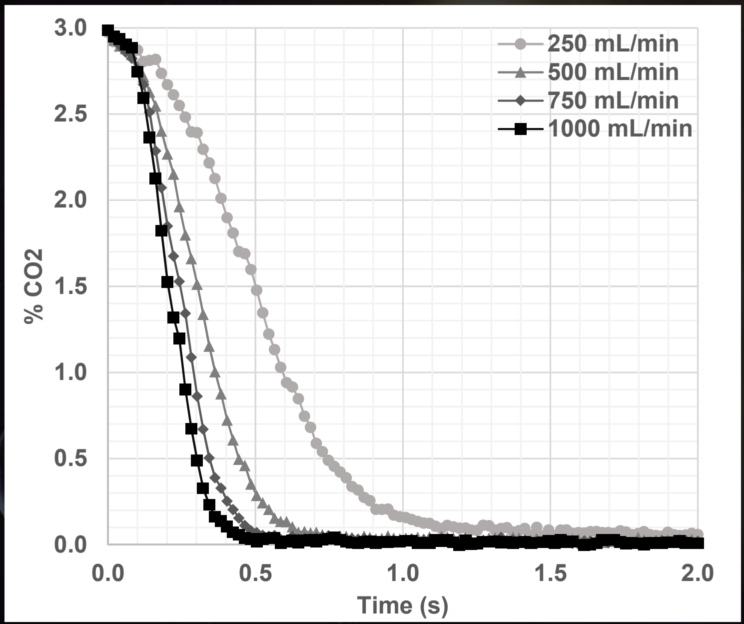




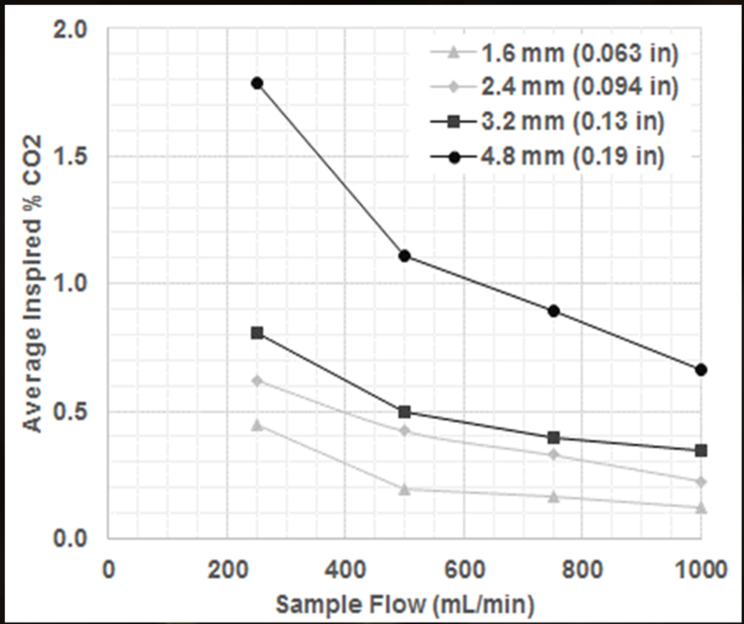
Data integrity decreases as line length and inner diameter increases for a constant sample rate of 1000 mL/min.

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).



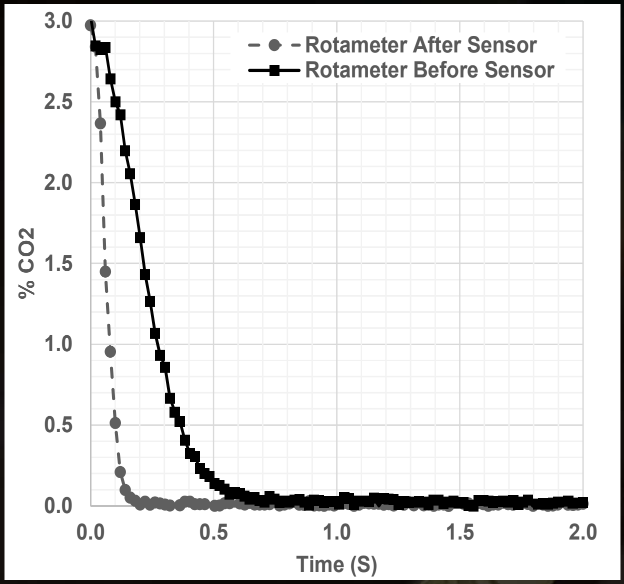
Inspired $\%CO_2$ based on measurements of different sample flow rates and sample line diameters with 3.0 m long sample tube time was assumed.

Rotameter Location and Pass-through Fittings

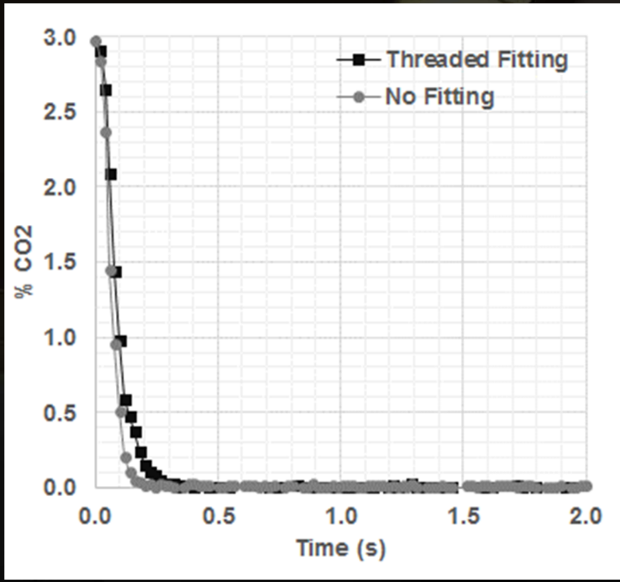
A rotameter has previously been positioned prior to the sensor to provide the proper flow rate from the cannula to the sensor external to the suit.

- 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.

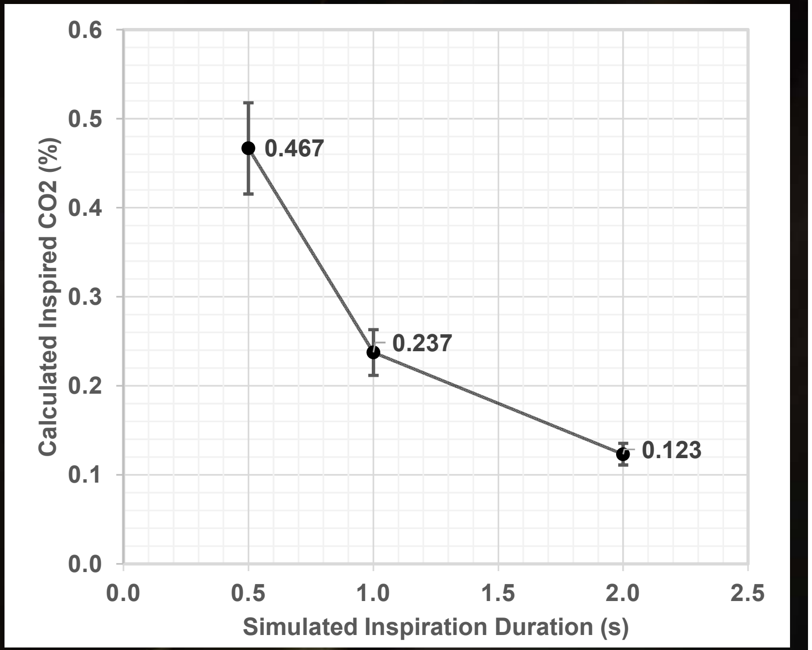


Threaded fittings or similar pass-throughs are needed to accommodate cannula sample line in the suit.



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.



Breath Trace Analysis

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  - o Only provides a simple and reasonable approximation of inspired CO_2 if the respiratory traces is a step decrease, representing a perfect and instantaneous washout of CO_2.
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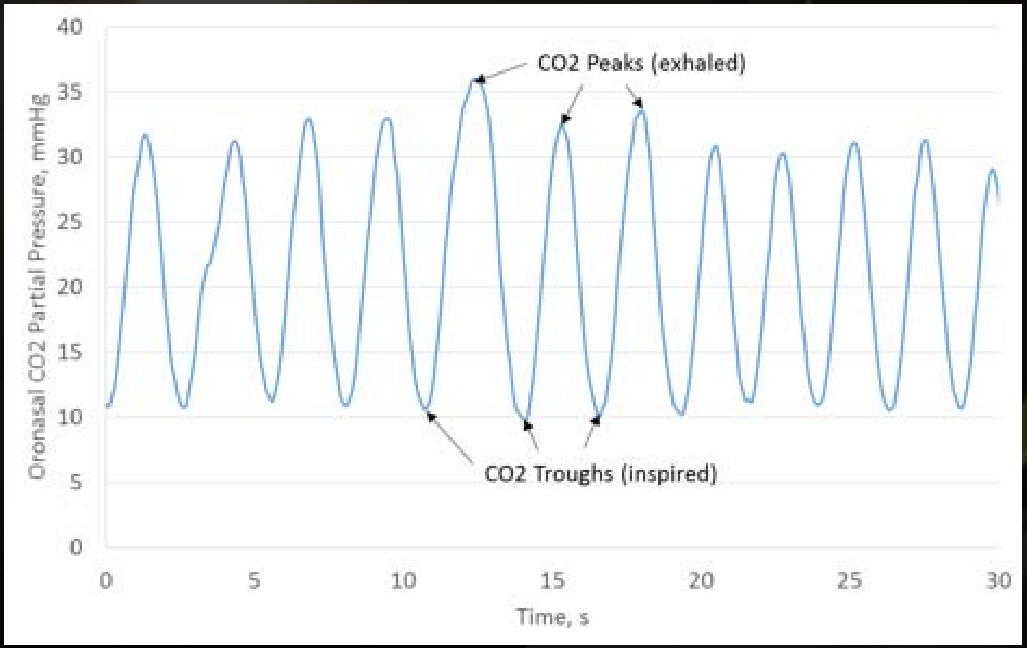
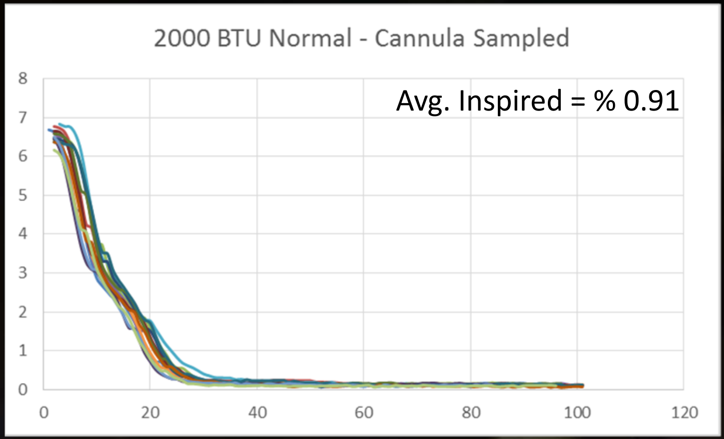
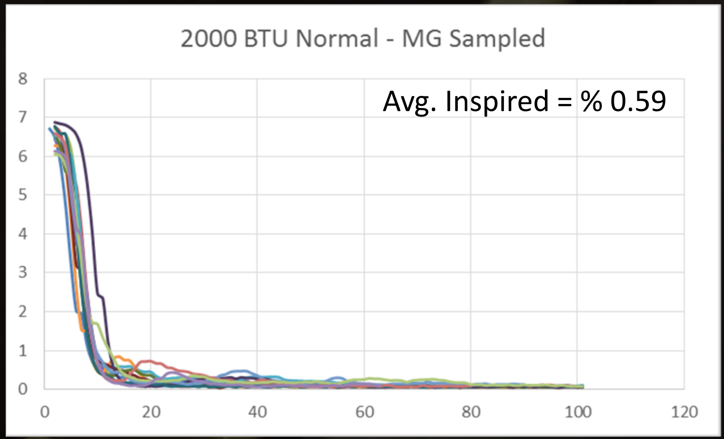


Determining sample probe type - Nasal Cannula vs Mouth Guard

- **Performed unsuited testing in B37 EPL using recommended sample probe setup.**
- **Tested two different sample probe types – Nasal Cannula and a Mouth sensor held in place by a mouth guard.**
- **Cannula resulted in higher inspired CO2 under same condition during unsuited testing**
  - Unsuited tests are in an open environment which is assumed to provide close to perfect washout
  - Possible dilution of inspired sample due to high sampling flow and low flow in/out of the nose
- **Continued concerns of breathing style associated with nasal cannula**

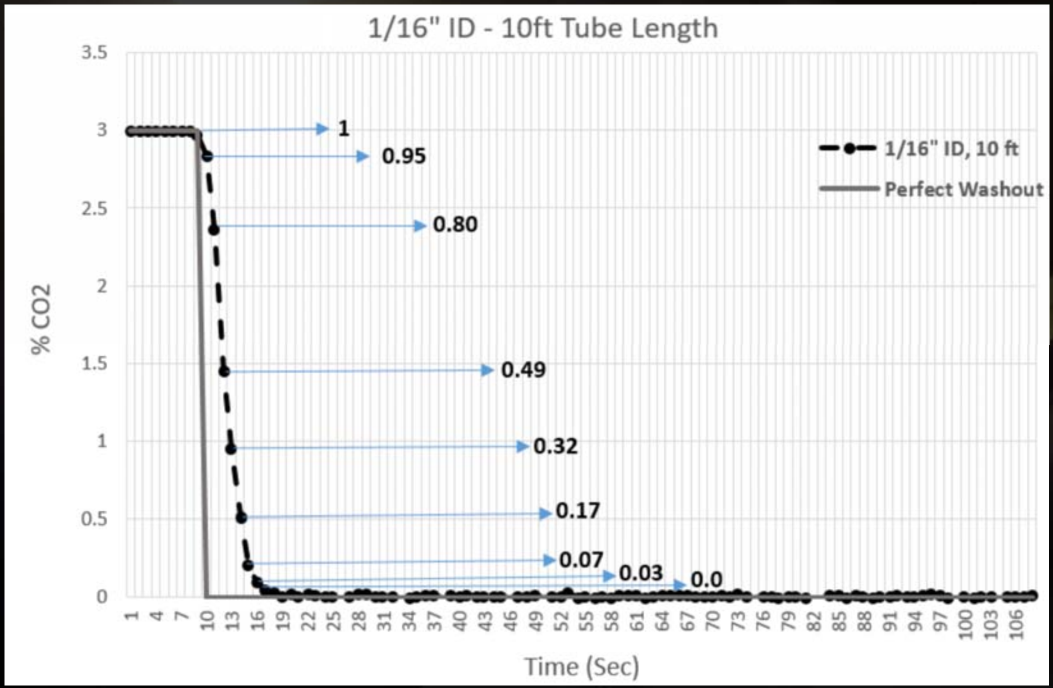




Metabolic Rate	Breathing Style	Mouthguard In (Y/N)	Sample Location	Inspired CO2
1000	Normal	N	Cannula	0.67
2000	Normal	N	Cannula	0.86
1000	Nose Only	N	Cannula	0.62
2000	Nose Only	N	Cannula	0.88
1000	Nose In Mouth Out	N	Cannula	1.13
2000	Nose In Mouth Out	N	Cannula	1.60
1000	Normal	Y	Cannula	0.87
2000	Normal	Y	Cannula	0.86
1000	Nose In Mouth Out	Y	Mouthguard	0.53
2000	Normal	Y	Mouthguard	0.55

Accounting for Hardware Induced Uncertainty

- If no mixing effects were present switching of benchtop valve from 3% to 0% would result in immediate drop in CO_2 value measured
- The scale of the mixing can be found for each data point prior to measurement of 0% gas.
  - Each data point should report 0% in perfect washout case, the percent difference between gas 1 and gas 2 is the degree of uncertainty in the measurement



Down selecting an in-suit sampling system