CO$_2$ Washout Testing of the REI and EM-ACES Space Suits

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When a space suit is used during ground testing, adequate carbon dioxide (CO$_2$) washout must be provided for the suited subject. Symptoms of acute CO$_2$ exposure depend on partial pressure of CO$_2$ (ppCO$_2$), metabolic rate of the subject, and other factors. This test was done to characterize inspired oronasal ppCO$_2$ in the Rear Entry I-Suit (REI) and the Enhanced Mobility Advanced Crew Escape Suit (EM-ACES) for a range of workloads and flow rates for which ground testing is nominally performed. Three subjects were tested in each suit. In all but one case, each subject performed the test twice. Suit pressure was maintained at 4.3 psid. Subjects wore the suit while resting, performing arm ergometry, and walking on a treadmill to generate metabolic workloads of about 500 to 3000 BTU/hr. Supply airflow was varied between 6, 5, and 4 actual cubic feet per minute (ACFM) at each workload. Subjects wore an oronasal mask with an open port in front of the mouth and were allowed to breathe freely. Oronasal ppCO$_2$ was monitored in real time by gas analyzers with sampling tubes connected to the mask. Metabolic rate was calculated from the total CO$_2$ production measured by an additional gas analyzer at the suit air outlet. Real-time metabolic rate was used to adjust the arm ergometer or treadmill workload to meet target metabolic rates. In both suits, inspired CO$_2$ was affected mainly by the metabolic rate of the subject: increased metabolic rate significantly ($P < 0.05$) increased inspired ppCO$_2$. Decreased air flow caused small increases in inspired ppCO$_2$. The effect of flow was more evident at metabolic rates $\geq$ 2000 BTU/hr. CO$_2$ washout values of the EM-ACES were slightly but not significantly better than those of the REI suit. Regression equations were developed for each suit to predict the mean inspired ppCO$_2$ as a function of metabolic rate and suit flow rate. This paper provides detailed descriptions of the test hardware, methodology, and results as well as implications for future ground testing in the REI-suit and EM-ACES.

Nomenclature

ACES = advanced crew escape suit
ACFM = actual cubic feet per minute
BTU = British thermal unit
CO$_2$ = carbon dioxide
EM-ACES = enhanced mobility advanced crew escape suit
EMU = extravehicular mobility unit
EVA = extravehicular activity
ISS = International Space Station
JSC = Johnson Space Center
NASA = National Aeronautics and Space Administration
NBL = neutral buoyancy laboratory
LEA = launch/entry/abort
ppCO$_2$ = partial pressure carbon dioxide
REI = rear entry I-suit
RER = respiratory exchange ratio

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I. Introduction

Carbon dioxide (CO_2) can build up quickly inside an enclosed environment if proper ventilation is not in place. Acute health effects which 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.

The NASA Johnson Space Center (JSC) Space Suit and Crew Survival Systems Branch, in conjunction with the EVA Physiology Laboratory, developed a protocol for evaluating CO_2 washout in various prototype space suits. Testing was performed on two space suits, the Rear Entry I-suit (REI) and Enhanced Mobility Advanced Crew Escape Suit (EM-ACES), with a focus on determining if the suit ventilation systems provided adequate CO_2 washout during ground-based testing. 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 Objectives

The primary objective of testing was to characterize the workloads and flow rates for which CO_2 is adequately washed away from the suited subject's oronasal area in the REI-suit and EM-ACES. The immediate goal of testing was to define acceptable workloads and flow rates for laboratory-based ground testing with the REI-suit and EM-ACES. The secondary objective of testing was to begin building a database of CO_2 washout test data that can be used to validate analysis models as well as help inform future space suit helmet and ventilation flow path designs. To accomplish these objectives, it was necessary to characterize both the variability between test days for the same subject and between subjects.

III. Test Plan Overview

For each suit tested, 3 test subjects were used. Each subject performed the test twice to allow for day-to-day data comparison to check for consistency in the test methodology. Suit pressure was maintained at 4.3 psid throughout testing, which is the standard operating pressure for both the REI-suit and EM-ACES.

In the REI-suit, CO_2 washout performance was tested with suited subjects at rest as well as working at metabolic rates of 1000, 2000, and 3000 BTU/hr for short, approximately 3-minute durations. These metabolic rate values were selected based on historical suited test data to bound the majority of ground-based suited testing that might be conducted in the future. During the EVA Walkback Test and Integrated Suit Tests, the lowest metabolic rate was ~975 BTU/hr and the highest rates were 3000 BTU/hr or more, representing a range between 40% to 75% of the specific subjects' VO_2max values. Workload above 3000 BTU/hr is not considered typical of nominal ground-based suited operations based on past history. Therefore, it was felt that the chosen set of metabolic rates should encompass most suited testing without requiring individual metabolic rate testing before each test.

In the EM-ACES, CO_2 washout performance was tested at rest as well as metabolic rates of 1000 and 2000 BTU/hr. The EM-ACES is primarily a launch/entry/abort (LEA) suit without a major amount of leg mobility. The lack of pressurized leg mobility precludes testing on a treadmill, as was done using the REI-suit, limiting the EM-ACES CO_2 washout testing to arm ergometer activities only. During nominal testing, suited subjects in the EM-ACES rarely perform activities likely to generate metabolic rates above 2000 BTU/hr, leading to the belief that testing up to metabolic rates of 2000 BTU/hr was adequate to bound the typical EM-ACES test conditions.

Supply airflow was varied at each workload from a high of 6 actual cubic feet per minute (ACFM), which is the standard advanced suit test air flow rate, down to a low of 4 ACFM to characterize CO_2 washout for a range of possible suit airflows. Oronasal CO_2 levels and trending in the helmet were monitored real-time via gas analyzers with sampling tubes positioned in the subject's oronasal area and a separate in-helmet location. Metabolic rate was calculated in real-time from the total CO_2 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 arm ergometer workload or 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**Error! Reference source not found.** describes the workload and flow rate combinations that were tested, as well as the order of the various test data points. Each test began with the standard 6 ACFM flow rate and a resting metabolic rate and the subjects gradually worked up to the higher metabolic rates. This was considered a conservative approach because CO_2 production is lower at lower metabolic rates. It also allowed the subjects to warm up before working at the higher workloads. For any given workload, air flow began at the nominal flow rate, 6

ACFM, and was then lowered, again taking a conservative approach. Suited subjects were allowed to take rest breaks between trials as needed. As noted above, the 3000 BTU/hr cases were only completed with the REI-suit.

Table 1. Test Point Matrix

Target Metabolic Rate	Supply Air Flow Rate					
	6 ACFM		5 ACFM		4 ACFM	
Rest	Data Point #1	Breaks as needed to adjust flow and rest subject	Data Point #2	Breaks as needed to adjust flow and rest subject	Data Point #3	Breaks as needed to adjust flow and rest subject
1000 BTU/hr	Data Point #4		Data Point #5		Data Point #6	
2000 BTU/hr	Data Point #7		Data Point #8		Data Point #9	
3000 BTU/hr	Data Point #10		Data Point #11		Data Point #12	

IV.   Test Hardware Description

A. Rear Entry I-Suit

The REI-suit (Fig. 1<mark>Error! Reference source not found.</mark>) is a planetary exploration suit prototype primarily constructed of softgoods, but incorporating hatch hardware and a limited number of bearings. The REI-suit represents a compromise between a hard/hybrid suit and an all soft suit such as the Apollo A7LB Suit. It employs a rear-entry door for donning and doffing. Bearings are located at the scye, upper arm, hip, and upper thigh (a 2-bearing hip). There is also a disconnect at the waist control ring and a boot disconnect at the ankle. The REI-suit nominal operating pressure is 4.3 psid. In the configuration used for this test, the suit weighed 84 pounds.

The REI-suit has a neck ring that accommodates a hemispherical helmet. The helmet is a 16 ×12-inch oval dome consisting of a detachable, transparent, hard

Figure 1. REI-suit overview.

pressure vessel encompassing the head and including a passive disconnect for attachment to the soft upper torso with a retaining ring and locking lever.

The REI suit is designed to 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 breathing air is delivered to the pressure garment via a certified gaseous breathing air system (Fig 2**Error! Reference source not found.**). The air enters the pressure garment at the blue connection located on the rear entry door ('Air In') and is routed through a vent plenum into the helmet. The return air (exhalent) is removed from the suit at the red 'Air Out' connection also on the rear-entry door.
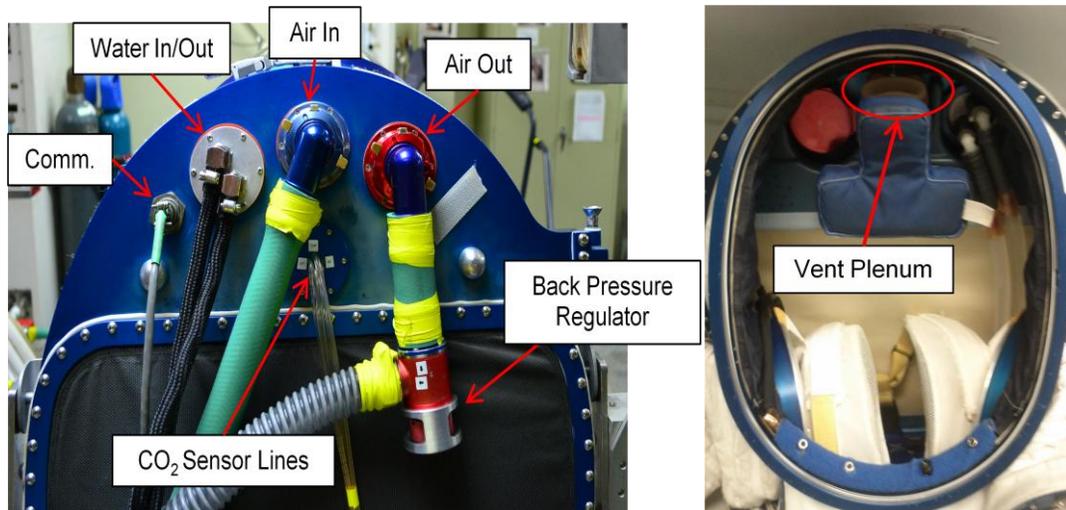
Figure 2. REI-suit external interfaces.

B. Enhanced Mobility Advanced Crew Escape Suit

The EM-ACES (Fig. 3==Error! Reference source not found.==) is optimized for nonpressurized activities such as those encountered during launch, dynamic on-orbit events, landing, and post-landing scenarios. However, through the addition of specific mobility features at the hips, upper arm, and shoulder, the EM-ACES is expected to provide capability for simplistic pressurized EVA-type activities. Its nominal working pressure is 4.3 psid. In the configuration used for this test, the EM-ACES weighed 28 pounds.

Like the REI-suit, the EM-ACES is designed to 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 breathing air is delivered to the pressure garment via a certified gaseous breathing air system (Fig. 4). The air enters the pressure garment at the connection located on the right thigh and is then routed through soft tubing along the interior of the pressure garment up to the helmet neck ring. The EM-ACES helmet is a modified Shuttle EMU bubble helmet that was removed from its original EMU neck disconnect and attached to a Shuttle ACES neck ring disconnect. The breathing gas delivery path through the ACES neck ring was further modified to route the gas to the front of the EMU ventilation pad. The return air (exhalent) is removed from the suit at the return air connection located on the right thigh.

Figure 3. EM-ACES overview.
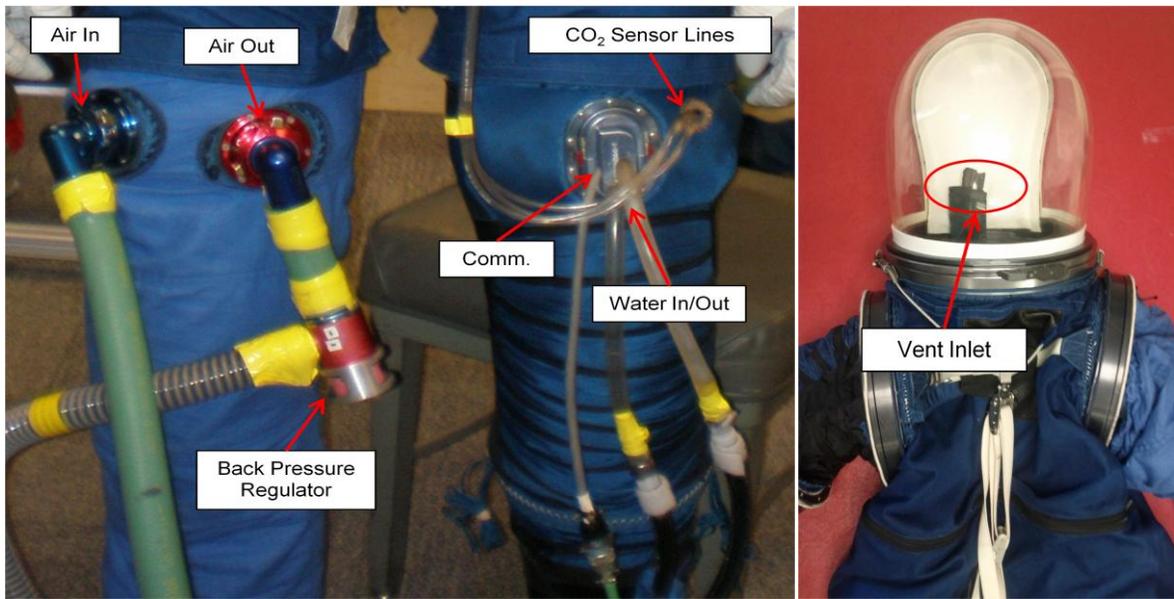
Figure 4. EM-ACES external interfaces.

V. Methods

A. CO_2 Measurement

The key parameter for indication of adequate CO_2 washout is the direct measurement of CO_2 in the subject's oronasal area. This represents the amount of CO_2 that the subject inspires with each breath. The test subjects wore an oronasal mask to provide a platform for sampling CO_2 in the oronasal area. The mask used, pictured in Fig. 5, was a Hans Rudolph 7450 series mask with a head net to hold the mask on the subjects' faces. The mask seals to the face except for a large opening right at the front of the mouth. Tygon sampling tubes were inserted at the right and left side of the opening to measure oronasal CO_2 content. Each signal was analyzed separately, therefore exact time syncing between the left and right side was not critical. Inspired CO_2 levels were determined by looking at the low points of the respiratory cycle (Fig. 6**Error! Reference source not found.**). Without direct flow measurement at the mouth, a time weighted average across the inspiration could not be calculated. The left and right side measurements were given equal weight and the average was used to determine CO_2 washout. One additional CO_2 sampling tube was placed in the top, center of the helmet to allow for observation of the CO_2 level at an alternate in-
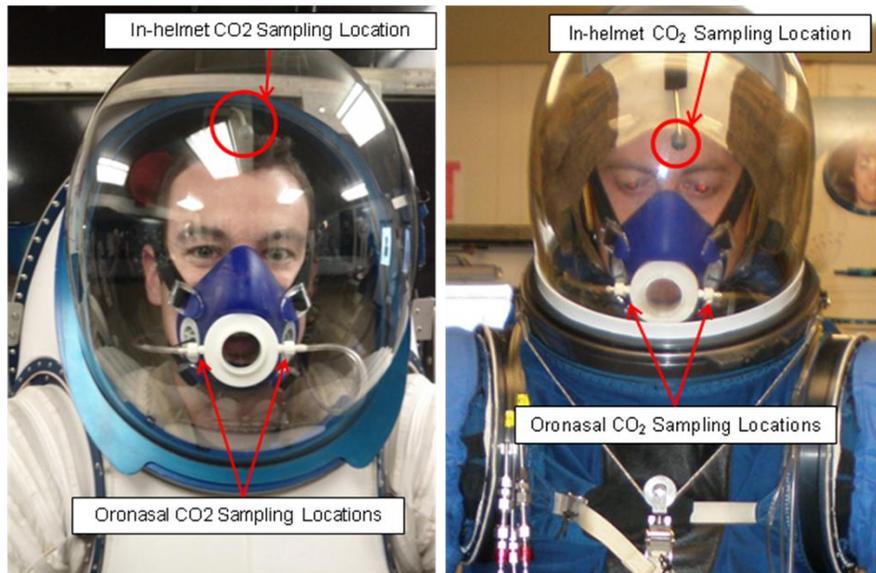
Figure 5. CO_2 sampling locations in the REI-suit (left) and EM-ACES (right).

helmet location. The sampling tubes were routed through a pass-through port in the suit hatch and out to AEI Technologies CD-3A CO_2 analyzers for real-time CO_2 measurement. Suit delta pressure forced airflow through the sampling tubes, and rotameters on the gas analyzers allowed the flow rate to be adjusted to the range required by the analyzers.
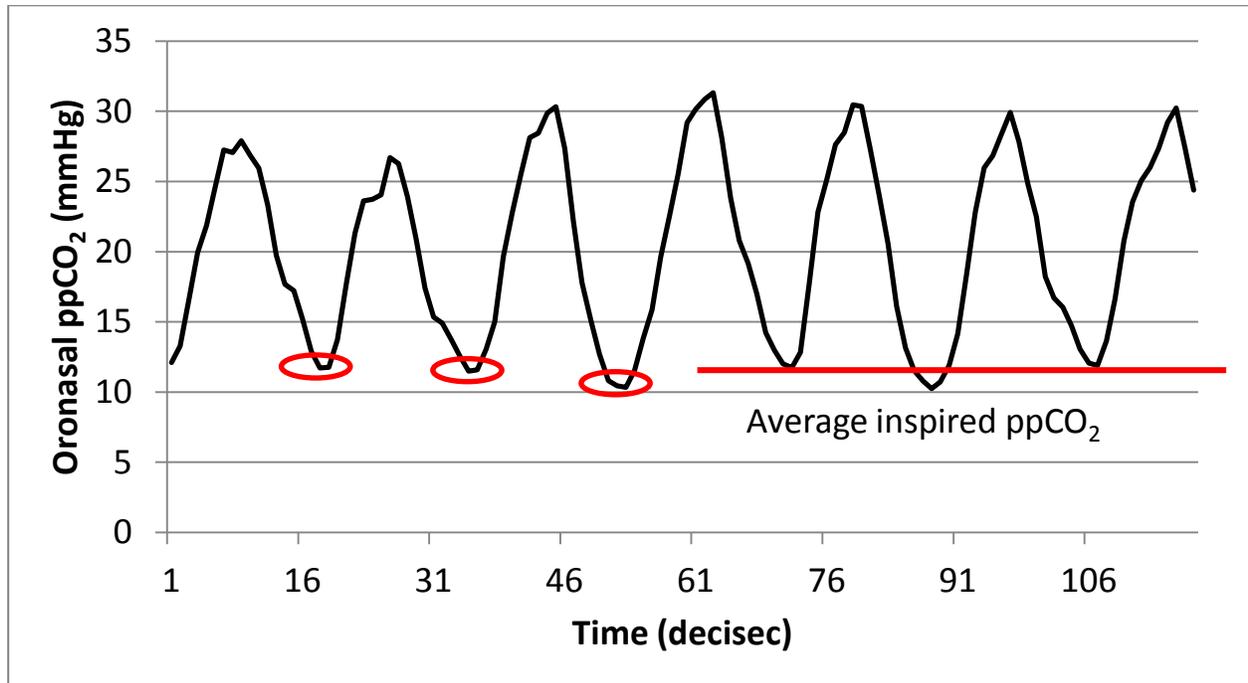
Figure 6. Inspired ppCO$_2$ was determined by the average values of the troughs seen during the respiratory cycle.

B. Metabolic Rate Measurement

In the ground-based suit test configuration, supply air provided from either the facility breathing air supply or K-bottles has a very low (less than 500 ppm or 0.05%) CO_2 concentration. Inside the space suit, the only significant source of CO_2 is the human being, and the amount of CO_2 produced is proportional to the person's workload. There is no CO_2 scrubbing capability in the suit, therefore the CO_2 produced is exhausted along with the bulk airflow out of the suit. 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. Metabolic rate was determined by NASA EVA Physiology Laboratory personnel through standard equations[1] using CO_2 production, the flow rate of breathing air, and the respiratory exchange ratio (RER). The same equipment, personnel and method are used to determine metabolic rate during extravehicular activity (EVA) training in the Neutral Buoyancy Laboratory (NBL) as an estimation of the metabolic rates expected for International Space Station (ISS) EVAs.

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 CO_2 analyzer on the suit air outlet line, which fed data into the metabolic rate calculations. The CO_2 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. At that point, a 3-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 CO_2 levels on a single display screen. The data was displayed real-time during test and recorded for post-test analysis.

VI. Data Analysis

A. Overview of Data Collected

The objective was to test the CO_2 washout with each suit using 3 subjects, running each subject through the complete protocol on 2 different test days. Because metabolic rate was a controlled variable, the test team expected no significant differences between test days of the same subject. The REI-suit test had 12 test points per day and the EM-ACES had 9 test points. Not all test points were completed for the REI-suit test. Due to an installation error of the flow meter on the first test day, data was collected at rest, 750, 1400, and 2000 BTU/hr instead of at rest, 1000, 2000, and 3000 BTU/hr. These missing points at 3000 BTU/hr were not made up. To allow for day-to-day data comparison, we were able to average the results of the 750 and 1400 BTU/hr trials to compare against this subject's 1000 BTU/hr trial on day 2. The second subject completed all test points except for the 3000 BTU/hr trial at 4 ACFM due to an issue with the suit. The third subject completed the rest, 1000, and 2000 BTU/hr trials, but did not complete the 3000 BTU/hr test points because the subject's heart rate could not be maintained below the test termination value.

For the EM-ACES, not all test points were completed either. Subject 1 completed all test points on both days. Subject 2 completed all test points on day 2 but only the test points at 5 and 4 ACFM on day 1, because the facility air supply could not supply the target flow rate of 6 ACFM. Subject 3 completed all test points only once.

B. REI-Suit Data Analysis

This test was an engineering pilot test. Statistical power was not a consideration for development of the number of subjects. Comparisons within the same subject and between different subjects were made through visual inspections of the graphical data and through numerical comparisons. With this initial look, 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 was very similar. Figure 7 demonstrates a clear example of a test point that looked similar between day 1 and day 2.
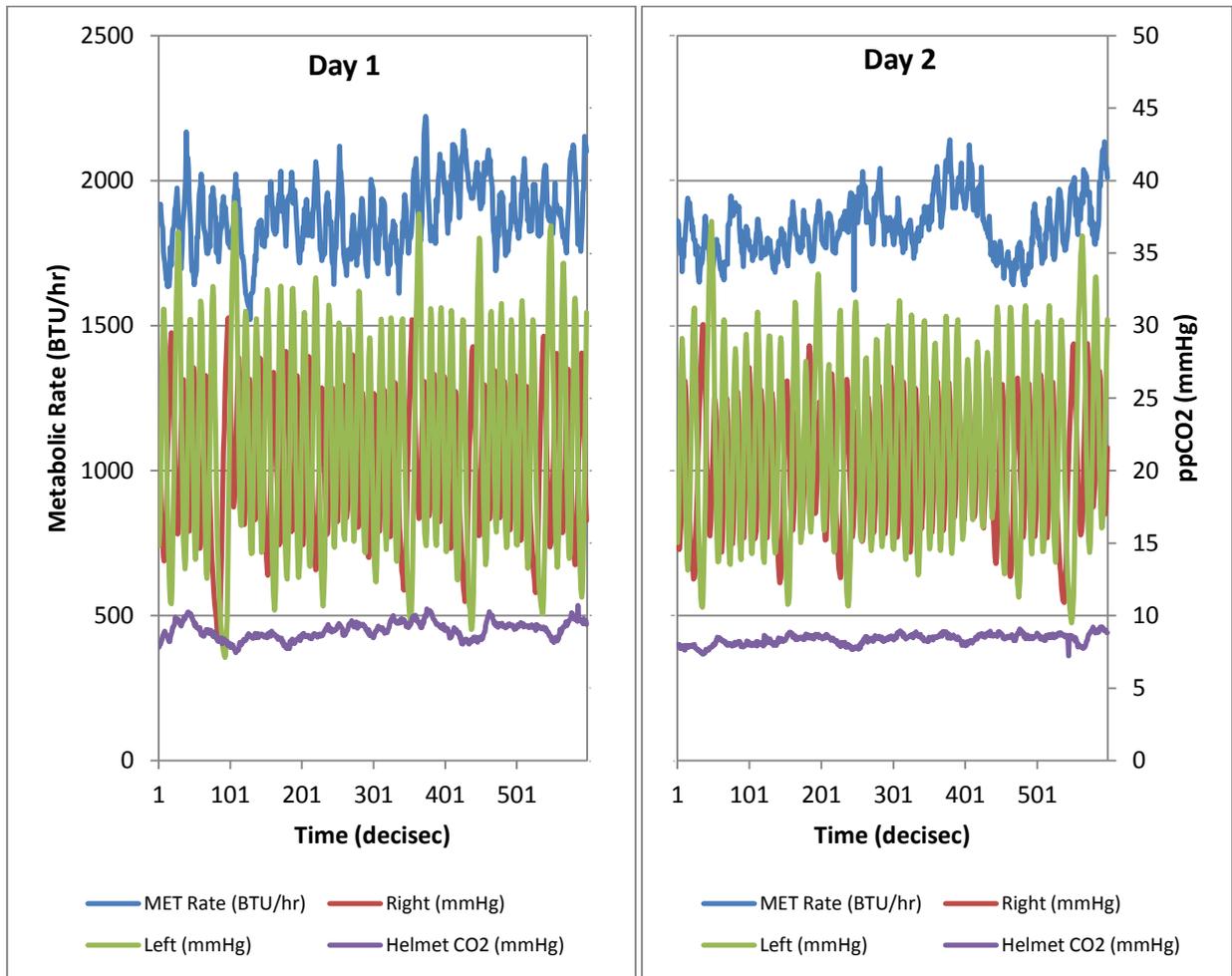
Figure 7. Example comparison of a test subject at the 2000 BTU/hr / 5 ACFM test points during the REI-suit test.

Figure 7 is a good qualitative example of how similar the data could be, but some test points within the same subject did not look as similar. The primary differences were rarely related to the low end oronasal $ppCO_2$ values, but often to the peak expired $ppCO_2$ values. Figure 8**Error! Reference source not found.** shows an example of the differences possible between test days. It is possible that flow differences in the data collection system may relate to these differences, but it could also be attributable to breathing differences such as nasal versus oral breathing or differences in respiratory rate and tidal volume. Without this data readily available, we are deferring to using the calculated oronasal inspired $ppCO_2$ as our primary outcome of interest with average oronasal $ppCO_2$ and the helmet $ppCO_2$ as supporting evidence.

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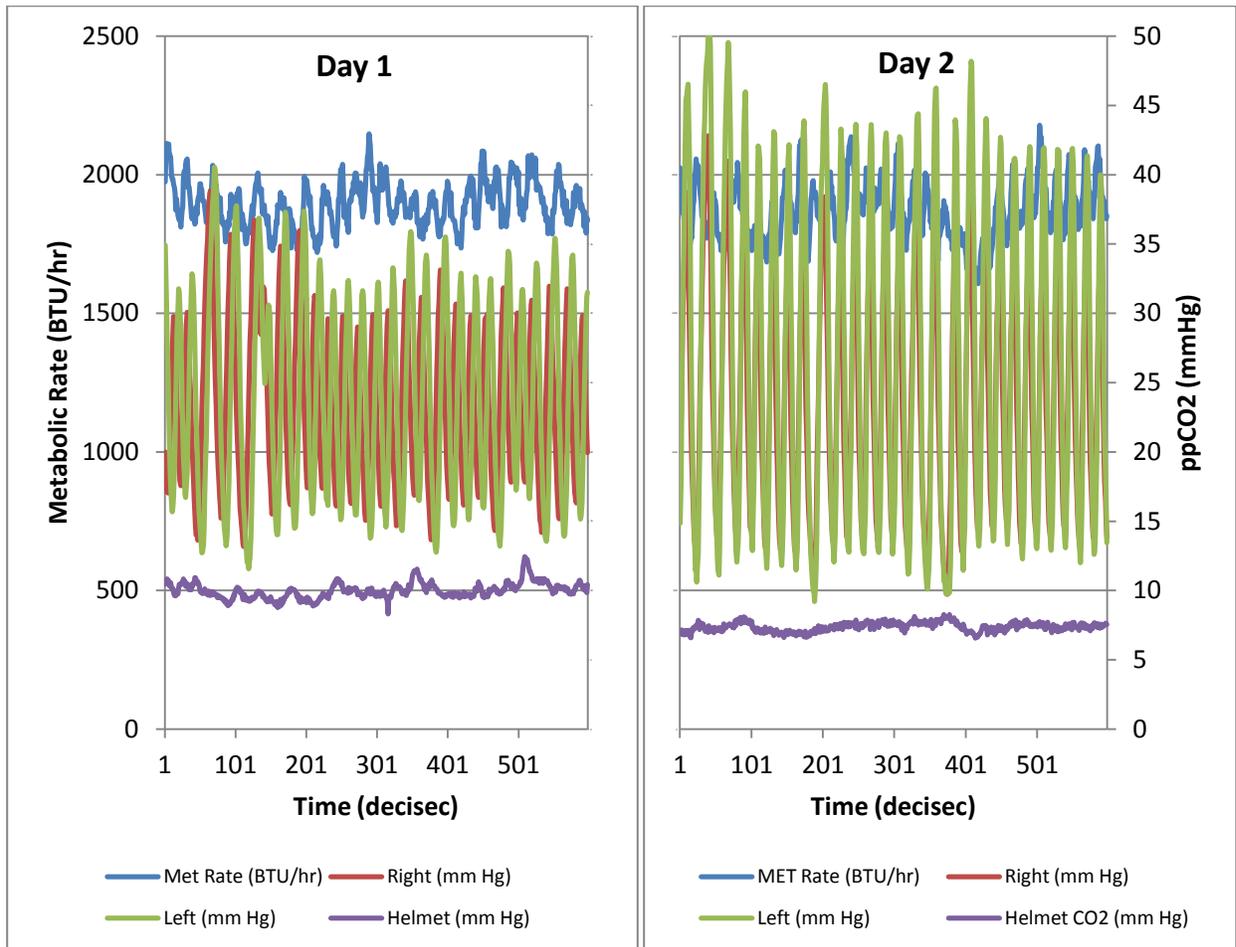
Figure 8. Example comparison of a test subject at the 2000 BTU/hr / 5 ACFM test points during the REI-suit test.

In addition to comparing the data graphically, data was reduced and compared side by side. This type of comparison was difficult to execute with statistical measures because slight differences in the metabolic rate and flow rate can account for notable differences in the outcome variables. Table 2 describes the differences for one of the test subjects between test days. Outside of the resting conditions and the 1000 BTU/hr and 6 ACFM trials, the exercise metabolic rates were similar. Flow differences are to be expected in SCFM as the test procedures control to ACFM, so flow was slightly lower on test day 2. There were only small differences noted for the exercise conditions as almost all were less than 1.0 mmHg different between conditions.

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Table 2. Day-to-day Differences for a Subject in the REI CO_2 Washout Test

| Target | | Differences - All data are Day 2 - Day 1 | | | | |
Metabolic Rate	Flow	Metabolic Rate (BTU/hr)	Flow (SCFM)	Average Oronasal ppCO$_2$ (mmHg)	Oronasal Inspired ppCO$_2$ (mmHg)	Helmet ppCO$_2$ (mmHg)
Rest	6 ACFM	186	-0.20	0.28	1.46	-0.28
Rest	5 ACFM	293	-0.44	2.06	1.94	0.63
Rest	4 ACFM	197	-0.35	0.58	0.55	0.62
1000 BTU/hr	6 ACFM	321	-0.18	0.32	0.70	0.79
1000 BTU/hr	5 ACFM	1	-0.45	-0.85	-0.64	-0.18
1000 BTU/hr	4 ACFM	25	-0.32	-1.02	0.59	-0.17
2000 BTU/hr	6 ACFM	83	-0.14	-0.95	-0.26	-0.38
2000 BTU/hr	5 ACFM	-50	-0.37	-0.07	0.56	-0.55
2000 BTU/hr	4 ACFM	-22	-0.48	-0.35	0.52	-0.51
3000 BTU/hr	6 ACFM	60	0.02	-1.19	-0.24	-0.08
3000 BTU/hr	5 ACFM	29	-0.10	-0.51	0.49	-0.12
3000 BTU/hr	4 ACFM	N/A	N/A	N/A	N/A	N/A

As expected, metabolic rate was the primary driver for CO_2 accumulation in the suit. Without consideration to flow rate, all ppCO$_2$ data was plotted as a function of metabolic rate (Fig. 9). Each outcome variable had a $R^2 > 0.80$ indicating a high correlation with metabolic rate.
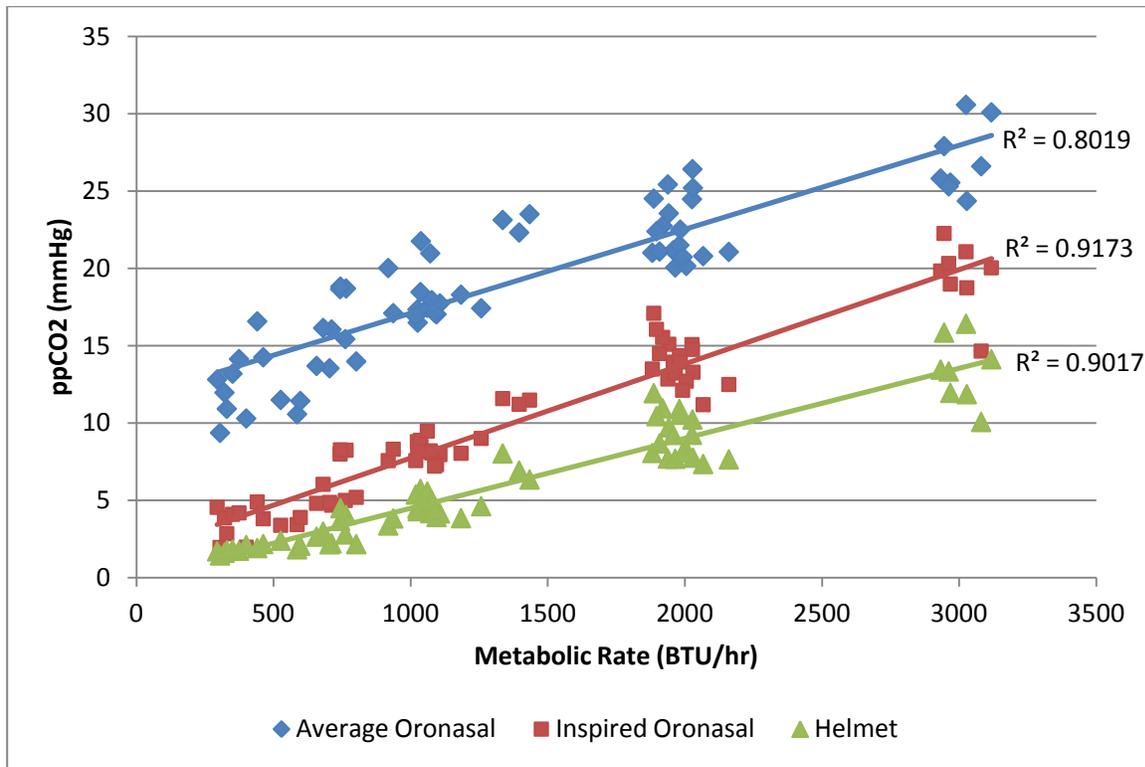
Figure 9. ppCO$_2$ variables as a function of metabolic rate in the REI-suit.

Although we expected metabolic rate to be the primary driver for accumulated CO_2, we also believe that the flow rate through the suit would be a significant factor. Figure 10 shows that when accounting for the different flow considerations, it was clear that flow was not a significant factor at lower metabolic rates, but did make a difference at the 2000 and 3000 BTU/hr conditions. This finding indicated a potential to include an interaction term involving metabolic and flow rate in our statistical model.
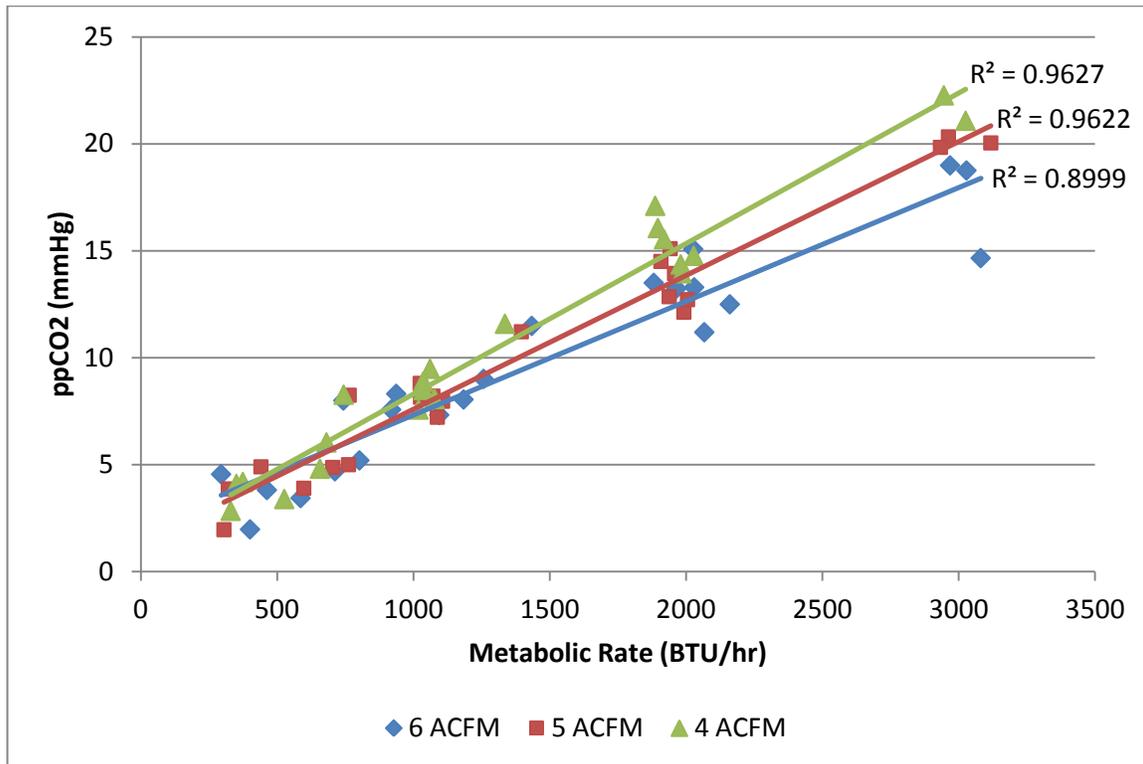
Figure 10. Inspired oronasal ppCO$_2$ as a function of metabolic rate for different REI suit flow rates.

Although the conditions were controlled to reasonable differences, it is still difficult to compare conditions directly and the slight differences preclude standard statistical tests such as a repeated measures ANOVA. To reduce the data to allow for direct comparison of conditions, a statistical regression model was needed. Input variables were metabolic rate, suit flow rate, and an interaction term of metabolic rate $\times$ flow rate. The outcome variable of interest was oronasal inspired ppCO$_2$.

Data were then used to predict the expected mean ppCO$_2$ for a given metabolic rate and flow rate combination as well as a high and low ppCO$_2$ at the 95% confidence interval. The predicted ppCO$_2$ was compared to the maximum exposure limits as described in NASA-TP-2010-216126 [2]. Because the maximum exposure limits were only presented in a table, a specific maximum exposure time given an estimated inspired ppCO$_2$ cannot be determined. Additionally, consideration should be given to how the increased cardiac output and tissue perfusion associated with exercise affects the CO_2 exposure recommendations. Although exercise increases cerebral blood flow, there is a complex interaction between respiratory control and arterial CO_2 (PaCO$_2$) that generally maintains a steady state cerebral CO_2, but this assumes a standard inspired ppCO$_2$ of almost zero [3]. Increase in inspired ppCO$_2$ will lead to increased PaCO$_2$, which may not be fully regulated by a change in arterial compliance and ventilation as normally expected. With ground-based testing, the test can be stopped at any point and with a reduction in metabolic rate and an increase in flow, the inspired ppCO$_2$ could be reduced from >25 mm Hg to <5 mm Hg within a minute. This is primarily a concern related to EVA during flight, which may couple increased acute CO_2 exposures with the chronic low level CO_2 exposure on the ISS.

Results from the statistical regression model are shown in Fig. 11. Of note is the dramatic difference between exposure limit durations between an inspired ppCO$_2$ of 11 mm Hg and 15 mm Hg, where the maximum exposure

time goes from 8 to 1 hour. This estimated oronasal inspired $ppCO_2$ value is seen primarily between a metabolic rate of 1500 and 2500 BTU/hr, which is well within the operational range of the REI suit. Although it may be within the operating range of the REI suit, it is extremely rare that these metabolic rates would be continuously seen for that period of time. A review of the data available to the test team from the EVA Walkback Test [4] and early Integrated Suit Tests [5-6] show a large amount of suited metabolic data above 2500 BTU/hr, but these tests were all for short durations of less than 10 minutes. The only case of a high sustained metabolic rate was for the 10-km walkback test. The average metabolic rate for the 6 subjects was 2374 BTU/hr for an average duration of 96 minutes [4]. Due to the high metabolic rates associated with this testing, flow was increased above the standard 6 ACFM to approximately 7-9 ACFM, with hopes of enhancing cooling.
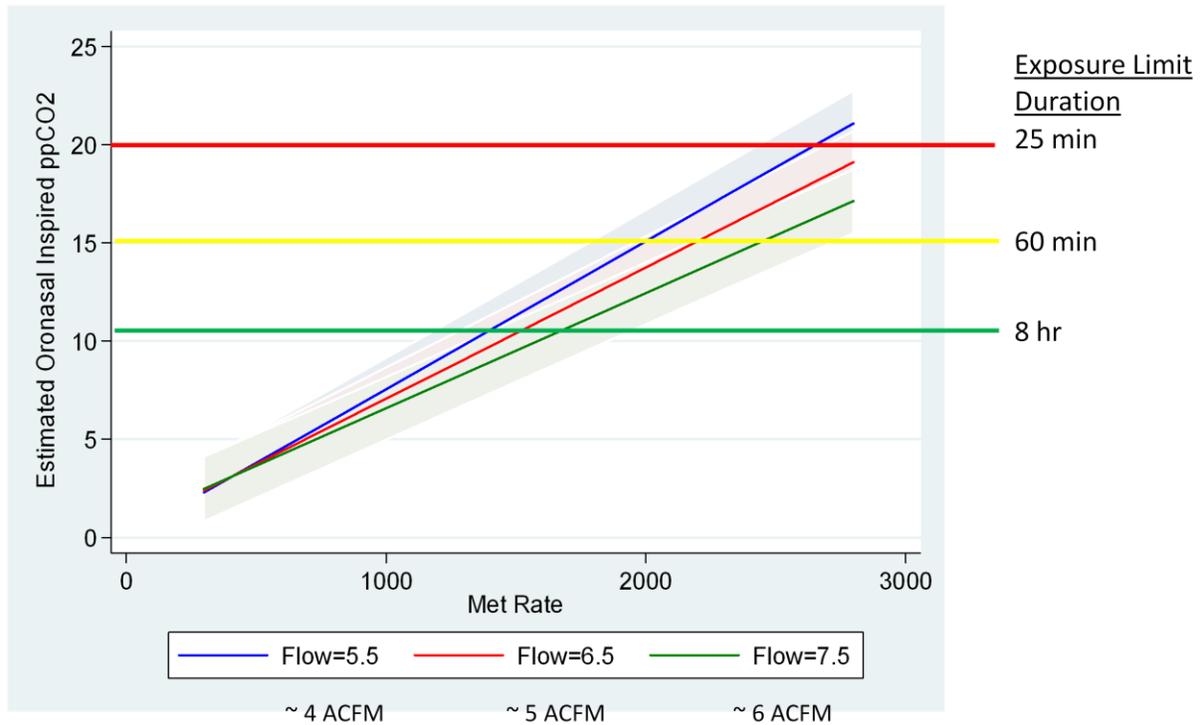
Figure 11. Statistical regression model showing the estimated inspired oronasal $ppCO_2$ at different metabolic and flow rates for the REI suit.

C. EM-ACES Data Analysis

With only 1 subject completing the full set of test conditions, we had less data for day-to-day comparison in the EM-ACES test. **Error! Reference source not found.**Figure 12 shows a day-to-day comparison for 1 subject at 1 condition. Qualitatively, it looks similar, but with slight differences in the left and right oronasal data. Data varies a bit from right to left on most conditions. Possible reasons include subtle changes to the mask on the face, oral versus nasal breathing, position of mask relative to helmet, airflow circulation patterns in the helmet, or rotameter adjustments to choke down flow from the sample lines. For any and all of these reasons, we have chosen to give equal weight to the left and right sides and average the results for CO_2 washout results.
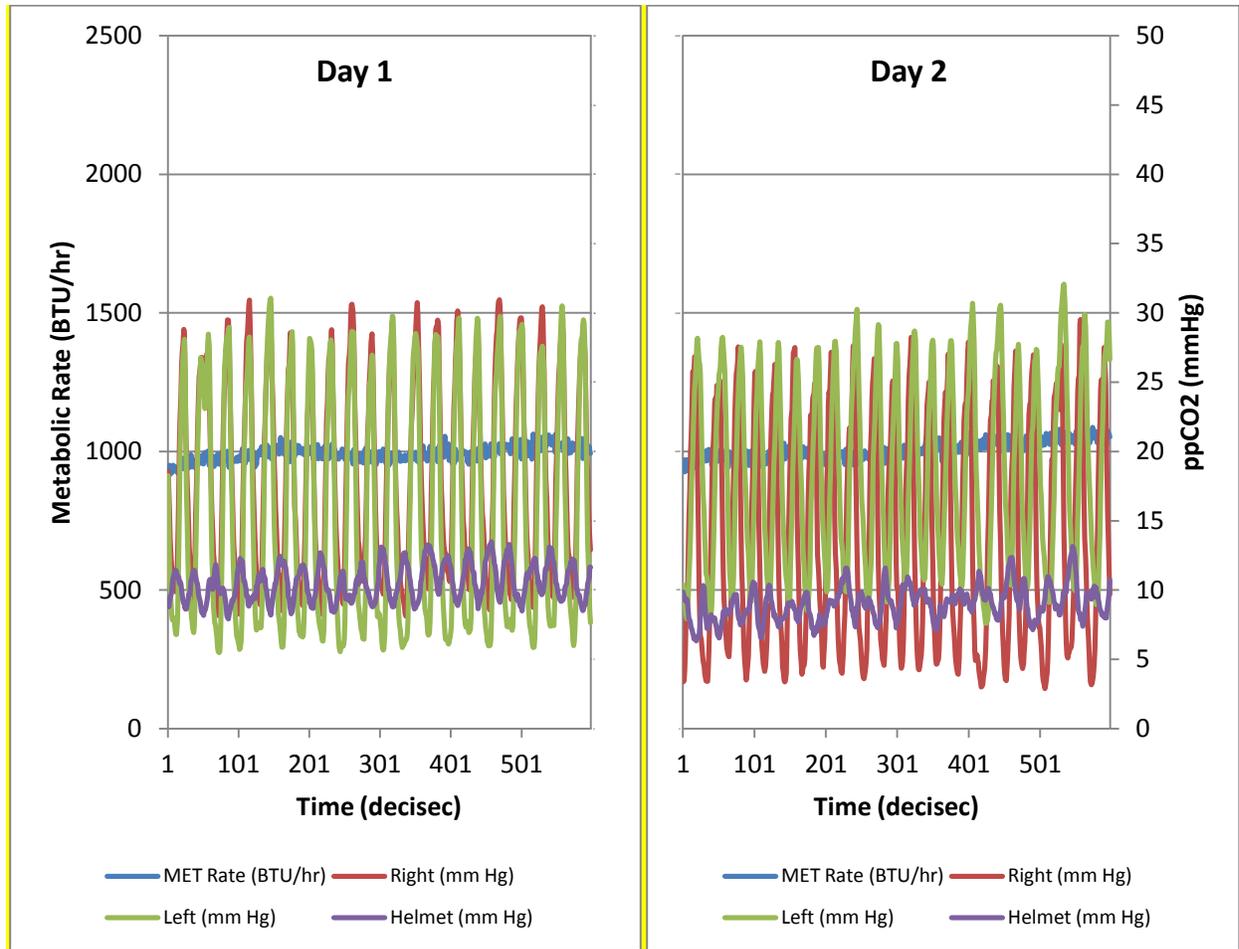
Figure 12. Example comparison of a test subject at the 1000 BTU/hr / 4 ACFM test points during the EM-ACES test. This example shows a bit of left/right variation between test days.

Figure 13 is another example of similar day-to-day results within the same subject at the same condition. This example points to a slight upward shift from day 1 to day 2. Possible reasons include all that were discussed above, but all of these slight differences point to the need to have at least 2 oronasal CO_2 measurements. Both Fig. 12 and 13 also show much higher helmet concentrations of CO_2 at the sample location on top of the head as compared to the REI-suit. Several aspects of the suit ventilation loop are different between these two suits. The REI-suit delivers breathing air through a manifold designed to blow from the top of the helmet down past the face with the air return located aft and to the right of the inlet in the helmet. The EM-ACES airflow inlet is through a non directional perforated air hose at the back of the neck with the air return at the right thigh. The EM-ACES also has a much smaller helmet compared to the REI-suit. Although the REI-suit likely has a better design for the air delivery, the location of the outlet may hinder overall performance. This accounts for much lower CO_2 at the top of the head compared to the EM-ACES, but slightly higher CO_2 at the oronasal area compared to the EM-ACES. It is possible that the net suit flow in the EM-ACES directing flow from the helmet to the thigh allowed for slightly better CO_2 washout.

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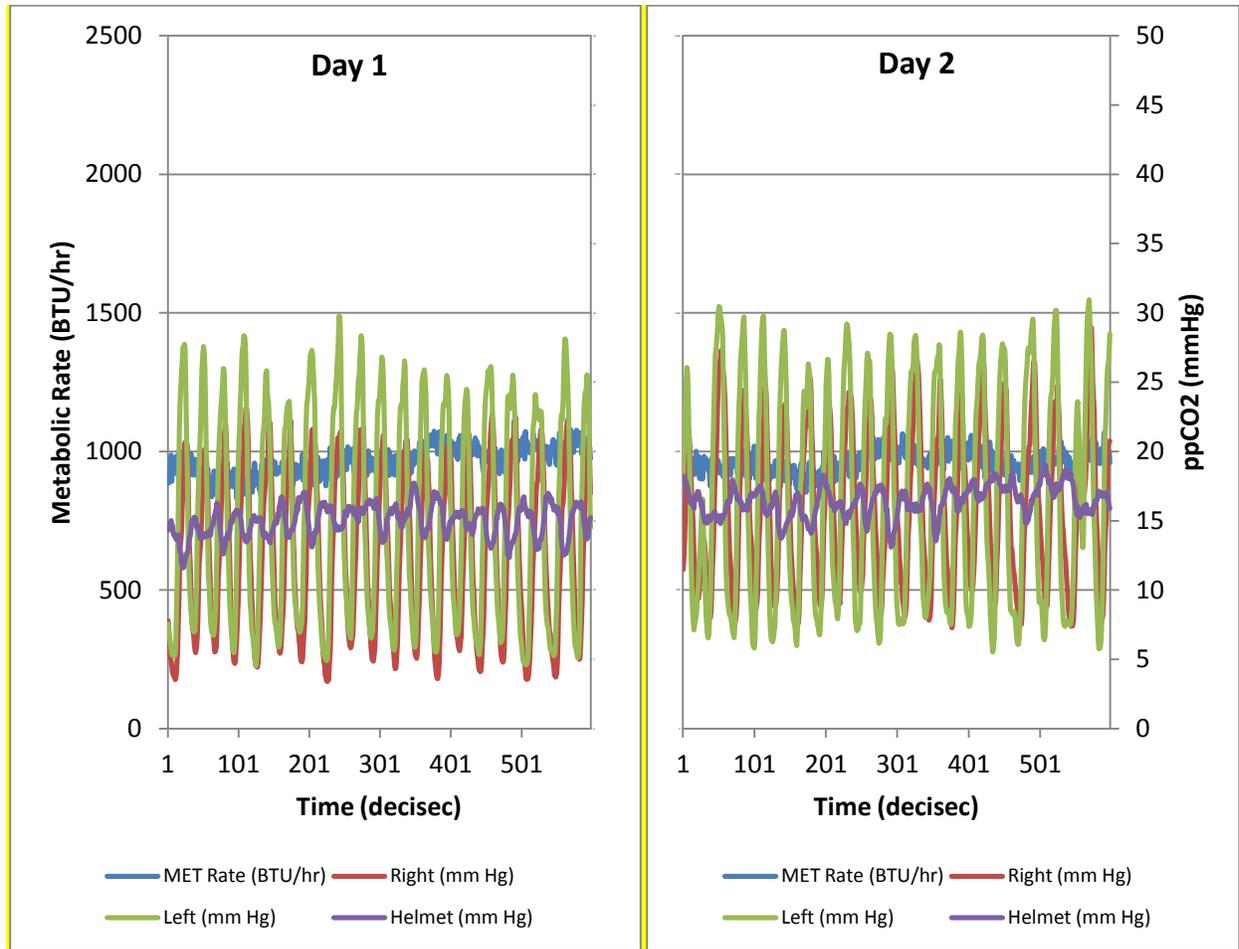
Figure 13. Example comparison of a test subject at the 1000 BTU/hr / 6 ACFM test points during the EM-ACES test. This example shows a slight upward shift from day 1 to day 2.

Day-to-day differences for 1 subject are shown in detail in Table 3. It seems that slight changes in metabolic rate and/or suit flow rate affect CO_2 washout in the EM-ACES more than the in REI-suit. In Table 2, a slight increase in metabolic rate coupled with a slight drop in suit flow lead to inspired oronasal $ppCO_2$ values 1.5 to 4.4 mm Hg greater. This finding is further confirmed by analysis of the second test subject at the 2000 BTU/hr trials. This data showed that a slight drop in metabolic rate at the same flow rates from day-to-day led to an inspired oronasal $ppCO_2$ that was between -1.1 and -4.0 mm Hg lower during the 2000 BTU/hr trials. Results from this subject's 1000 BTU/hr trials were not consistent with this pattern, indicating that while it is not a primary variable head position in the EM-ACES may notably affect CO_2 washout results.

Table 3. Day-to-day Differences for One Subject in the EM-ACES CO$_2$ Washout Test

Target		Differences - All data are Day 2 - Day 1				
Metabolic Rate	Flow	Metabolic Rate (BTU/hr)	Flow (SCFM)	Oronasal ppCO$_2$ (mm Hg)	Oronasal Inspired ppCO$_2$ (mm Hg)	Helmet ppCO$_2$ (mm Hg)
Rest	6 ACFM	-40	-0.13	1.12	1.15	-2.61
Rest	5 ACFM	134	-0.29	2.18	1.70	-0.21
Rest	4 ACFM	26	-0.43	0.58	1.62	-0.08
1000 BTU/hr	6 ACFM	16	-0.13	2.94	2.51	1.10
1000 BTU/hr	5 ACFM	67	-0.32	4.14	3.50	4.23
1000 BTU/hr	4 ACFM	97	-0.33	2.94	2.86	4.73
2000 BTU/hr	6 ACFM	116	-0.15	1.35	2.44	2.62
2000 BTU/hr	5 ACFM	157	-0.18	2.54	4.40	1.53
2000 BTU/hr	4 ACFM	266	0.25	-0.18	1.82	1.49

As with the REI-suit, metabolic rate was the primary driver for oronasal ppCO$_2$, but was less clearly linked to the values at the top of the head in the helmet. Again, this could be because of head position, lack of ventilation in this area or other factors discussed above. Although metabolic rate was the primary driver, the R^2 correlations were much lower in the EM-ACES for metabolic rate and ppCO$_2$ variables (Fig. 14

). In addition to the head in helmet position issues, there were also less data points overall, which could have affected the correlation strength.
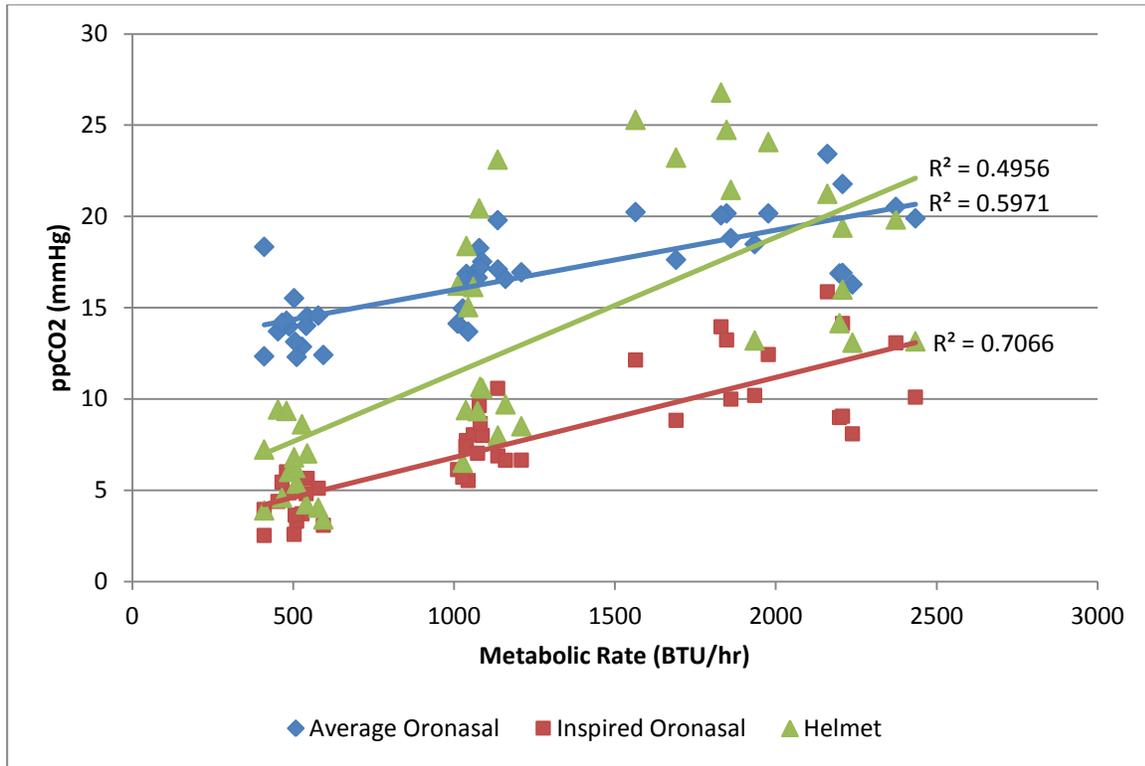
Figure 14. ppCO$_2$ variables as a function of metabolic rate during the EM-ACES CO$_2$ washout test.

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In addition to metabolic rate, the test team knew that flow rate through the suit should be a significant factor. Figure 15 shows that when accounting for the different flow conditions, although the correlation was not as convincing as with the REI-suit, flow was not a significant factor at lower metabolic rates, but did make a difference at higher metabolic rates. This is likely due to having less overall data points, additional metabolic rate variation at the higher metabolic rates, and varying head positioning within the helmet during exercise. The additional metabolic rate variation was due to subject fatigue during heavy workloads on the arm ergometer. Given a strong statistical model for predicting CO_2 washout in the REI-suit, the EM-ACES results still indicated that a model may be possible.
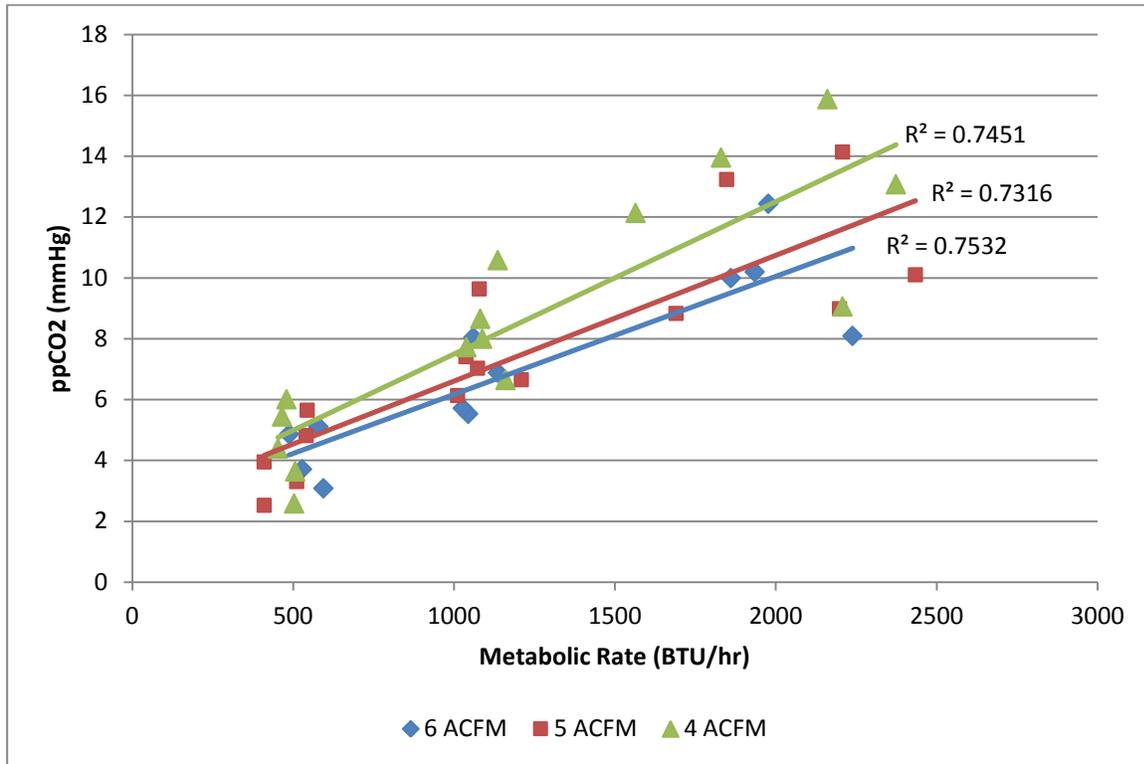
Figure 15. Inspired oronasal ppCO$_2$ as a function of metabolic rate for different EM-ACES suit flow rates.

As with the REI-suit, a statistical regression model was needed to facilitate direct comparison of CO_2 washout performance at different possible combinations of metabolic and flow rates for the EM-ACES. Input variables were metabolic rate, suit flow rate, and an interaction term of metabolic rate × flow rate. The outcome variable of interest was oronasal inspired ppCO$_2$.

The data was used to predict the expected mean ppCO$_2$ for a given metabolic rate and flow rate combination as well as a high and low ppCO$_2$ at the 95% confidence interval. The predicted ppCO$_2$ was then compared to the maximum exposure limits as described in NASA-TP-2010-216126 (2).

Results from the statistical regression model are shown in Fig. 16. The general interpretation of the model results is almost identical to the REI-suit with a slight shift towards better CO_2 washout in the EM-ACES. Although enhanced with additional mobility in the arms, the EM-ACES does not have the range of motion capabilities of the REI-suit and is also likely to only operate at metabolic rates less than 1500 BTU/hr for any extended period of time.
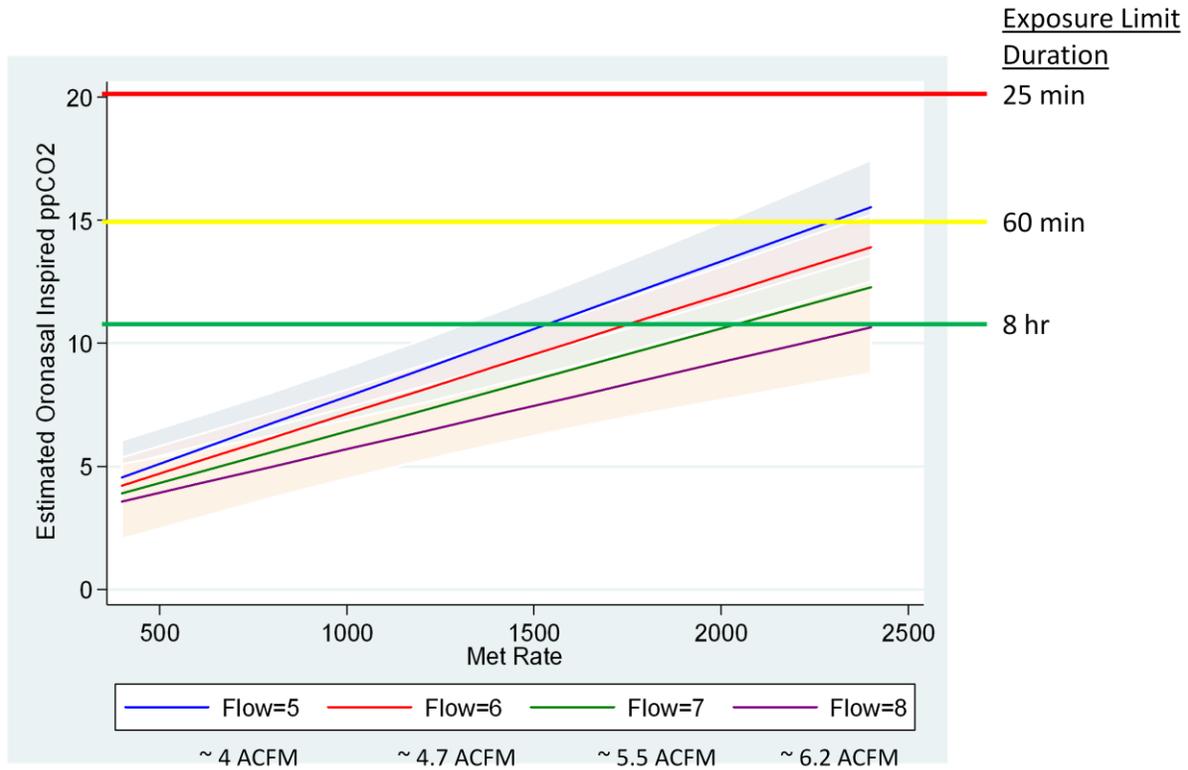
Figure 16. Statistical regression model showing the estimated inspired oronasal ppCO$_2$ at different metabolic and flow rates for the EM-ACES.

CO$_2$ washout performance looked to be similar with slight differences between the 2 suits. A summary of results in presented in Table 4. Actual metabolic rate and suit flow were very similar between suits. The average oronasal ppCO$_2$ and inspired ppCO$_2$ were higher in the EM-ACES at rest, but higher in the REI during exercise. The biggest difference between suits was the helmet ppCO$_2$ as measured by the CO$_2$ sampling line at the top of the head. Reasons for these differences have been discussed and will be further analyzed by modeling and/or future testing with more fixed points in the helmet.

Table 4. CO$_2$ Washout Test Results for REI Suit and EM-ACES

Target		EM-ACES						REI					
Metabolic Rate (BTU/hr)	Suit Flow (ACFM)	Metabolic Rate (BTU/hr)	Flow (SCFM)	Average Oronasal ppCO$_2$ (mm Hg)	Oronasal Inspired ppCO$_2$ (mm Hg)	Helmet ppCO$_2$ (mmHg)	Number of test points in average	Metabolic Rate (BTU/hr)	Flow (SCFM)	Average Oronasal ppCO$_2$ (mm Hg)	Oronasal Inspired ppCO$_2$ (mm Hg)	Helmet ppCO$_2$ (mmHg)	Number of test points in average
Rest	6	547	7.64	13.45	4.19	5.51	4	543	7.72	13.00	3.94	2.04	6
Rest	5	483	6.73	14.30	4.05	5.54	5	522	6.81	13.05	4.08	2.00	6
Rest	4	482	5.41	14.16	4.41	7.27	5	486	5.55	13.27	4.23	2.23	6
1000	6	1067	7.67	15.59	6.54	11.42	4	1080	7.70	18.50	8.33	4.10	7
1000	5	1082	6.71	16.50	7.37	12.77	5	1066	6.80	18.37	8.34	4.50	7
1000	4	1101	5.46	17.59	8.32	14.49	5	1045	5.56	18.92	8.74	5.45	7
2000	6	2003	7.67	18.43	10.18	17.95	4	2022	7.70	22.11	13.13	7.96	6
2000	5	2076	6.74	19.26	11.05	18.93	5	1957	6.82	22.03	13.54	8.62	6
2000	4	2027	5.50	20.23	12.82	21.82	5	1949	5.56	23.35	15.30	10.83	6

VII. Conclusions and Recommended Forward Work

At all flow rates, metabolic rates $\leq$ 1000 BTU/hr could be tolerated indefinitely from a CO$_2$ perspective. At 1500 BTU/hr, it would likely take about 3 hours at the lowest suit flow rate before any acute CO$_2$ related problems might be expected. At metabolic rates $\geq$ 2000 BTU/hr, the flow rate has a significant effect on exposure limits. At metabolic rates of 2500 to 3000 BTU/hr, there is less than 1 hour before acute CO$_2$ symptoms could be expected. In addition to the potential for CO$_2$ related symptoms, subjects experienced exertional fatigue and increased heat storage when working at high metabolic rates. Time at 2500 BTU/hr or above should therefore be minimized for several physiologic reasons.

It should also be noted that acute CO$_2$ related problems are easily resolved by reduction in the inspired ppCO$_2$. In the case of ground-based testing, this can be accomplished by reducing workload and thus the expected metabolic rate and/or by increasing the suit air flow. Therefore, the suited subject can quickly be returned to a low level of ambient ppCO$_2$ and is in a much safer situation than someone during flight.

Normal operations in the REI suit are expected to be at ~ 1500 BTU/hr with spikes above 2000 BTU/hr. Normal operations in the EM-ACES are expected to be $\leq$ 1500 BTU/hr. Additionally, the suit test team monitors all subjects for symptoms of high CO$_2$ throughout testing, and will terminate testing if any issues arise.

Given that (1) nominal operations are expected to be in a zone where CO$_2$ symptoms are unlikely to occur, (2) the suit test team monitors for CO$_2$ related symptoms, and (3) ppCO$_2$ can quickly be reduced by decreasing workload and increasing flow, the REI-suit and EM-ACES CO$_2$ washout is acceptable at flow rates equal to or greater than 4 ACFM. If expected metabolic rates are $\geq$ 2000 BTU/hr for extended periods of time, then a minimum of 5 ACFM should be used.

Further testing should evaluate how differences in the suit ventilation loop affect CO$_2$ washout performance. For instance, if the REI suit was modified to have the air outlet pickup downstream in the torso or leg, it is highly likely that CO$_2$ washout performance would improve. Additionally, testing with several sensors in fixed locations in the helmet will provide key information for the suit ventilation modeling team. This data could be used in conjunction with the oronasal CO$_2$ washout data to predict performance of future suit and helmet designs.

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Acknowledgments

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