

Carbon Dioxide Washout Testing Using Various Inlet Vent Configurations in the Mark-III Space Suit

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Requirements for using a space suit during ground testing include providing adequate carbon dioxide (CO₂) washout for the suited subject. Acute CO₂ exposure can lead to symptoms including headache, dyspnea, lethargy, and eventually unconsciousness or even death. Symptoms depend on several factors including inspired partial pressure of CO₂ (ppCO₂), duration of exposure, metabolic rate of the subject, and physiological differences between subjects. Computational Fluid Dynamics (CFD) analysis has predicted that the configuration of the suit inlet vent has a significant effect on oronasal CO₂ concentrations. The main objective of this test was to characterize inspired oronasal ppCO₂ for a variety of inlet vent configurations in the Mark-III suit across a range of workload and flow rates. Data and trends observed during testing along with refined CFD models will be used to help design an inlet vent configuration for the Z-2 space suit. The testing methodology used in this test builds upon past CO₂ washout testing performed on the Z-1 suit, Rear Entry I-Suit, and the Enhanced Mobility Advanced Crew Escape Suit. Three subjects performed two test sessions each in the Mark-III suit to allow for comparison between tests. Six different helmet inlet vent configurations were evaluated during each test session. Suit pressure was maintained at 4.3 psid. Suited test subjects walked on a treadmill to generate metabolic workloads of approximately 2000 and 3000 BTU/hr. Supply airflow rates of 6 and 4 actual cubic feet per minute were tested at each workload. Subjects wore an oronasal mask with an open port in front of the mouth and were allowed to breathe freely. Oronasal ppCO₂ was monitored real-time via gas analyzers with sampling tubes connected to the oronasal mask. Metabolic rate was calculated from the CO₂ production measured by an additional gas analyzer at the air outlet from the suit. Real-time metabolic rate measurements were used to adjust the treadmill workload to meet target metabolic rates. This paper provides detailed descriptions of the test hardware, methodology and results, as well as implications for future inlet vent designs and ground testing.

Nomenclature

<i>ACFM</i>	=	actual cubic feet per minute
<i>BTU/hr</i>	=	British thermal unit per hour
<i>CFD</i>	=	Computational Fluid Dynamics
<i>CFG</i>	=	configuration

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CO_2	=	carbon dioxide
<i>EM-ACES</i>	=	Enhanced Mobility Advanced Crew Escape Suit
<i>EMU</i>	=	extravehicular activity mobility unit
<i>EVA</i>	=	extravehicular activity
<i>JSC</i>	=	Johnson Space Center
<i>ISS</i>	=	International Space Station
<i>LCVG</i>	=	liquid cooling and ventilation garment
<i>l/min</i>	=	liters per minute
<i>mmHg</i>	=	millimeters of Mercury
<i>NASA</i>	=	National Aeronautics and Space Administration
<i>ppm</i>	=	parts per million
<i>ppCO₂</i>	=	partial pressure carbon dioxide
<i>psi</i>	=	pounds per square inch
<i>psi</i>	=	pounds per square inch differential
<i>REI</i>	=	Rear Entry I-Suit
<i>RER</i>	=	respiratory exchange ratio
<i>SCFM</i>	=	standard cubic feet per minute

I. Introduction

Carbon dioxide (CO_2) can build up quickly inside an enclosed environment if adequate ventilation is not in place. Acute health effects that can be brought on by exposure to high CO_2 concentrations include headache, dizziness, shortness of breath, sweating, increased blood pressure, and, in severe cases, unconsciousness and death. Maintaining adequate CO_2 washout during an extravehicular activity (EVA) is required to avoid these negative health effects. Likewise, maintaining adequate CO_2 washout during space suit ground testing is necessary for test subject safety.

There are a number of ways to increase the CO_2 washout within a space suit helmet; however, the quantifiable impacts of variables such as airflow configuration and helmet shape are not well understood. The NASA Johnson Space Center (JSC) Space Suit and Crew Survival Systems Branch, in conjunction with the EVA Physiology Laboratory, measured oronasal CO_2 concentrations in the Mark-III suit for a variety of airflow configurations with a focus on better understanding which helmet airflow configurations provide the best CO_2 washout during ground-based testing. A reconfigurable helmet inlet vent was developed specifically for this test and is only intended for ground use in this test. Data and trends obtained from this test will be used to help define inlet vent configurations for future space suits to maximize CO_2 washout. More stringent CO_2 washout requirements may be necessary for cases in which the subject cannot be quickly returned to a low level of ambient $ppCO_2$, such as during spaceflight. These cases were out of the scope of this test series and were therefore not examined in depth.

II. Test Objective

The main objective of this test was to evaluate six helmet inlet ventilation configurations to determine which configuration maximizes CO_2 washout in the test subject's oronasal area in the Mark-III suit. Secondary test objectives included characterizing general trends between vent configuration and oronasal CO_2 washout, and obtaining CO_2 test data in the oronasal region that can be used to refine corresponding Computational Fluid Dynamics (CFD) modeling predictions. Test parameters were selected to focus on slightly higher manned suit test workloads and flow rates, which have typically been useful in characterizing oronasal CO_2 washout. To accomplish these objectives, it was necessary to characterize both variability between test days for the same subject and between subjects.

III. Test Plan Overview

Three test subjects were used, with each subject performing 2 days of testing at roughly the same time of day, to allow for data comparison between tests for consistency in the test methodology. The suit pressure was maintained at the standard operating pressure of 4.3 psid at all times. Supply airflow was varied between 6 actual cubic feet per minute (ACFM) (nominal air flow rate) and 4 ACFM for the 2000 BTU/hr test cases, and remained at 6 ACFM for the 3000 BTU/hr test cases.

Test subjects walked on a treadmill at varying speeds to generate metabolic rates (workloads) of approximately 2000 and 3000 BTU/hr for short (~2-minute) durations. At the end of each 2-minute data collection period or test "run," the inlet vent configuration was reconfigured to produce the next helmet air flow configuration to be tested.

Simplified predictions for the flow paths within the Mark-III helmet for each configuration, which were based on CFD models,¹ are shown in Figures 1 through 6. Previous CO₂ washout tests² and analysis have shown that the most challenging CO₂ washout conditions occur at higher metabolic rates and lower airflow rates. These conditions were therefore targeted to identify CO₂ washout differences between the vent configurations being tested. These values were also selected based on historical suited test data, which represent the higher end of ground-based suited testing.

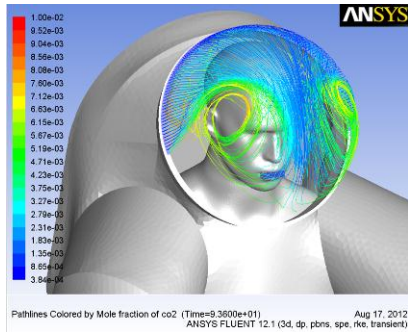


Figure 1. CFG A.

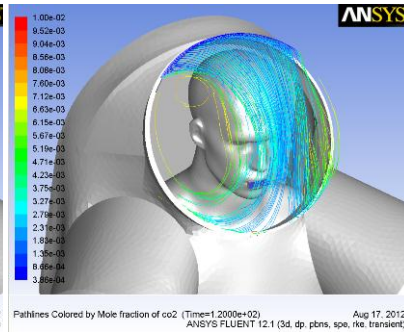


Figure 2. CFG B.

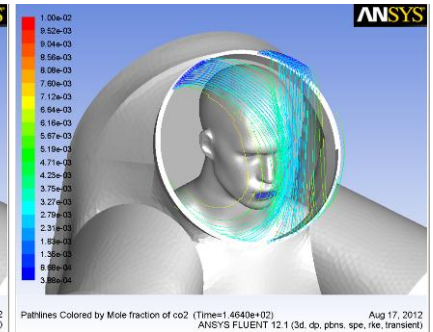


Figure 3. CFG C.

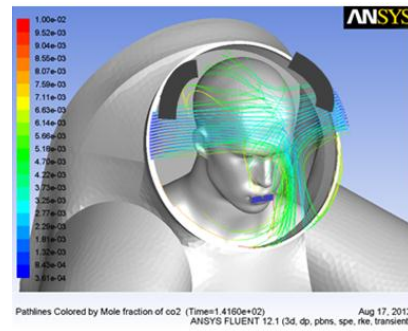


Figure 4. CFG D.

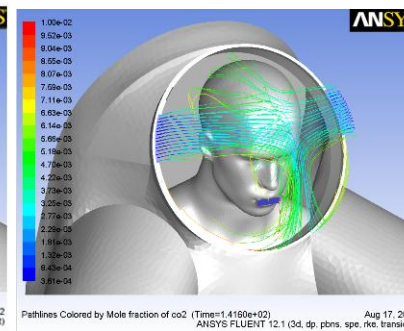


Figure 5. CFG E.

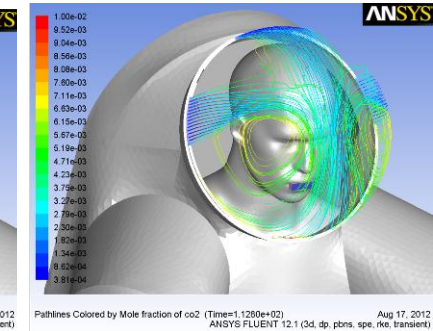


Figure 6. CFG F.

Oronasal CO₂ levels and trending in the helmet were monitored real-time via gas analyzers with sampling tubes positioned in the subjects' oronasal area and a separate in-helmet location. Metabolic rate was calculated in real-time from the total CO₂ production as measured by an additional gas analyzer at the air outlet from the suit. The real-time metabolic rate was used to monitor and adjust the treadmill speed to meet the target metabolic rates. Heart rate was also monitored to ensure that the suited subjects stayed below 85% of age-predicted heart rate maximum, which is the standard cut-off for non-physician monitored testing at JSC.

Table 1 and Table 2 show the test matrices containing workload, supply airflow rate, and inlet vent configuration (CFG) combinations along with test order for each day of testing. Each day, oronasal CO₂ levels associated with each vent configuration were evaluated at both the standard 6 ACFM and the reduced 4 ACFM flow rates while test subjects generate a metabolic rate of 2000 BTU/hr. Suited subjects were allowed to take rest breaks, as needed. After all 2000 BTU/hr runs (Runs #1-12) were completed, the test plan included data points to evaluate each airflow vent configurations at 3000 BTU/hr. Data at 3000 BTU/hr was not obtained on configurations D and E during actual testing due to high oronasal CO₂ values obtained during 2000 BTU/hr testing. This is discussed more in the Data Analysis section.

Table 1. Test Variables Matrix for Test Subject Day 1

Metabolic Rate	Airflow	Inlet Vent Configuration					
		CFG A	CFG B	CFG C	CFG D	CFG E	CFG F
2000 BTU/hr	6 ACFM	Run #1	Run #2	Run #3	Run #4	Run #5	Run #6
		Break(s) as needed by suited subject					
2000 BTU/hr	4 ACFM	Run #7	Run #8	Run #9	Run #10	Run #11	Run #12
		Break(s) as needed by suited subject					
3000 BTU/hr	6 ACFM	Run #14	Run #17	Run #16	Run #18	Run #15	Run #13

Table 2. Test Variables Matrix for Test Subject Day 2

Metabolic Rate	Airflow	Inlet Vent Configuration					
		CFG A	CFG B	CFG C	CFG D	CFG E	CFG F
2000 BTU/hr	6 ACFM	Run #6	Run #5	Run #4	Run #3	Run #2	Run #1
Break(s) as needed by suited subject							
2000 BTU/hr	4 ACFM	Run #12	Run #11	Run #10	Run #9	Run #8	Run #7
Break(s) as needed by suited subject							
3000 BTU/hr	6 ACFM	Run #17	Run #14	Run #15	Run #13	Run #16	Run #18

IV. Test Hardware Description

A. Mark-III Suit

The Mark-III suit, shown in Figure 7, represents a rear-entry hybrid space suit configuration composed of hard elements such as a hard upper torso and hard brief section, and of soft components such as the fabric elbows and knees. The Mark-III has a neck ring that accommodates a 13.5-inch hemispherical dome helmet consisting of a detachable, transparent, hard pressure vessel encompassing the head. The Mark-III suit hardware and ancillary support equipment provide the necessary functions and interfaces to conduct manned pressurized suit operations when combined with (a) a suitable gas supply system, (b) cooling water supply, and (c) suitable communication system.

The Mark-III suit was designed to nominally receive certified breathing air at 5 to 6 ACFM to both inflate the pressure garment and provide a breathable atmosphere for the suited subject. The Mark-III has also been approved for testing at 4 ACFM when enhanced monitoring of the test subject’s oronasal CO₂ concentration is present. Breathing air was delivered to the pressure garment via a certified gaseous breathing air system using the interface shown in Figure 8. The return air (exhalent) is removed from the Mark-III suit via ducts located on the legs and arms of an International Space Station (ISS) Extravehicular Activity Unit (EMU) liquid cooling and ventilation garment (LCVG), which was worn by each test subject. The exhaust air is then directed out of the suit at the red “Air Out” connection on the rear-entry door also shown in Figure 8.



Figure 7. Mark-III Suit overview.

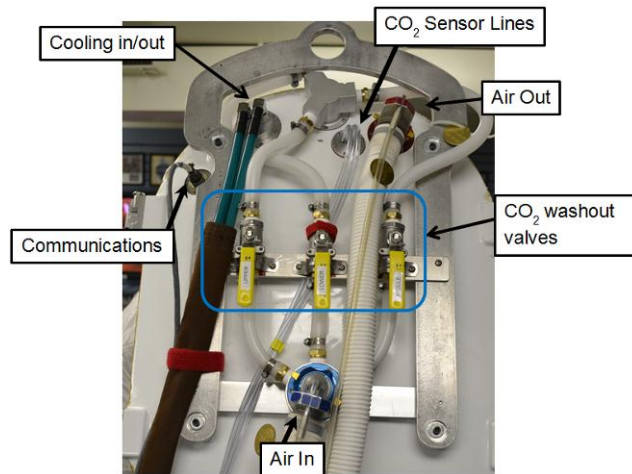


Figure 8. Mark-III Suit external interfaces.

B. Helmet Ventilation Inlet Vent and Flow Configurations

The suit inlet breathing air was directed through a set of tubes and valves shown in Figure 8 to direct flow to the suit inlet ducts, which are shown in Figure 9, to be easily reconfigured. This inlet vent was specifically designed and fabricated to produce various flow patterns within the Mark-III test subject’s oronasal region that corresponded to similar simplified CFD models analyzed in 2013.¹ The 2013 simplified CFD models predicted the resulting flow patterns and CO₂ washout in the oronasal region for each of these six vent configurations. During testing, the three valves located on the exterior of the Mark-III hatch, were configured to supply airflow to produce airflow configurations A through F, which are similar to those analyzed in 2013.



Figure 9. Front view of helmet inlet vent.

V. Methods

C. Carbon Dioxide Measurements

The key parameter for indication of adequate CO₂ washout is the direct measurement of CO₂ in the subject's oronasal area. This represents the amount of CO₂ that the subject inspires with each breath. The test subjects wore an oronasal mask to provide a platform for sampling CO₂ in the oronasal area. The mask, pictured in Figure 10, was a Hans Rudolph 7450 series mask with a headnet to hold the mask on the subjects' faces. The mask seals to the face except for a large opening at the front of the mouth. Tygon sampling tubes were inserted at the right and left side of the opening to measure oronasal CO₂ content. Each signal was analyzed separately; therefore, exact time syncing between the left and right side was not critical. Inspired CO₂ levels were determined by looking at the low points of the respiratory cycle (shown in Figure 11). Without direct flow measurement at the mouth, a flow rate-weighted average across the inspiration cycle could not be calculated. Although a flow rate-weighted average would be preferred, the majority of the inspiration by volume occurs near the lowest end of the displayed CO₂ levels in Figure 11. The test setup used to obtain and analyze CO₂ measurements was identical to previous CO₂ washout testing with the Rear Entry I-Suit (REI) suit in 2012.² The left- and right-side measurements were given equal weight, and the average was used to determine CO₂ washout. One additional CO₂ sampling tube was placed in the top center of the helmet, just below the inlet vent, to allow for observation of the CO₂ level at an alternate in-helmet location. The sampling tubes were routed through a pass-through port in the suit hatch, through a rotameter that controlled flowrate to 1.0 l/min per sample line, and then out to AEI Technologies CD-3A CO₂ analyzers for real-time CO₂ measurement. Suit delta pressure forced air flow through the sampling tubes, and rotameters on the gas analyzers allowed the flow rate to be adjusted to the range required by the analyzers.



Figure 10. CO₂ sampling locations.

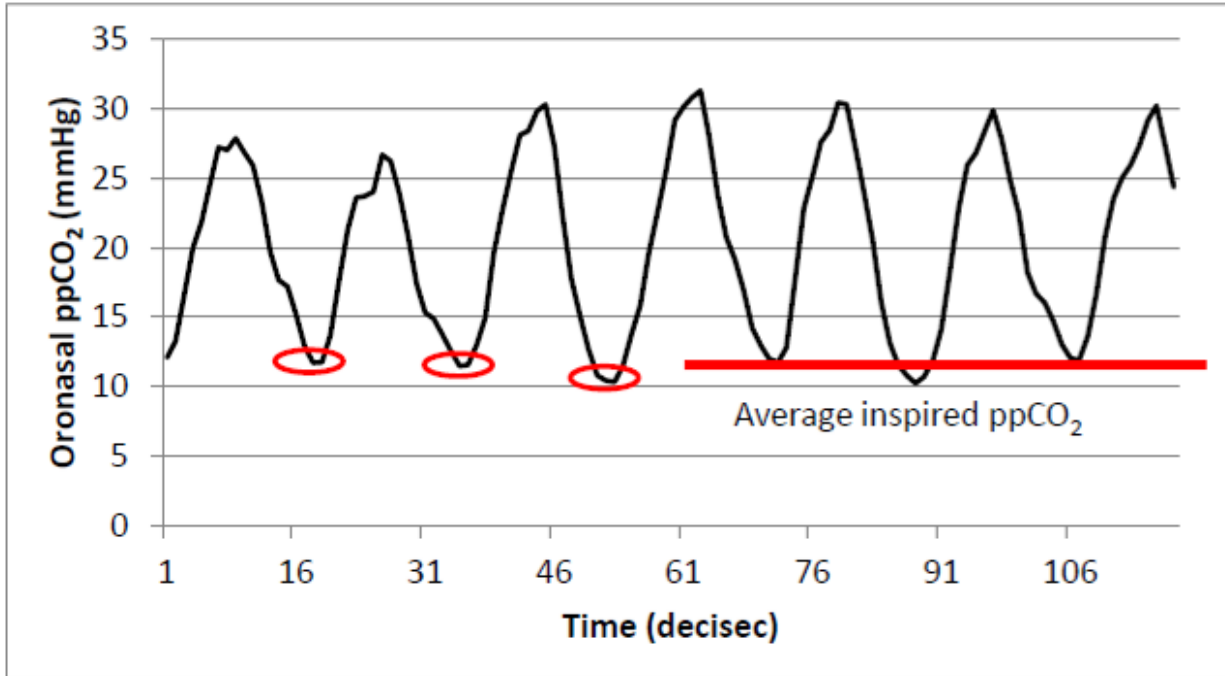


Figure 11. Inspired ppCO₂ was determined by the average values of the troughs seen during the respiratory cycle.

D. Metabolic Rate Measurement

In the ground-based suit test configuration, supply air provided from either the facility breathing air supply or the K-bottles has a very low (less than 500 ppm or 0.05%) CO₂ concentration. The only significant source of CO₂ inside the space suit is the human being, and the amount of CO₂ produced is proportional to the person’s workload. There is no CO₂ scrubbing capability in the suit; therefore, the CO₂ produced is exhausted along with the bulk airflow out of the suit. We assume that the ventilation rate and direction of airflow ensures proper gas mixing throughout the suit and that there are no pockets of expired air that accumulate somewhere in the suit. The suit is also known to leak in small amounts, typically through the joints or bearings. Given the suit’s airflow and mixing characteristic and steady-state exercise protocols, we assume that gas sampled at the exhaust umbilical is representative of the subject and not affected by the known leak rate.

Since different people expend different amounts of energy while walking at the same speed, it is necessary to have a way to calculate the actual energy expenditure (metabolic rate) of each individual subject to control the test for specific workloads. This test used a method that has been adapted for use in space suits from the industry standard method used in the exercise physiology field. The NASA EVA Physiology Laboratory personnel determined the metabolic rate through standard equations³ using CO₂ production, the flow rate of breathing air, and the respiratory exchange ratio (RER). We assume a constant RER of 0.85 for this study. The same equipment, personnel, and method were used to determine metabolic rate during EVA training in the Neutral Buoyancy Laboratory as an estimation of the metabolic rates expected for International Space Station EVAs, and in previous CO₂ washout testing with the REI suit in 2012.²

The system used for metabolic rate measurement consisted of a Kurz flow meter on the suit air inlet line and an AEI Technologies CD-3A infrared CO₂ analyzer on the suit air outlet line, which fed data into the metabolic rate calculations. The Kurz flow meter outputs data in standard cubic feet per minute (SCFM) based on a temperature of 25°C (77°F) and pressure of 14.7 psi. The CO₂ level measured by this system has been shown to track closely to the subject’s workload and can be an effective method of controlling to a desired workload. During the test, the Environmental Physiology Laboratory personnel would monitor the metabolic rate at each workload until it appeared to have stabilized which was most often determined when the 30-sec average metabolic rate was clearly in the target zone. At that point, a 2-minute data collection trial was “started” (by marking the start time in the metabolic system data collection program). In some cases, workload had to be adjusted during the data collection period to keep the metabolic rate at the desired level.

A LabVIEW program was used to calculate and display metabolic rate as well as in-suit CO₂ levels on a single display screen. The data were displayed real-time during each test and recorded for post-test analysis. Because the CO₂ being used for the oronasal CO₂ analysis was sampled directly at the source of CO₂ production, it was important to add this back into the metabolic rate calculation. This was not done real time, but rather was done post hoc; on average, the CO₂ sampled directly from the oronasal area accounted for 25-75 BTU/hr depending on ppCO₂.

VI. Data Analysis

A. Overview of Data Collected

The objective of the test was to determine which vent configuration provided the most CO₂ washout using three subjects, running each subject through the complete protocol on two different test days. Because the vent metabolic rate and vent configuration were controlled variables, the test team expected no significant differences between test days of the same subject. Testing was scheduled to include 15 to 16 test points each day, with the first 12 test points at 2000 BTU/hr being the primary focus of data collection. All three subjects completed the 2000 BTU/hr trials both days at each of the six different vent configurations. Because of the physical difficulty of completing the 3000 BTU/hr trials, they were not all completed. On the first day of testing at 3000 BTU/hr, subject 1 completed vent configurations A and B, subject 2 did not attempt any test points, and subject 3 completed A, B, and F. On Day 2, subject 1 and subject 3 completed all targeted vent configurations at 3000 BTU/hr and subject 2 completed A, B, and F.

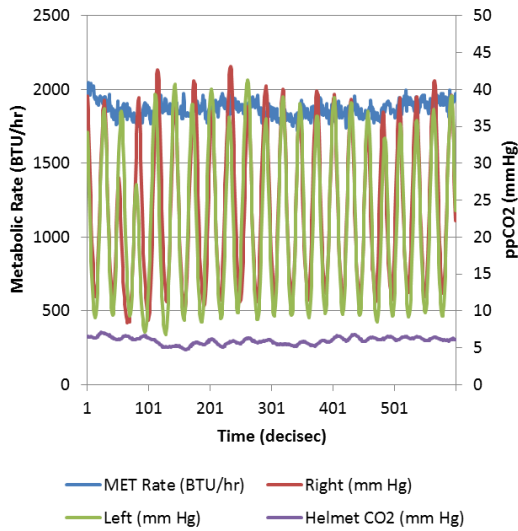
One of the ways to ensure some measure of precision was to test each subject on different days. Variability in the suit ventilation rate and subject metabolic rate can occur between test days and even test conditions. The test is structured to control to the metabolic rate of the suited subject, but this is often a moving target based on posture, how much weight the subject rests on the treadmill frame, and even slight gait differences. For this reason, we target a range of $\pm 10\%$ for metabolic rate data collection. Even with this target, there are fatigue- and oronasal-inspired CO₂ test termination criteria that may not allow for data collection during the target metabolic rate for the preferred amount of time. Due to these differences in flow and metabolic rate, a normalization scheme is needed to ensure fair comparison between the conditions. Based on mathematical analysis and previous test data, we know that increased metabolic rate and decreased suit flow rate will lead to increased inspired CO₂. Due to the cumbersome units associated with the normalization scheme, the normalized data will be reported as the CO₂ washout score, a metric specifically created for this study, but that may be relevant for future studies as well. The CO₂ washout score is the metabolic rate in BTU/hr divided by the average inspired ppCO₂ in mmHg and then further divided by the suited flow rate in SCFM. In this case, a higher CO₂ washout score is associated with better overall CO₂ washout. This is shown in Eq. (1).

$$\text{CO}_2 \text{ Washout Score} = \text{Metabolic Rate (BTU/hr)} \div \text{Inspired CO}_2 \text{ (mmHg)} \div \text{Suit flow rate (SCFM)} \quad (1)$$

B. Day-to-Day Variability Within Subjects

The number of test subjects used for this test was based solely upon the number of subjects used in similar CO₂ washout testing performed at JSC. Statistical power was not a consideration for development of the number of subjects. Comparison within the same subject and between different subjects were made throughout visual inspection of the graphical data and through numerical comparisons. With these pilot data, the test team hoped to get a feel for the day-to-day variations. In most cases, the test day comparison across the same subjects appeared similar. An example of this is shown in Figure 12. Aside from the left- to right-side synchronization, the average, low and high oronasal ppCO₂, helmet ppCO₂ are visually similar. This figure is very representative of the variability seen in the ppCO₂ values when the metabolic rate was similar between trials. Future tests need to consider the high degree of variability within the data results and use data from this tests and previous CO₂ washout tests to prospectively define the necessary sample size and repeated measures necessary to have confidence in the data results.

Sub 3 – Configuration A – Day 1



Sub 3 – Configuration A – Day 2

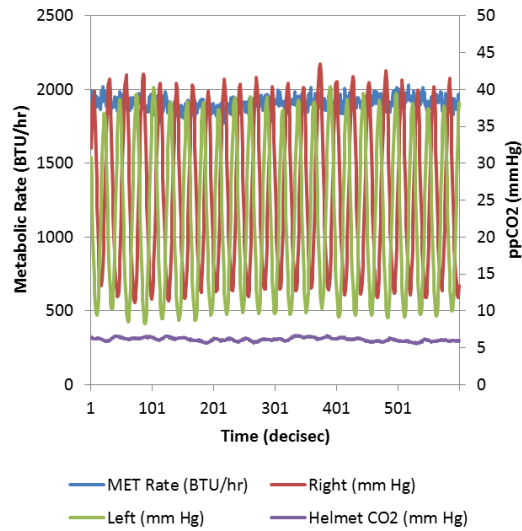
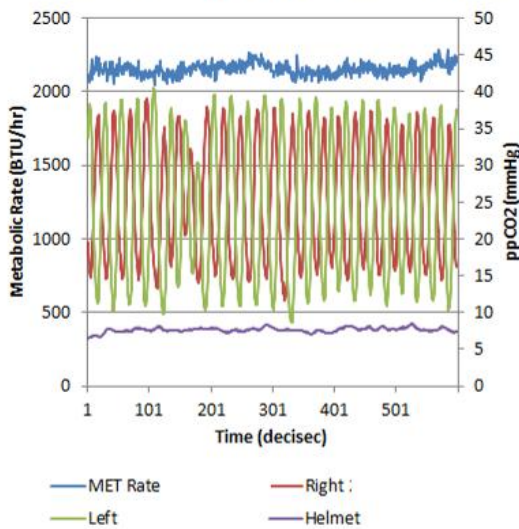


Figure 12. Example comparison for the same test subject at 2000 BTU/hr using configuration A showing similar overall test results. This similarity was observed for all test subjects.

The visual differences between subjects 1 and 3 appeared to range from negligible to clearly apparent. Figure 13 demonstrates an example of a test point that looked similar between subjects 1 and 3 at the same metabolic rate, flow rate, and vent configuration.

Sub 1 – Configuration B – Day 1



Sub 3 – Configuration B – Day 1

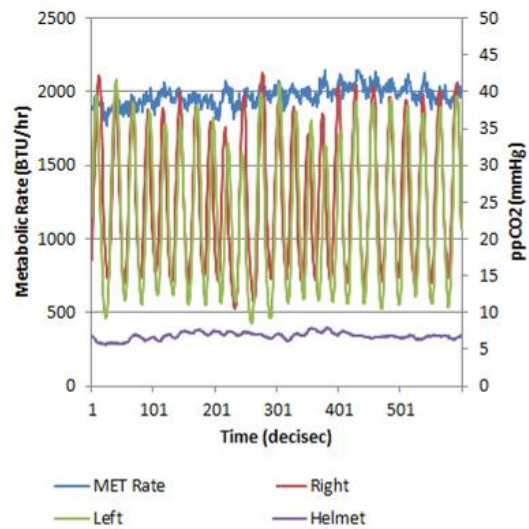
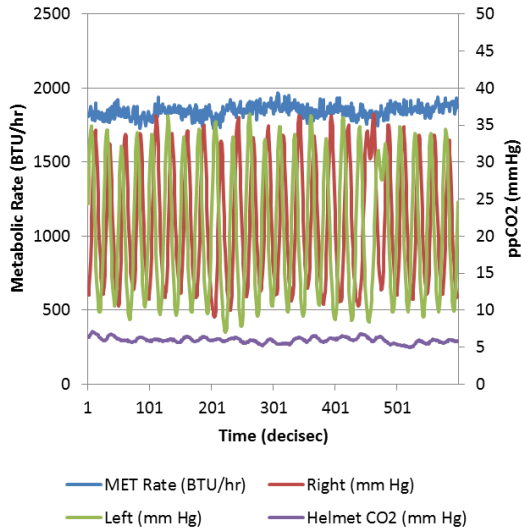


Figure 13. Example comparison between test subjects at 2000 BTU/hr using configuration B showing visually similar results.

Whereas Figure 13 shows how similar the data between subjects 1 and 3 looked, Figure 14 demonstrates some of the larger visual variability that was observed. In this case, subject 3 had peak ppCO₂ values that were approximately 5 mmHg greater than subject 1. Throughout the test, both subjects 1 and 3 had similar respiratory rates, so the likely differences in peak exhaled ppCO₂ relate to tidal volume differences contributing to different subject ventilation rates. Based on these observed differences and the very apparent differences between subject 2 and the others (Figure 15), we recommend that the subject pool needs to have its ventilatory variables such as total

ventilation, tidal volume, and respiratory rate characterized via standard metabolic gas analysis at the target metabolic rates using similar activities. It would be valuable to further include a measurement of total aerobic capacity while doing this respiratory characterization so that an index of percent maximum effort could also be used to describe subject to subject differences.

Sub 1 – Configuration F – Day 2



Sub 3 – Configuration F – Day 2

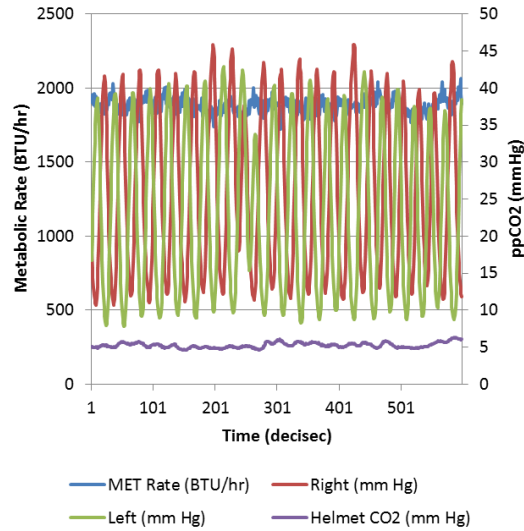
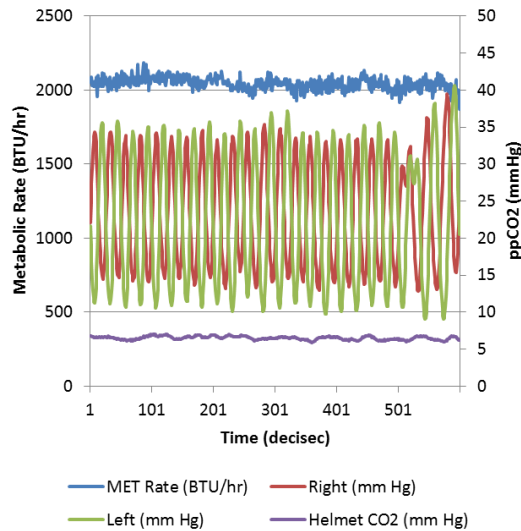


Figure 14. Example comparison between test subjects at 2000 BTU/hr using configuration F. This example shows variability in peak expired ppCO₂ values.

Sub 1 – Config C – Day 1



Sub 2 – Config C – Day 1

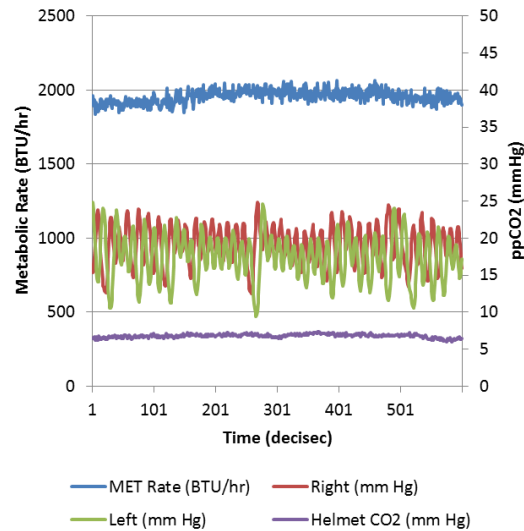


Figure 15. Example comparison between test subjects at 2000 BTU/hr using configuration C. This example shows extreme ppCO₂ variability across the respiratory cycles.

This pattern of shallow, frequent breathing was present through all test points for subject 2. Subject 2 had a greater average respiratory rate (40 breaths/min) at 2000 BTU/hr conditions as compared to subject 1 (24 breaths/min) and subject 2 (23 breaths/min). In the case of suited CO₂ washout, we have been working on the

assumption that the subject inside the suit could be modeled simply as a metabolic load producing CO₂, but this respiratory variation indicates that this is an inadequate assumption. Future studies must characterize the subject pool as described above and need to include more than three subjects to ensure confidence in the results.

Although the results indicating between subject variability are of interest and will most definitely apply to the development of a flight EVA suit CO₂ requirement verification method, these differences do not preclude the ability to compare between the different suited ventilation configurations. The subject-to-subject variability does preclude the use of a single average value for a CO₂ washout score across the subjects. In this case, it is best to evaluate both the individual subject data and the combined data.

The one consistent trend for each subject was that the CO₂ washout performance for vent configuration E was the worst at both 4 and 6 ACFM flow rates. An example of this difference is in Figure 16, which shows an approximately 7 mmHg increase in inspired oronasal ppCO₂. Configuration D also scored low, but primarily at 4 ACFM. The remaining configurations had no consistent differences. These data are summarized numerically in Table 3 and graphically in Figure 17.

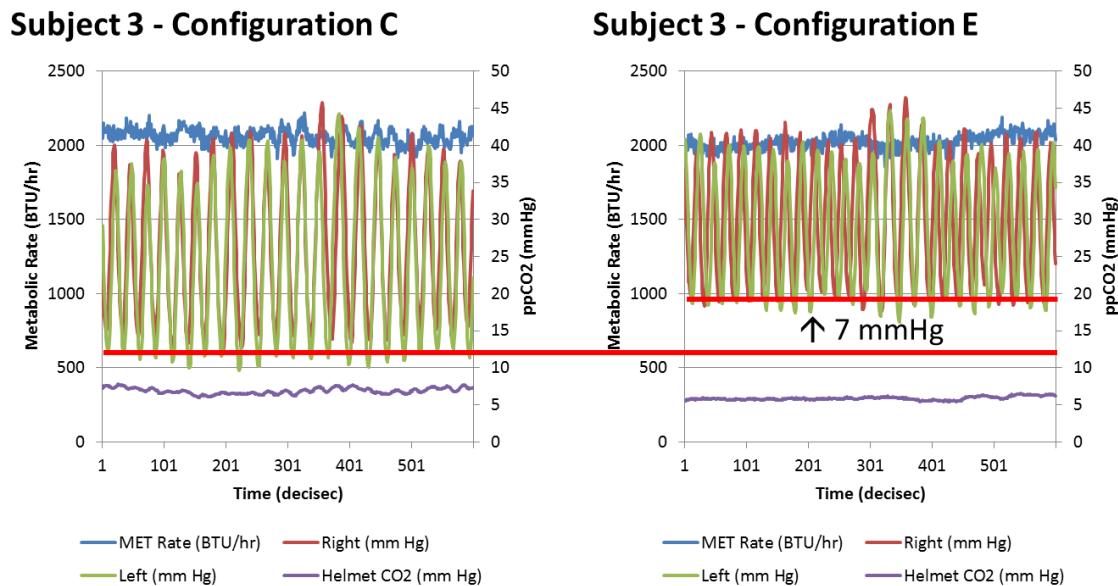
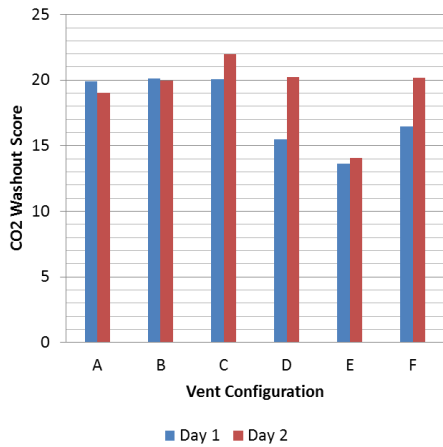


Figure 16. Example comparison between vent configuration C and E at 2000 BTU/hr using subject 3. This example shows a large increase in inspired oronasal ppCO₂ with configuration E.

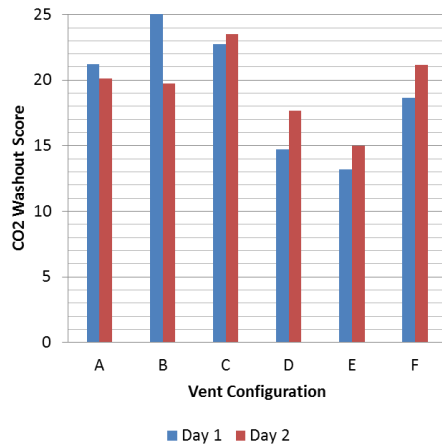
Table 3. CO₂ Washout Scores for Each Vent Configuration across Different Individual Subjects at 2000 BTU/hr at 6 and 4 ACFM

Target BTU/hr		2000 BTU/hr											
		6 ACFM						4 ACFM					
Target Flow		A	B	C	D	E	F	A	B	C	D	E	F
Ventilation Configuration													
Subject 1	Day 1	19.9	20.1	20.1	15.5	13.6	16.5	21.2	25.1	22.8	14.7	13.2	18.7
	Day 2	19.0	19.9	22.0	20.3	14.1	20.2	20.1	19.7	23.5	17.7	15.0	21.2
	Average	19.5	20.0	21.0	17.9	13.9	18.3	20.7	22.4	23.1	16.2	14.1	19.9
Subject 2	Day 1	14.9	14.0	15.6	13.6	12.6	13.9	18.3	17.9	18.6	17.2	15.9	18.2
	Day 2	14.4	13.4	14.5	14.1	13.3	15.8	18.9	18.2	18.4	17.8	16.9	18.2
	Average	14.6	13.7	15.1	13.9	12.9	14.8	18.6	18.1	18.5	17.5	16.4	18.2
Subject 3	Day 1	21.0	18.9	18.2	18.2	13.2	19.1	20.6	20.5	20.9	16.1	14.0	19.0
	Day 2	20.0	19.7	19.3	20.3	14.7	20.9	23.2	21.8	22.3	21.4	15.7	25.1
	Average	20.5	19.3	18.8	19.2	13.9	20.0	21.9	21.1	21.6	18.8	14.8	22.0

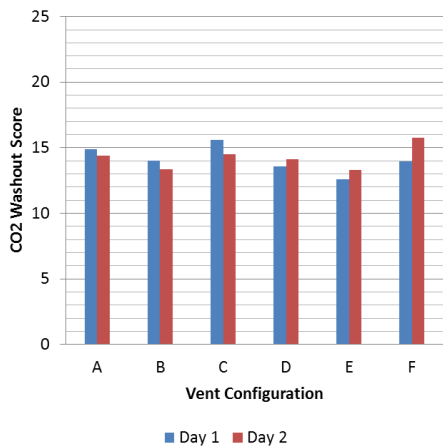
Subject 1 – 6 ACFM – 2000 BTU/hr



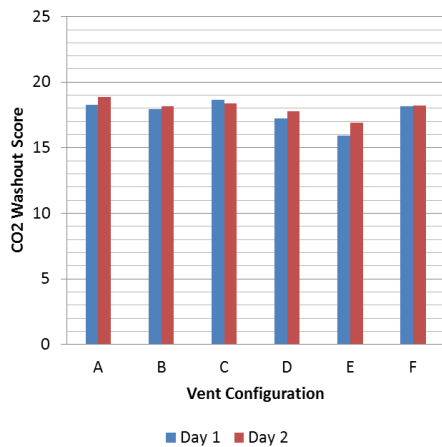
Subject 1 – 4 ACFM – 2000 BTU/hr



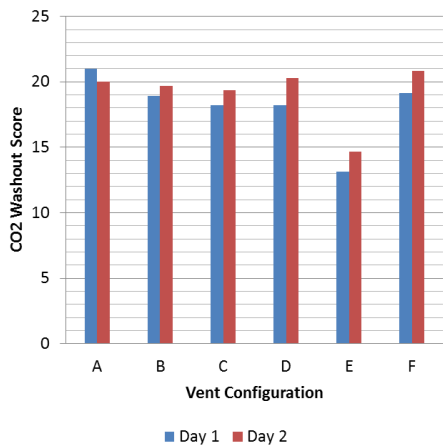
Subject 2 – 6 ACFM – 2000 BTU/hr



Subject 2 – 4 ACFM – 2000 BTU/hr



Subject 3 – 6 ACFM – 2000 BTU/hr



Subject 3 – 4 ACFM – 2000 BTU/hr

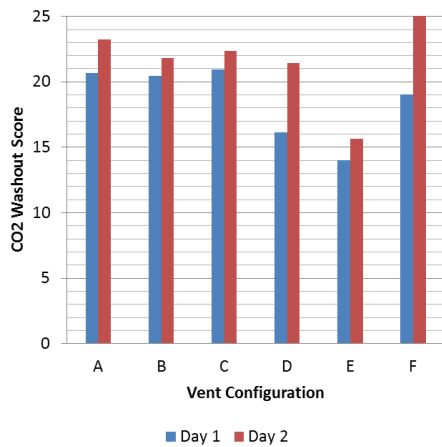


Figure 17. CO₂ Washout Scores for each vent configuration across different individual subjects at 2000 BTU/hr at either 6 or 4 ACFM.

The primary purpose of this evaluation was to determine whether a certain vent configuration provided the best CO₂ washout. The data at 2000 BTU/hr demonstrated that configurations D and E had the worst performance and these configurations were dropped for the 3000 BTU/hr testing. The differences between configurations A, B, C, and F could not be determined at 2000 BTU/hr conditions at both 6 and 4 ACFM, and the testing at 3000 BTU/hr did not provide any indication that one of those configurations performed better than the others. Therefore, our recommendation is to move forward with either configuration A, B, C, or F, and to let other engineering considerations drive the decision. The rationale to eliminate configurations D and E is shown in Figure 18, which shows the average CO₂ washout score for each subject at each configuration.

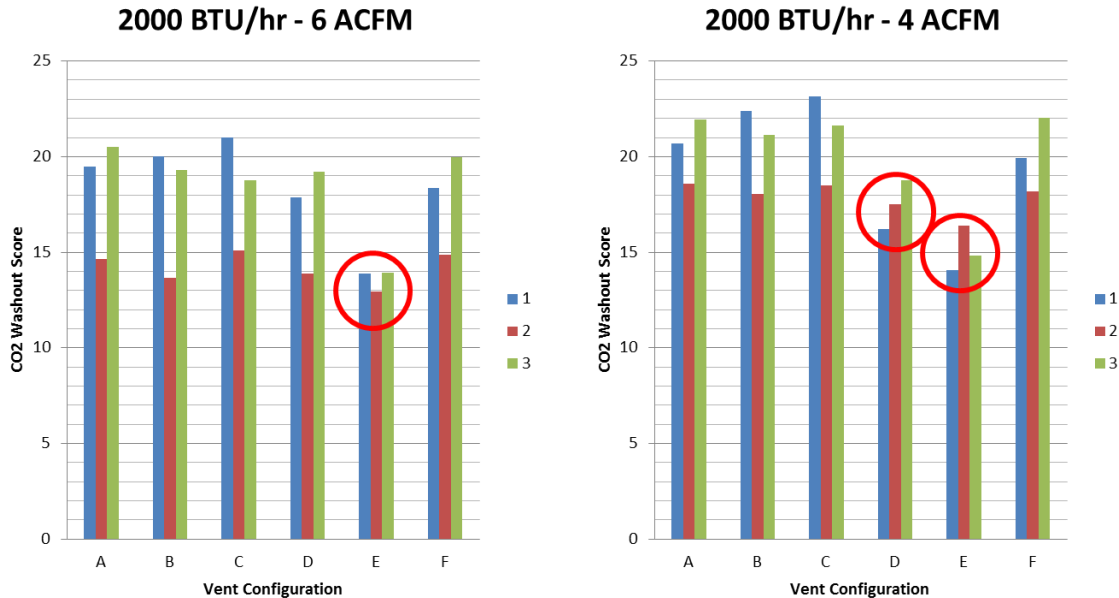
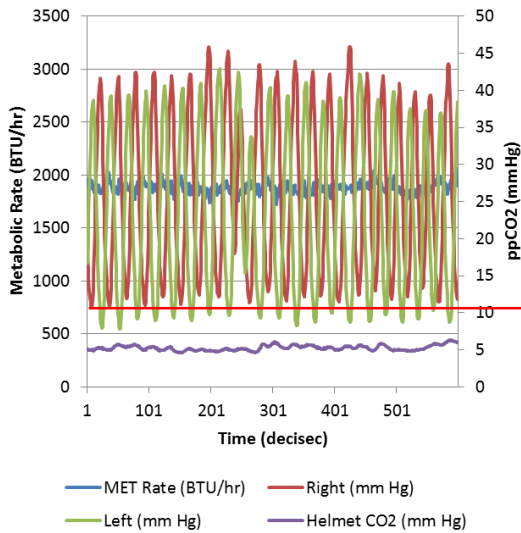


Figure 18. Average CO₂ Washout Scores for each subject at each vent configuration at 2000 BTU/hr at either 6 or 4 ACFM.

As previously assumed and demonstrated, certain factors such as metabolic rate and suit flow rate clearly continued to affect CO₂ washout. Figure 19 demonstrates the effect on both oronasal and ambient helmet ppCO₂ by increasing the metabolic rate from 2000 to 3000 BTU/hr while keeping all other variables including subject, test day, vent configuration, and suit flow rate constant. In this example, the oronasal inspired ppCO₂ increased by approximately 5 mmHg and the ambient helmet ppCO₂ increased by 4 mmHg. Figure 20 demonstrates a similar effect; however, this time only the suit flow rate was changed from 6 to 4 ACFM. All other factors including subject, test day, vent configuration, and metabolic rate were held constant. The magnitude change in the inspired oronasal and ambient helmet ppCO₂ was also about 4 to 5 mmHg.

Configuration F - 2000 BTU/hr



Configuration F - 3000 BTU/hr

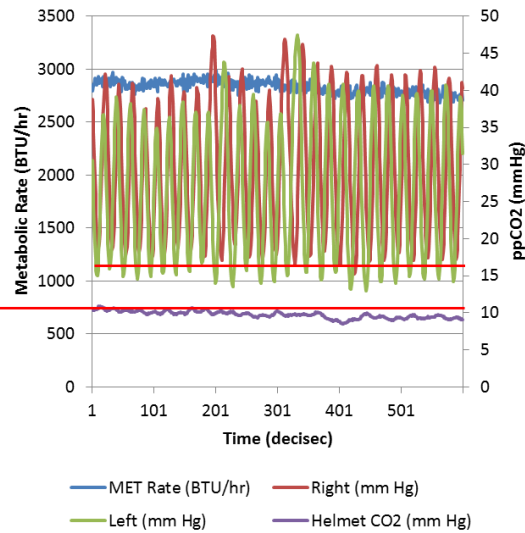
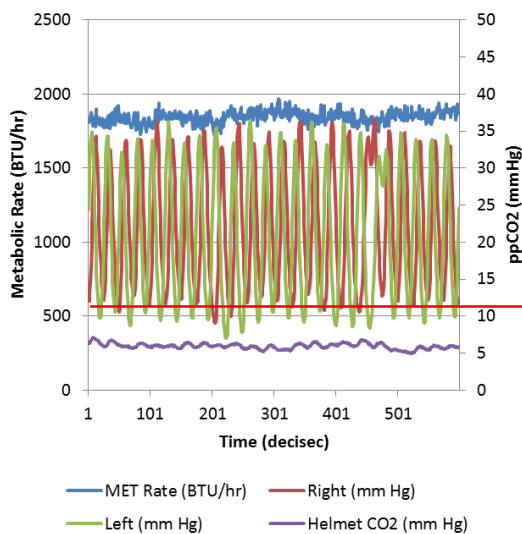


Figure 19. CO₂ washout performance differences due to increased metabolic rate. Subject, test day, suit flow rate, and vent configuration were constant.

Configuration F – 6 ACFM



Configuration F – 4 ACFM

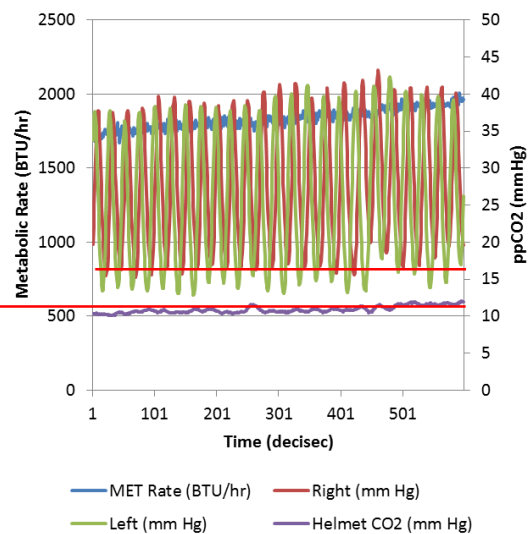


Figure 20. CO₂ washout performance differences due to decreased suit flow rate. Subject, test day, metabolic rate, and vent configuration were constant.

One final consideration for CO₂ washout performance is head position. We have typically assumed that the head position will be oriented forward; however, if the crewmember will be performing tasks requiring different orientations, head position should also be considered. For all of these tests, the subject’s head was facing forward, but at the end of one trial, we had one test subject orient his or her face toward the right at about a 45-degree angle. This subject was able to walk safely, thus we proceeded to collect data for 1 minute with the head turned right and then 1 minute following by returning the head to the forward position. The right side turn increased overall inspired ppCO₂ with a larger increase from the right side sampling site. Figure 21 shows these 2 minutes with the left side of

the figure showing what occurred with a rightward turn of the head and the right side of the figure showing an improvement to CO₂ washout performance within about 10 to 20 seconds with a forward-facing orientation.

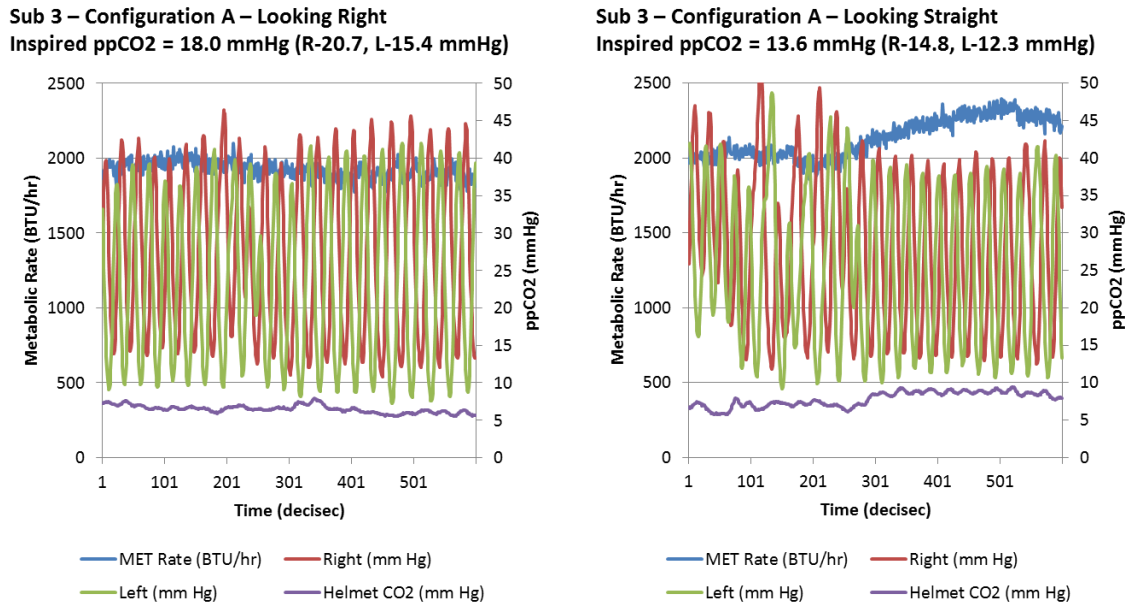


Figure 21. CO₂ washout performance differences due to head position. Subject, test day, metabolic rate, suit flow rate, and vent configuration were constant.

VII. Conclusion and Recommended Forward Work

These data continue to build upon previous test results, but the data have introduced new requirements for testing including more complete subject respiratory and fitness characterization. Metabolic rate and suit flow rate continue to be significant drivers for CO₂ washout performance. Now, clear data support that the vent configuration that determines how suit flow is delivered is also important. The difference between using a flow rate-weighted average over the inspired breath rather than just the bottom value as the true inspired ppCO₂ must also be evaluated.

As shown in previous tests, there are significant differences between test subjects. Several factors must be considered, including determination of the correct sample size, as we move from small sample size pilot and engineering tests to the development of a method for verification of a CO₂ washout requirement for a flight EVA suit. The oronasal face mask allows for consistency between test points and is good for relative comparisons, such as was done during this test, but may overestimate the true inspired ppCO₂ due to increased dead space and reduced flow around the oronasal area. An alternative solution minimizing the distortion around the oronasal area should be considered for transition to a method for flight EVA suit requirements verification.

Head position can also affect CO₂ washout. In most cases, it is logical that the head will be facing forward. However, if there any indication that the crewmember's head will face in different directions for extended periods of time, then those positions should be considered as well.

An algorithm that accounts for the complete CO₂ inhalation during the inspiratory cycle should be developed. The current analysis method allows some overall error, but was sufficient for accurate relative comparisons between suits inlet vent configurations, metabolic rates, and flowrates.

Perform a CFD analysis of the as tested vent and test configuration for comparison against the test results described in this paper. At the time of this paper, only the simplified CFD analysis performed in 2013 was available for comparison of test and CFD data.

Additional tests and corresponding CFD analysis using various helmet sizes and shapes will be needed to better understand the impact of helmet shape.

Further work should continue to address the areas listed above, with a focus on reducing the profile of the oronasal mask to minimize airflow disturbances in the helmet and allow for less-invasive measurements of oronasal CO₂ levels.

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