Nominal Spacesuit Carbon Dioxide Levels

This technical bulletin provides updates to verification testing recommendations listed in NASA-STD-3001 Volume 2 [V2 11039] Nominal Spacesuit Carbon Dioxide Levels. This update is focused on the changes to measurement and verification methods and does not address or assume any changes to the physiological exposure limits as listed in the standard. ***Note the underlined/bolded section below.***

NASA has performed an assessment of the verification testing method outlined in NASA-STD-3001 Volume 2 and has determined that the test setup referenced (ICES-2018-15 Bekdash et al., July 2018) requires updating.

[V2 11039] Nominal Spacesuit Carbon Dioxide Levels The spacesuit **shall** limit the inspired CO_2 partial pressure (P_ICO_2) in accordance with Table 11.3-1—Spacesuit Inspired Partial Pressure of CO_2 (P_ICO_2) Limits.

[Rationale: Spacesuit design (flow rate, helmet shape, etc.) and crewmember metabolic rates (average and transient) affect the extent to which CO_2 accumulates inside a spacesuit and is inspired by crewmembers. Inspired CO_2 partial pressure levels in Table 11.3-1 are based on review of scientific literature combined with past EVA experience, prescribed standardized human-in-the-loop testing, suit inlet CO_2 of <2 mmHg, and suit ventilation utilized in heritage designs. ***Verification methods would utilize the standardized testing method as published in ICES-2018-15, Bekdash, et al., July 2018.***

Note: Off-nominal CO_2 values are not included within this NASA Technical Standard due to the unique circumstances of each mission (expected human performance, duration of exposure, access to medical care, etc.) and would be derived as a lower-level program/project requirement.]

Table 11.3-1—Spacesuit Inspired Partial Pressure of CO_2 (P_ICO_2) Limits †

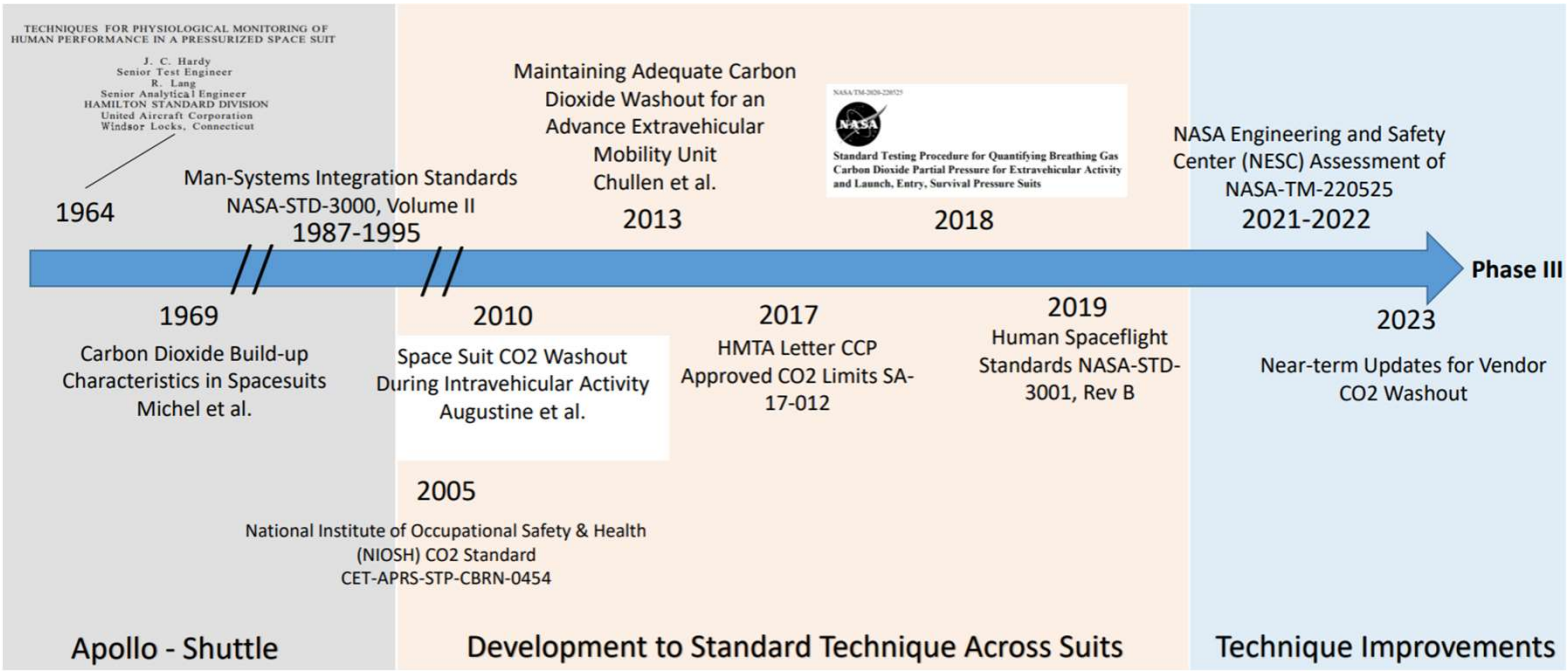
P_ICO_2 (mmHg)	Allowable Cumulative Duration (hours per day)
$P_ICO_2 > 15.0$	Do Not Exceed
$12.5 < P_ICO_2 \leq 15.0$	≤ 0.5
$10.0 < P_ICO_2 \leq 12.5$	≤ 1.0
$7.0 < P_ICO_2 \leq 10.0$	≤ 2.5
$4.0 < P_ICO_2 \leq 7.0$	≤ 7.0
$P_ICO_2 \leq 4.0$	indefinite

The requirements in Table 11.3-1 are to be met in the presence of the expected average and transient metabolic rates for the full suited duration, including prebreathe, checkout, EVA, and repressurization time. Total duration in the suit is not to exceed 14 hours.

† The values in Table 11.3-1 are based on Shuttle and ISS EVA experience, representing a frequency of up to 4 EVAs over a 14-day mission or up to 5 EVAs during a 6-month mission. If additional frequency of EVAs beyond the existing experience base is required, monitoring of crewmembers for hypercapnic signs and symptoms will be necessary until a sufficient experience base is generated.

Ground prototype of NASA's new Exploration Extravehicular Mobility Unit (xEMU). *Image from NASA Headquarters*

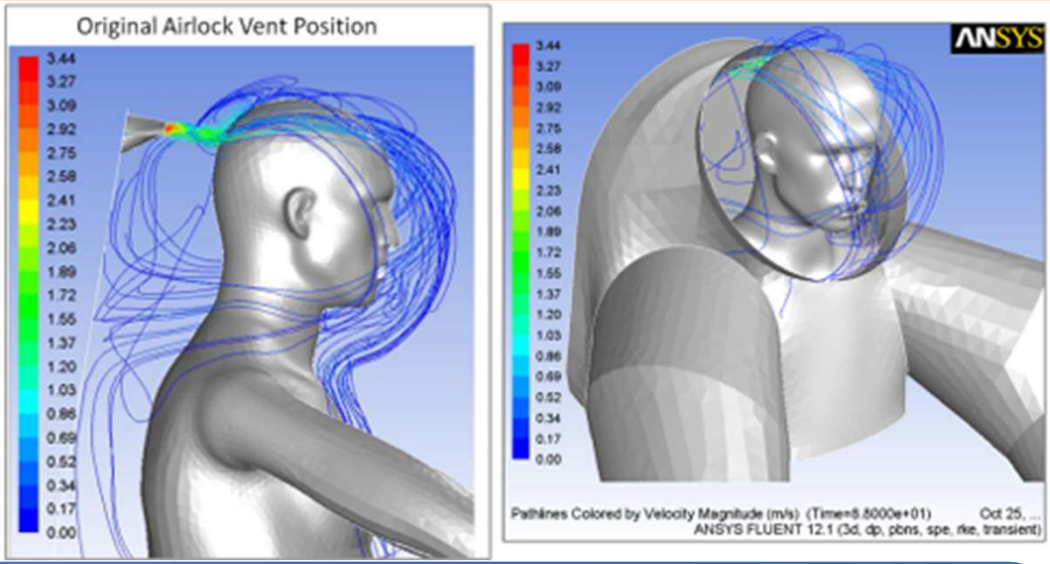
NASA has over 70 years of historical testing of suited CO_2 levels – the values in NASA-STD-3001 are considered reasonable and safe based on years of data collection.



The purpose of developing a CO_2 washout suit testing methodology is to quantify CO_2 washout of suit hardware and determine the CO_2 levels a crewmember would be exposed to in different scenarios. NASA sought to modify the test methodology to quantify inspired CO_2 in spacesuits **in a simple and repeatable manner.**

"Inspired CO_2" is the term for the level of CO_2 that actually enters a person's oronasal passages when breathing in. Most inspired CO_2 in a spacesuit typically results from incomplete washout of the suit gases, not poor CO_2 scrubbing by the portable life support system (PLSS).

Inspired CO_2 = baseline level CO_2 exiting the PLSS to the helmet + rebreathed CO_2 from imperfect washout

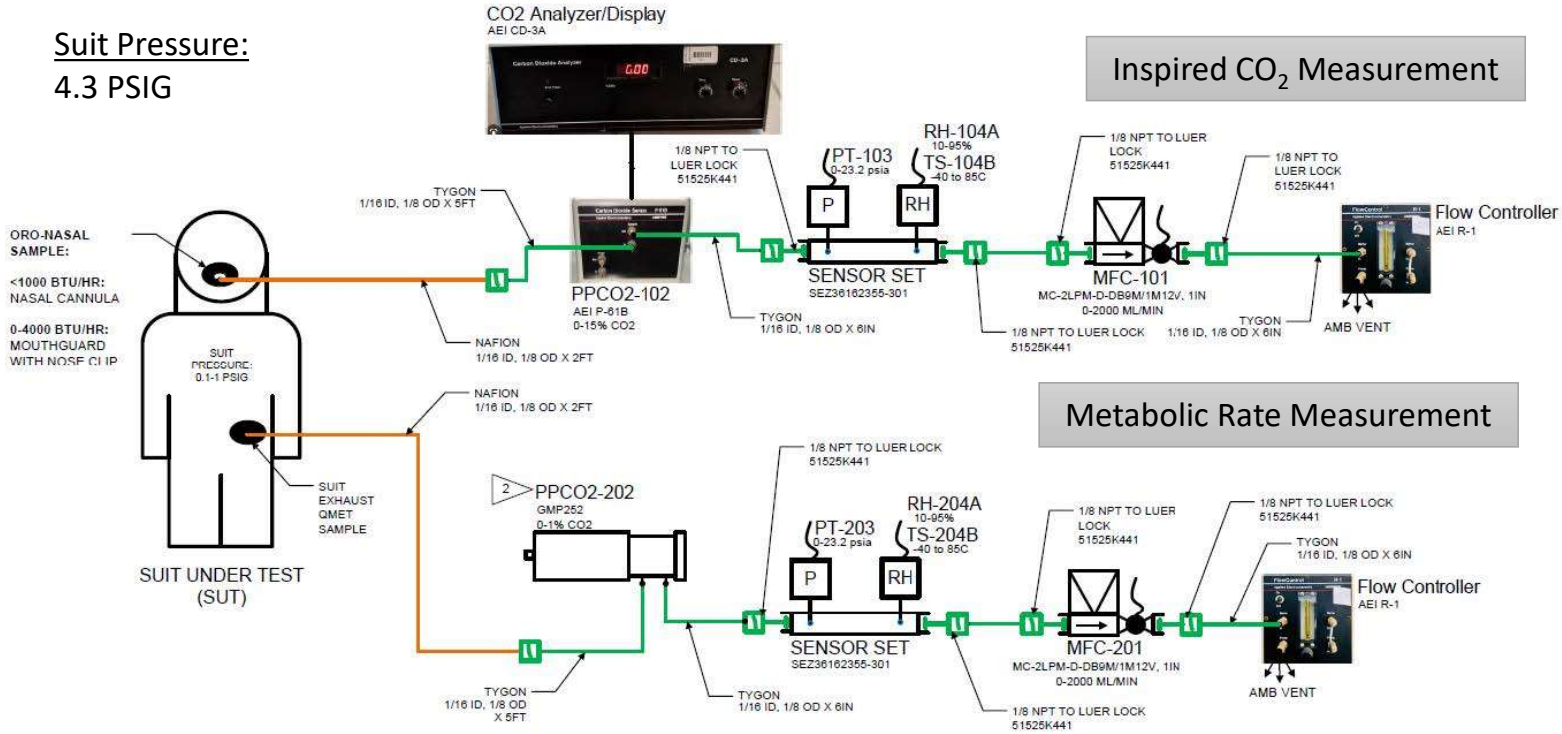


Computational Fluid Dynamics (CFD) flow patterns from suit evaluation. Source: Maintaining Adequate Carbon Dioxide Washout for an Advanced Extravehicular Mobility Unit, Chullen et al. (2013)

Based on the NASA assessment, the following test methodology updates have been implemented into the *Interim Inspired $ppCO_2$ Test System (IPTS)*:

- CO_2 sensor calibrated at test-like conditions to reduce uncertainty.
- More frequent sensor calibration to account for sensor drift coupled with minimum specified instrument warm-up times.
- Humidity, temperature, and pressure sensors added near the CO_2 sensor to reduce uncertainty/error.
- Overall line length was shortened whilst increasing the length of the Nafion tube segment to reduce the impact of water vapor on the $ppCO_2$ measurement.
- Side-stream sample flow rate was reduced to mitigate impact of measurement on the $ppCO_2$ measurement under low minute volume conditions.
- Side-stream sample flow rate is controlled and continuously recorded using a mass flow controller.
- Inspired $ppCO_2$ computed primarily with baseline method using Time Weighted Average (TWA) method for comparison to prior data sets.
- Nose clips must always be worn in conjunction with the mouthpiece sample line.
- Minimum breath count for analysis was set at 30 with goal of >60 breaths per measurement which resulted in longer test time interval of ~5 minutes at condition.
- LabVIEW code performing the data-acquisition was updated to address jitter in the sample logging.
- Kline-McClintock uncertainty assessment performed on the aggregate measurement with the updated setup.

Inspired CO_2 measurement is sampled at the subject oronasal region with sample line lengths shown in the drawing below. Metabolic rate measurement sample line is attached to the exhaust umbilical from the suit. The line length configurations were changed from 5’ to 10’ in the IPTS to operate with the suit exhaust location.

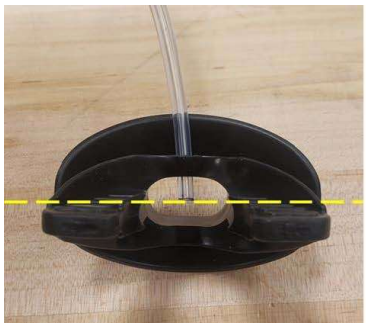


Interim Inspired $ppCO_2$ Test System (IPTS): NASA Drawing SIZ36162356

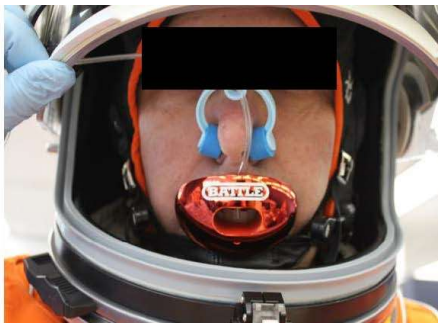
IPTS Equipment Overview

- IPTS hardware set-up for in-suit measurement of CO_2 includes additional instrumentation to monitor humidity, temperature, pressure, and flow conditions within the data collection loops to measure inspired CO_2 and metabolic rate.
- Inspired CO_2 measurements were captured at the oronasal region using a modified, commercially available mouthpiece (A); Subjects required to don nose clip for all conditions (B); A sample tube from the mouthpiece was routed up and out of the EMU helmet bubble singlepass-through using feed port adapters to the IPTS assembly (C - circle).

A



B

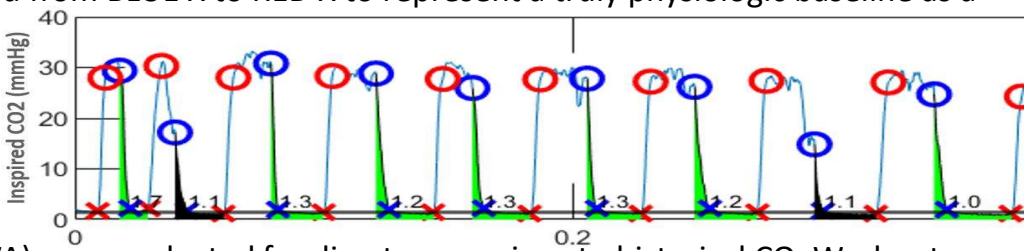


C

- The IPTS calibration assembly (NASA Drawing: SIZ36162356) is used to calibrate the IPTS at both vent and super ambient pressure conditions prior to conducting test points at those conditions.
- To test the updated IPTS system and compare it to the historical system referenced in NASA-STD-3001, 3 subjects underwent suited testing in the EMU at various metabolic rates.

Baseline Analysis Method

- Points for analysis were chosen from the BLUE circle to the RED X in the figure below to account the start of inspiration.
- The average value was then taken over 20-80% of the inspired segment to avoid edge effects (baseline
- Baseline inspired values were calculated as average across waveforms of entire test case as represented by the black horizontal line across the waveform valleys.
- Waveforms highlighted green are good breaths while black are bad breaths.
- Additionally, values were assessed from BLUE X to RED X to represent a truly physiologic baseline as a comparison.



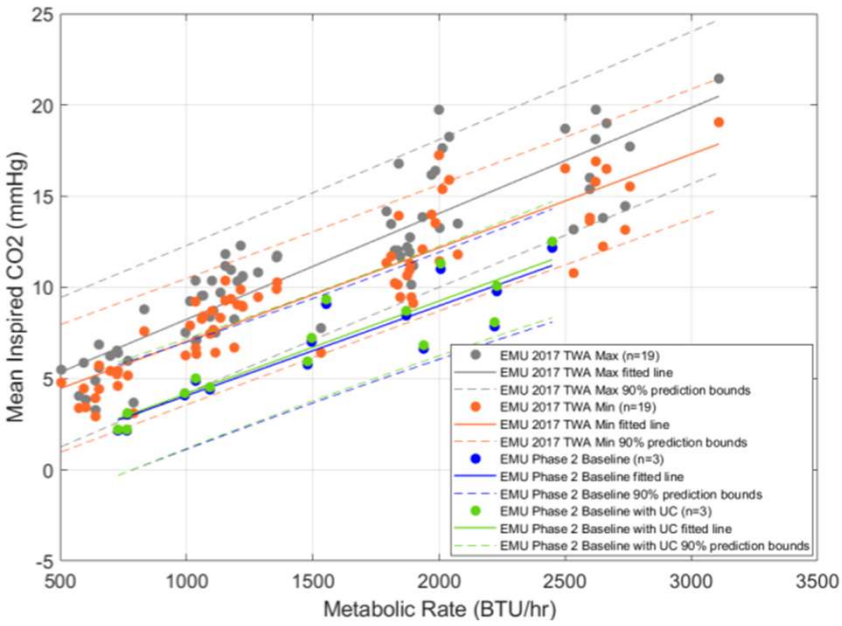
Time-Weighted Analysis Method

- The Time-Weighted Analysis (TWA) was conducted for direct comparison to historical CO_2 Washout testing.
- Maximum TWA PCO_2: Full integrated time weighted average area from start of inspiration to start of exhalation.
- Minimum TWA PCO_2: Integrated time weighted average area from start of inspiration to start of exhalation with known error accounting for sampling hardware induced measurement uncertainty.
- Both values (maximum and minimum) are provided to bound the possible range of inspired PCO_2 values.

Outcome

NASA performed limited EMU suit CO_2 washout testing (n=3) with the updated IPTS methodology to compare against the original testing. The updated methodology suggested that the CO_2 exposure level in the suit was potentially less than what was measured with the original method. Thus, the current limits in the Standard may be less conservative than originally assumed.

The overall impact is that there is no margin for exceedances above the current limits specified in NASA-STD-3001 Volume 2 during suit verification testing. Essentially, NASA will be very strict on meeting the standard as written and will not be open to exceedances.



Comparison of historic 2017 EMU CO_2 Washout (n=19) to 2024 IPTS EMU CO_2 Washout testing (n=3): Analysis of the 2024 EMU "Phase 2" testing using the baseline approach with Kline McClintock Uncertainty compared to 2017 historic EMU testing dataset using the TWA approach.

Comparison of 2017 EMU CO_2 Washout testing (n=19) to 2024 EMU CO_2 Washout Testing (n=3): Analysis using the TWA Max and Min approach

EMU 2017 (Original Data Set)

Target Metabolic Rate (BTU/hr)	TWA Max (mmHg)		TWA Min (mmHg)	
	Mean	SD	Mean	SD
Resting	5.72	2.19	4.86	1.91
1000	9.95	1.56	8.52	1.31
2000	13.61	2.89	11.71	2.55
3000	17.01	2.34	14.82	2.14

IPTS EMU (Phase II) 2024 + Uncertainty (Updated Dataset)

Target Metabolic Rate (BTU/hr)	Met Rate (BTU/hr)		TWA Max (mmHg)		TWA Min (mmHg)	
	Mean	SD	Mean	SD	Mean	SD
Resting	752	21	4.96	0.52	4.34	0.59
1000	1040	50	7.11	0.70	6.18	0.79
1500	1509	39	9.96	1.82	8.69	1.85
2000	1939	68	11.51	2.21	9.97	2.17
2500	2299	129	12.66	2.32	10.97	2.21

Recommendation: For future Spacesuit CO_2 Washout testing, incorporate changes to the setup as indicated for the interim until the new methodology is published and the Standard is revised to reference this updated methodology (expected in 2025).