JSC/EC5 U.S. Spacesuit Knowledge Capture (KC) Series Synopsis

All KC events will be approved for public using NASA Form 1676.

This synopsis provides information about the Knowledge Capture event below.

Topic: CO2 Washout Testing of NASA Space Suits

Date: October 2, 2012 **Time:** 10:30-12:30 pm **Location:** JSC/B5S/R3102

DAA 1676 Form #: 38113

A PDF of the presentation is also attached to the DAA 1676 and this is a link to all lecture material and video: \\js-ea-fs-03\pd01\EC\Knowledge-Capture\FY13 Knowledge Capture\20121002 Norcross_CO2 Washout\For 1676 Review and Public Release

*A copy of the video will be provided to NASA Center for AeroSpace Information (CASI) via the Agency's Large File Transfer (LFT), or by DVD using the USPS when the DAA 1676 review is complete.

Assessment of Export Control Applicability:

This Knowledge Capture event has been reviewed by the EC5 Spacesuit Knowledge Capture manager in collaboration with the author and is assessed to not contain any technical content that is export controlled. It is requested to be publicly released to the NESC and JSC Engineering Academy, as well as to STI for distribution through NTRS or NA&SD (public or non-public) and with video through DVD or Large File Transfer request or YouTube viewing with download of any presentation material.

*Jason Norcross' personal contact information has been removed in the final PDF of the original PowerPoint presentation, which is attached to this 1676, and will be used for distribution.

Presenter: Jason Norcross

Synopsis: During the presentation "CO2 Washout Testing of NASA Spacesuits," Jason Norcross discussed the results of recent carbon dioxide CO2 washout testing of NASA spacesuits including the Rear Entry I-suit (REI), Enhanced Mobility Advanced Crew Escape Suit (EM-ACES), and possibly the ACES and Z-1 EVA prototype. When a spacesuit is used during ground testing, adequate CO2 washout must be provided for the suited subject. Symptoms of acute CO2 exposure depend on the partial pressure of CO2 (ppCO2) available to enter the lungs during respiration. The primary factors during ground-based testing that influence the ppCO2 level in the oronasal area include the metabolic rate of the subject and air flow through the suit. These tests were done to characterize inspired oronasal ppCO2 for a range of workloads and flow rates for which ground testing is nominally performed. During this presentation, Norcross provided descriptions of the spacesuits, test hardware, methodology, and results, as well as implications for future ground testing and verification of flight requirements.

Biography: Jason Norcross is the lead for the EVA Physiology Laboratory and a lead scientist for the Human Health and Countermeasures Element in the Human Research Program (HRP). He has research interests in environmental physiology, human health and performance in EVA suits, and decompression sickness. Recently, he was the lead for the Human Health and Performance sub-team as part of the

Exploration Atmospheres Action Team, which studied the implications of choosing an alternative environment to facilitate robust EVA operations. He is a frequent presenter at both the Aerospace Medical Association annual meeting and HRP Investigators' Workshop. He came to the Johnson Space Center in 2005 as an employee with Wyle Laboratories and has worked in the Exercise Physiology Laboratory and EVA Physiology, Systems and Performance Project before his current roles. Norcross was graduated from the University of California, Davis with a bachelor of science degree in exercise science in 1999 and a master of science in exercise science in 2002.

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CO_2 Washout Testing of NASA Space Suits

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Presentation Outline

- Background
- Test Objectives
- Test Plan Overview
- Test Hardware Description
- Methods
- Data Analysis
- Conclusions
- Recommended Forward Work

(Test Hardware Description through Recommended Forward Work: REI Suit and EM-ACES)

- Z-1 Test Quicklook Results
- EVA Suit CO_2 Washout Comparison
- ACES Test Quicklook Results
- MMSEV Test Quicklook Results
- Lessons Learned

Background

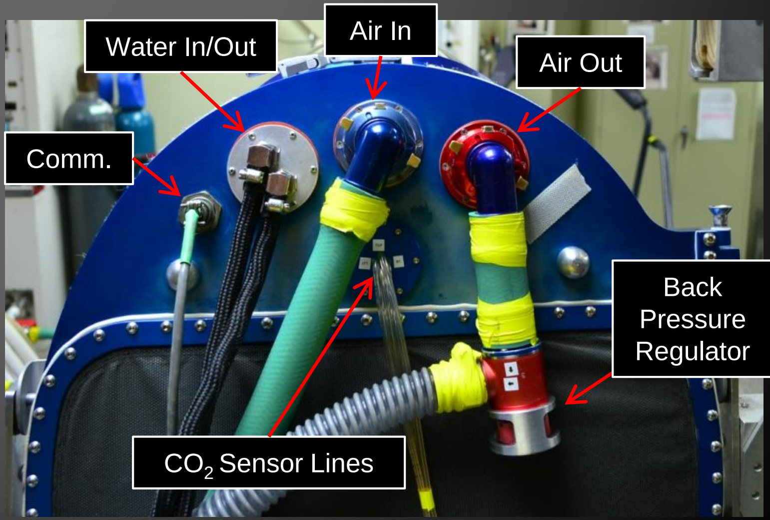
Life Support Inputs
Dry Air
O_2
LCG Cold Water

Metabolic Outputs
CO_2
Heat
Humidity

The suit ventilation loop handles suit pressurization, O_2 delivery, CO_2 washout, humidity removal and contributes to heat removal

- Carbon dioxide (CO_2) can build up quickly inside an enclosed environment if proper ventilation is not in place
- Acute health effects of high CO_2 exposures include:
  - Headache,
  - Dizziness
  - Shortness of breath
  - Sweating
  - Increased blood pressure
  - Unconsciousness
  - Death
- Maintaining adequate CO_2 washout during EVA or ground based suit testing is critical to crew and subject safety

The liquid cooling garment (LCG) is the primary control for heat removal



Background

Carbon dioxide (CO_2) can build up quickly inside an enclosed environment if proper ventilation is not in place and lead to acute health effects

- Maintaining adequate CO_2 washout during an extravehicular activity (EVA) is required to avoid negative health and performance effects
- Likewise, maintaining adequate CO_2 washout during space suit ground testing is necessary for test subject safety

The NASA 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 to determine 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.
- Results from these tests all assume perfect CO2 removal in the system

CO_2 Exposure Limits

NASA/TP-2010-216126 (Law et. al, 2010)

Table 1. Physiological tolerance time for various CO_2 concentrations and acute health effects of high concentrations of CO_2.

PHYSIOLOGICAL TOLERANCE			ACUTE HEALTH EFFECTS	
$ppCO_2$		Maximum Exposure Limit (min)	Duration of Exposure	Effects
mm Hg	%			
3.8	0.5%	Indefinite		
7.5	1.0%	Indefinite		
11	1.5%	480		
15	2.0%	60	Several hours	Headache, dyspnea upon mild exertion
23	3.0%	20	1 hour	Headache, sweating, dyspnea at rest
30	4.0%	10	(4-5%) Within few minutes	Headache, dizziness, increased blood pressure, uncomfortable dyspnea
38	5.0%	7		
45	6.0%	5	1-2 minutes ≤16 minutes Several hours	Hearing, visual disturbances Headache, dyspnea Tremors
53	7.0%	<3	(7-10%) Few minutes 1.5 minutes to 2 hours *9% for 5 minutes*	Unconsciousness, near-unconsciousness Headache, increased heart rate, shortness of breath, dizziness, sweating, rapid breathing *Lowest published lethal concentration*
68	9%	N/A		
75	10%	N/A	(>10-15%) 1 minute to several minutes	Dizziness, drowsiness, severe muscle twitching, unconsciousness
113	15%	N/A		
128	17%	N/A	(17-30%) Within 1 minute	Loss of controlled and purposeful activity, unconsciousness, convulsions, coma, death

CO2 Exposure Limits

NASA/TP-2010-216126 (Law et. al, 2010)

Table 2. Key CO_2 concentrations discussed in this paper. 1% = 7.5 mm Hg.

% CO_2	$PPCO_2$ (mm Hg)	Note [Reference]
0.03%	0.23	Ambient outdoor CO_2 level on Earth
	2	Relief of symptoms on Expedition 6 [1]
0.3-0.7%	2.3-5.3	Typical spacecraft CO_2 concentrations [2]
0.5%	3.4	**New NIOSH Recommended Exposure Limit** [3]
	>4	Lethargy, malaise, listlessness, and fatigue on Expedition 6 [1]
	4.9	Derived threshold corresponding to 90% negative predictive value for CO_2-related symptoms [4]
	5	Safe chronic CO_2 level in terms of performance [5] **Empiric threshold established by flight surgeons**
	2.7 to <6	Headaches on STS-112/ISS-9A [1]
	Up to 7.5	Headache on STS-113/ISS-11A [1]
1%	7.5	**NIOSH Permissible Exposure Limit** [6]
	8	**EMU EVA termination limit** with baseline Caution and Warning System [7]
1.2%	9	Slight performance decrement after chronic exposure [5]
	10	**Orlan EVA termination limit** with crew at rest [8]
	12.4	**EMU EVA termination limit** with enhanced Caution and Warning System [7]
1.99%	14.9	Maximum CO_2 concentration on Apollo 13 [9]
2%	15	Headache, exertional dyspnea start [10] **ISS Off-Nominal $ppCO_2$ Level** [11]
	20	**ISS Emergency $ppCO_2$ Level** [11] **Orlan EVA termination limit** [8]
3%	23	Sweating, resting dyspnea start [10] **NIOSH Short-Term Exposure Limit** [3]
4%	30	**NIOSH Immediately Dangerous to Life or Health limit** [3]
4-5%	30-38	Dizziness, lethargy, uncomfortable dyspnea start [10]

Partial Pressure Considerations for CO_2 Exposure

CO_2 effects are primarily due to the partial pressure

Most instruments measure %CO_2

Pressure Condition	Total Pressure psia (mmHg)	$ppCO_2$ mmHg	% CO_2
Earth/ISS Cabin	14.7 (760)	10	1.32 %
Ground Based Suit Test	14.7 + 4.3 = 19.0 (982)	10	1.02 %
EVA Suit	4.3 (222)	10	4.50 %
MMSEV/Suitport	8.2 (424)	10	2.36 %

Spacesuits / Spacecrafts Tested

Rear Entry I-Suit (REI)

Multi Mission Space Exploration Vehicle (MMSEV)

Z-1 Suitport Compatible Suit

Enhanced Mobility Advanced Crew Escape Suit (EM ACES)

Modified Advanced Crew Escape Suit (ACES)

CO_2 Washout Test Objectives

REI, EM-ACES, Z-1

Primary Objective: Characterize the workloads and flow rates for which CO_2 is adequately washed away from the suited subject's oronasal area in several prototype spacesuits

- Immediate goal: Define acceptable workloads and flow rates for laboratory-based ground testing

Secondary Objective: 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 design efforts

CO_2 Washout Test Protocol

REI-Suit, EM-ACES, Z-1

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	

<u>Other parameters</u>

- All testing at 4.3 psid
- 3 subjects per suit evaluation
- Each subject repeats test twice on different days
- Rest was standing in donning stand
- 1000 BTU/hr test point used arm ergometry
- 2000 and 3000 BTU/hr used arm ergometry or treadmill depending on suit capability

Test Plan Overview

All testing was performed at 4.3 psid (standard suit operating pressure)

Three test subjects were tested in each suit

- Each subject performed the test twice to allow for day-to-day data comparison

In the REI-suit and Z-1, CO_2 washout performance was tested at rest, 1000, 2000, and 3000 BTU/hr for 3-minute steady-state durations

- 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

In the EM-ACES, CO_2 washout performance was tested at rest,1000 and 2000 BTU/hr

- Since it is primarily a launch/entry suit, suited subjects in the EM-ACES rarely perform activities likely to generate metabolic rates above 2000 BTU/hr

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

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.

- Real-time metabolic rate was used to monitor and adjust the arm ergometer workload or treadmill speed to meet the target metabolic rates.

Integration of Science and Engineering

Life Science Responsibilities

- Custom integrated metabolic and CO_2 washout data collection system
- Data analysis
- Quicklook test reports
- Integration with SD for test termination criteria related to CO_2
- Serve as test conductor role (responsible for completing data collection)

Engineering Responsibilities

- Spacesuits and suit support
- Experienced suited test subjects with proper fit-check
- Data collection system integration into suited ventilation loop
- Pre-test documentation – CPHS, TRR, etc.
- Serve as test director role (oversee subject and hardware safety)

Test Hardware Description – REI Suit

Nominal operating pressure: 4.3 psid

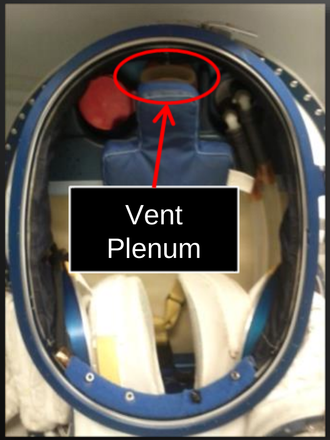
Planetary exploration suit prototype primarily constructed of softgoods, but incorporating hatch hardware and a limited number of bearings.

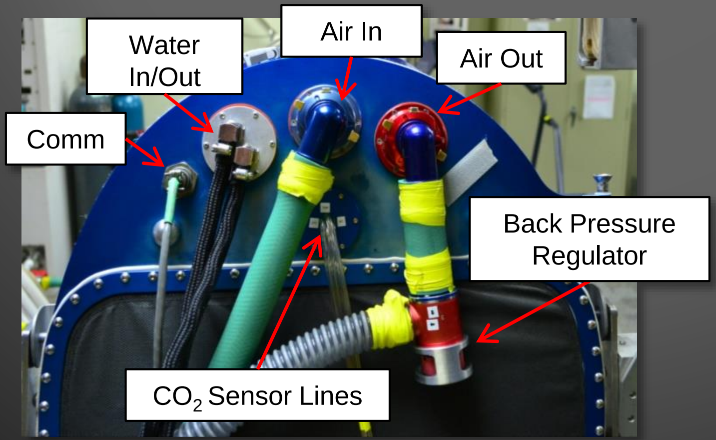
Bearings are located at the scye, upper arm, hip, and upper thigh (a 2-bearing hip)

Neck ring that accommodates a 16 ×12-inch oval dome hemispherical helmet.

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.

- Breathing air is delivered at the blue connection located on the rear entry door ('Air In') and is routed through a vent plenum into the helmet.
- Return air is removed from the suit at the red 'Air Out' connection on the rear-entry door.





Test Hardware Description – EM-ACES

Nominal operating pressure: 4.3 psid

Optimized for non-pressurized activities such as those encountered during launch, dynamic on-orbit events, landing and post landing scenarios.

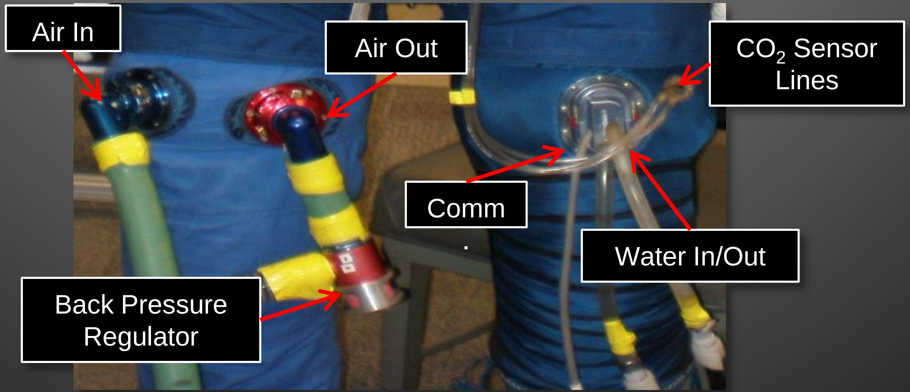
Addition of specific mobility features at hips, upper arm, and shoulder provide capability for simplistic, pressurized EVA activities

Helmet is a modified Shuttle EMU bubble helmet

- Removed from original EMU neck disconnect and attached to ACES neck ring disconnect

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.

- Breathing air is delivered at the blue connection located on the right thigh ('Air In') and is routed through soft tubing to the helmet neck ring
- Return air is removed from the suit at the red 'Air Out' connection also on the right thigh



Methods – CO_2 Measurement

Key parameter for indication of adequate CO_2 washout is direct measurement of CO_2 in the oronasal area

- Represents amount of CO_2 that the subject inspires with each breath

Test subjects wore an oronasal mask to allow for CO_2 sampling in the oronasal area

Tygon sampling tubes were inserted at the right and left side of the opening to measure oronasal CO_2

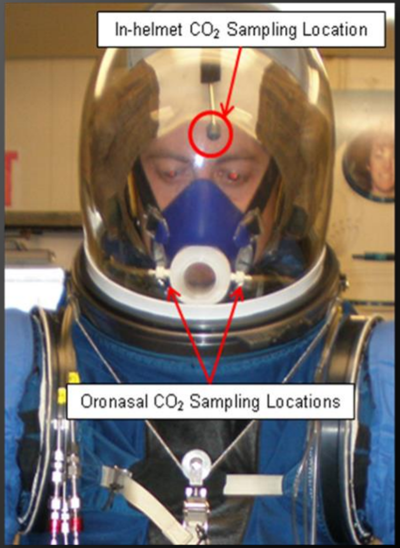
- Each signal analyzed separately - exact time syncing between the left and right side was not critical

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-helmet location

The sampling tubes were routed through a pass-through port in the suit hatch, through a rotameter that controlled flow rate to 1.0 l/min per sample line and then out to CO_2 analyzers for real-time CO_2 measurement

Suit delta pressure forced airflow through the sampling tubes

Rotameters on the gas analyzers allowed the flow rate to be adjusted to the range required by the analyzers

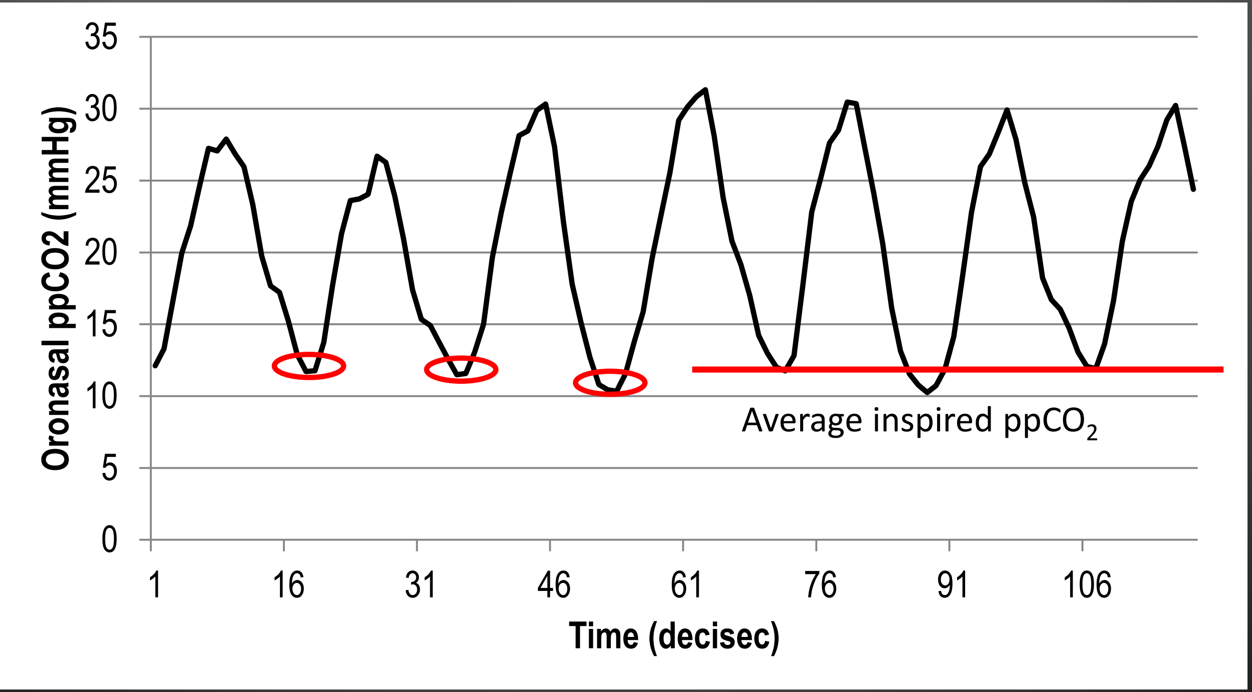


Methods – CO_2 Measurement

Inspired CO_2 levels determined by looking at the low points of the respiratory cycle

- Without direct flow measurement at the mouth, a time weighted average across the inspiration cycle could not be calculated
- While a time weighted average would be preferred, the majority of the inspiration by volume occurs near the bottom of the cycle
- Some error associated with this method, but it allows for accurate relative comparisons between suits, metabolic rates and flow rates

Left and right side measurements were given equal weight and the average was used to determine CO_2 washout



Methods – Metabolic Rate Measurement

Necessary to have a way to calculate the actual energy expenditure (metabolic rate) of each individual subject to control the test for specific workloads

Method used has been adapted for use in space suits from the Exercise Physiology industry standard

- Metabolic rate determined through standard equations using CO_2 production, the flow rate of breathing air, and the respiratory exchange ratio (RER) – assumed constant of 0.85

System used 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

- 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 testing, personnel would monitor the metabolic rate at each workload until it appeared to have stabilized, and then begin a 3-minute data collection trial

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.

Data was displayed real-time during test and recorded for post-test analysis

Data Analysis - Overview

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.
  - 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.
- Subject 2 completed all test points except for the 3000 BTU/hr trial at 4 ACFM due to an issue with the suit.
- Subject 3 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

Data Analysis – Overview

CO_2 washout testing in the REI-Suit and EM-ACES was an engineering pilot test

Statistical power was not a consideration in the number of test subjects

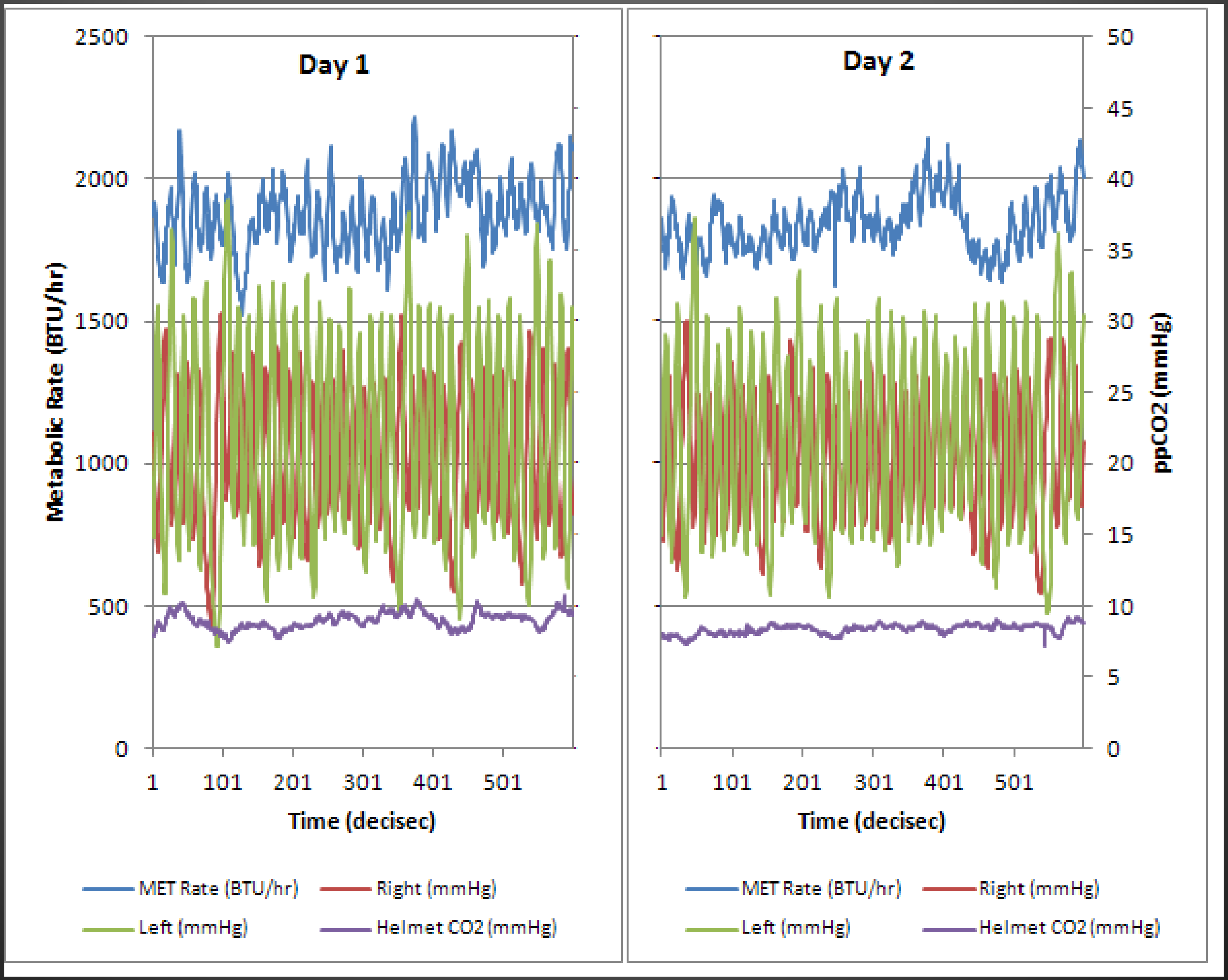
Comparisons within the same subject and between different subjects were made through visual inspections of the graphical data and through numerical comparisons.

- In most cases, test day comparisons across the same subjects were very similar
- In some cases, test days across the same subject showed significant variation
  - Often related to peak expired $ppCO_2$ values

Data Analysis – REI-Suit

Example comparison of subject at 2000 BTU/hr / 5 ACFM test points during the REI-Suit Test

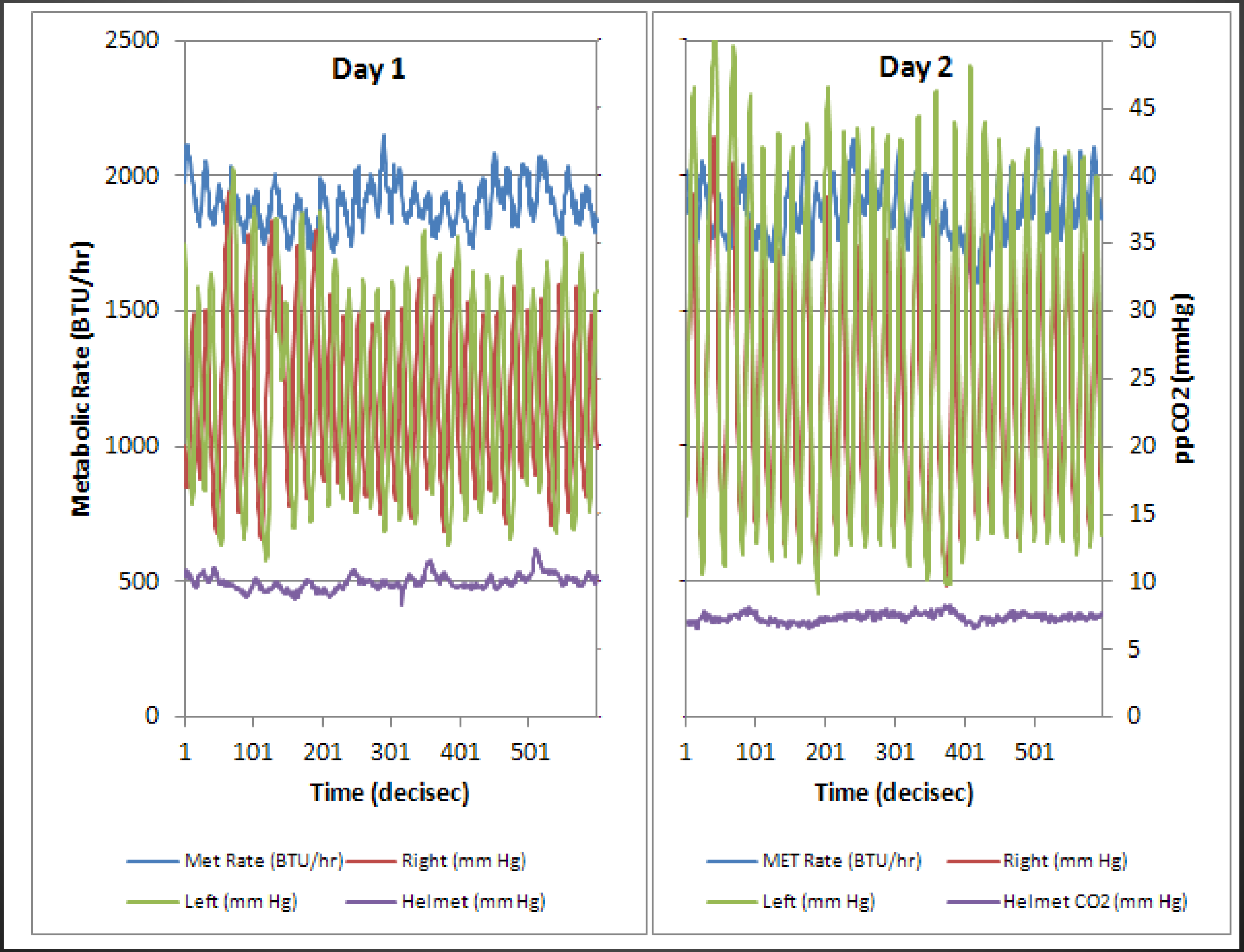
- Example of how **similar** day-to-day data was in some cases



Data Analysis – REI-Suit

Comparison of subject at 2000 BTU/hr / 5 ACFM test points during the REI-Suit Test

- Example of how **different** day-to-day data was in some cases



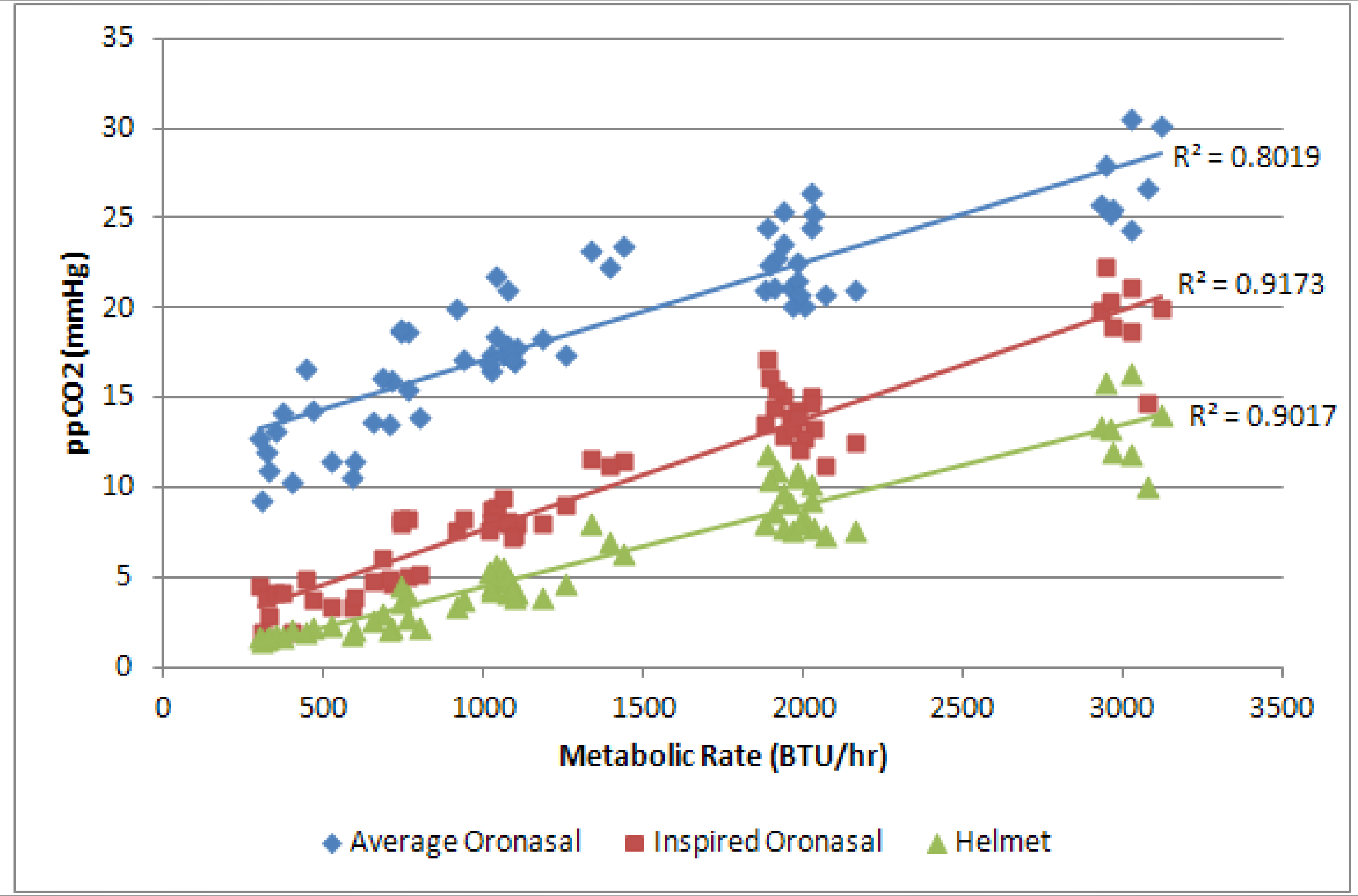
Data Analysis – REI Suit

Day-to-day differences for subject in REI-Suit for all metabolic and flow rates

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
	5 ACFM	293	-0.44	2.06	1.94	0.63
	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
	5 ACFM	1	-0.45	-0.85	-0.64	-0.18
	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
	5 ACFM	-50	-0.37	-0.07	0.56	-0.55
	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
	5 ACFM	29	-0.10	-0.51	0.49	-0.12
	4 ACFM	N/A	N/A	N/A	N/A	N/A

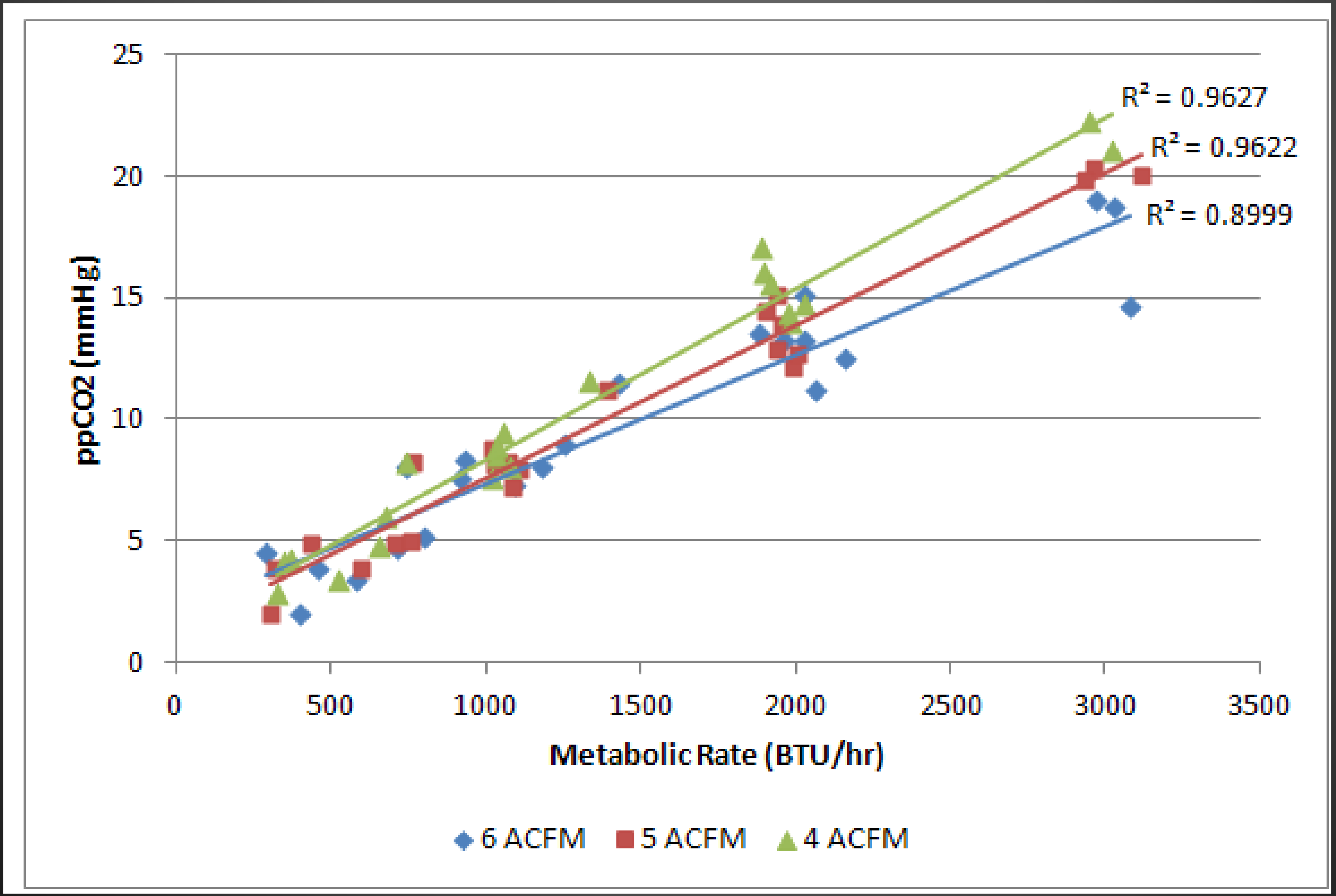
Data Analysis – REI Suit

$ppCO_2$ variables as a function of metabolic rate in the REI-suit



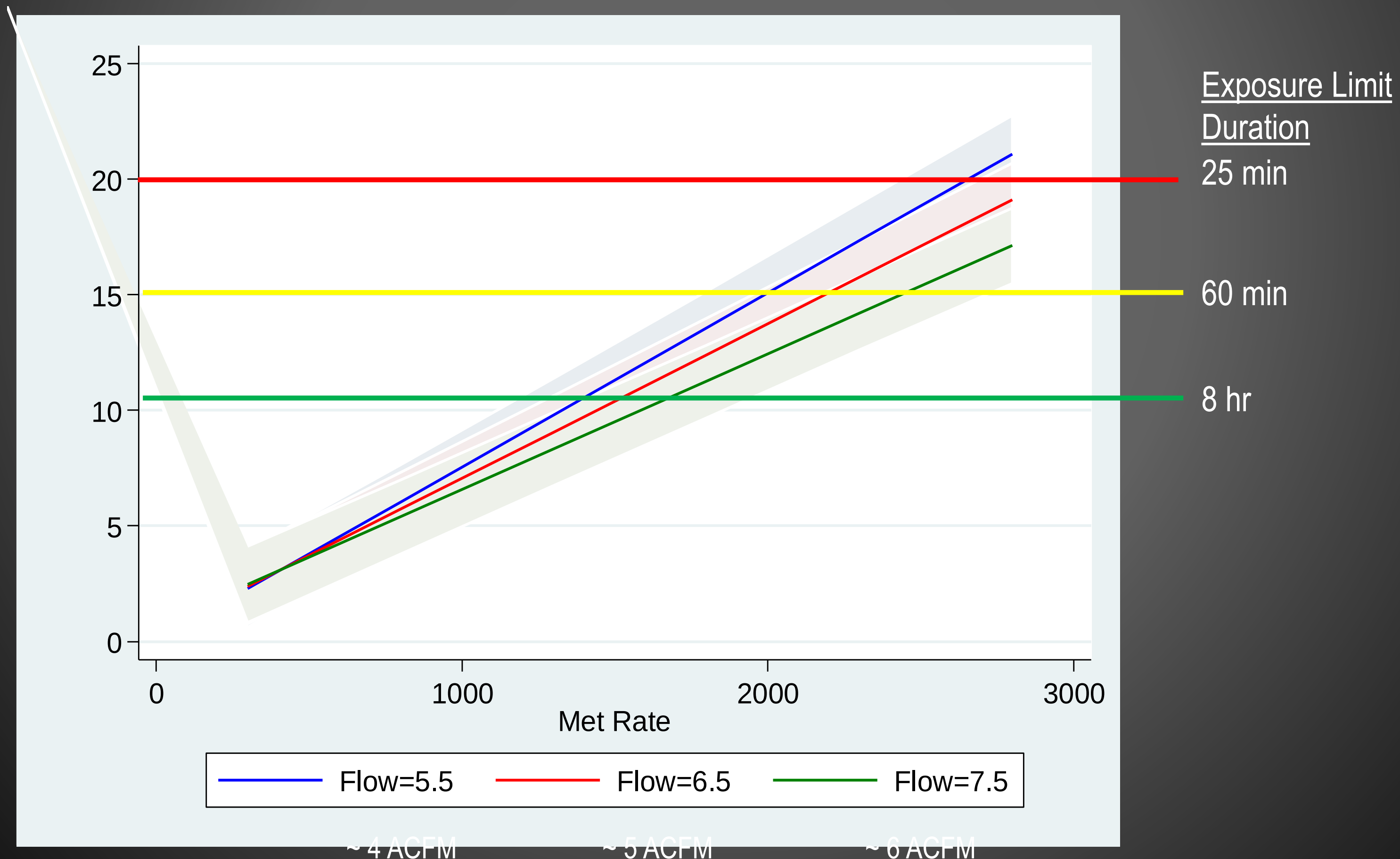
Data Analysis – REI Suit

Inspired oronasal $ppCO_2$ as a function of metabolic rate for different REI suit flow rates



Data Analysis – REI-Suit

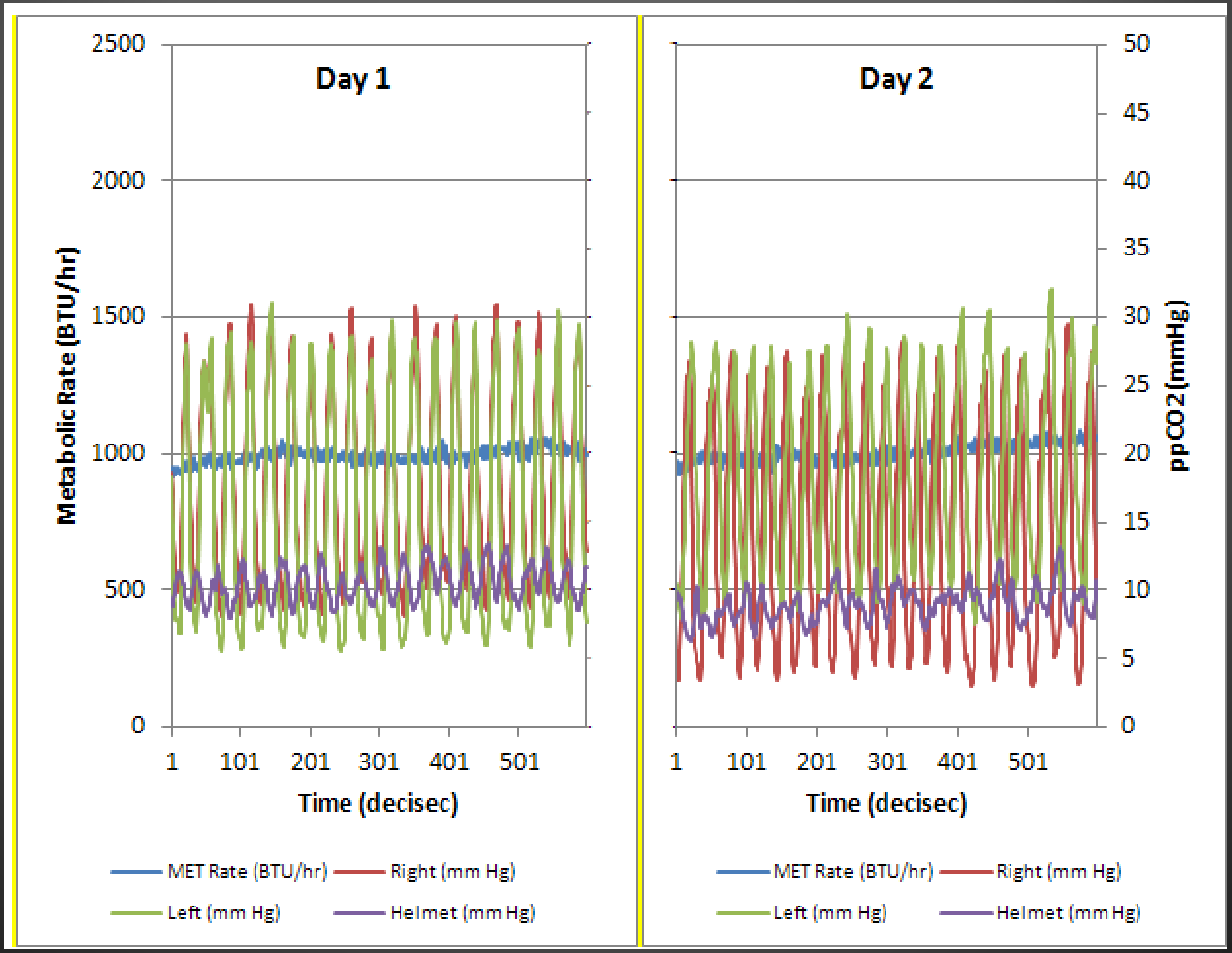
Statistical regression model showing the estimated inspired oronasal $ppCO_2$ (mmHg) at different metabolic rates (BTU/hr) and flow rates (SCFM)



Data Analysis – EM-ACES

Example comparison of subject at 1000 BTU/hr / 4 ACFM test points during the EM-ACES Test

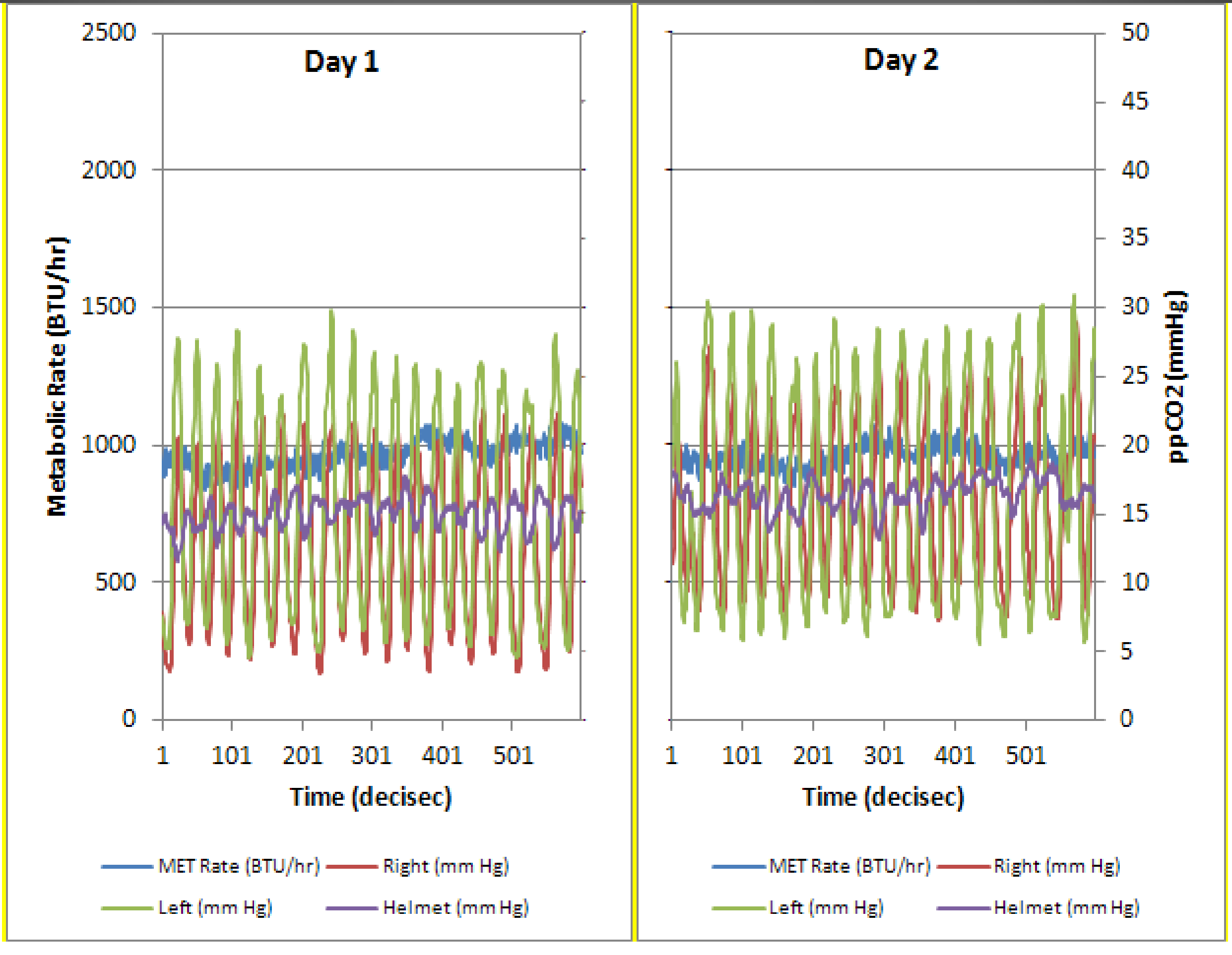
- Shows some left/right variation between test days



Data Analysis – EM-ACES

Example comparison of subject at 1000 BTU/hr / 6 ACFM test points during the EM-ACES Test

- Shows a slight upward shift from day 1 to day 2



Data Analysis – EM-ACES

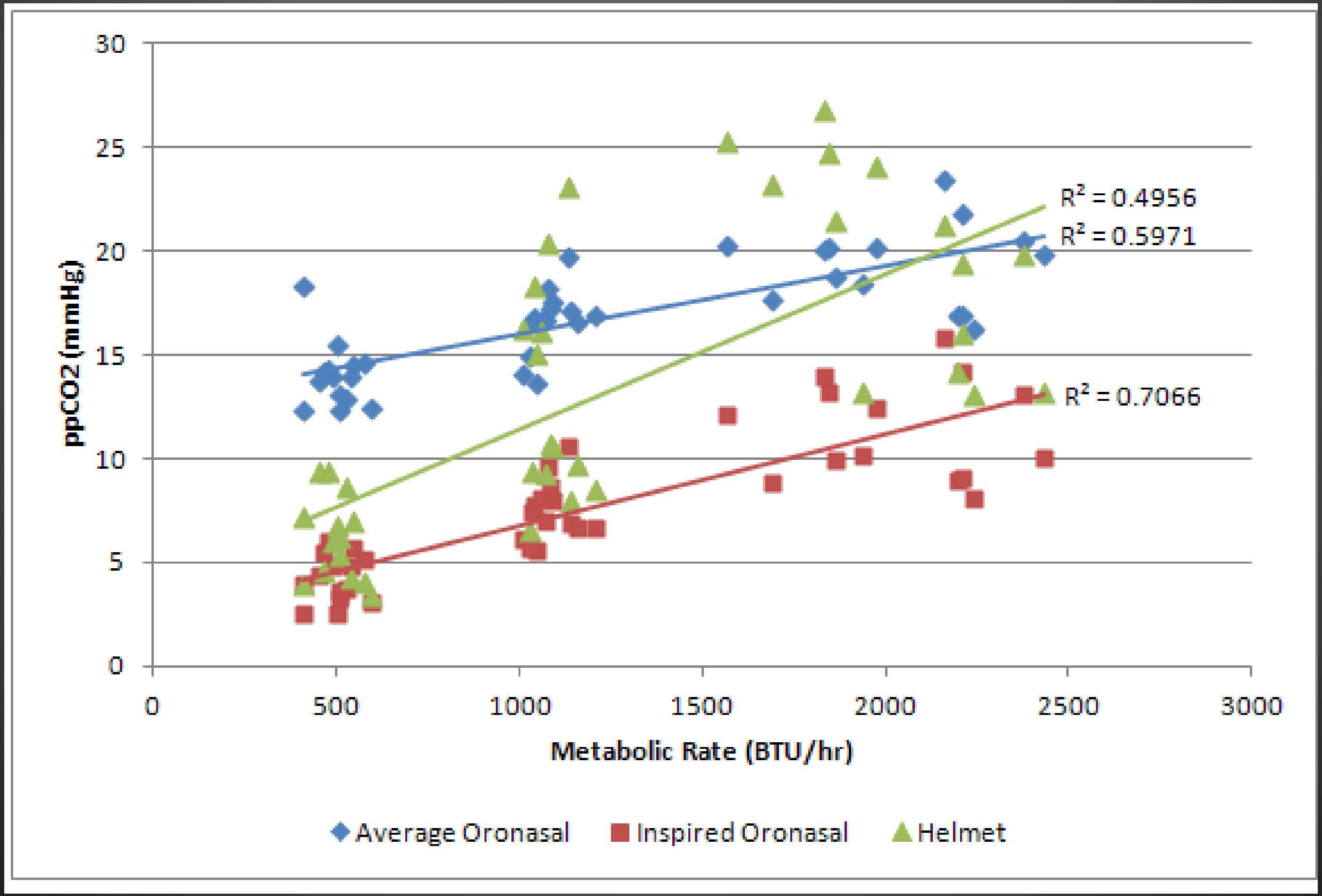
Day-today differences for one subject in the EM-ACES test for all metabolic and flow rates

Only 2 subjects completed testing both days

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
	5 ACFM	134	-0.29	2.18	1.70	-0.21
	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
	5 ACFM	67	-0.32	4.14	3.50	4.23
	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
	5 ACFM	157	-0.18	2.54	4.40	1.53
	4 ACFM	266	0.25	-0.18	1.82	1.49

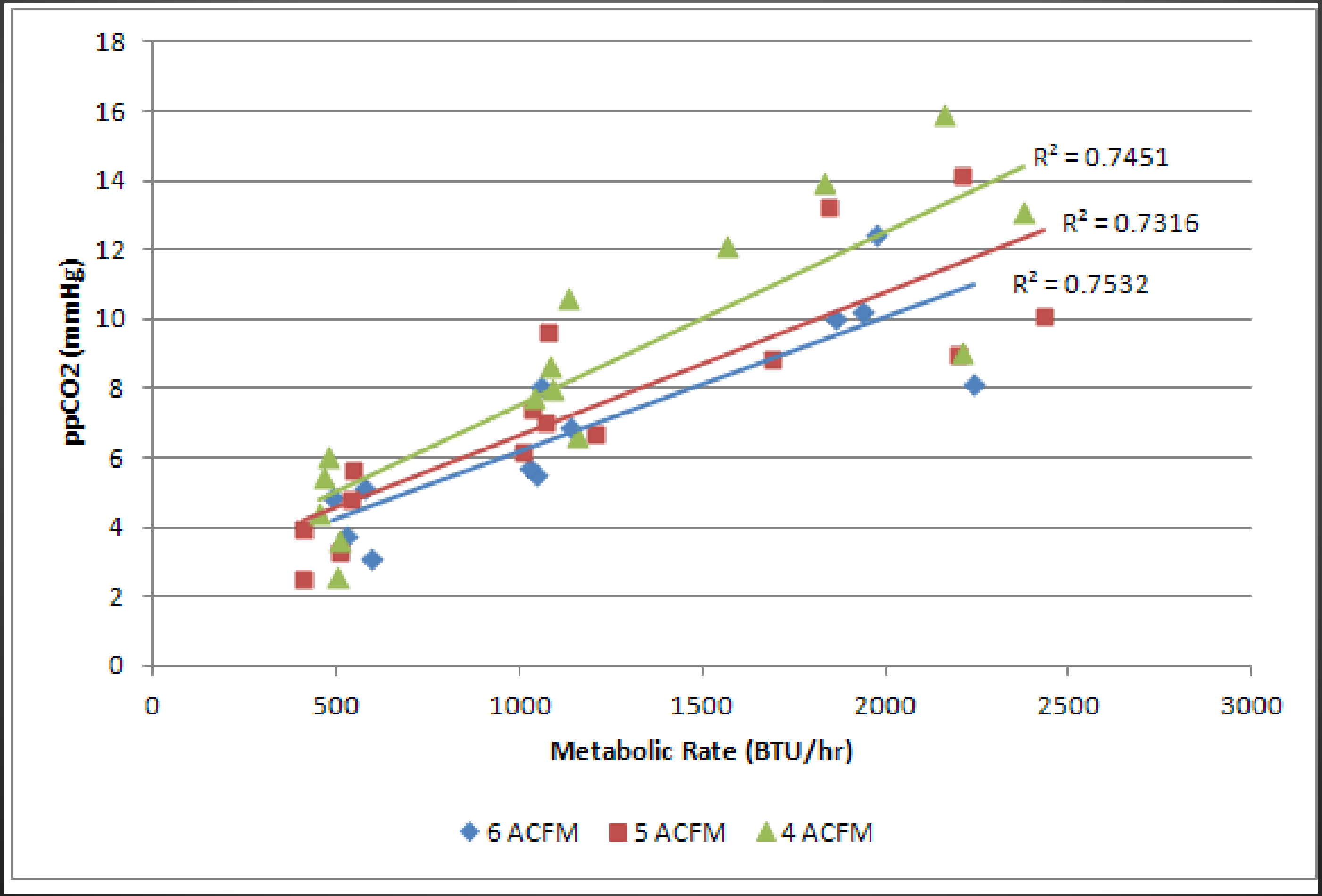
Data Analysis – EM-ACES

$ppCO_2$ variables as a function of metabolic rate in the EM-ACES



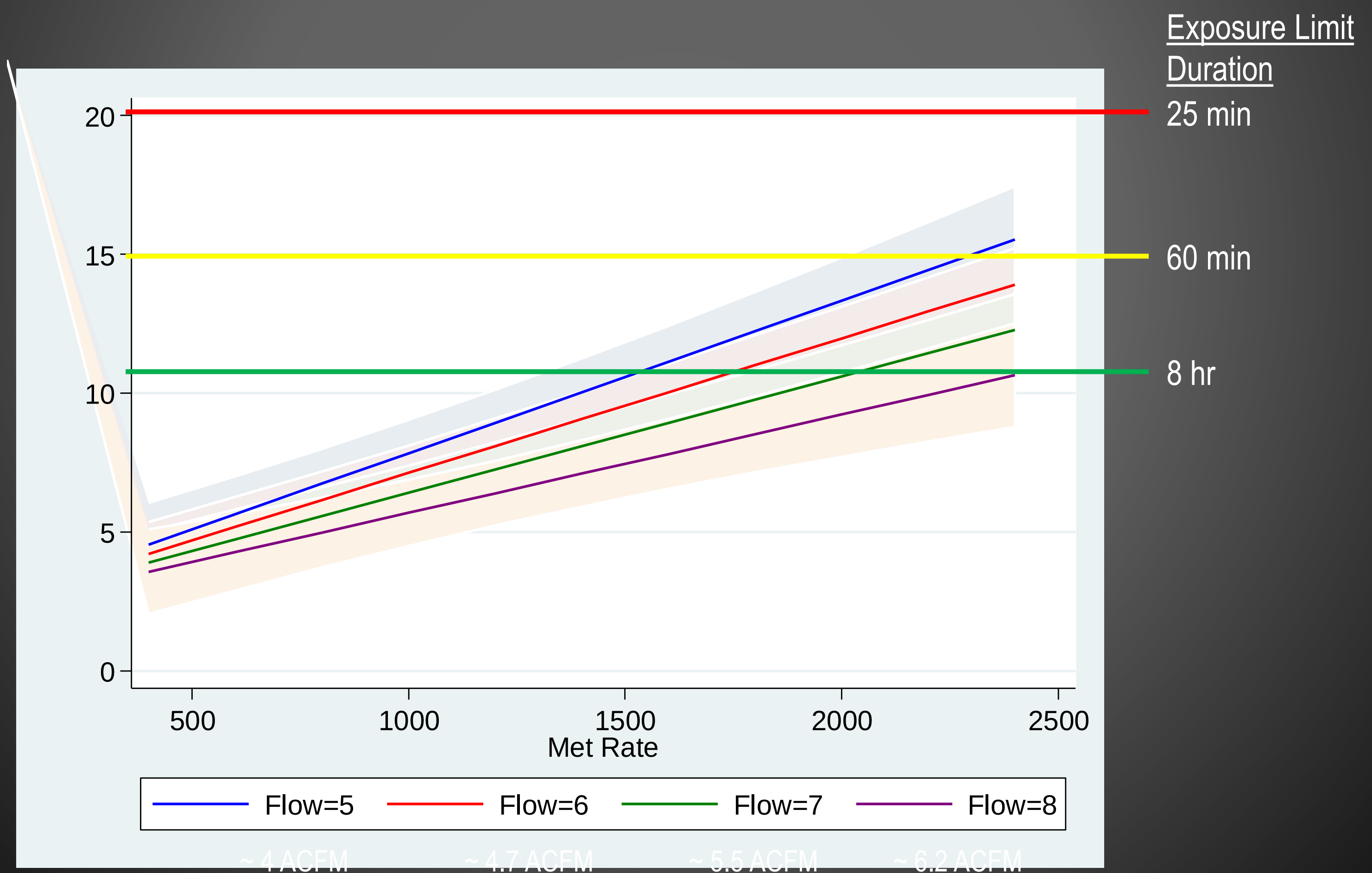
Data Analysis – EM-ACES

Inspired oronasal $ppCO_2$ as a function of metabolic rate for different EM-ACES suit flow rates



Data Analysis – EM-ACES

Statistical regression model showing the estimated inspired oronasal $ppCO_2$ (mmHg) at different metabolic rates (BTU/hr) and flow rates (SCFM)



Data Analysis – Comparison Between Suits

CO_2 washout performance was similar with slight differences between the 2 suits

- Actual metabolic rate and suit flow were very similar between suits.
- 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.
  - Helmets were different shapes/sizes
  - Air flow pathways were notably different
  - Results will be further analyzed by modeling and/or future testing with more fixed points in the helmet.

Data Comparison – 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

Conclusions for REI Suit and EM-ACES

- At all flow rates, metabolic rates ≤ 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 ≥ 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.
- 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.
- 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.

Conclusions for REI Suit and EM-ACES

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 ≤ 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 the following,

(1) nominal operations are in a zone where CO_2 symptoms are unlikely to occur

(2) the suit test team monitors for CO_2 related symptoms

(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.

Recommended Forward Work

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

Z-1 CO_2 Washout

Initial Results Quicklook

Initial Thoughts – Z-1 Test Results

Z-1 testing showed the greatest variability from test day to test day and between left and right analyzers

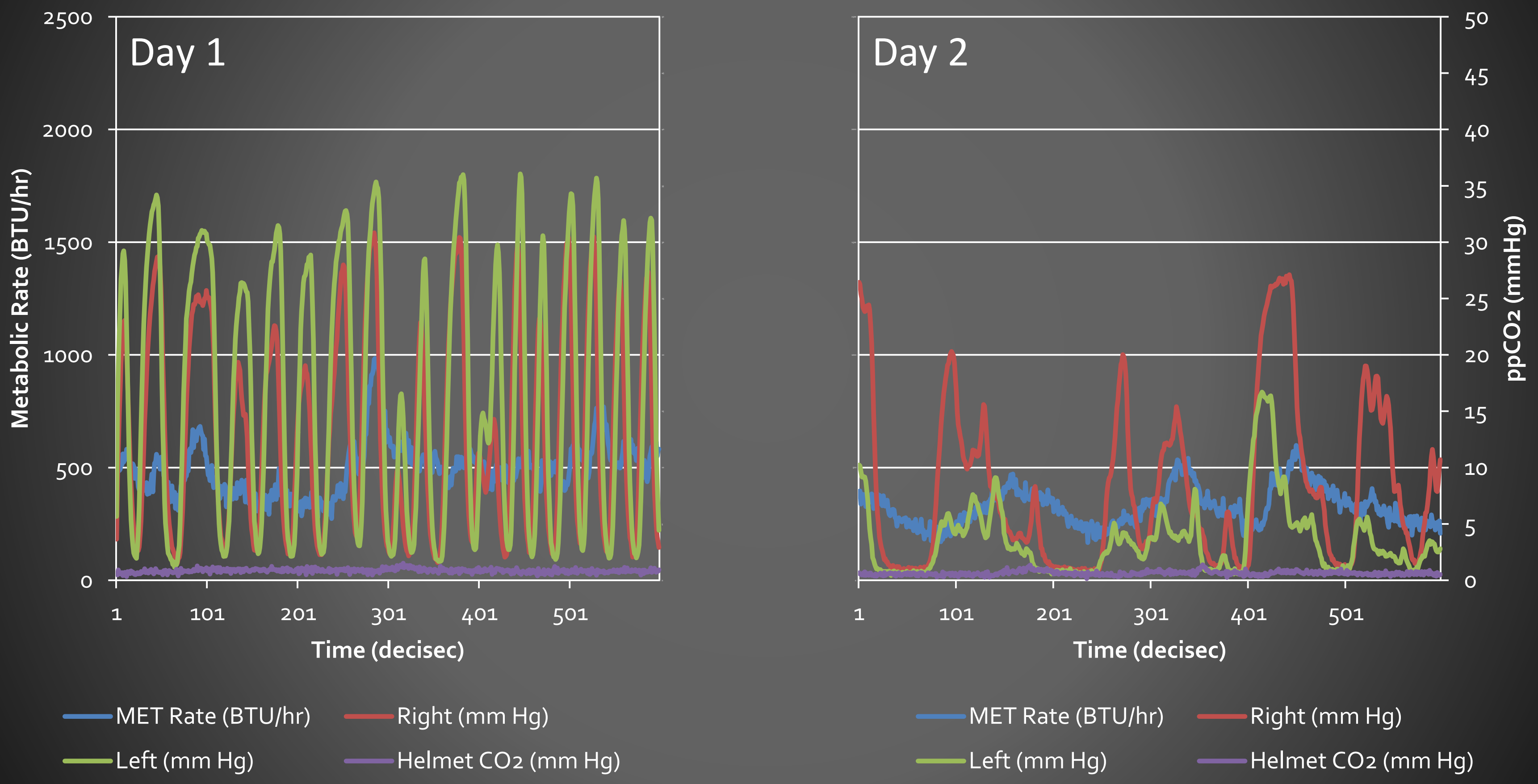
The oronasal analyzer from the right seems to be a bit consistent than the analyzer on the left

- Differences in tubes, fittings, analyzers, flow patterns, mask fit, rotameters
- Best solution is to average the data coming from both as this is what we have done with past test or possibly to consider using the data from the right side only and comparing
  - Numerical differences were not very large with this comparison
- Could be alleviated with some data collection changes
  - Use suit flow to drive air into CO_2 analyzer
    - Need to determine if increased pressure truly affected CO_2 analyzer integrity
  - Use vacuum pump to drive air into CO_2 analyzer
    - Need larger rotameters - needs 1.5-2.0 l/min flow out instead of 1 l/min
    - We need to sample deeper into the outlet using more consistent placement

Differences between tests and between subjects are still fairly small numerically, although this is quite a bit of variation graphically

Subject Induced Variability

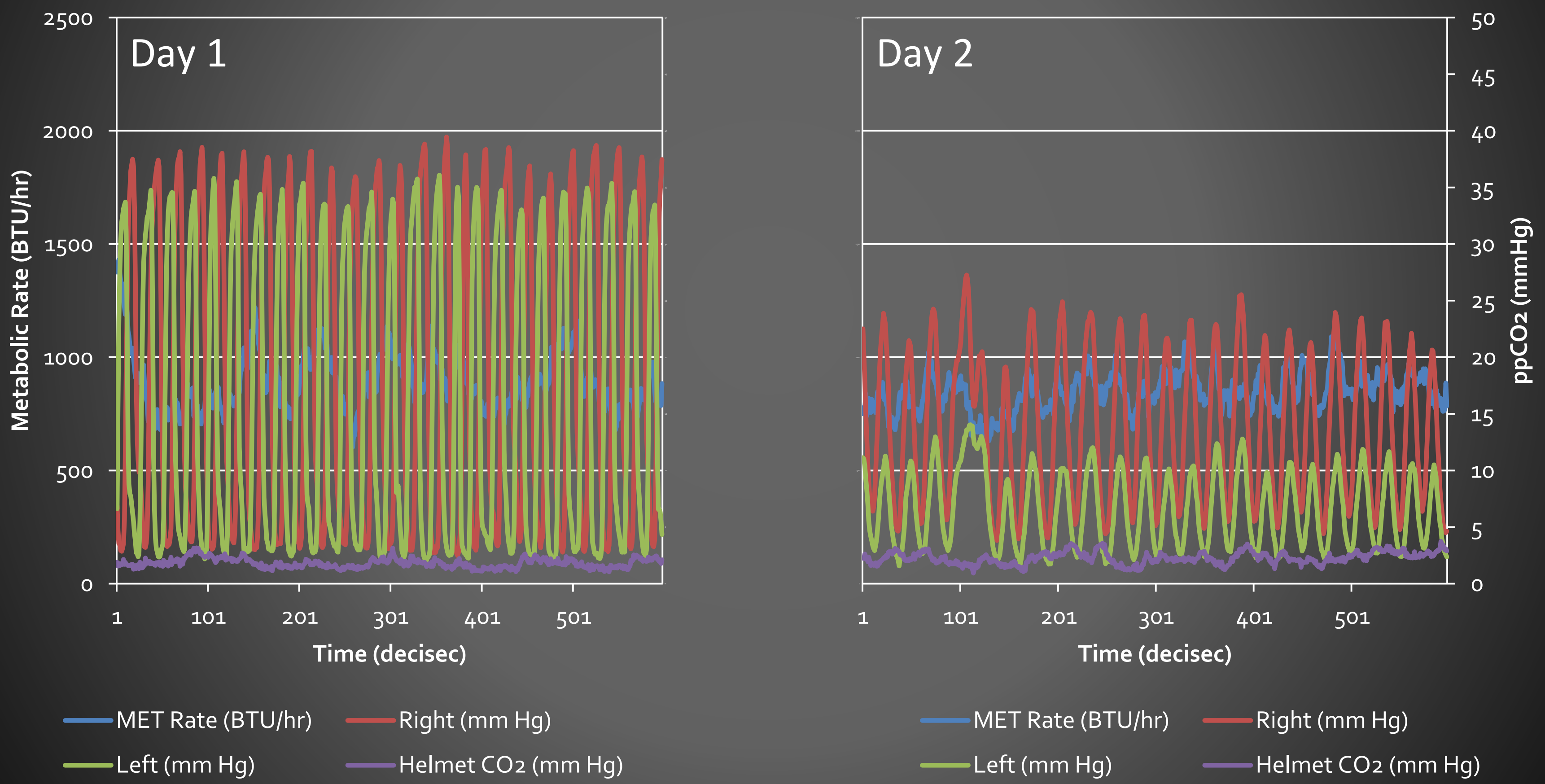
Rest – 6 ACFM



Large Day to Day Variance Example

1000 BTU/hr – 6 ACFM

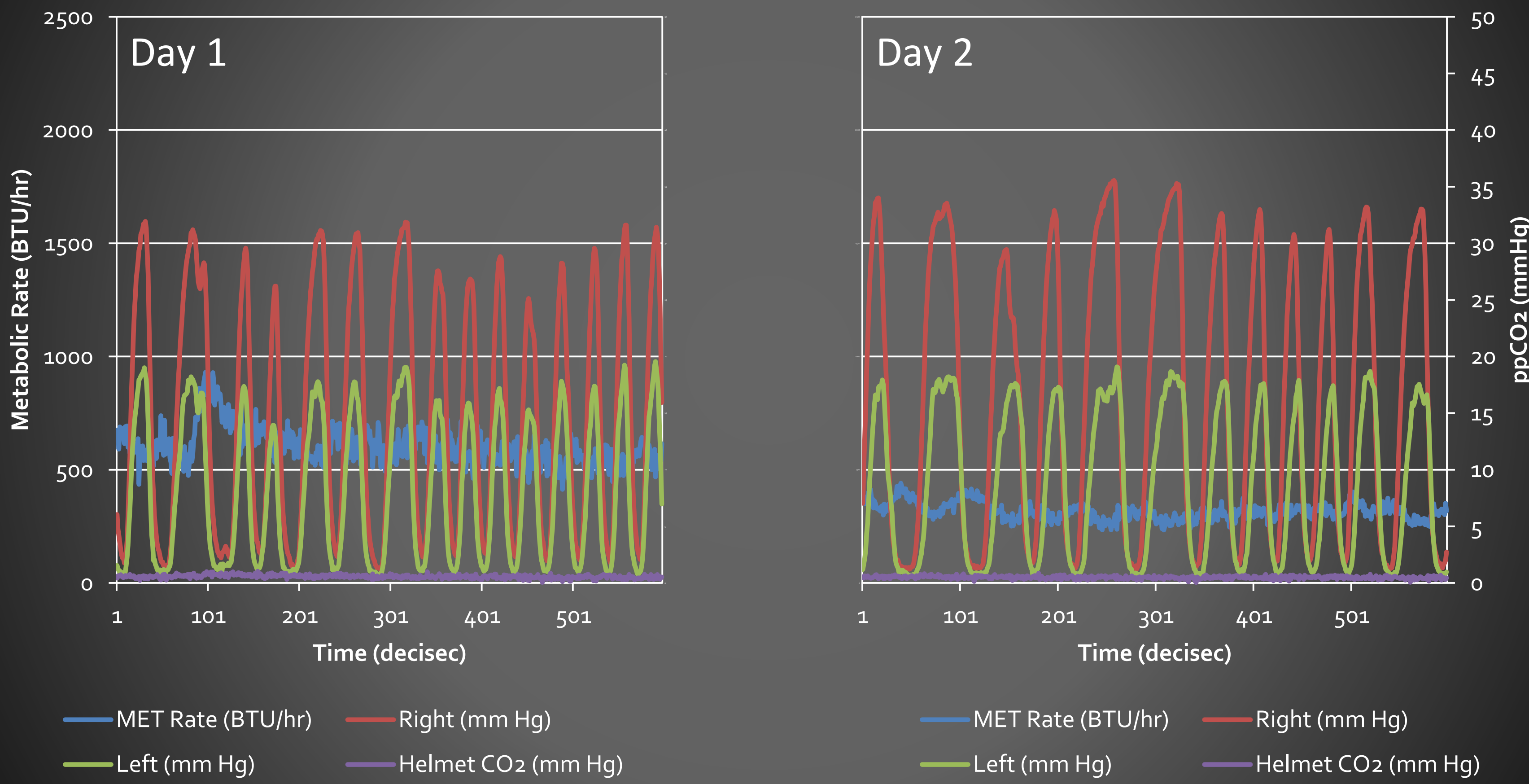
- likely a methods issue



Left to Right Variance Example

Rest – 5 ACFM

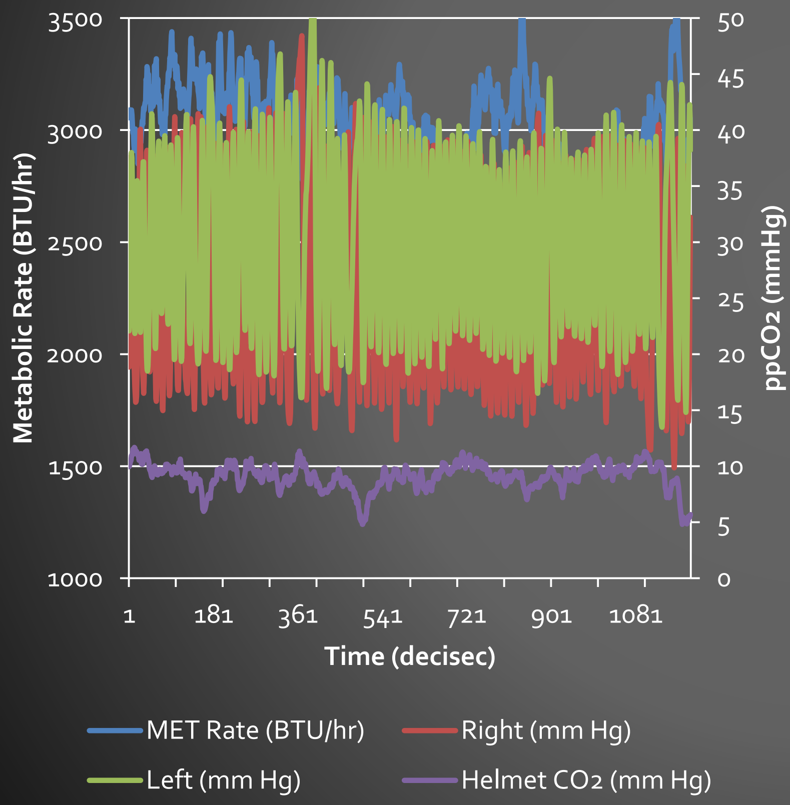
- likely a methods issue (not seen in all tests)



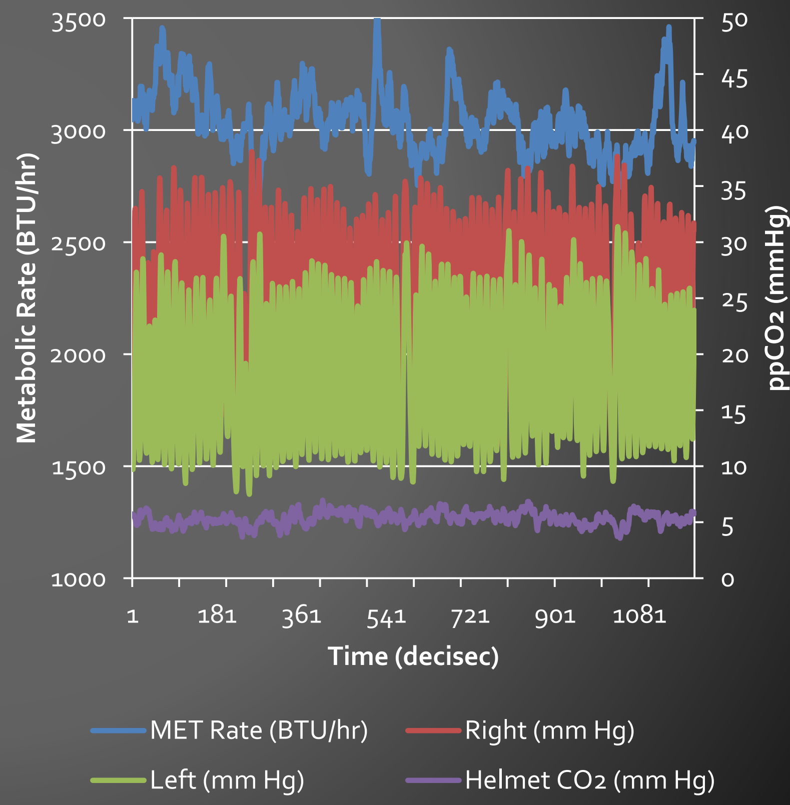
Average Test Variability

3000 BTU/hr – 6 ACFM

Day 1



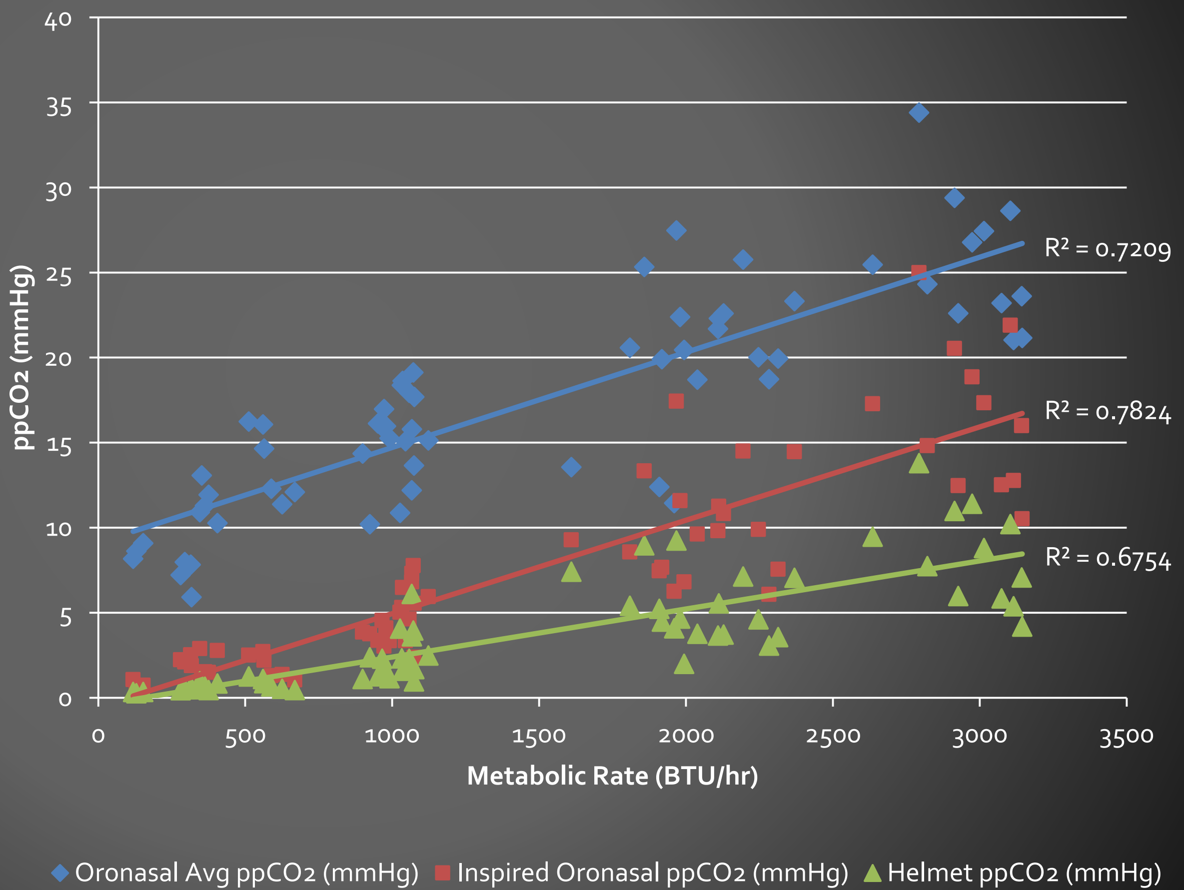
Day 2



Z-1 Met rate vs. $ppCO_2$

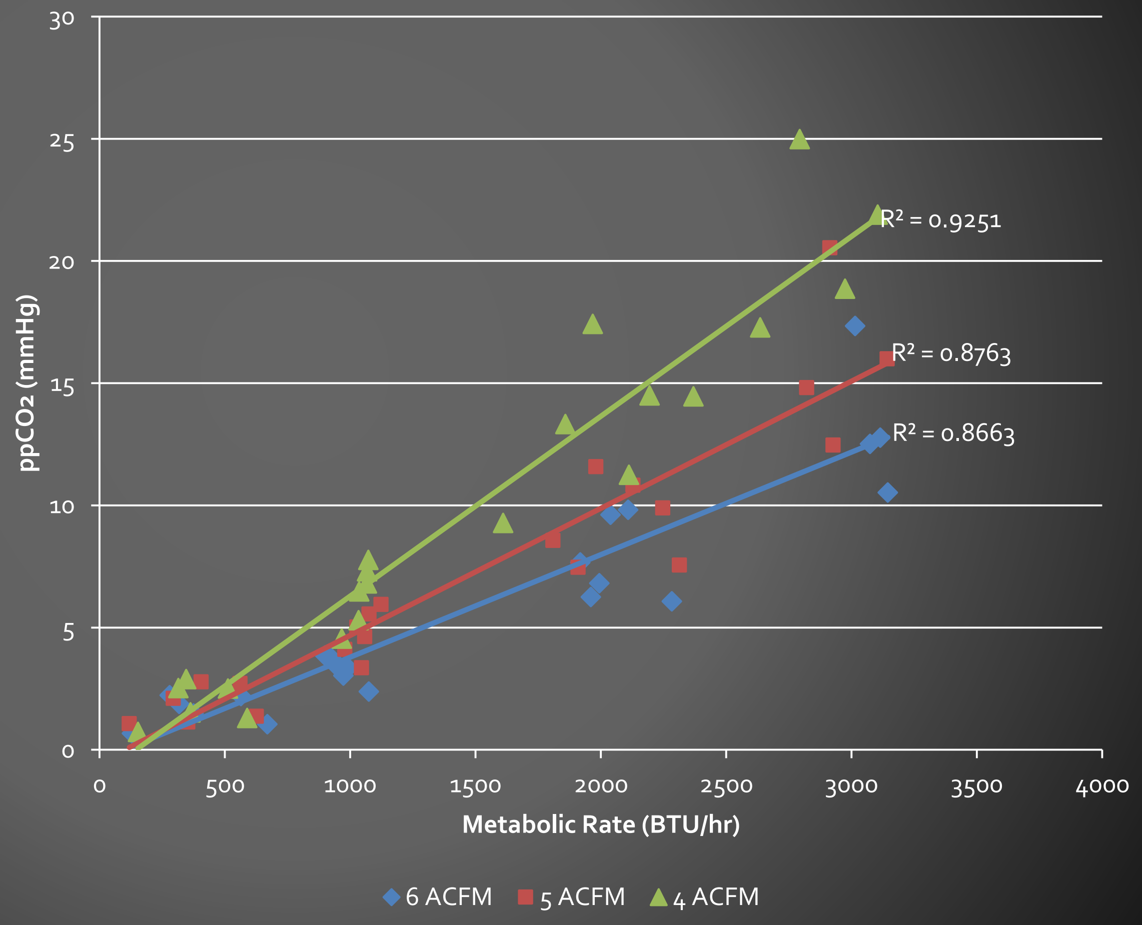
Metabolic rate is the primary driver for CO_2 production

Clearer differences are seen when flow rate is considered

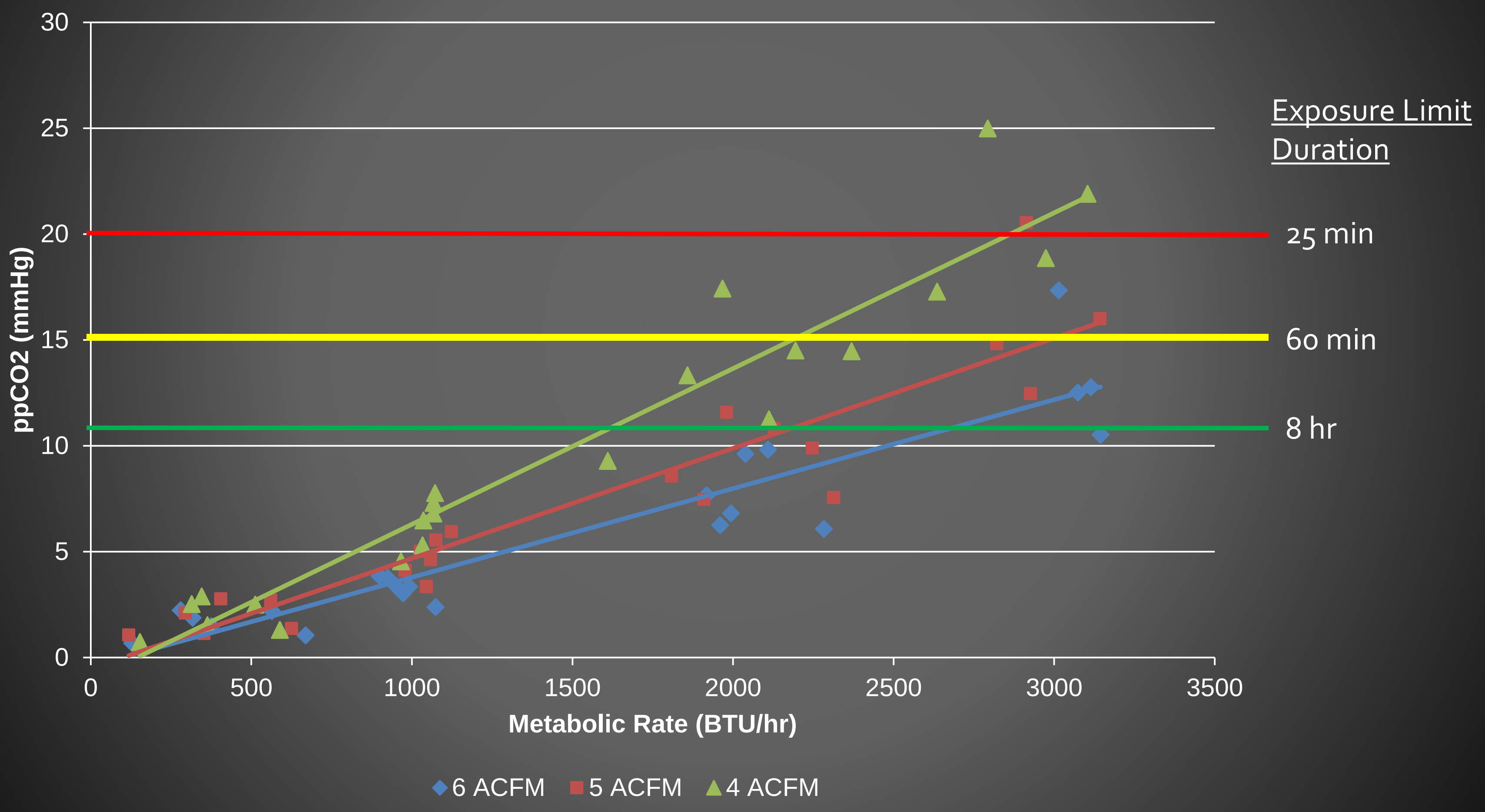


Z-1 Flow effects on oronasal $ppCO_2$

Flow has a notable effect on oronasal CO_2 washout at all flow rates at met rates > 1000 BTU/hr



Z-1 CO_2 Washout Implications



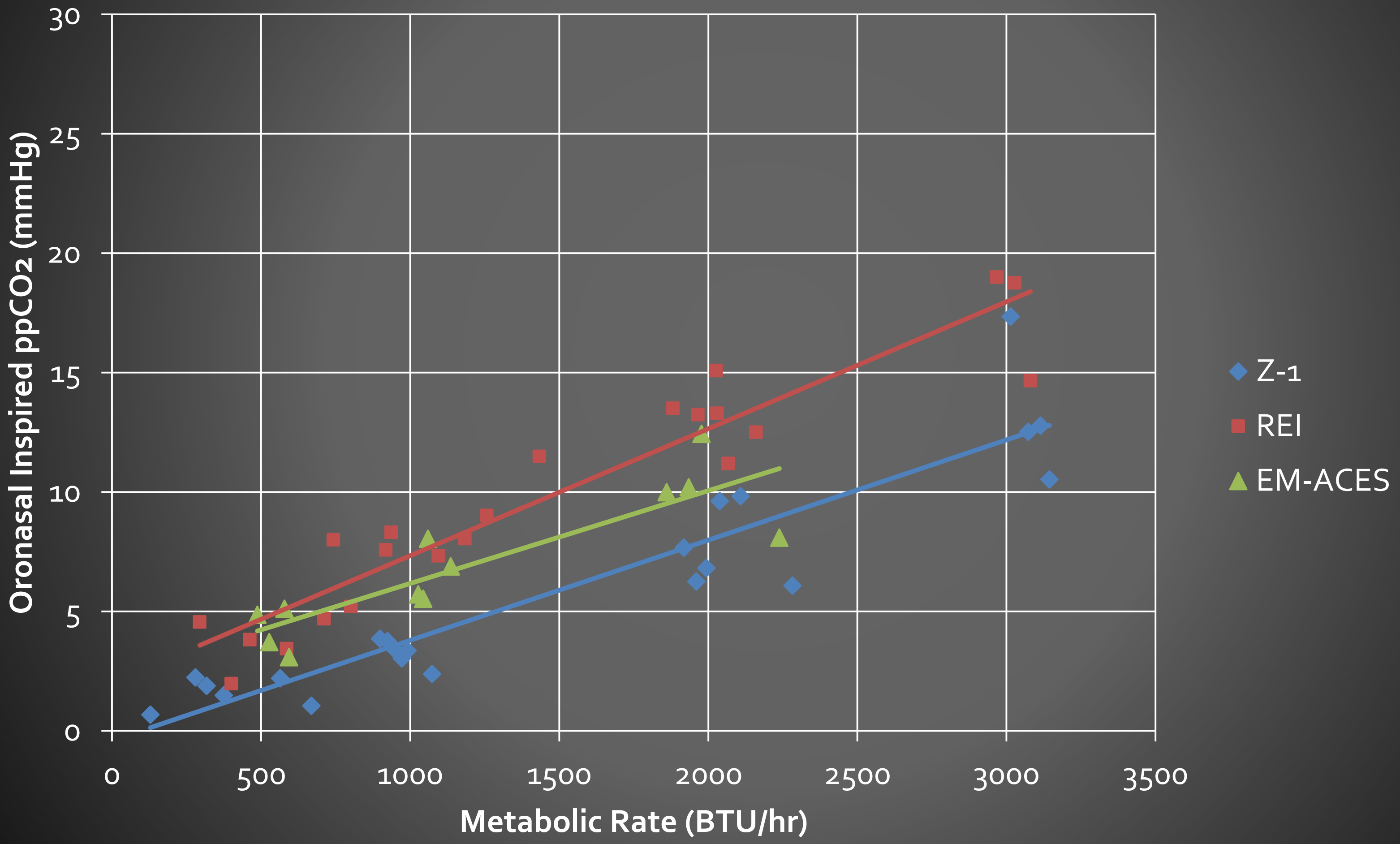
EVA Suit CO_2 Washout Comparisons

REI Suit

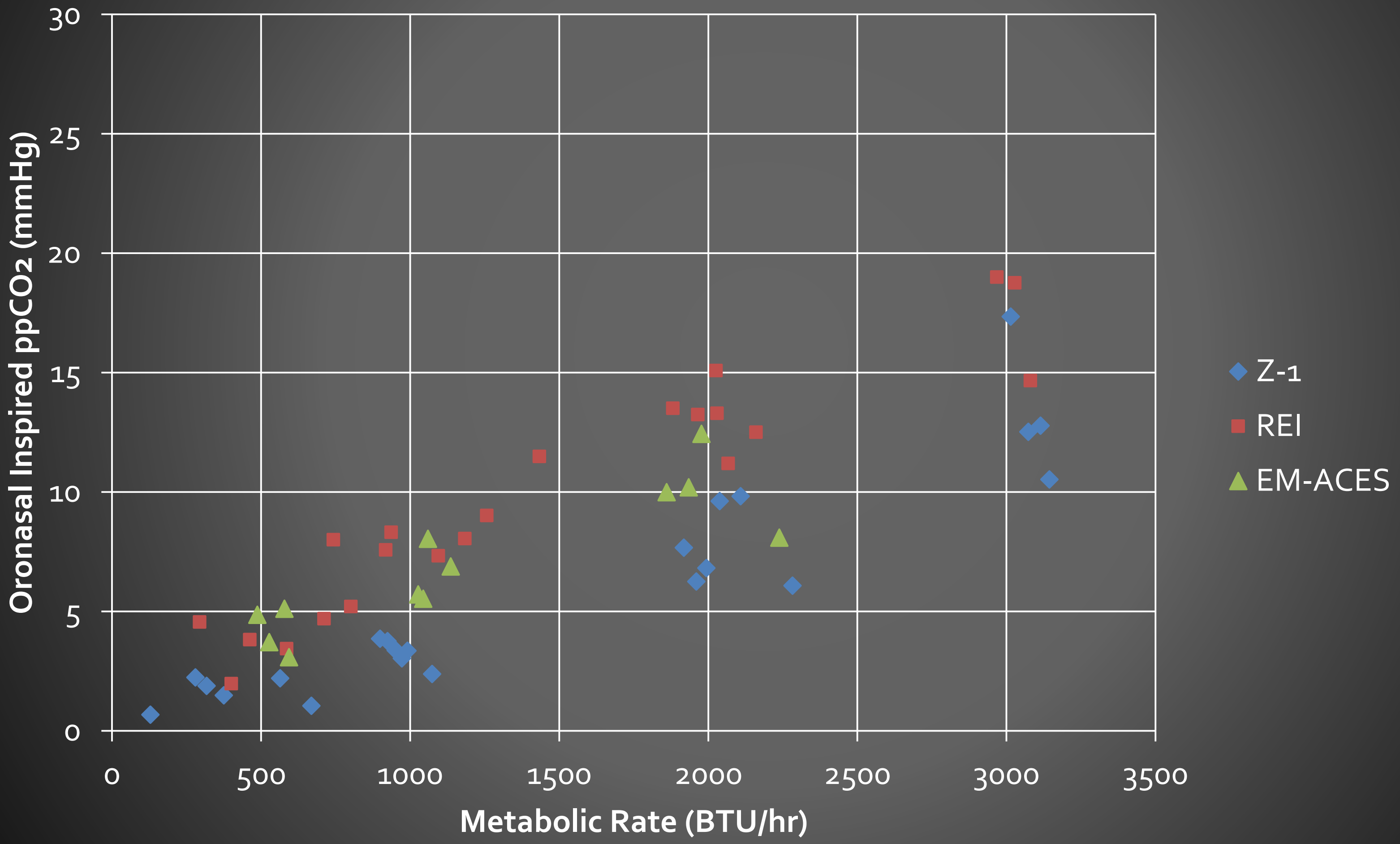
EM-ACES

Z-1

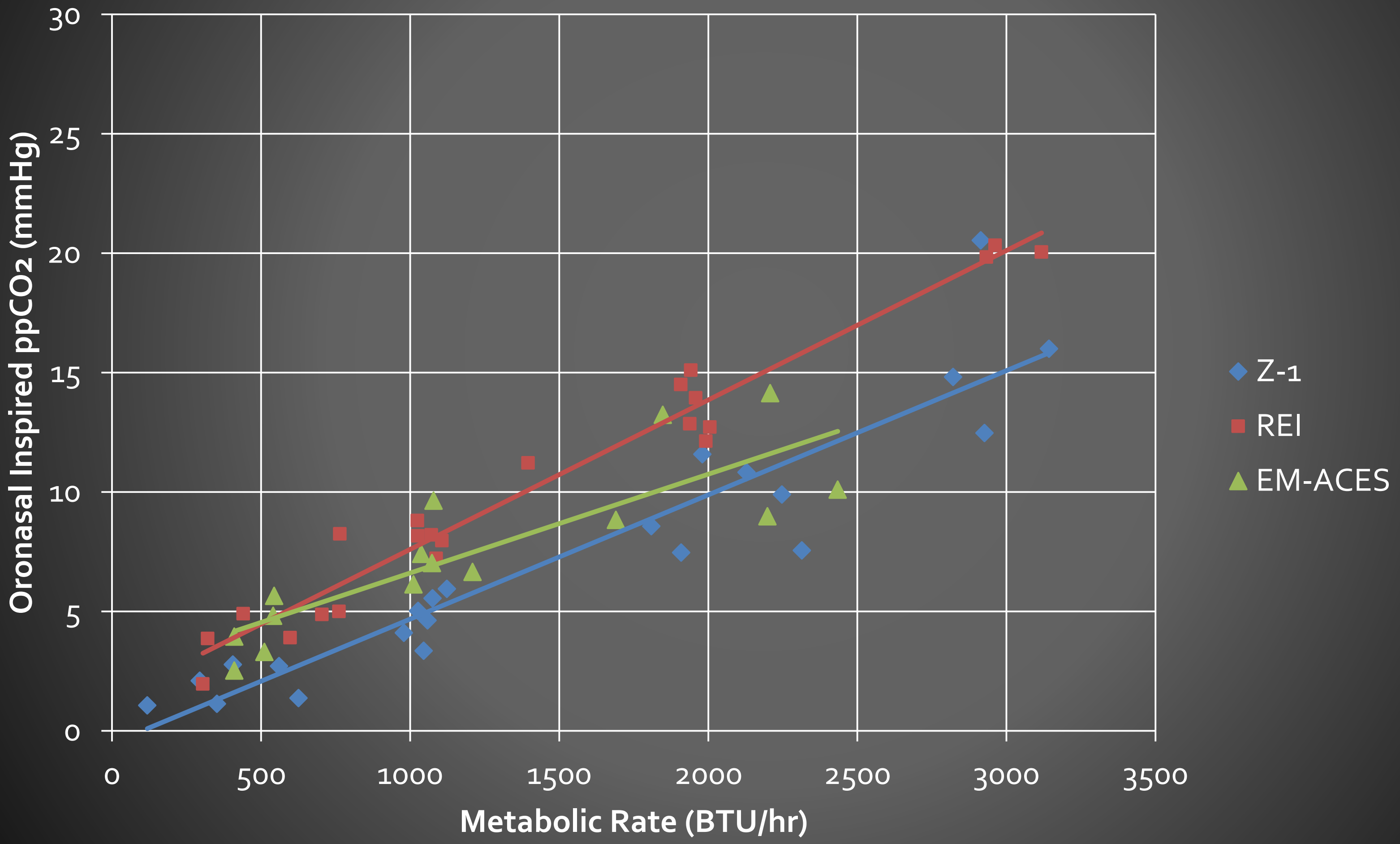
6 ACFM – Suit Comparison



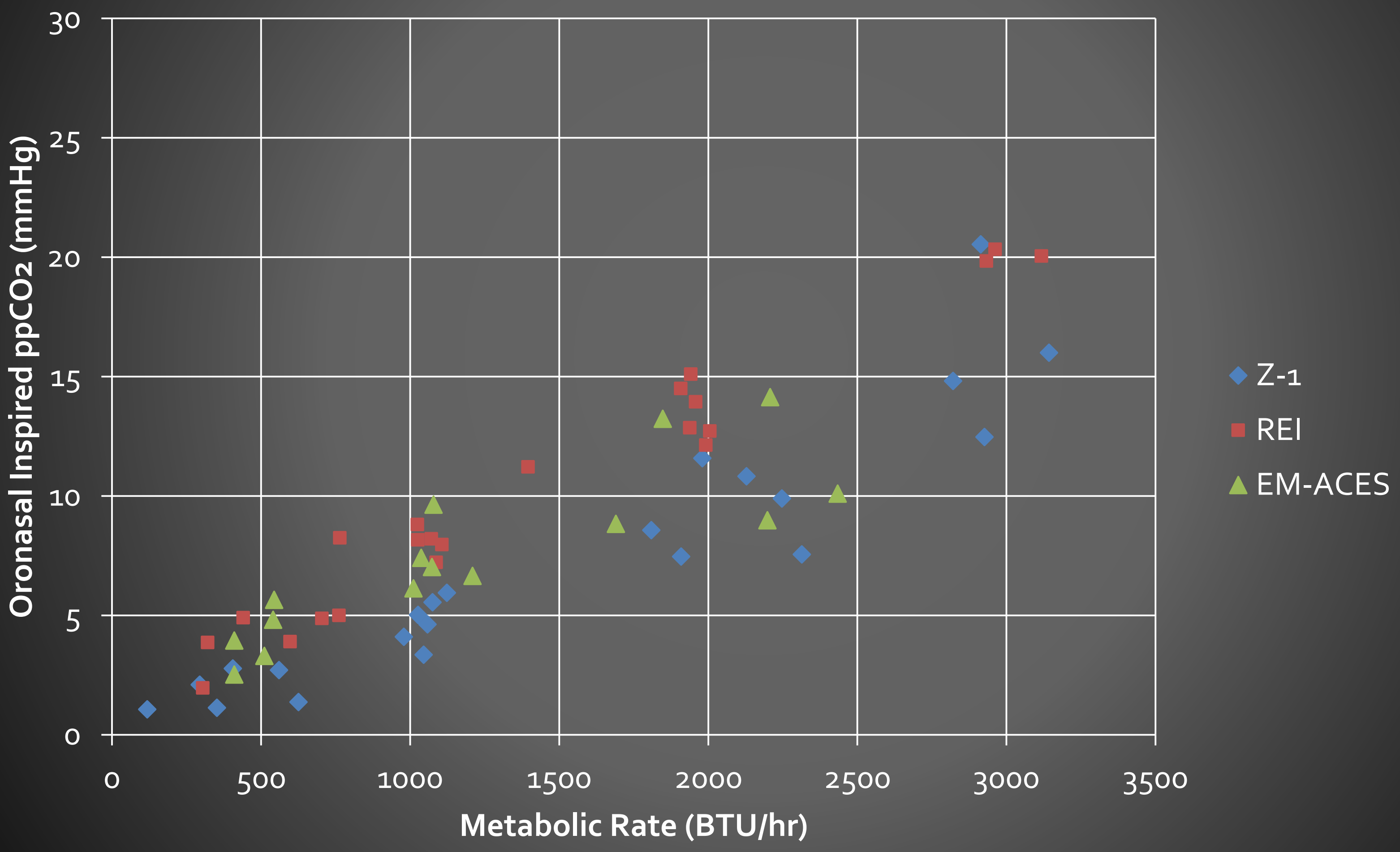
6 ACFM – Suit Comparison



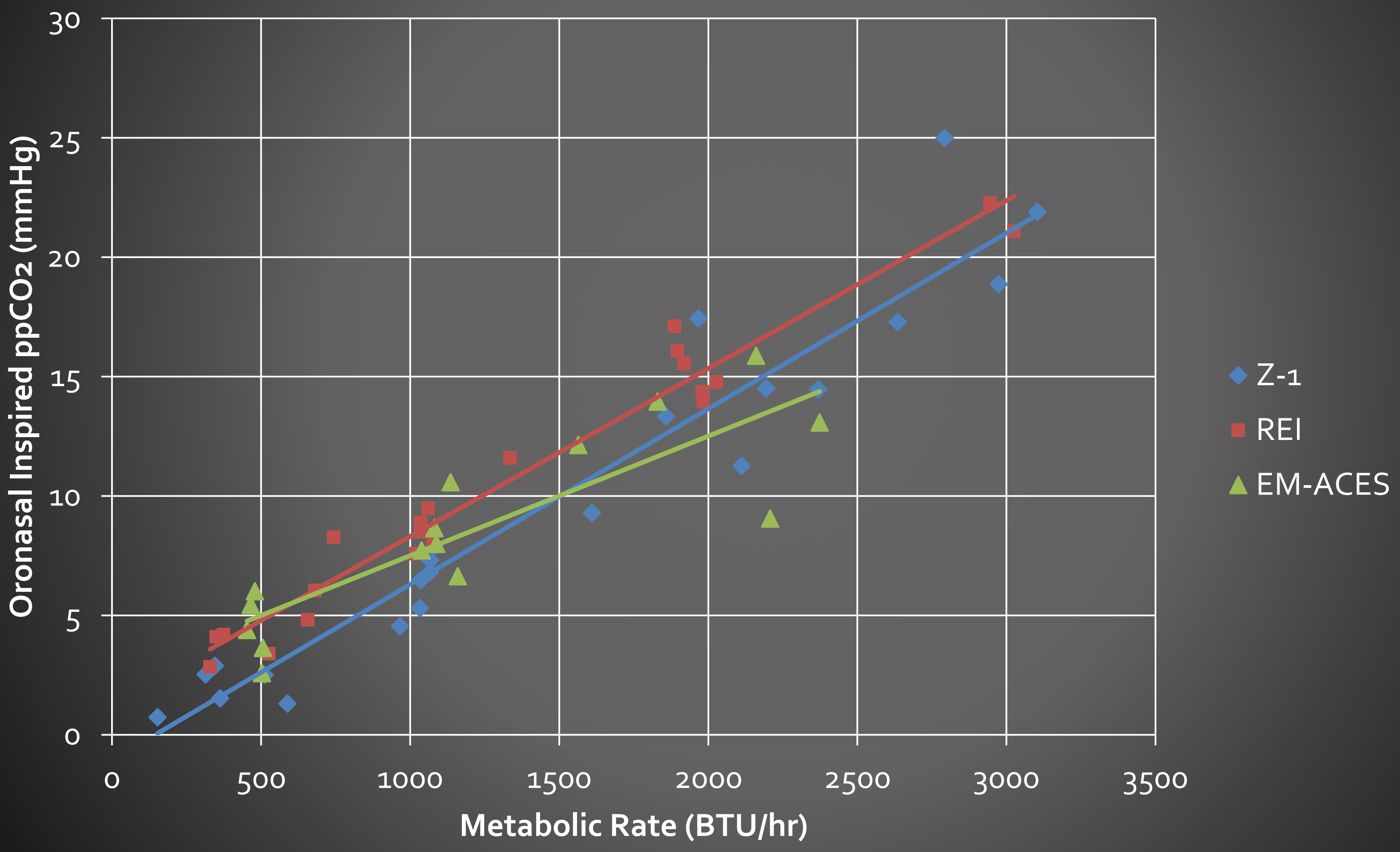
5 ACFM – Suit Comparison



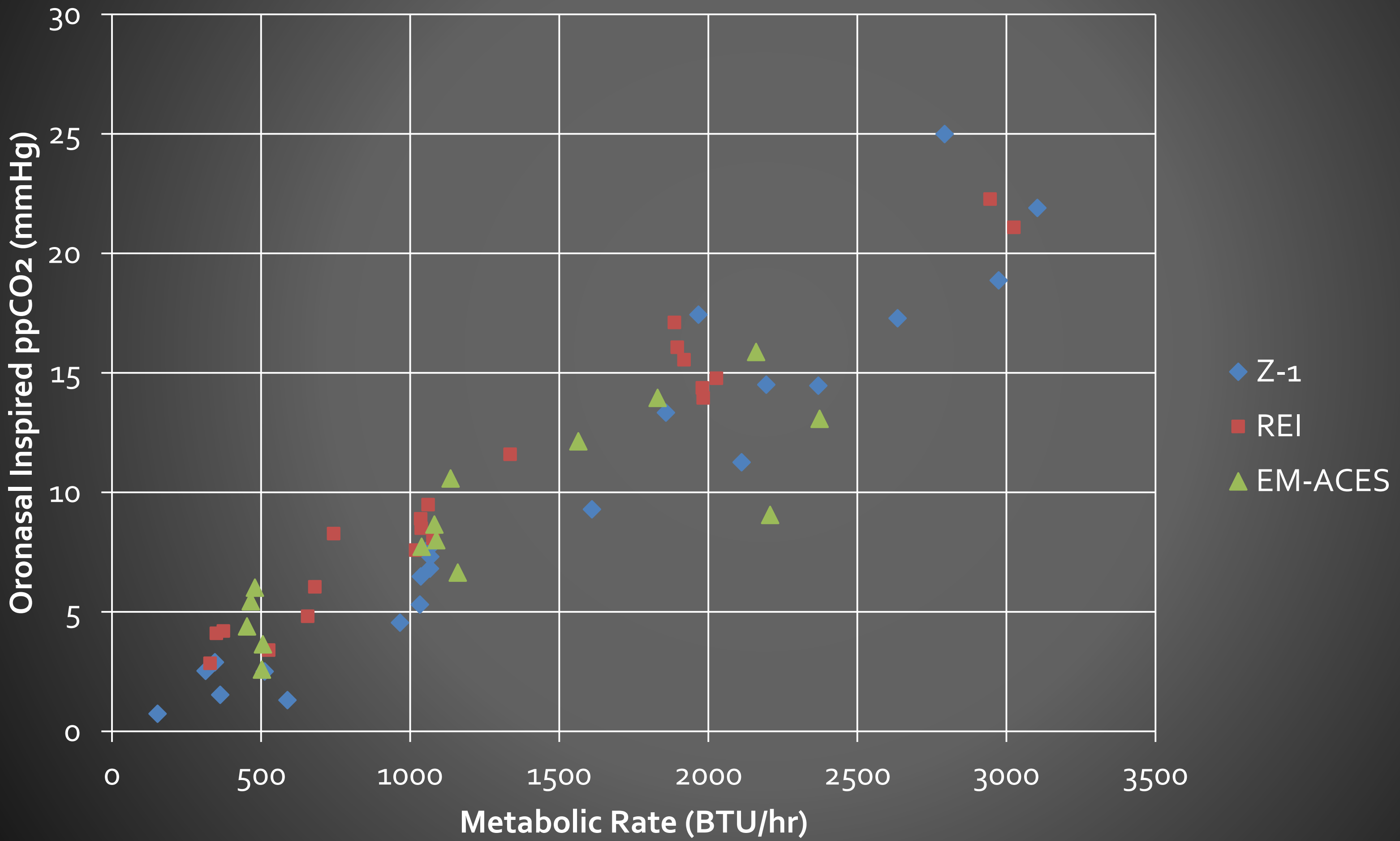
5 ACFM – Suit Comparison



4 ACFM – Suit Comparison



4 ACFM – Suit Comparison



ACES CO_2 Washout

Initial Results Quicklook

ACES Test Objectives

Primary Objective: Characterize the workloads, flow rates and suit pressures for which CO_2 is adequately washed away from the suited subject's oronasal area in several prototype spacesuits

- Immediate goal: Define acceptable workloads and flow rates for laboratory-based ground testing using vent and 4.3 psid test pressures

Secondary Objective: 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 design efforts

ACES CO_2 Washout Test Protocol

Test Variables

- Metabolic Rate: Rest, 1500 BTU/hr, 2500 BTU/hr
- Suit Flow: 6, 4, 2 SCFM
- Suit Pressure: 4.3 psid, vent pressure
- Head Position: looking left, straight and right (only at rest)

Test Order

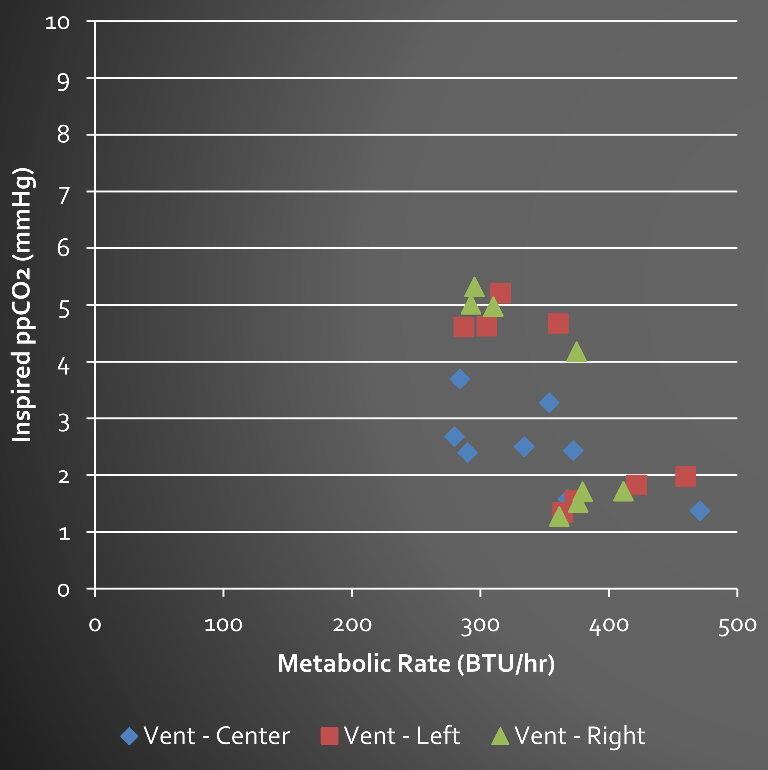
- Resting Conditions
  - Head Position at 4.3 psid and vent pressure
- Exercise at 4.3 psid
  - 1500 BTU/hr at 6, 4, 2 SCFM
  - 2500 BTU/hr at 6, 4 SCFM
- Exercise at vent pressure
  - 1500 BTU/hr at 6, 4, 2 SCFM
  - 2500 BTU/hr at 6, 4 SCFM

Other Parameters

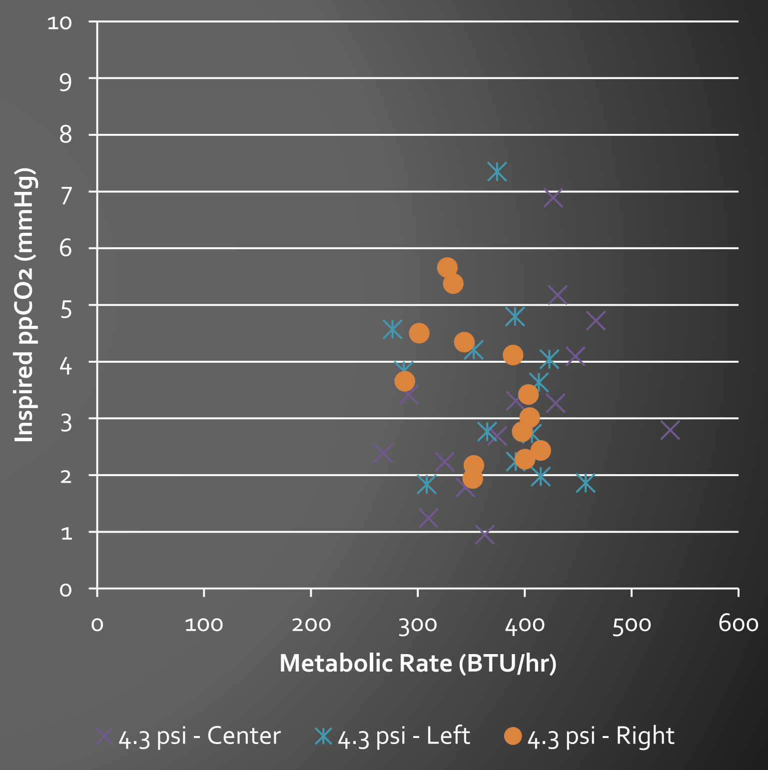
- 4 subjects total
- Some subjects repeated some test parameters
- Rest was in the mockup vehicle chair (lying on back with hips and knees ~ 90°
- 1500 and 2500 BTU/hr test point used arm ergometry

Head Position at Rest - ACES

Vent Pressure – no differences

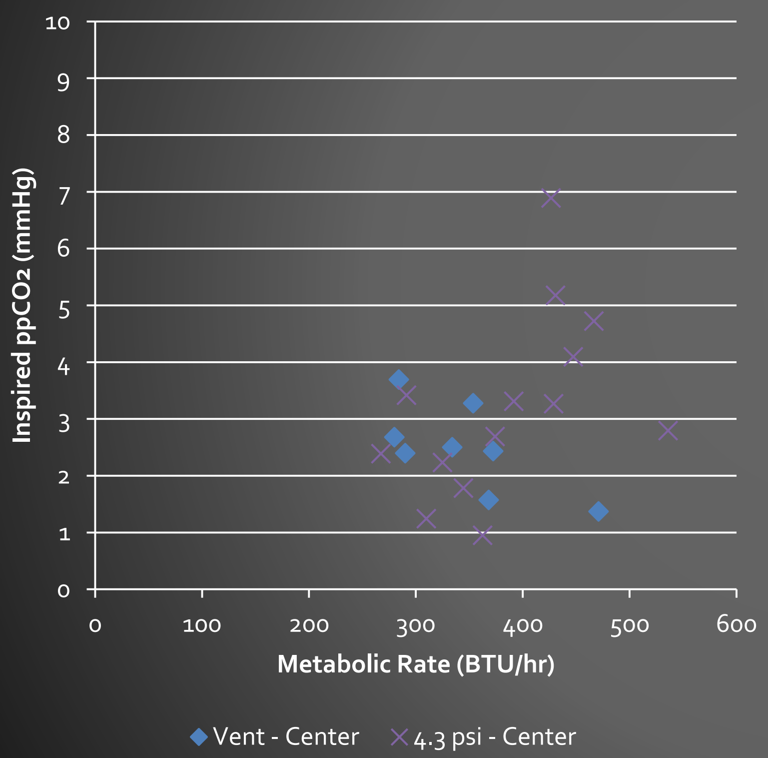


4.3 psi – no differences

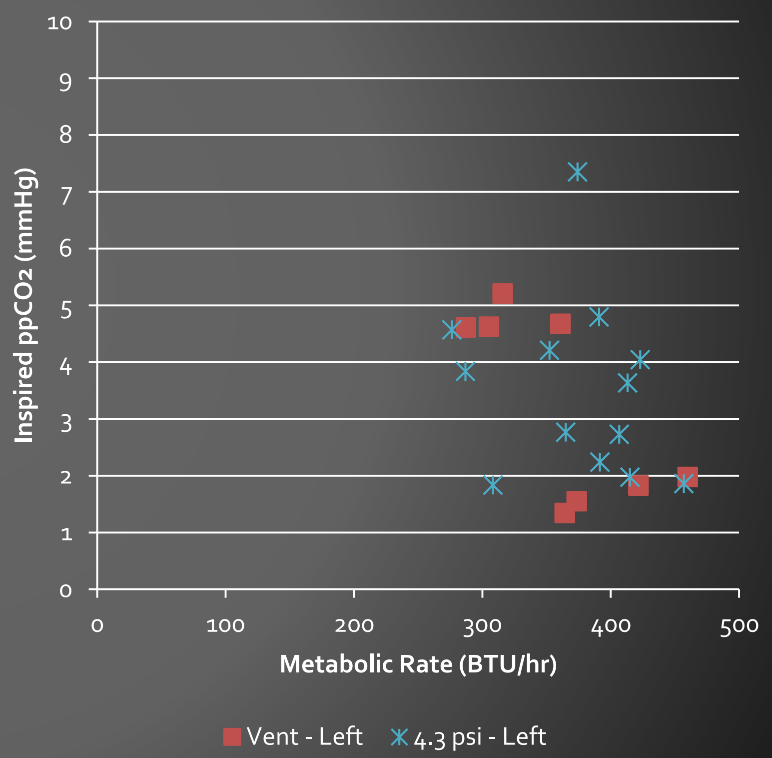


Pressure Effects – Rest w/ ACES

Center – no differences

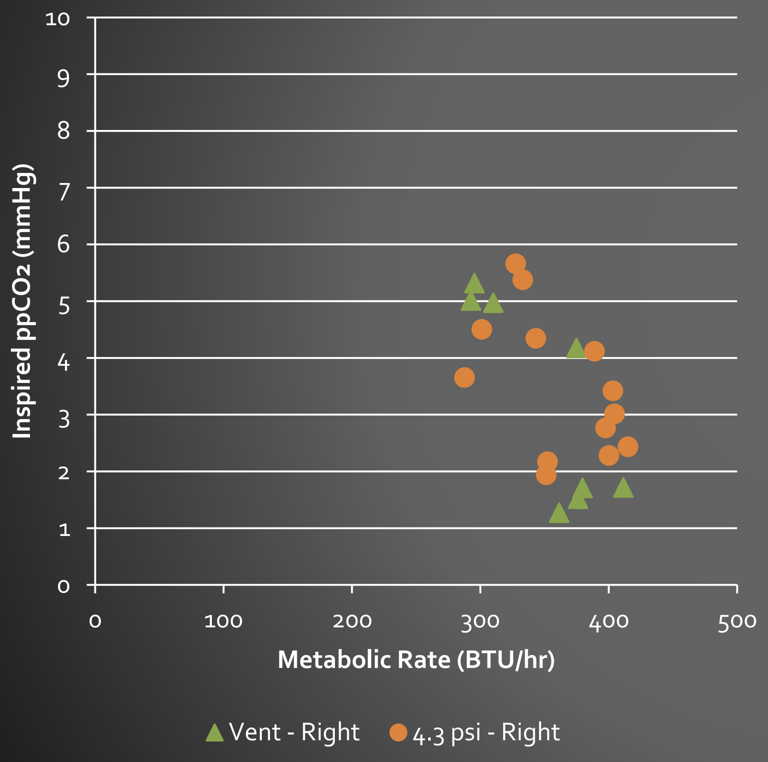


Left – no differences



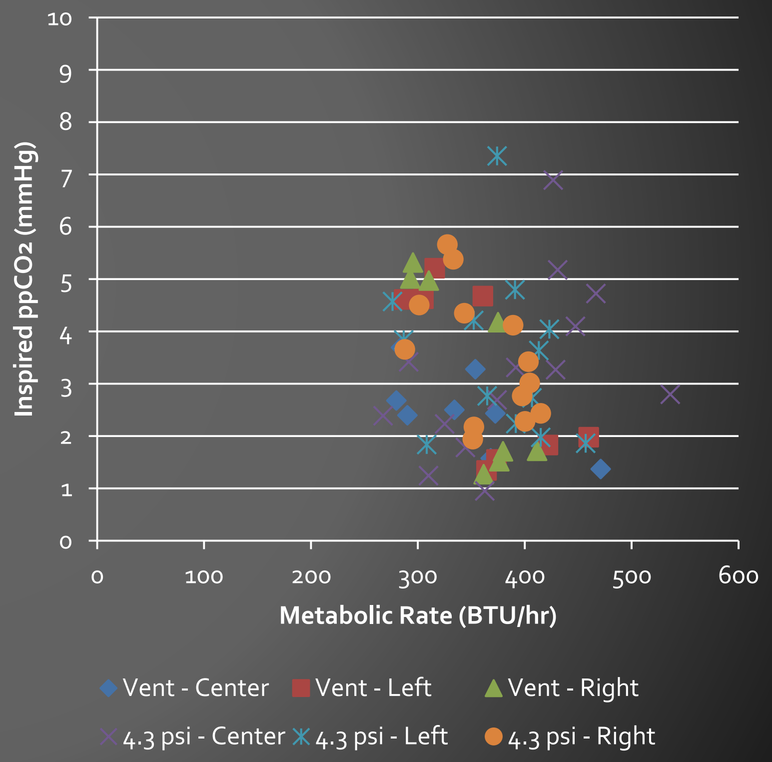
Pressure Effects – Rest w/ACES

Right - No differences



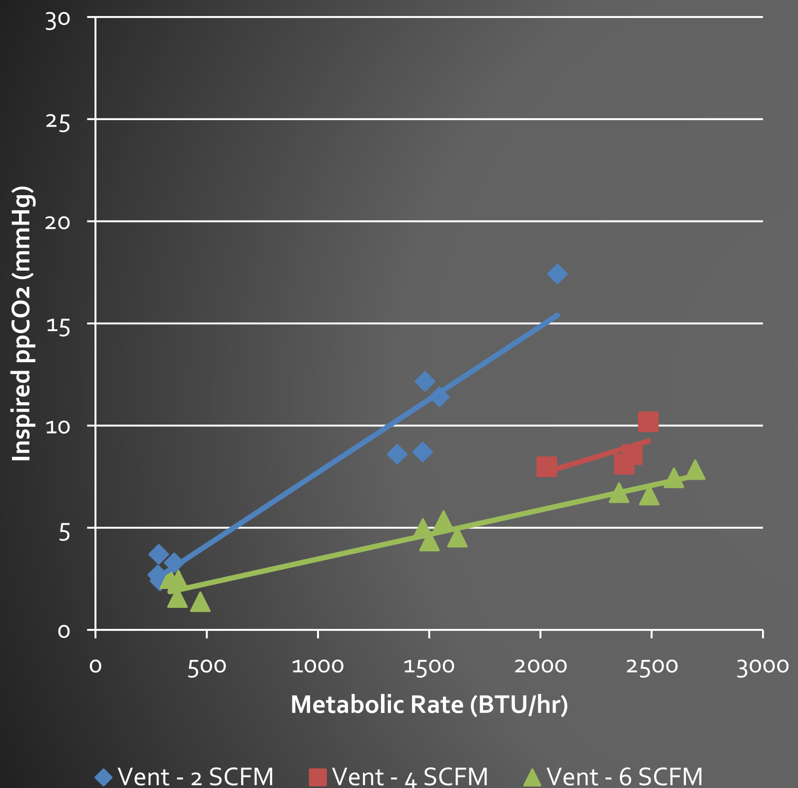
<u>All Resting Data</u>

No differences. All data is widely overlapping.

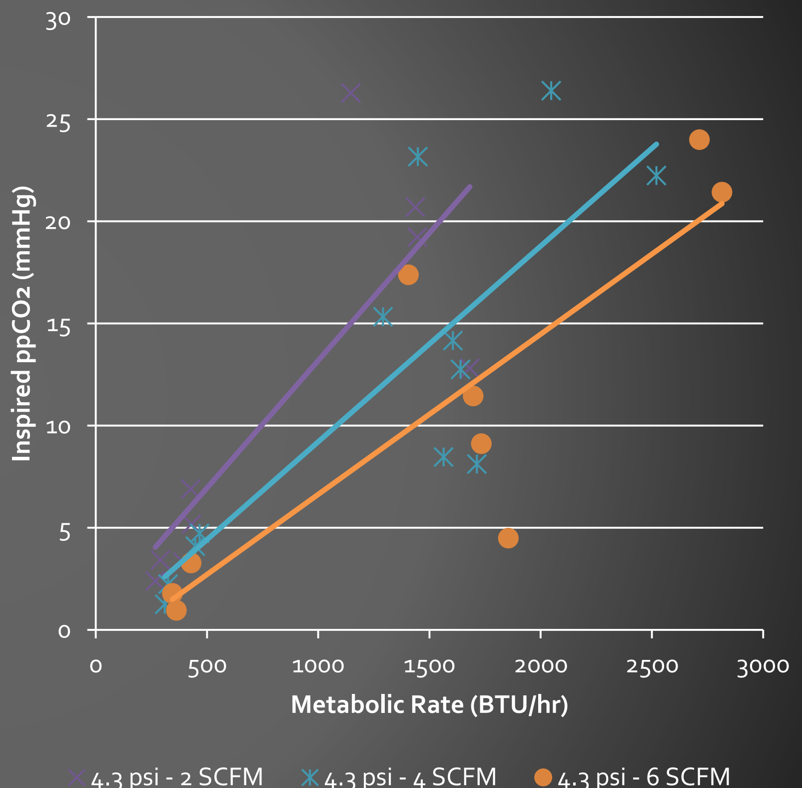


CO_2 Washout – Flow Effects w/ACES

Vent



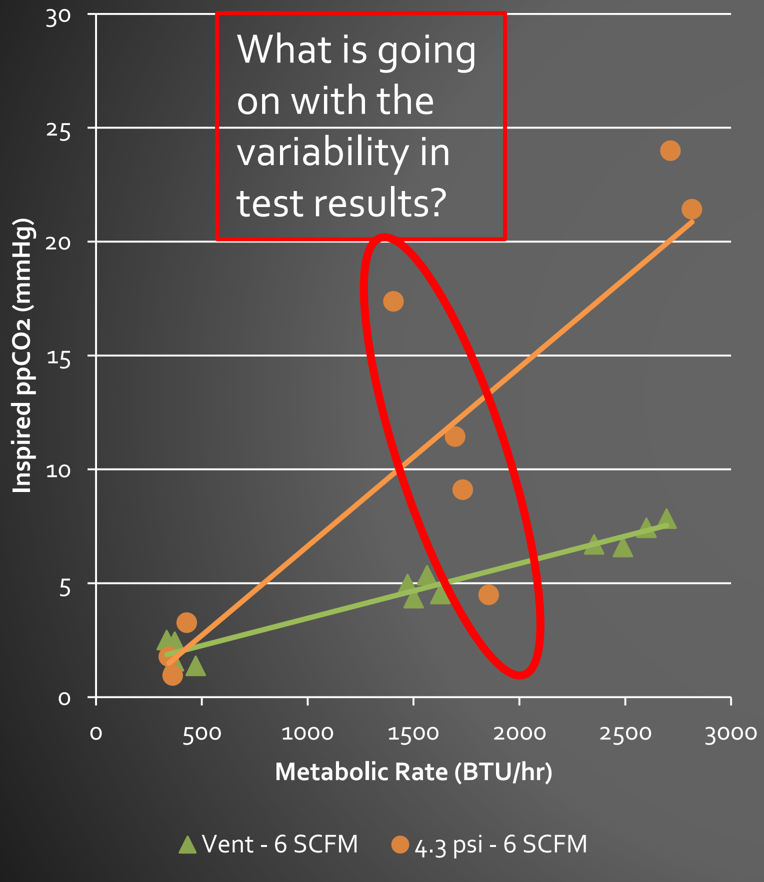
4.3 psi



Results clearly show that at metabolic rates > rest, flow impacts CO_2 washout performance

Results show an improvement with CO_2 washout with increased flow, but results are widely different at the 1000-2000 BTU/hr range, which limits predictive reliability

CO_2 Washout – Pressure Effects w/ACES



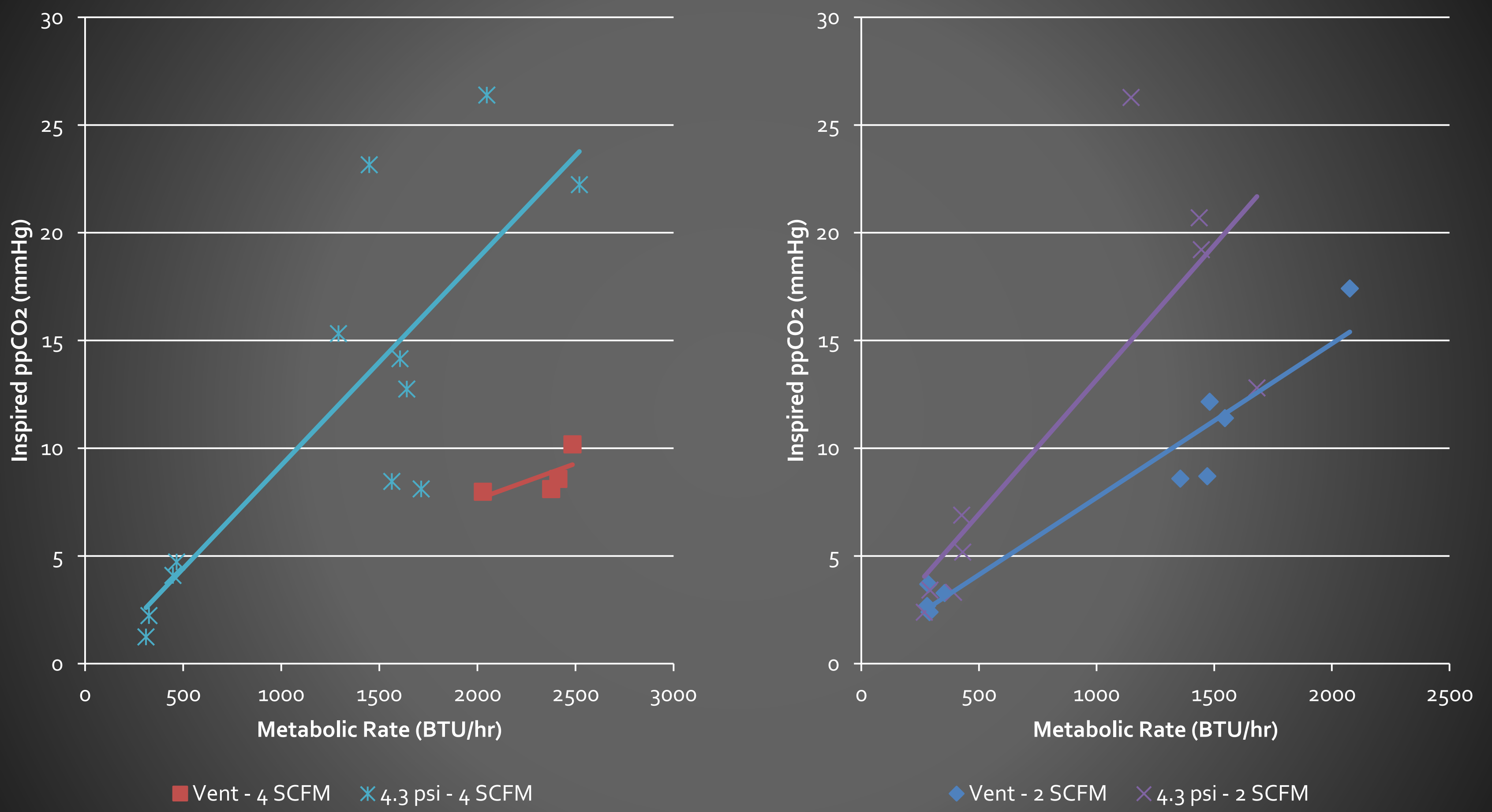
Results clearly indicate the likelihood that pressure affects CO_2 washout

- Maybe back pressure limits flow out of the helmet?
- Suit fits differently when pressurized, which may affect head position

Wide variability at 1500 BTU/hr data point

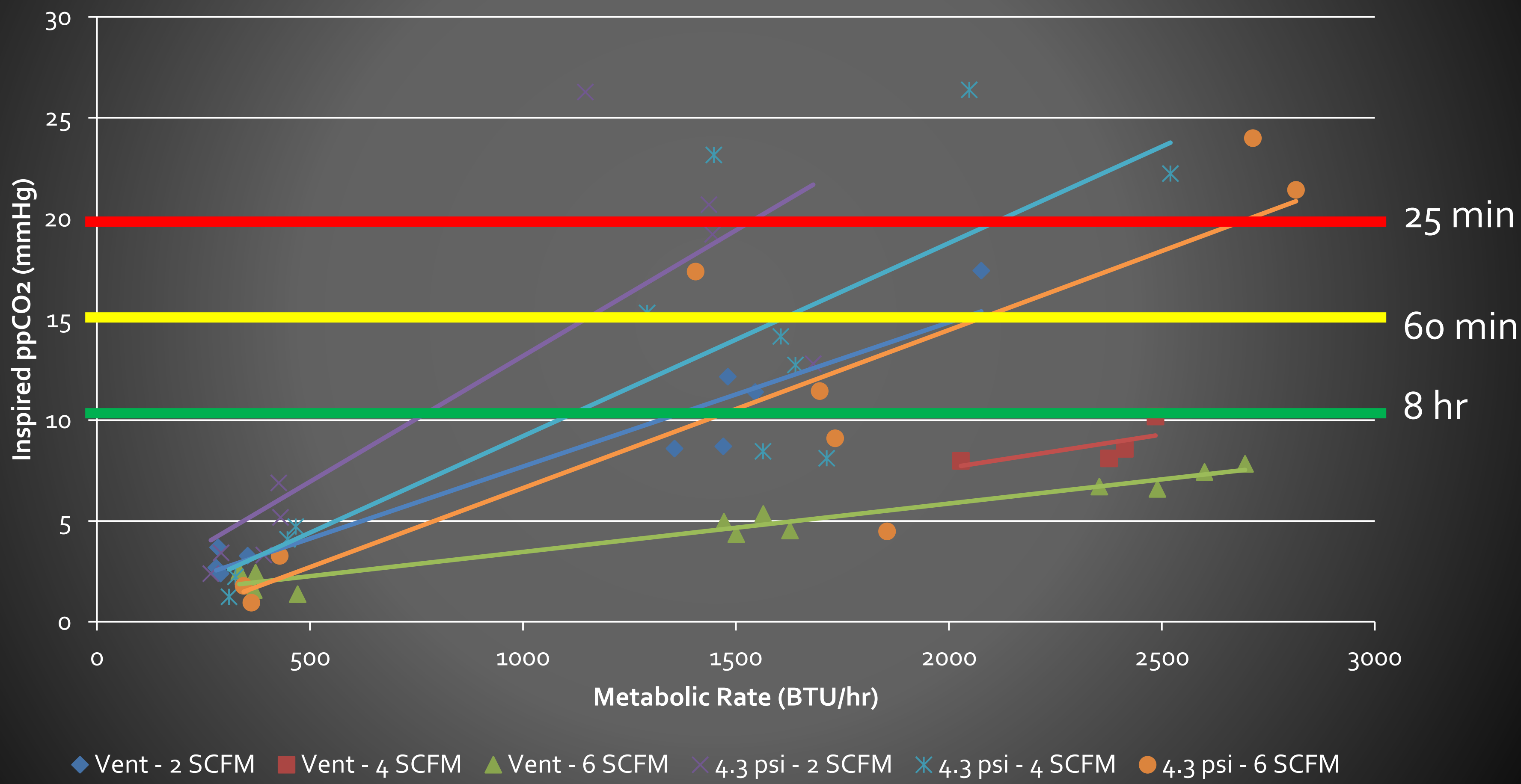
- Head position in suit?
- DAQ issues?

CO_2 Washout – Pressure Effects w/ACES



The pressure difference seems to be independent of flow rate with CO_2 washout much better at vent pressure than at 4.3 psi

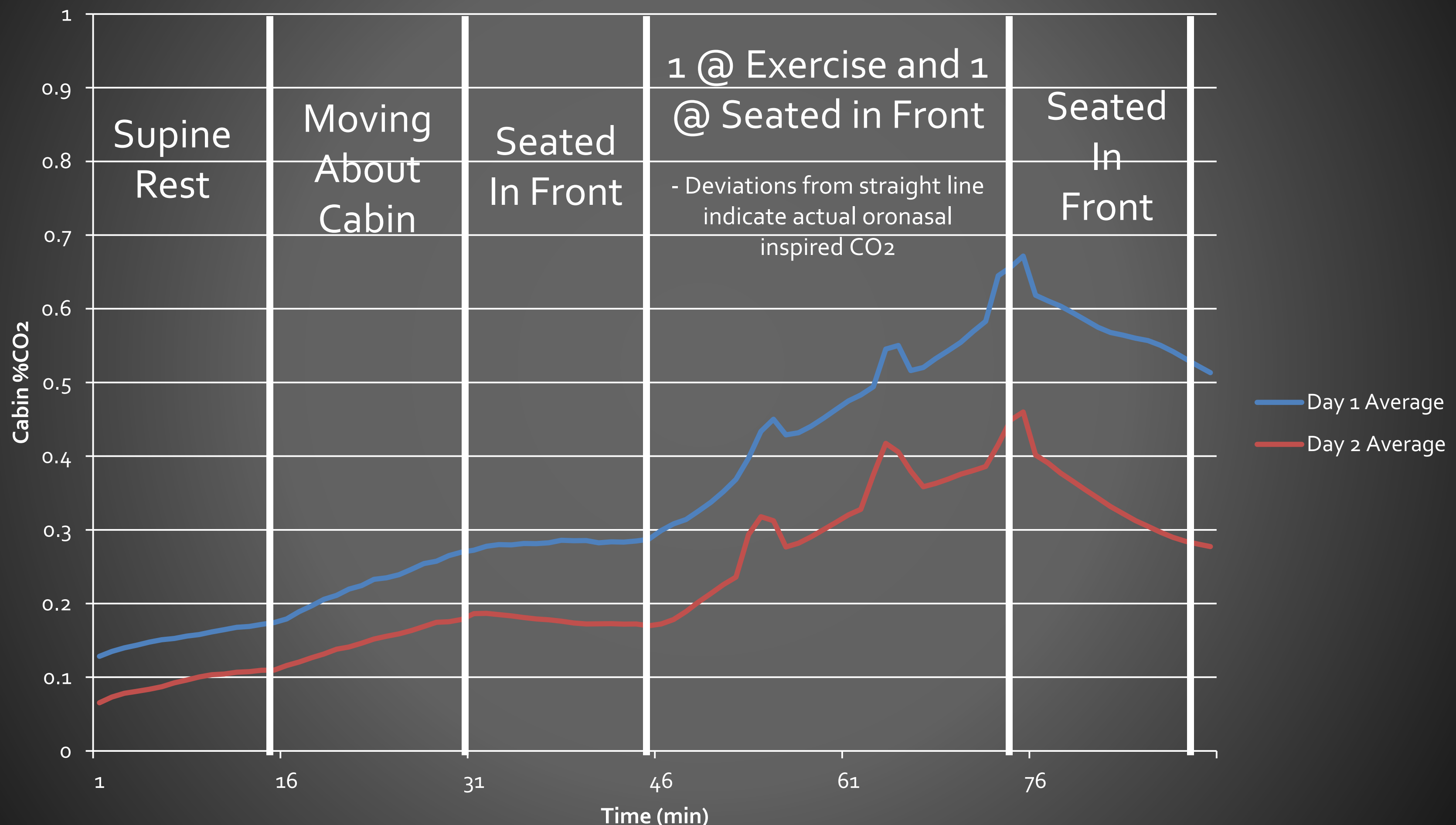
CO_2 Exposure Limits



MMSEV CO_2 Washout

Purpose – inform requirements for MMSEV habitability testing and to provide initial feedback on changes to the cabin ventilation system

MMSEV CO_2 Washout



- All data was for 2 subjects in MMSEV with hatches and suitports closed
- MMSEV CO_2 washout was markedly improved after adjustments to the ventilation system

Lessons Learned

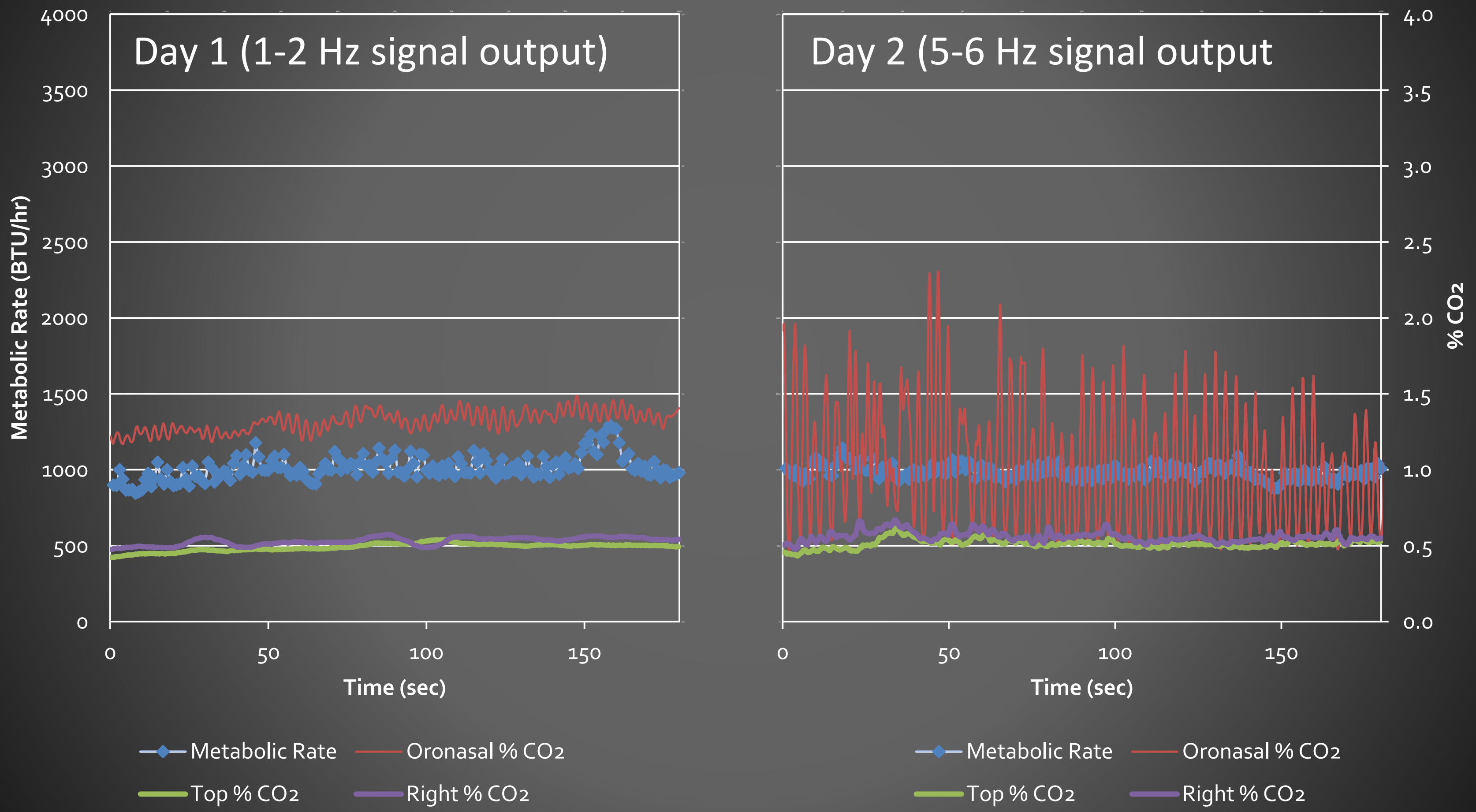
Oronasal Mask

Sampling Rate for Oronasal CO_2

Integrated DAQ System

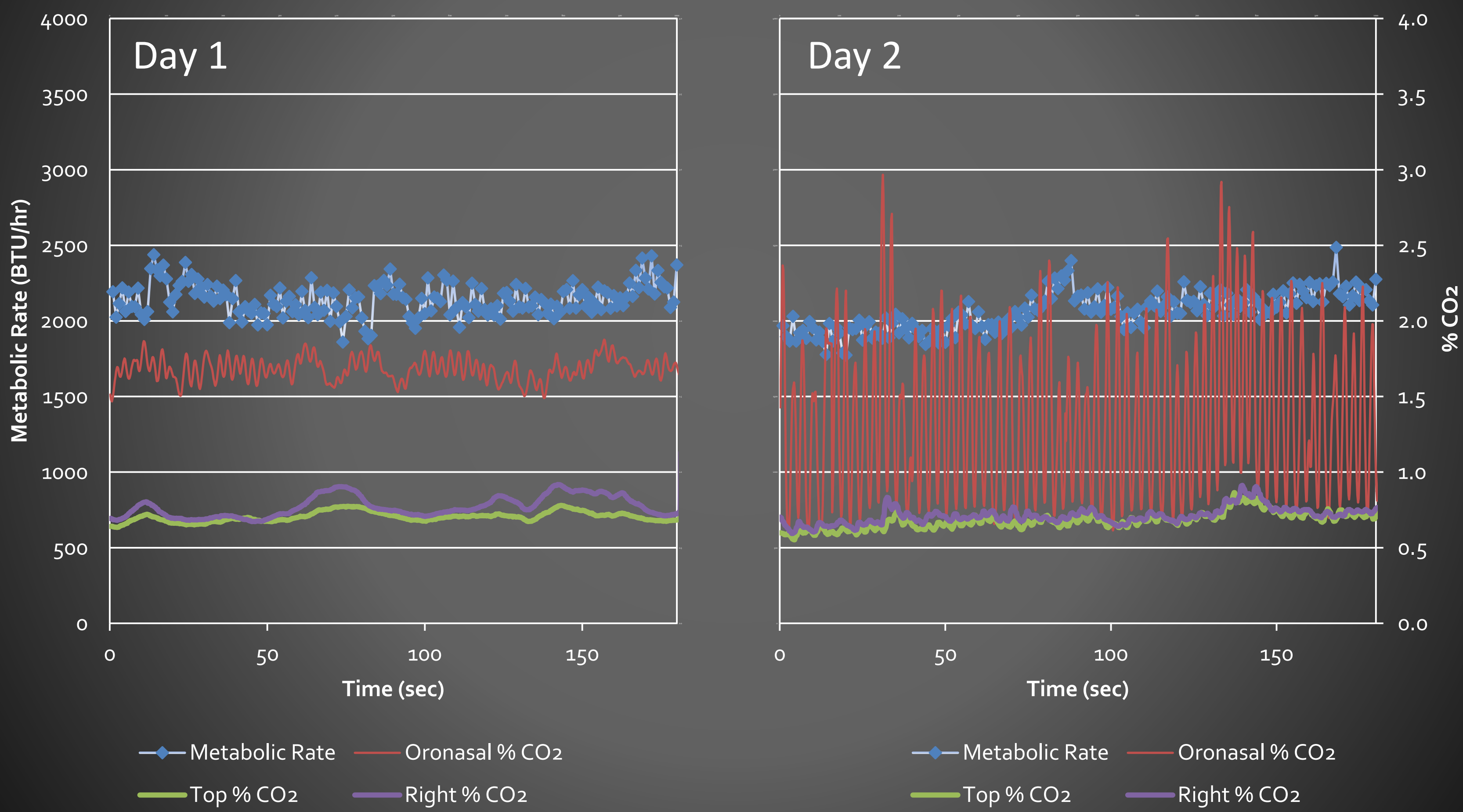
Initial CO_2 Sensor Placement

Example Difference 1000 BTU/hr – 4 ACFM



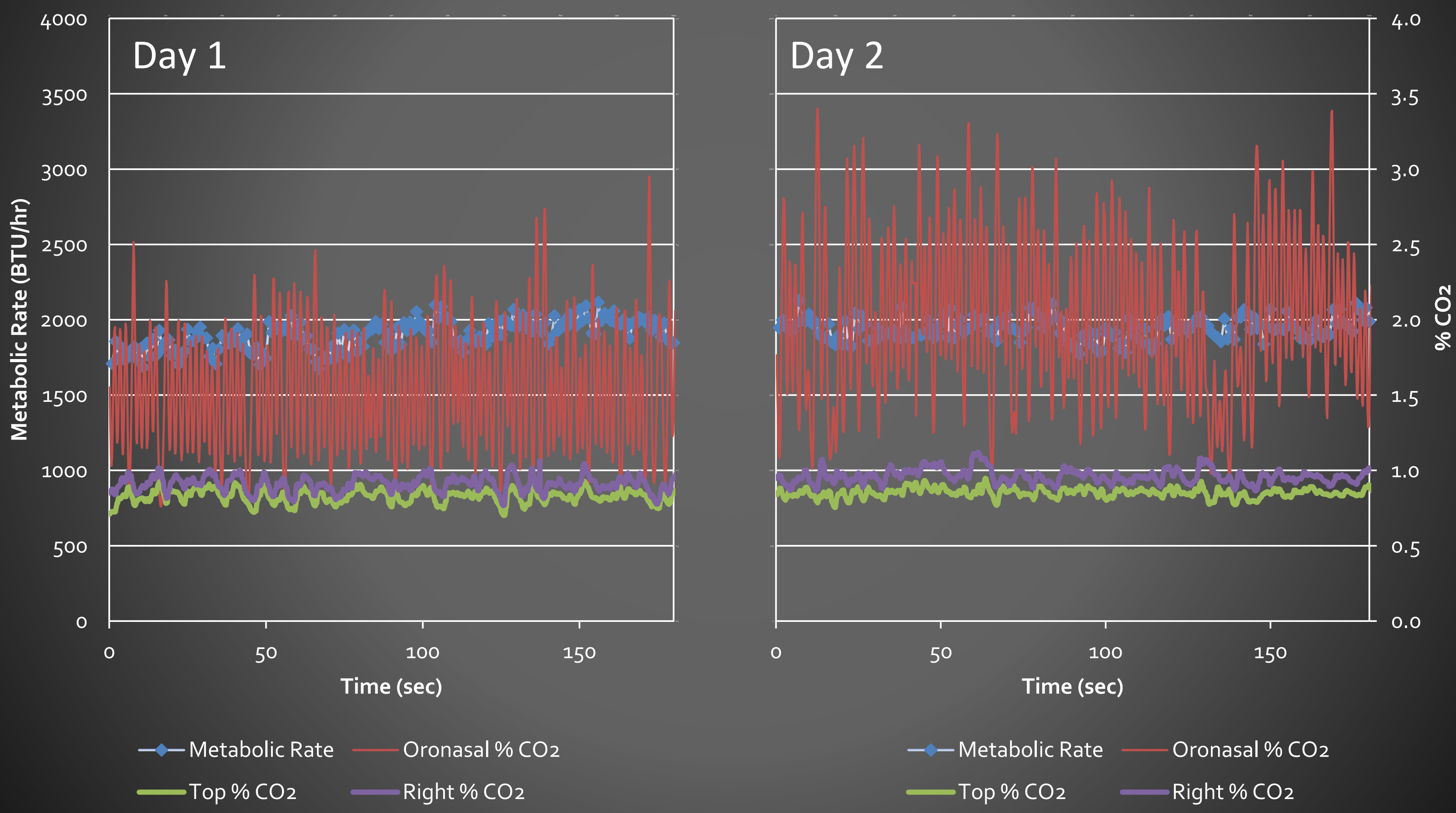
- Differences were due to CO_2 data output rate change and possibly placement of the oronasal sampling port.

Oronasal Placement Diferences
2000 BTU/hr – 6 ACFM



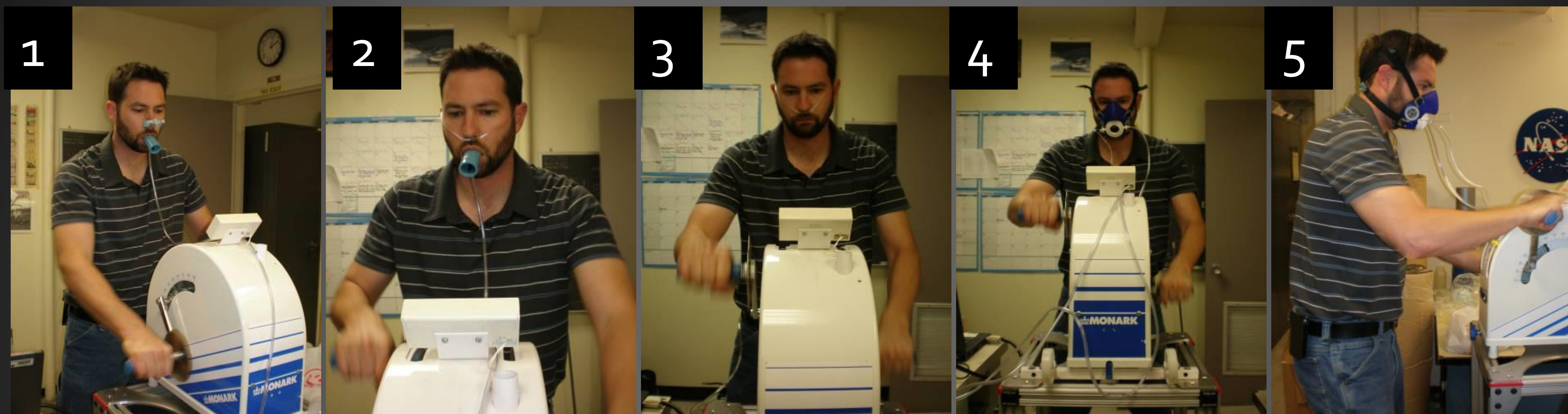
- CO_2 data output rate was the same (5-6 Hz) between tests

Oronasal Placement Differences
2000 BTU/hr – 5 ACFM



- Not all differences were huge
- Post hoc, this looks similar to some differences we see with the oronasal mask

Oronasal CO2 Measurement Options



(1) Mouthpiece and nose clip
(2) Mouthpiece and nasal cannula
(3) Nasal cannula only (mouth kept closed)
(4) Oronasal mask (valves in place) – 1 air entry/exit point available
(5) Oronasal mask (valves removed) – 3 air entry/exit points available

Oronasal CO2 Measurement Options Results (n=1)

Test Set-up	Trough % CO_2	Average % CO_2	Peak % CO_2	Notes
(1) Mouthpiece and nose clip	0.08	2.06	~5	Reference Condition
(2) Mouthpiece and nasal cannula	0.19	2.22	~4.5-5	Assumed 50/50 mix between mouth and nose and averaged the 2 equally
(3) Nasal cannula only (mouth kept closed)	0.24	2.34	~4.5-5.5	
(4) Oronasal Mask (valves in place)	0.08	2.12	~4-5.5	Assumed 50/50 mix for left and right side and averaged
(5) Oronasal Mask (valves removed)	0.22	1.46	~2-5	Assumed 50/50 mix for left and right side and averaged

CO_2 Washout Initial DAQ System

- Metabolic rate data acquisition system was separate from the oronasal/helmet CO_2 data collection system
- CO_2 analyzers initially only output a signal at 1-2 Hz and eventually this was improved to 5-6 Hz
- Oronasal CO_2 analyzer range of 0-5% CO_2
- Non oronasal CO_2 analyzers had range of 0-2.5% CO_2

<u>Upgraded DAQ</u>

- Metabolic rate and oronasal/helmet CO_2 data collection system integrated into one visual display and one data output file
- All CO_2 analyzers had range of 0-15% and all were same make/models
- All CO_2 analyzers had data output frequencies of 25 Hz

Thank You

Advanced Suit Lab

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Amy Ross

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Richard Rhodes

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Nathan Smith

Pete Meeh

John Harris

Crew Escape Lab

Dick Watson

Dustin Gohmert

Kris Cyrus

Mike Dang

Joe Lopez

Bill Owens

EVA Physiology Lab

Jill Klein

Jim Wessel

Igor Kofman