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Standard Testing Procedure for Quantifying Breathing Gas Carbon Dioxide Partial Pressure for Extravehicular Activity and Launch, Entry, Survival Pressure Suits

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1. PURPOSE

1.1. This standard test and analysis protocol establishes the procedure for determining the partial pressure of inspired carbon dioxide (P_ICO_2) exposure level experienced by persons operating a pressurized suit.

1.2. The purpose of this Standard Testing Procedure (STP) is to describe the test conditions and procedures necessary to acquire data in support of certification that manufacturer submitted Extravehicular Activity (EVA) and/or Launch, Entry, Survival (LES) suit designs maintain safe levels of carbon dioxide (CO_2) in the helmet during suited operations. The STP shall be used to measure the in-suit inhaled and exhaled dry-gas partial pressure of CO_2 (PCO_2), followed by calculation of the water vapor saturated P_ICO_2 during the inhalation portion of the breathing cycle, while a human test subject is performing work at levels anticipated during suited operations in ground and flight environments. The procedure is designed to test the evaluated suit on a human test subject as a dynamic system, generate repeatable results under defined laboratory conditions, and perform consistent analysis on acquired samples.

1.3. This STP is used to evaluate space suits in a hyperbaric environment (above atmospheric pressure). Changes would need to be made to the test equipment/setup to accommodate a hypobaric environment.

1.4. There is no specific EVA or LES suit performance requirement to meet or pass/fail criteria associated with this STP.

2. ACRONYM LIST

ATA – atmospheres absolute
BTU – British thermal unit
CO_2 – carbon dioxide
EVA – Extravehicular Activity
F_ICO_2 – dry-gas concentration of carbon dioxide as decimal percent
HITL – human in the loop
HSBG – human subject breathing gas
Hz – hertz
ID – inner diameter
$IsoP_ICO_2$ – the same PICO2 over a range of PB (mm Hg)
LES – Launch, Entry, Survival
mL/min – milliliters per minute
mm Hg – millimeters of mercury
PB – ambient pressure (mm Hg)
PCO_2 – dry-gas partial pressure of carbon dioxide (mm Hg)
Pg – suit test gauge pressure (mm Hg)
P_ICO_2 – inspired (water vapor saturated) partial pressure of carbon dioxide (mm Hg)
psia – pounds per square inch absolute
psid – pounds per square inch differential
PVC – polyvinyl chloride
STP – Standard Testing Procedure
TWA – time weighted average

3. TEST EQUIPMENT

3.1. A person knowledgeable in the appropriate technical field for this work can select equipment with the necessary resolution and conduct the test. The specific test equipment listed in this section are recommendations; however, as long as the minimum specifications for all equipment are met alternative equipment may be used for this procedure.

3.2. The list of necessary test equipment and materials follows:

3.2.1. CD-3A Carbon Dioxide Gas Analyzer (AEI Technologies) or equivalent. Table 1 lists the minimum acceptable specifications of the required gas analyzer:

Table 1. Minimum Acceptable Specifications

Speed of Response	90% of final value in ≤ 25 milliseconds
Range	0% – 7% CO_2 range
Accuracy	± 0.02% CO_2
Sampling Frequency	50 Hz

3.2.2. The output of the CD-3A sensor is dry-gas fraction of carbon dioxide (F_ICO_2). For monitoring purposes during tests, PCO_2 is calculated from ambient pressure (P_B) combined with suit test gauge pressure (Pg) and reported in units of millimeters of mercury (mm Hg).

3.2.3. 120 inches (305 cm) length, 0.063 inches (1.59 mm) inner diameter (ID), Tygon Polyvinyl Chloride (PVC) flexible tubing (U.S. Plastics) or equivalent non-CO_2 absorbing flexible tubing.

3.2.4. 12 inches (30cm) length, 0.054 inches (1.27 mm) inner diameter (ID), Nafion Tubing (Perma Pure LLC) or equivalent tubing.

3.2.5. Inline Tube-to-Tube barbed orifice fitting (Bird Precision) or equivalent. Sized based on suit operating pressure and sampling line length to ensure adequate pressure drop prior to sensor inlet and flow rate to the sensor.

3.2.5.1. A suit pressurized to 19 psia, including the 120 inches sample line length and Nafion tubing, requires an orifice size of 0.013 inches (0.33 mm).

3.2.6. Mouth Piece: Open-hole mouth/lip guard (Battle Sports Science, SKU: 8200BSS) or equivalent. See Figure 1.

Figure 1. Battle Sports Science bite-style mouth guard with open hole at front.

3.2.7. Data Acquisition System: A data acquisition system consisting of a National Instruments USB-6212 BNC M Series DAQ and a customized LabVIEW software application is used to record breath-by-breath PCO_2 of respired carbon dioxide. The system records at a minimum rate of 50 Hz to adequately resolve the breath-by-breath data [1, 2]. Equivalent data acquisition hardware and software products are permitted as long as an equivalent resolution of the data is achieved.

4. TESTING REQUIREMENTS AND CONDITIONS

4.1. Calibration. Prior to beginning any testing, all measuring equipment must have been calibrated within the preceding 2 hours or as specified by the equipment manufacturer using a method traceable to the National Institute of Standards and Technology (NIST). Equipment calibration records shall be available for examination and laboratory technicians will check calibration prior to the conduct of testing. A statement that all test equipment is within calibration shall be attested by the lab technician on each test report.

4.2. Air Flow Sampling. Air shall be sampled at the location of the mouth guard to achieve an at sensor inlet flow rate of 1000 ± 100 mL/min @ 1 ATA, room air temperature (20ºC to 25ºC). The suit's gas pressure drives air flow from the sample tube inlet at the mouth guard to the CO_2 sensor.

4.2.1. The sample probe is installed into the mouth guard as shown in Figure 2.

4.2.2. The orifice is installed in the sample line, outside of the suit, and as close to the CO_2 sensor inlet port as possible.

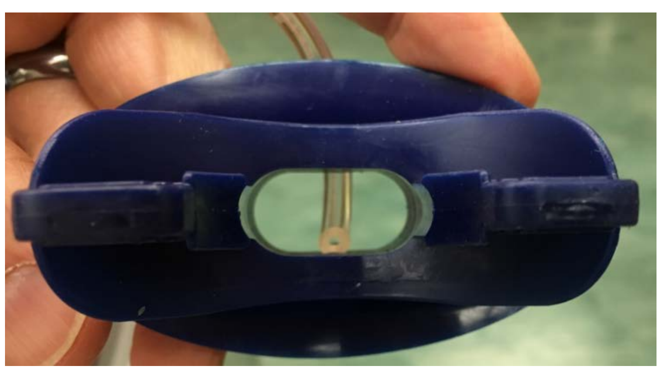


Figure 2. Mouth guard with sample probe inserted to perform sampling.

4.3. Gas Supply. The gas supply shall meet the following specification, or equivalent: CGA-G7.1, grade D.

4.3.1. Calculation of inspired CO_2 and metabolic rate assumes that the test subject is the only generator of CO_2 inside the suit. Additionally, the presence of CO_2 from other sources can adversely affect the CO_2 calculations.

4.4. Minimization of Sampling Induced Errors. When sampling for CO_2, mixing of the sample gas in the sample lines before delivery to the CO_2 analyzer must be minimized in order to get the most accurate results. Examples of sampling system components that can result in errors are:

4.4.1. Changes in the sample tubing diameter. 0.125 inches ID tubing is worse than 0.063 inches ID tubing. This STP has baselined 0.063" ID tubing as it was found to have an acceptable amount of mixing without significant pressure drop while providing a practical line diameter to accommodate implementation with various suit architectures and pressures [2]. A 0.063 inches ID tubing is required for proper execution of this STP. If larger diameter tubing is absolutely needed, results will be worse, but it may be possible to account for this in the calculations. These instances will be addressed on a case-by-case basis and it is expected that all efforts be given to follow the sampling methodology outlined in this STP.

4.4.2. Tubing connections that have large changes in internal diameters will cause mixing and result in poor washout data. Rotameters and barb to National Pipe Thread fittings are examples of this. This STP does not use flow meters between the sample inlet and the CO_2 analyzer. Suit penetrations should strive to use no fittings to pass the sampling tube between the suit wall. If a fitting is required, the fitting should maintain the same ID as the tubing.

4.4.3. The longer the sample tubing, the more mixing between the sample tubing opening and the CO_2 analyzer. This STP uses a 10 ± 0.5 feet sample line length as this was found to acceptably accommodate suited activity while minimizing sampling hardware induced errors [2]. A 10 ± 0.5 feet sample line is required for proper execution of this STP. If longer line lengths are needed, results will be worse, but it may be possible to account for this in the calculations. These instances will be addressed on a case by case basis and it is expected that all efforts be given to follow the sampling methodology outlined in this STP.

4.4.4. The lower the sample flow rate, the more mixing occurs between the sample tubing opening and the CO_2 analyzer. This STP uses 1000 mL/min sample flow rate. If lower flow rates are needed, results will be worse, but it may be possible to account for this in the calculations. These instances will be addressed on a case-by-case basis and it is expected that all efforts be given to follow the sampling methodology outlined in this STP.

4.5. Safety. Normal laboratory safety practices must be observed. This includes safety precautions related to CO_2 gas exposure and limiting overexertion of the test subject. These precautions and test termination criteria shall be documented in the test report including any incidents where a criterion is met during testing.

4.6. Generation of metabolic work rates and monitoring during test. Metabolic rate can be generated by any means (e.g., treadmill, arm ergometer, walking in place), and should be monitored in accordance with published best practices [3, 4].

5. PROCEDURE

5.1. General. This procedure describes the method for measurement of inhaled and exhaled dry-gas PCO_2 in the spacesuit which is used to calculate P_ICO_2. This procedure describes the required sample size, subject demographics, test equipment, data collection methods, human-in-the-loop (HITL) test protocol requirements, and data analysis methods.

5.2. Number of Test Samples and Subject Demographics

5.2.1. This standard test protocol does not require a specific number or demographic of subjects to complete testing. These factors are driven by the allowable confidence interval associated with meeting the respired CO_2 requirements for a specific suit architecture. However, it is recommended that subjects which can adequately reach and maintain all desired metabolic workloads be selected.

5.2.2. It is also possible to set up a Bayesian driven study design that is updated after each subject, to end once the requirement level is reached within a predetermined degree of precision of respired PCO_2 value being less than a cutoff value. An example of number of subjects versus precision of measurement, modelled from a prior suit test, is shown in Figure 3. This only serves as an example and will need to be created on a per test basis.

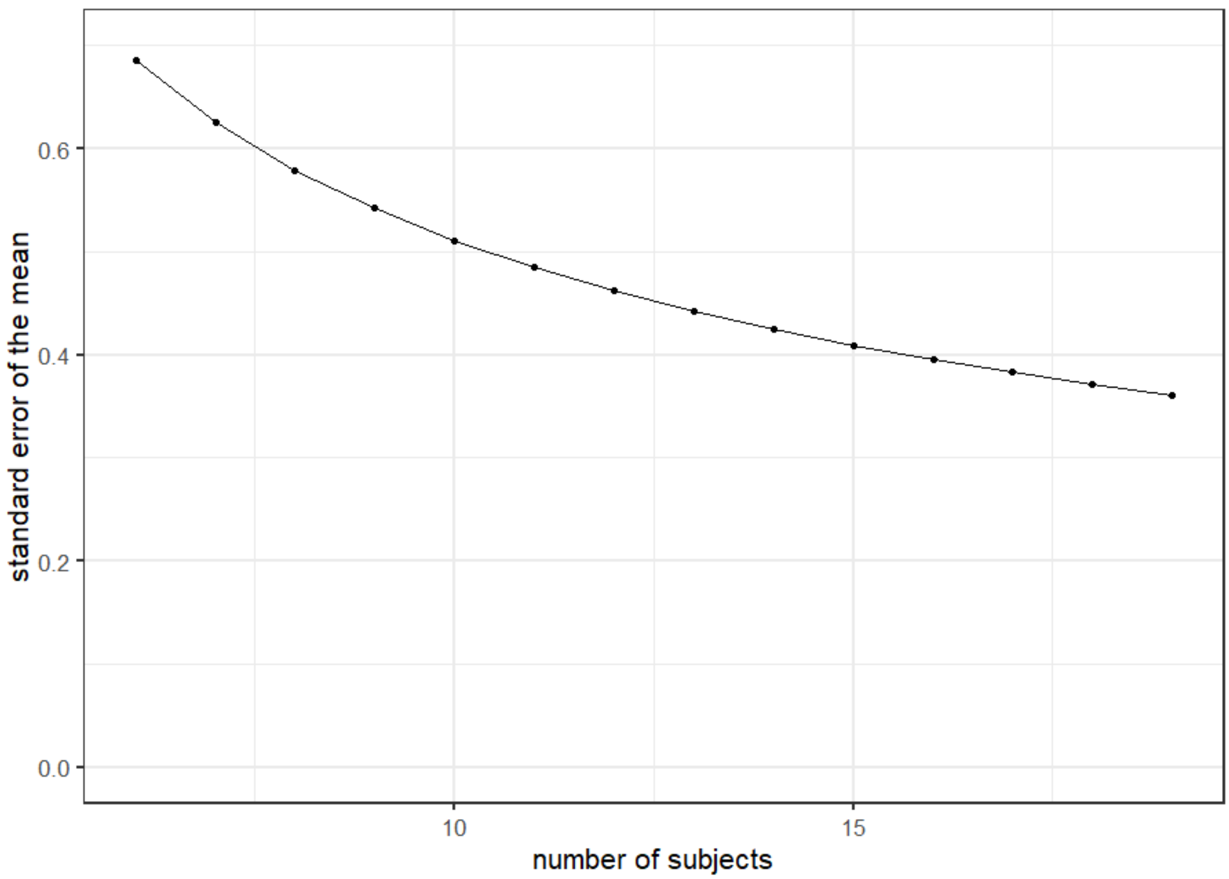


Figure 3. Effect of suited subject sample size on precision of respired PCO_2 measurement.

5.3. Test Equipment

5.3.1. Test facility staff will install the sampling probe into the mouth guard, in accordance with paragraph 3.2 of this STP.

5.3.2. A 10 ± 0.5 feet sample line will be routed from the suit to the CO_2 sensor in accordance with paragraph 3.3 of this STP, and allowing for enough line length in the suit helmet for subject to move head and body unencumbered while conducting the test.

5.3.3. The distal end of the sampling tube is spliced to insert the 0.063 inches orifice.

5.3.4. A 1-foot length Nafion tube is connected the inlet port of the CO_2 sensor and the terminus of the sampling tube.

5.3.5. A flow meter is connected to the exhaust port of the CO_2 sensor to verify adequate flow is achieved through the system in accordance with paragraph 3.2 of this STP. An example total flow path schematic is shown in Figure 4. The flow meter is removed after verifying the flow rate to the sensor is within specifications, otherwise it may result in a back pressure to the sensor, which will alter the calibration.

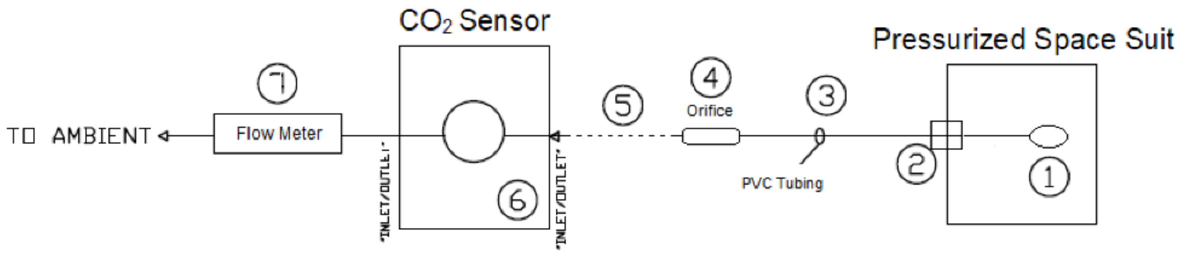


Figure 4. Example air sampling configuration. (1) Mouth guard sample probe; (2) Suit pass-through port, open port potted with room temperature vulcanizing silicone (3) 10 feet, 1/16 inches ID Tygon® PVC tubing; (4) Orifice sized to achieve 1000 mL/min to sensor (0.140 inches ID in this test for 19 psia suit); (5) Nafion Tubing; (6) Infrared CO_2 sensor, AEI Technologies CD-3A measuring at a 50 Hz sampling frequency; (7) Flow meter for sample flow rate verification.

5.3.6. An arm ergometer or treadmill may be used to generate required workloads depending on the suit and test configuration. See paragraph 4.6 for best practice when recording in suit metabolic workloads.

5.4. Conducting the PCO_2 Measurement Test

5.4.1. PCO_2 sampling equipment will be installed and verified prior to subject arriving for suited testing.

5.4.2. Don suit per suit operating procedures, and have subject place mouth guard in mouth.

5.4.3. Pressurize the suit to the target pressure, and assume a physical position representative of expected operations in order to replicate suit fit and head positioning in the helmet as closely as possible to the anticipated flight operations position. For example, standing may be expected for a planetary suit, and recumbent in a seat may be expected for an LES suit.

5.4.4. Confirm sample gas flow rate through CO_2 sensor is 1000 ± 100 mL/min. Disconnect flow meter from CO_2 sensor outlet.

5.4.5. Subject performs exercise to achieve target metabolic rate.

5.4.6. Test conductor verifies subject has reached a steady state and has maintained within ±10% of target metabolic rate for at least 5 minutes.

5.4.7. Record PCO_2 for the duration listed in Table 2 in section 5.4.7.2.

5.4.7.1. These durations are based on analysis of 19 subjects collected during ideal (unsuited) measurement of inspiration and expiration and data collected with this method in the Extravehicular Mobility Unit space suit. The durations allow for collection of enough breath data such that there will be an adequate number of acceptable traces for analysis.

5.4.7.2. During this data collection period, this STP follows a standardized data collection position within the suit. The subject's head will be centered and facing forward, the subject should be breathing normally, and the subject should not talk or turn their head.

Table 2. PCO_2 Data Collection Periods

Target Metabolic Workload (BTU/hr)	PCO_2 Data Collection Duration in Minutes
Resting	6
≤1000	4
1000 < and ≤2000	4
≤3000	2

5.4.8. Confirm record of data and continue with test until all test points are completed.

5.4.9. End suit test per suit operating procedure.

6. CALCULATION OF TIME WEIGHTED AVERAGE PCO_2

6.1. General. This STP defines standard criteria from which acceptable breath traces are identified and the method used to calculate a time weighted average (TWA) PCO_2, accounting for any uncertainty in measurement. These criteria must be broad and robust enough to exclude erratic breath traces but not exclude true results from a suit design that results in poor washout. It is also important to understand that the inhalation portion of the respiratory trace is the only component necessary for calculation of PCO_2 and ultimately 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, which is defined as the points immediately following the peak expiration that are decreasing and lead to an inspiratory plateau that is followed by an increase in PCO_2.

6.2. Appendix A provides definition of the breath trace analysis methodology and methods for selection of breath traces that can and cannot be used for calculation of PCO_2.

6.3. Identifying Acceptable Breath Traces.

6.3.1. Expiratory upstroke should be continuously increasing and followed by a peak PCO_2 that can be clearly identified. Inspiration start is defined as the data point immediately following this point.

6.3.1.1. *Rationale:* The peak PCO_2 point is the only component of the respiratory waveform needed to define start of inspiration. It is acceptable that noise is present during the expiration phase and plateau if the concentration trend is continually increasing to a peak point followed by a rapid change in slope indicating inspiration. Sharp drops in PCO_2 followed by returns to higher values (i.e. data collection errors, noise, or washout effects) are acceptable during the expiration if the overall increasing trend remains and it is possible to locate the peak point. A healthy individual with no respiratory abnormalities will have peak values typically between 30-50 mm Hg.

6.3.2. Peak PCO_2 value shall be followed by a sharp decrease in measured PCO_2, which is continuously decreasing and passes below the average total PCO_2 value measured until an inspiratory plateau is reached with no sharp rises in measured PCO_2 present at any point-preceding end of inspiration.

6.3.2.1. *Rationale:* Unlike expiration, signal clarity during the inspiration phase is necessary for proper calculation of TWA PCO_2. Interrupts in the inspiration data stream, such as sharp increases in PCO_2, are indicative of noise or collection errors and these breaths should not be included in a washout performance calculation.

6.3.3. Inspiration end shall be defined as the point immediately preceding a sharp increase in measured PCO_2 that is continuously positive and passes through a minimum value of at least the total average measured PCO_2.

6.3.3.1. *Rationale:* The end of inspiration is the final point before an increase in PCO_2 indicated by increasingly larger measured PCO_2 values that approach the expiratory phase as described in 6.3.1.

6.3.4. All data shall be visually assessed prior to final data reporting to verify any automated computational errors did not occur (assuming automated processes are used).

6.3.4.1. *Rationale:* Due to noise effects resulting from the HITL nature of this test, it is likely that fully automating the analysis in a way that accounts for all subject differences in breathing patterns and data is not possible. In the case of disagreement with identification, it is recommended that multiple reviewers manually interpret the data and a consensus is reached.

6.4. Time Weighted Average PCO_2 Calculation

6.4.1. General. The TWA PCO_2, represents the quantity of CO_2 inspired by the subject, excluding adjustments for pressure and water vapor saturation. It is the total breath trace area calculation taken from between the inspiration start and inspiration end points identified in 6.2 of this STP. Two PCO_2 values reported for this calculation: (1) Maximum TWA PCO_2, which is defined as the TWA PCO_2 calculated without accounting for any sampling hardware induced measurement uncertainty; and (2) Minimum TWA PCO_2, which is defined as the TWA PCO_2 calculated after scaling of the breath traces to account for sampling hardware induced measurement uncertainty. Both (1) and (2) are required for final reporting of the P_ICO_2 value in Section 6.4.

6.4.2. Maximum TWA Calculation

6.4.2.1. Maximum TWA PCO_2 is calculated for each breath identified in section 5.2 of this STP.

6.4.2.2. The total area between the identified inspiration start and inspiration ends is calculated using an approximate integral via the trapezoidal method with unit spacing.

6.4.2.3. This total area per breath, calculated in 5.3.1.2, is divided by the time duration between inspiration start and end for that breath to result in the maximum TWA PCO_2.

6.4.2.4. All individual PCO_2 maximum TWAs, calculated in 6.4.2.3, are reported as individual breath data points which can then be used to characterize the spacesuit performance.

6.4.3. Minimum TWA PCO_2 Accounting for Uncertainty in Measurement

6.4.3.1. It is not possible to fully eliminate all error to sampled data resulting from measurement hardware. The magnitude of the errors associated with the hardware setup described in the STP has been previously determined and is applied to all HITL sampled data in order to fully characterize the range of PCO_2 that may be experienced by the subject.

6.4.3.2. Scale of sampling error resulting from hardware induced mixing effects can be found for each data point in the inspiration phase using the benchtop assessment method described in [2].

6.4.3.3. The scaling factors listed in Table 3 are only applicable to measurements taken using the exact hardware setup described in this STP. Deviations in hardware configuration such as line lengths longer than 10 feet, or tubing inner diameters greater than 0.063 inches will result in different degrees of measurement uncertainty. These instances will be addressed on a case-by-case basis and it is expected that all efforts be given to follow the sampling methodology outlined in this STP.

Table 3. Breath Trace Scaling Factors for Calculation of Minimum PCO_2

Breath Sample Point	Scaling Factor
1	1
2	0.95
3	0.8
4	0.49
5	0.32
6	0.17
7	0.07
8	0.03
9	0

6.4.3.4. The first nine PCO_2 values measured following the inspiration start point are multiplied by the scaling factors shown in Table 3 to result in a new breath trace for calculation of a Minimum TWA PCO_2 (example shown in Appendix B).

6.4.3.5. The total area between the identified inspiration start and inspiration ends of the breath traces in 6.3.3.3 is calculated using an approximate integral via the trapezoidal method with unit spacing.

6.4.3.6. This total area per breath, calculated in 6.3.3.4, is divided by the time duration between inspiration start and end for that breath to result in the minimum TWA PCO_2.

6.4.3.7. All individual PCO_2 minimum TWAs, calculated in 6.3.3.5, are reported as individual breath data points which can then be used to characterize the spacesuit performance.

6.5. Final Reporting of P_ICO_2

6.5.1. All final reporting of human subject breathing gas (HSBG) concentrations is done as maximum and minimum P_ICO_2 with units of mm Hg.

6.5.2. Each maximum and minimum average PCO_2 value, calculated in 6.4.2.4 and 6.4.3.7 respectively, are converted to a P_ICO_2 using equations described in Appendix C. P_ICO_2 is the relevant physiological measurement for CO_2 dose. Appendix C describes the importance of standardized reporting of HSBG concentrations in units of P_ICO_2 for direct comparison of suit conditions to exposure requirements.

APPENDIX A

Computational Method for Automatically Determining Acceptable and Unacceptable Breath Trace

Identification of acceptable breath traces from within a data set is essential for accurate calculation of PCO_2. Due to the variability associated with HITL testing (e.g., subject size, suit fit, physiology, etc.), ventilation designs, suit configuration (LES or EVA) there is a need to standardize this breath trace selection methodology.

To automatically calculate the total PCO_2 inhaled by a subject, a computational method for detecting inspiration start and end points in the respiratory waveform should is used.

Figure 5 shows that the respiratory trace has a sloped decrease and increase after inspiration start and end, respectively. Time instants of dominant slopes contact with inspiration start and end points could be references in detection of the inspiration start and end.

A parametric global method based on a penalized contrast [5] to simultaneously find all the dominant slopes contact with the inspiration start and end in the respiratory waveform is applied. The reason a parametric method is used is that generalizing the procedure is straightforward when the number of changes is known. When the number is unknown, a penalty term, which is responsible for over- or under-fitting, should be added to the contrast function. For example, if the number of change points were over or under estimated, less drastic changes could be possibly missed out or unnecessarily added. In the extreme case, the most drastic changes or every point could be considered as a change point.

Several methods exist to calculate the optimal number of change points in large data sets [6-8]; however, in this standard test protocol, a simple and intuitive method which considers the signal characteristics of the respiratory waveform is used. Specifically, the number of zero crossings are counted (red circles in

Figure 5 a) in a demeaned and smoothened waveform (red dashed line in Figure a). This waveform is achieved by subtracting a mean of the waveform and smoothened the demeaned waveform with a moving average using a Gaussian window of length 100. Given the number of change points, an optimization algorithm based on dynamic programming with early abandonment was used to minimize the contrast function [9]. Figure 5b shows all the detected slopes (green dashed lines) in the respiratory waveform. A step-by-step flow chart for automatically detect the inspiration start and end was presented in Figure 6. As described in the flow chart, we detected the inspiration start and end by tracking differences between adjacent samples in the negative time direction based on time instants of dominant slopes. Figure 5c shows the inspiration start (blue circle) and end (red cross) in the respiratory waveform. Even though significant noise is present during the expiration phase and plateau (Figure 5c), we were successful in automatic detection of the inspiration start and end by choosing a point clearly on the inspiratory down- and up-slope. Finally, PCO_2 was calculated as the area underneath the inhalation portion of the curve as shown in Figure 5c (green area).

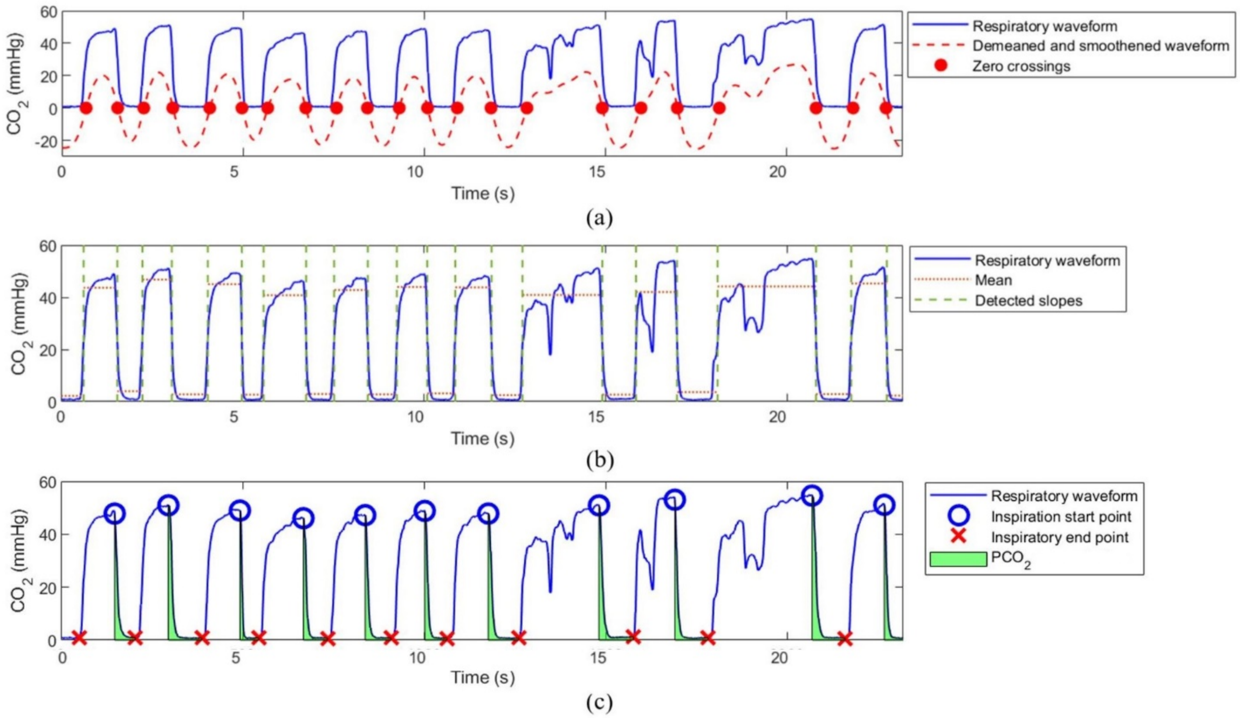


Figure 5. Procedure for calculating PCO_2: (a) A simple method for counting the number of change points, (b) Detected slopes, (c) PCO_2 inspiration start and end points.

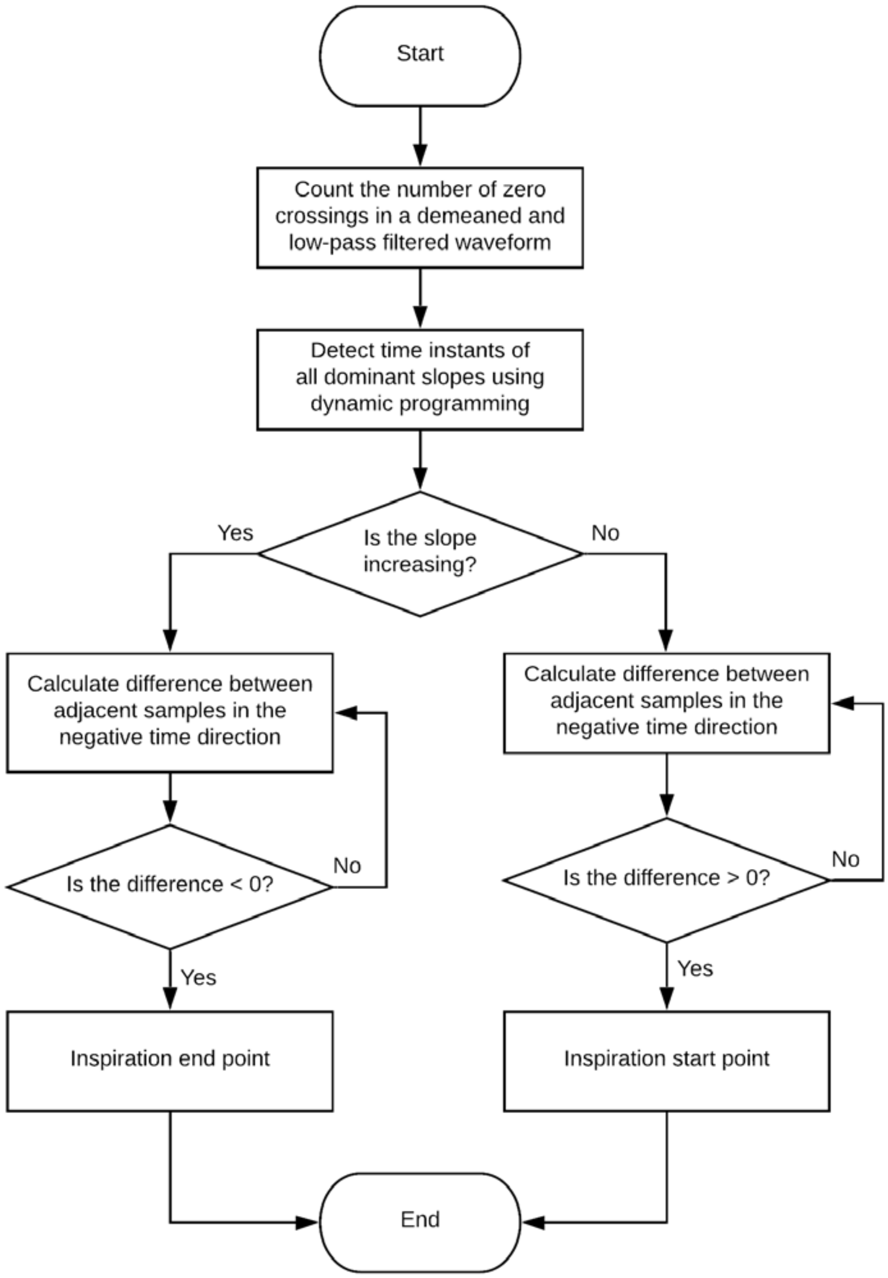


Figure 6. Flow chart of the procedure for detecting inspiration start and end points.

Determination of Acceptable and Unacceptable Breaths

Identification of acceptable breath traces from within a data set is essential for accurate calculation of the in-suit PCO_2. Due to the variability associated with HITL testing (e.g., subject size, suit fit, physiology, etc.), ventilation designs, suit configuration, there is no single method that can be applied across all suit configurations and tests. Considering this, guidelines for determining acceptable traces for analysis have been established to provide a consistent framework by which this analysis can be completed. The following are descriptions of acceptability criteria at each phase of the breath (Figure 7):

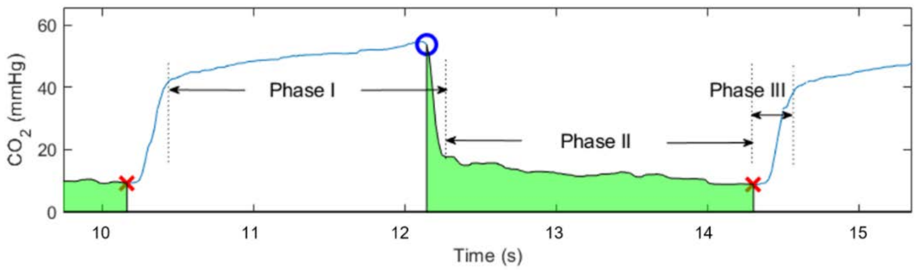


Figure 7. Three phases of a breath cycle trace.

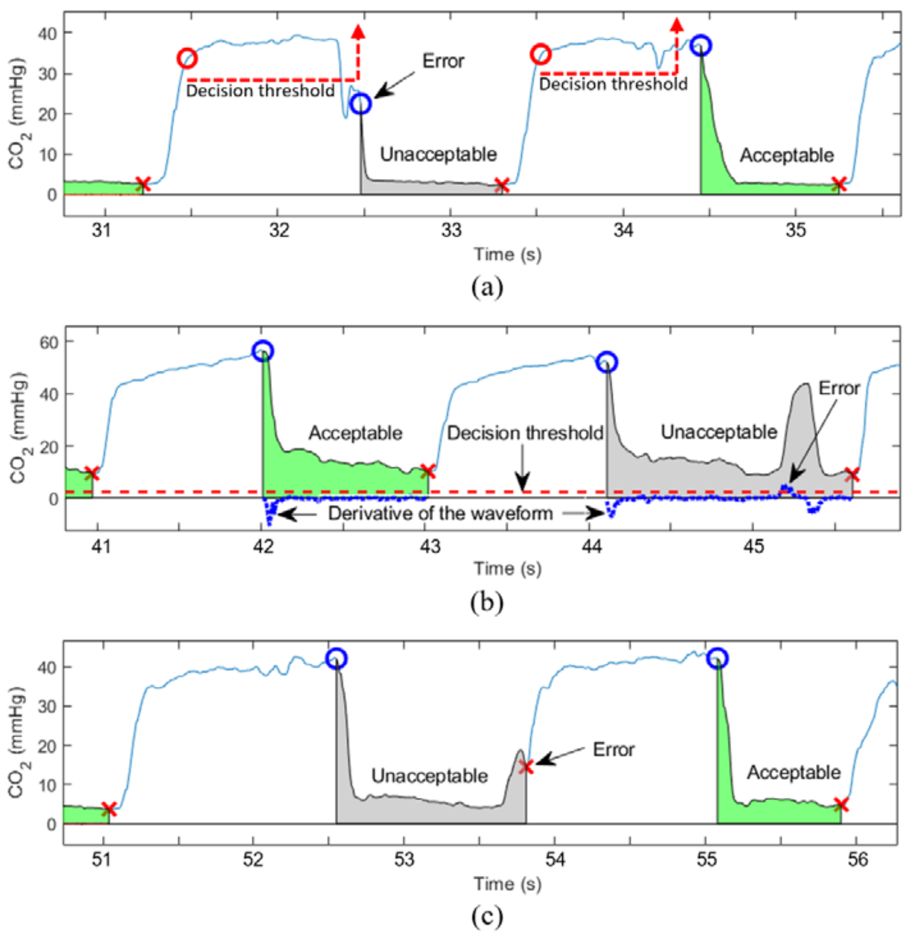


Figure 8. Examples of acceptable and unacceptable breaths: (a) Phase I, (b) Phase II, (c) Phase III.

i. Phase I (plateau during the expiration phase and sloped decrease after inspiration start): Breath is acceptable if the amplitude of inspiration start (blue circle: **O**) is greater than 90% of the amplitude of the starting point in the plateau period (red circle: **O**) as shown in Figure 8a. The knee point detection algorithm provides the point of maximum curvature (red circle: **O**) after the inspiration end (red cross: **X**) which is a mathematical measure of how much a function differs from a straight line [10]. If the amplitude of inspiration start (blue circle: **O**) is less than 90% of the amplitude of the starting point in the plateau period (red circle: **O**) (Figure 8a), the breath is unacceptable. The shape of the plateau between the inspiration end and the next inspiration start is variable depending on the type of suit. This guideline provides a consistent and mathematically justifiable answer regardless of the shape of the plateau during Phase I.

ii. Phase II (plateau during the inspiration phase): Breath is acceptable if the plateau during Phase II is maintained flat without an error in measurement. To detect unexpected error during Phase II, a decision threshold derived from the first derivative of the waveform of Phase II is set (Figure 8b). If the amplitude of the first derivative of the waveform is greater than 3 (mmHg/s), the breath is unacceptable.

iii. Phase III (Sloped increase after inspiration end): Breath is acceptable if the inspiration slope is continuously increasing without an error in measurement. During the process to find an inspiration end point from a sloped increase (Figure 7), this unwanted peak (Figure 8c) can be detected as a fake inspiration end point before reaching to the start point of Phase III. The inspiration end point is therefore a wrong choice and the breath unacceptable if 90% of the amplitude at the inspiration end point is greater than the average of adjacent inspiration end points.

APPENDIX B

Scaling Breath Data for Minimum TWA PCO_2 Calculation

Benchtop testing conducted in [2], demonstrated that even if pure sources of gas are used, mixing effects remain as a result of the measurement hardware. If no mixing effects were present, switching the benchtop valve from 3% to 0% would result in immediate drop in F_ICO_2 value measured, however a square wave during testing was not observed. The scale of the mixing can be found for each data point prior to measurement of 0% gas as each data point should report 0% in a perfect washout case. The percent difference between gas 1 (3%) and gas 2 (0%) is the degree of uncertainty in the measurement. Each acceptable breath collected is scaled with these percent differences to identify the area of inspiration that is affected by hardware induced mixing effects. 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 the potential minimum (excluding uncertainty) and maximum TWA PCO_2 value. Both values are reported. Figure 9 plots an "inspiration trace" collected in the benchtop testing between two known gasses illustrating the mixing effect and indicating the scaling factors for each data point between gas 1 and gas 2. Figure 10 illustrates the area that is removed from the calculation when these scaling factors are applied.

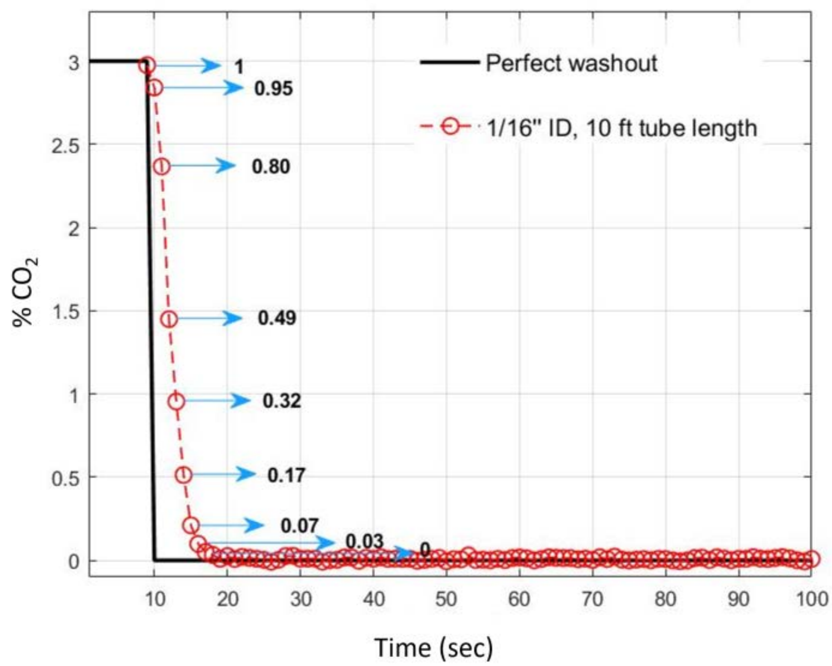
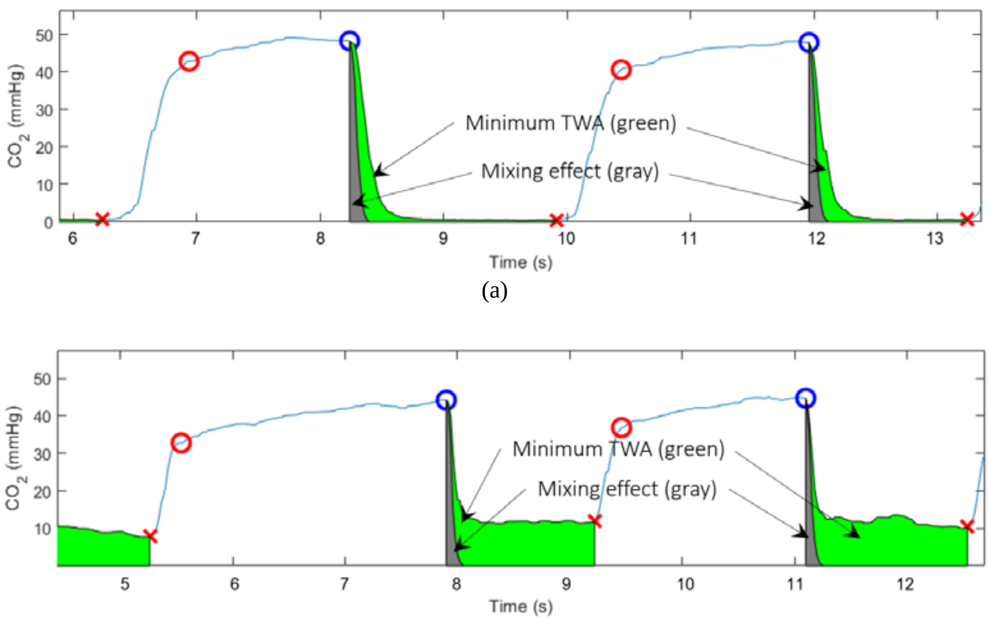


Figure 9. Perfect washout versus actual measurement using the benchtop system.



(a)

(b)

Figure 10. Area of mixing uncertainty (gray) is subtracted from total breath trace area when calculating minimum TWA PCO_2 (green): (a) Example inspiration unsuited, (b) Example inspiration suited.

APPENDIX C

Defining Inspired CO_2 (P_ICO_2)

Table 4 is an example of how the same P_ICO_2 of 15 mm Hg is realized under hyperbaric, normobaric, and hypobaric tests of a spacesuit.

Table 4. Examples of IsoP_ICO_2 Conditions

P_B Psia , mm Hg	Sensor dry-gas F_ICO_2	❶PCO_2 mm Hg	❹P_ICO_2 mm Hg	condition
19.0 , 982	0.016	15.7	15.0	Suit tested at 1 ATA with 4.3 psid
14.7 , 760	0.021	16.0	15.0	Suit tested at 1 ATA with 0 psid
4.3 , 222	0.085	19.0	15.0	Suit tested at vacuum with 4.3 psid

IsoP_ICO_2 is the same P_ICO_2 over a range of P_B.

❶ $PCO_2 = P_B \times F_ICO_2$ or if a target P_ICO_2 is desired, then compute the required PCO_2 as:

❷$PCO_2 = P_B \times [P_ICO_2 / (P_B - 47)]$ with mm Hg unit, where 47 is the partial pressure of water vapor (PH_2O) in mm Hg at 37°C body core temperature.

Also,

❸ $F_ICO_2 = P_ICO_2 / (P_B - 47)$ or $F_ICO_2 = PCO_2 / P_B$ with mm Hg unit, and

❹ $P_ICO_2 = (P_B - 47) \times F_ICO_2$ with mm Hg unit.

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