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Standardized Measurement Method for Determining the Partial Pressure of Carbon Dioxide Within Space Suits

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Johnson Space Center
Houston, Texas

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ACRONYMS & DEFINITIONS

ARC	Ames Research Center
ANCOVA	Analysis of Covariance
ATA	Atmospheres Absolute
BTU	British Thermal Units
CO_2	Carbon Dioxide
CTSD	Crew and Thermal Systems Division
EEPL	EVA and Environmental Physiology Laboratory
EHP	Extravehicular Activity and Human Surface Mobility Program
EMU	Extravehicular Mobility Unit
EVA	Extravehicular Activity
DAQ	Data Acquisition
FOMTSC	Familiarization, Operation, Maintenance, Test, Service, and Calibration
FWA	Flow Weighted Average
GSFC	Goddard Space Flight Center
HITL	Human-In-The-Loop
ICWTS	In-suit CO_2 Washout Test System
IPTS	Interim $PPCO_2$ Test System
JSC	Johnson Space Center
KSC	Kennedy Space Center
LES	Launch, Entry, Survival
MSFC	Marshall Space Flight Center
mmHg	Milimeters of Mercury
NASA	National Aeronautics and Space Administration
NESC	NASA Engineering Safety Center
NDIR	Non-Dispersive Infrared
OCHMO	Office of the Chief Medical Officer
$PaCO_2$	Partial Pressure of Carbon Dioxide in Arterial Blood
$PiCO_2$	Partial Pressure of Inspired CO_2
$ppCO_2$	Partial Pressure Carbon Dioxide
STP	Standard Test Procedure
TWA	Time Weighted Average
VO_{2peak}	Maximum Oxygen Consumption

EXECUTIVE SUMMARY

The purpose of this technical publication is to describe updated hardware and testing methodology to measure the partial pressure of carbon dioxide ($ppCO_2$) within a space suit. The In-suit CO_2 Washout Test System (ICWTS) developed by NASA from 2023-2025 serves as an updated standard to quantify space suit CO_2 washout performance. This system replaced the prior method detailed in NASA TM-2020-220525 "*Standard Testing Procedure for Quantifying Breathing Gas Carbon Dioxide Partial Pressure for Extravehicular Activity and Launch, Entry, Survival Pressure Suits"*. The standard testing procedures were updated to address recommendations from NASA TM-20230006648 - NESC-RP-21-01684 *Verification of Testing Standard for Carbon Dioxide (CO_2) Partial Pressure in Extravehicular Activity (EVA) Suits.*

Development of the ICWTS hardware and methodology stemmed from collaborative efforts between the NASA Crew and Thermal Systems Division (CTSD) and EVA and Environmental Physiology Laboratory (EEPL) with guidance from partners in support of the Extravehicular Activity and Human Surface Mobility Program (EHP) and subject matter experts (SMEs) across a variety of NASA centers:

- Aerospace Environmental Protection Laboratory (AEPL) at Brooks, San Antonio
- Naval Medical Research Unit – Dayton (NAMRU-D)
- Johnson Space Center (JSC):
    - Space Medicine Operations Division
    - Biomedical Research and Environmental Sciences Division
- Office of the Chief Health and Medical Officer (OCHMO)
- NASA Engineering and Safety Center (NESC) including SMEs from supporting centers:
    - Glenn Research Center (GRC)
    - Marshall Space Flight Center (MSFC)
    - Ames Research Center (ARC)
    - Goddard Space Flight Center (GSFC)
    - Johnson Space Center (JSC)
    - Kennedy Space Center (KSC)

Herein we describe updated hardware, procedures, and test conditions with ICWTS to support the characterization and eventual certification of EVA and/or Launch, Entry, Survival (LES) suits. These procedures measure the in-suit inhaled and exhaled dry-gas partial pressure of CO_2 ($ppCO_2$), followed by calculation of the water vapor-saturated partial pressure of inspired CO_2 ($PiCO_2$) during the inhalation portion of the breathing cycle, while a human test subject is performing work at prescribed levels. In addition, results from an Extravehicular Mobility Unit (EMU) suited test series are also presented in this document. The referenceable procedures in the Appendix are designed to test a space suit undergoing evaluation with a human test subject as a dynamic system, generate repeatable results under defined laboratory conditions, and perform consistent analysis on acquired samples.

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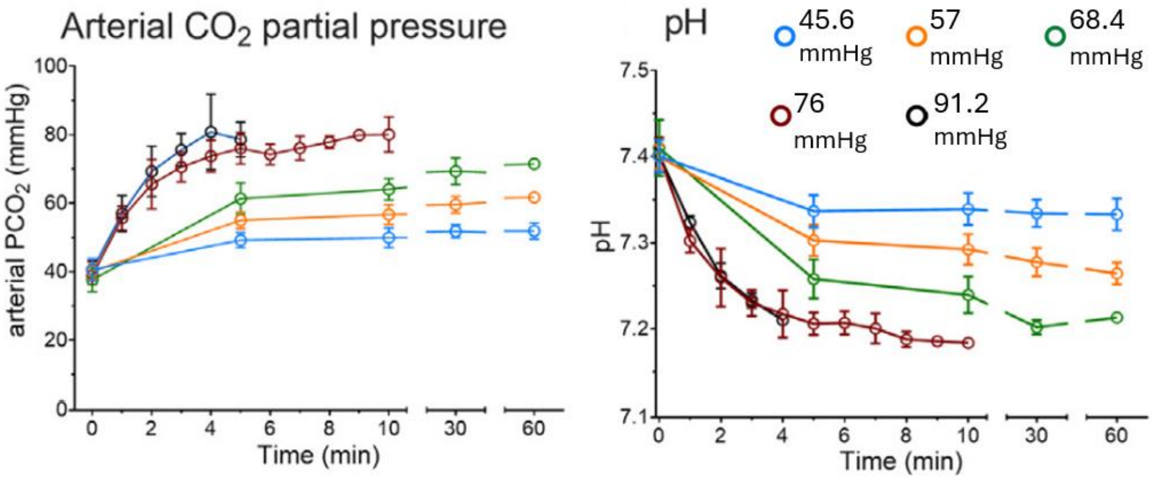
1 INTRODUCTION AND BACKGROUND

Humans generate carbon dioxide (CO_2) as a waste product of metabolism, the process by which body energy reserves are converted to the energy needed to drive chemical reactions at the cellular level of the body. Inadequate removal of CO_2 from the space suit system can lead to general discomfort, impaired cognitive function, or more serious medical emergencies. Cellular-derived CO_2 transports from tissues to the blood, where blood gas CO_2 concentration increases relative to the concentration within the lung's alveoli. The resulting concentration differential permits simple chemical diffusion to drive CO_2 into alveoli to be exhaled. Arterial blood carbon dioxide (p_aCO_2) has a normal value of 35-45 mmHg, well above environmental levels [1]. Elevated environmental CO_2 dampens the diffusion process by reducing the gradient; this results in more CO_2 recirculating in the body, acidifying blood and cerebrospinal fluid pH, raising p_aCO_2, and disrupting homeostasis (although this relationship is not linear due to various epigenetic and physiological processes to maintain normal levels). Figure 1.1 illustrates p_aCO_2 and pH responses to increased levels of environmental CO_2 [2]. This helps to contextualize the impact of p_aCO_2 and pH at environmental CO_2 levels associated with the NASA Standard 3001 whose limits are far lower than what is illustrated in the figure.

Figure 1.1: Examples of Arterial CO_2 at increased levels of environmental CO_2 [2]



Reference is made throughout this document to the measure of $ppCO_2$ (the partial pressure of CO_2, in mmHg), as would be measured by an environmental sensor that is *outside* of a human test subject. For clarity, the current document deliberately abstains from common annotations of pulmonary and blood gas measurements in this testing as the NASA Standard 3001 for nominal spacesuit CO_2 levels references methodology to measure the environmental $ppCO_2$ [3] and includes the same assumptions used here. Calculations are provided in Appendix 5.4 to translate $ppCO_2$ to P_iCO_2 (partial pressure of CO_2 in humidified, inhaled air). The limitation of this approach should be clear: The sensors used to validate the NASA Standard 3001 compliance are *indirect* measurements of a human crewmember's expected physiological response. It is therefore important to address the uncertainty arising from the gap between measurable, elevated atmospheric CO_2 and its associated physiological impacts considered in the ICWTS development.

US Navy studies on submariners have shown human tolerances as high as 38 mmHg of $ppCO_2$ for up to 72 continuous hours [4], while a more recent spaceflight-focused study demonstrated no operationally relevant performance effects in one hour of 32 mmHg $ppCO_2$ exposure during EVA-like exercise [5].

A comprehensive review of CO_2 physiology and the relevant considerations to the measurement of CO_2 washout is previously provided by Conkin et. al. (2019) [1]. These include relevant dose thresholds, interactions with the spacesuit environment, effects of EVA physical workload, variability in the human response, and expected mitigations for extended spaceflight effects on normal physiological responses. Such considerations are applied in the ICWTS design where relevant, particularly the effect of physical workload.

Suit development as early as the Apollo Program necessitated characterization of CO_2 washout performance within the spacesuit helmet [6]. Early Gemini EVA events were a steppingstone in capabilities of such activities and were limited in biomedical and performance data; however, post-EVA analysis showed the need to further refine suit performance due to the nature of EVA and associated workload [6], [7]. In particular, the effectiveness of CO_2 removal in a suit was a priority for surface EVA (i.e. high workload) tasks. Studies completed in the 1960s in preparation for Apollo missions investigated placement of breath sampling lines, metabolic measurements, CO_2 analysis methods, and flow conditions within both Apollo and Gemini suits to designate safe operating conditions during these early Lunar EVAs [7]. Sampling at the mouth with a nose clip was deemed the most efficient measurement method of inspired CO_2 within a pressurized helmet (Figure 1.2).

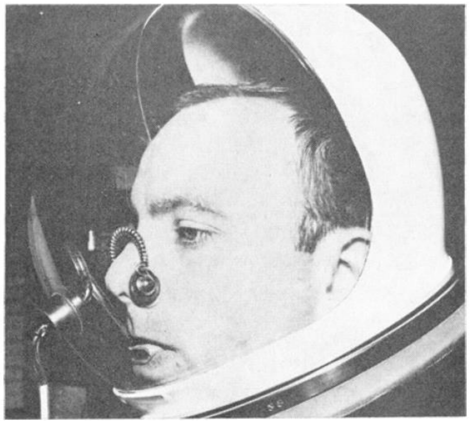


Figure 1.2: Apollo program early characterization of helmet CO2 washout performance (sampling location at the mouth with nose clip).

As a result of physiologic data found in early tests, acceptable maxima were established at 7.6 mmHg for nominal operations and 15.0 mmHg for emergency operations for Apollo Lunar Surface EVAs [7]. Limitations, however, were noted in the sampling of CO_2 such that placement of sensor locations for side sampling were susceptible to flow conditions. It was recommended for sensors to be nearest to the mouth or placed in-mouth for sampling.

Following early characterization of the Apollo helmet CO_2 washout performance within a pressurized environment, there have been a plethora of studies, techniques, and hardware investigations across multiple NASA program life cycles [3], [8], [9], [10], [11]. Early characterization of inspired CO_2 partial pressure values was captured in NASA Standards (NASA-STD-3000) in mid-1980s. The inspired CO_2 standard was again updated in NASA-STD-3001 to include a wider, more conservative, range relative to the previous standard [3], [8]. Across the evolution of CO_2 washout standards and characterization efforts, it was observed that no standard test or hardware methodology was implemented for pressure suited performance qualification. The need to generate a standard set of hardware and data collection procedures was deemed crucial for current commercially-developed space suit performance qualification and future pressure suited verification processes. A standard set of procedures was developed by NASA and released as NASA/TM-2020-220525 [12]. This standard methodology used a set of CO_2 analyzers with sampling at the mouth similar to the approach listed in early Apollo suit testing (Figure 1.3).


[redacted]

Figure 1.3: Placement of the breath sampling line for testing per NASA/TM-2020-220525.

Left: tygon tubing placed mid-breath stream of subject mouthguard. Tygon tubing in this configuration required passthrough at the helmet feedport to an out-of-suit CO2 analyzer. Right: placement of mouthguard with center tubing in mid-breath stream with subject usage of nose clip.

This method was initially characterized in 2017 using the extravehicular mobility unit (EMU) given its legacy spaceflight EVA heritage on the International Space Station (ISS) [13], [14]. As noted in early characterization, the placement and setup of CO_2 hardware was susceptible to flow conditions and by nature the pressurized suited environment is prone to data noise due to the limited space, flow conditions, and style of suited tasks and motions.

Review of this released standard procedure was conducted per NESCF NASA TM-20230006648 - NESC-RP-21-01684 [15]. The outcome report made recommendations to improve performance via hardware, process, and analysis method updates that would decrease the uncertainty of NASA’s standard hardware and procedures. As a result, NASA produced hardware updates as part of the ICWTS capability as an updated standard test procedure addressing uncertainty bands presented in the initial output. The updated ICWTS implements a Non-dispersive Infrared (NDIR) CO_2 sensor placed within (or immediately outside) the pressurized suit environment with short sample lines delivering breath analysis from a mouthguard sampling location with customizable bite piece. This mouthguard integrates a novel, at-the-mouth, bi-directional, flow sensing capability for breath-by-breath flow rate analysis (Figure 1.4).


[redacted]

Figure 1.4: ICWTS breath sampling location and embedded flow meter at the mouth. Left: the mouthguard front view with side sampling line delivering breath-by-breath data to the in-suit NDIR sensor on the subject back. Right: the electrical pass-through helmet feedport for power.

Additionally, the ICWTS test stand provides collection of environmental data including temperature, humidity, absolute pressure, flow, and background $ppCO_2$ readings for sampling conditions. Evaluation of the updated CO_2 washout methodology in the EMU was conducted in 2025.

2 GENERAL IMPLEMENTATION OF ICWTS

The methodology for usage of the ICWTS hardware during pressurized suited testing is detailed below. Sub-sections outline the various considerations for subject selection, hardware preparation, ICWTS setup, and system procedural steps. These recommendations can be used to build future test plans and procedures for qualifying exploration-class space suit systems. Full system procedural steps are detailed in Appendix 5.2.

2.1 Subject Selection

Ideally, subjects should be selected from the pool of astronaut crew. Barring this, “astronaut-like” subjects may also be selected who meet the following criteria: aged 25-55, Exploration Suit-relevant anthropometrics which fall within the 1st-99th percentiles, and a successful completion of an Air Force Class III physical or equivalent. An equal proportion of male and female subjects is recommended. Physical fitness can also affect the variables of interest in this testing, therefore, it is recommended to select subjects of comparable fitness to the astronaut population who are subject to VO_{2peak} minimum standards of 32.9 ml/kg/min for microgravity EVA qualified astronauts and 36.5 ml/kg/min for planetary EVA qualified astronauts per NASA-STD-3001 standards [16]. Subject-specific heart rate maximums should be used for monitoring according to test termination criteria (Appendix 5.3). In the absence of a VO_{2peak}-derived heart rate maximum, a common, though less accurate, method is to use the Gellish formula: 207 – (0.7 * Age in years). [17], [18]. Additionally, subjects should not have facial hair which interrupts the normal gas flow path and mouthpiece fit. Subject suit fit and indexing within the suit should permit necessary movements without significant impedance and limit excess internal free volume. Suit internal accessories which may alter the ventilation flow path should be included (e.g., communications systems, liquid cooling and ventilation garments).

2.2 Bite Piece Preparation

To minimize the disruption of nominal gas flow over the breathing orifices and, increase subject comfort during testing, a moldable commercial off-the-shelf SCUBA diving bite piece (SeaCure Custom Mouthpiece, Surprise AZ) may be custom fit to the subject and ICWTS NDIR sensor mouthguard. Once fit, it is required to manually trim a portion of the fitting gasket to reduce the protrusion of the mouthguard away from the face into the breathing air’s flow path (Figure 2.1). The complete procedures used in the 2025 EMU validation test for bite piece fitting are included in Appendix 5.1.

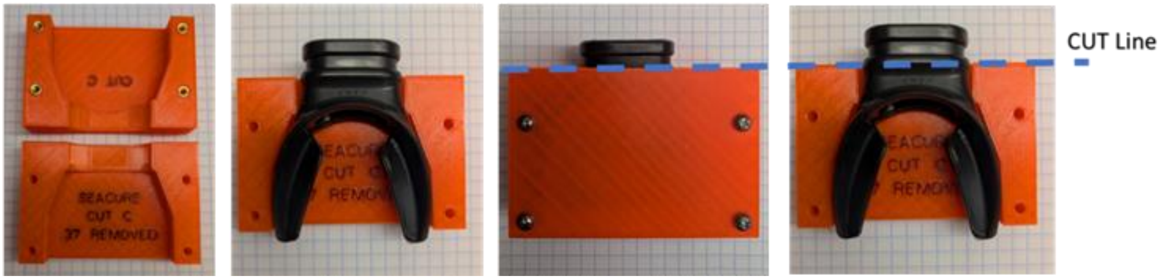


Figure 2.1: Mouthpiece preparation

2.3 ICWTS Overview

The ICWTS is fully detailed by the NASA Johnson Space Center Crew and Thermal Systems Division in the document titled “CTSD-ADV-2127 - Familiarization, Operation, Maintenance, Test, Service, and Calibration (FOMTSC) Procedures for the In-suit CO_2 Washout Test System (ICWTS)” [19]. As the purpose of the current document is to provide testing procedures, a cursory overview of the ICWTS’ precise usage will be provided, and a reader is encouraged to consult CTSD-ADV-2127 for further details shown in Appendix 5.2 before proceeding with testing development.

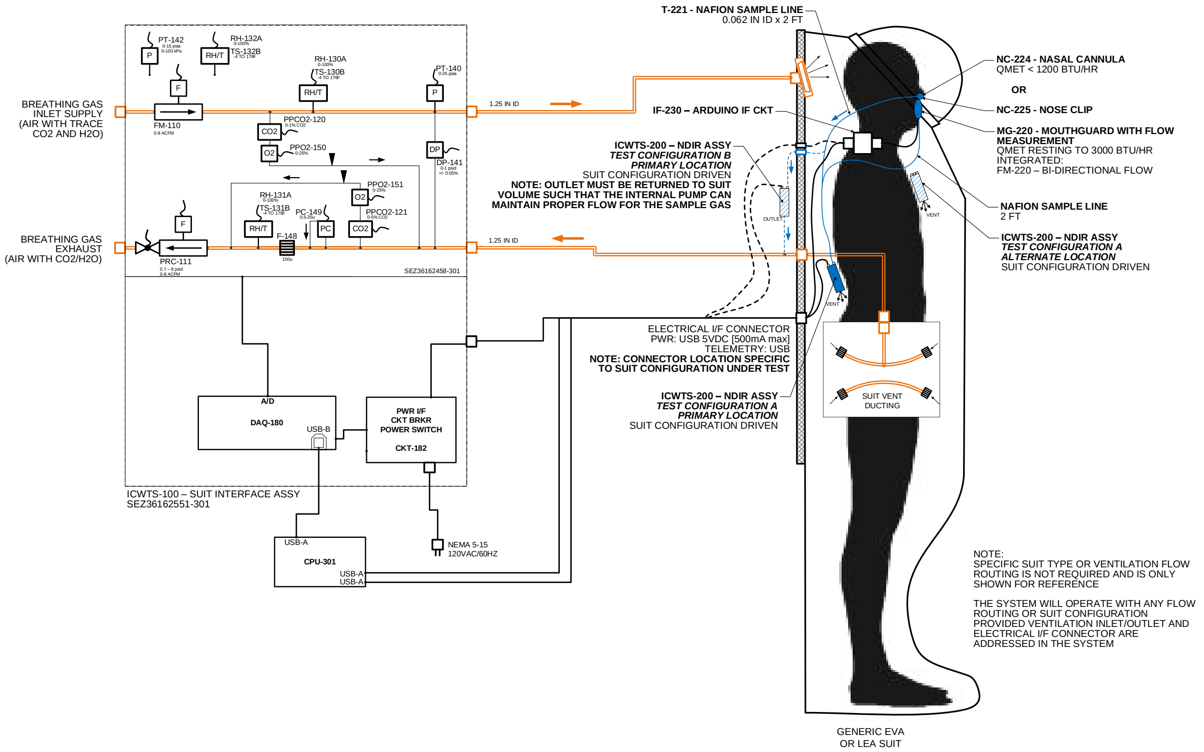


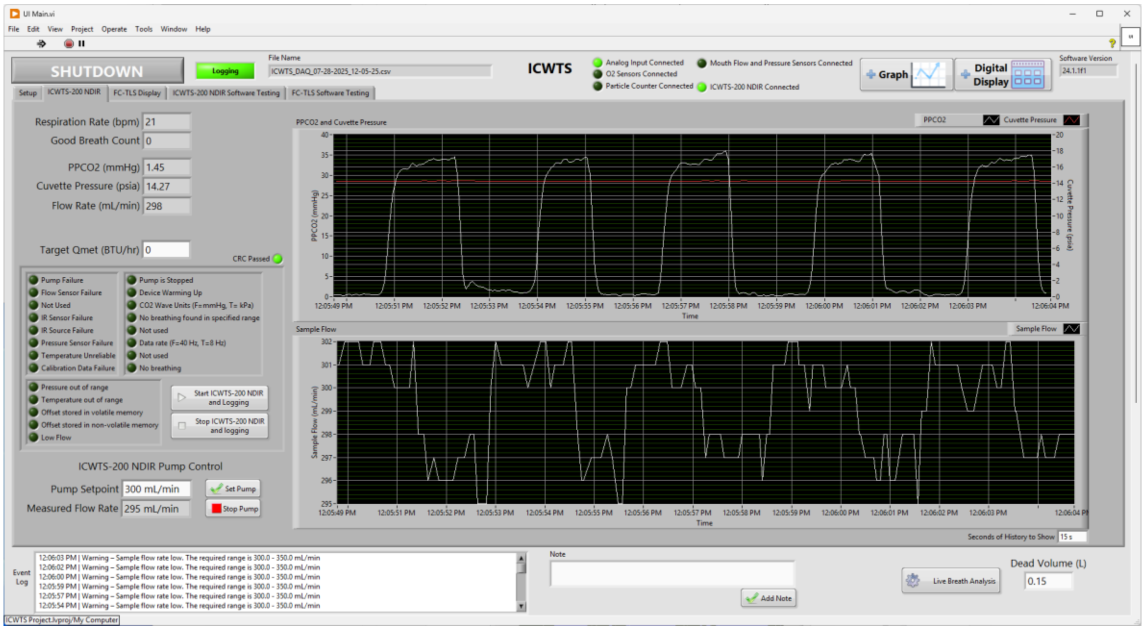
Figure 2.2: Diagram for NDIR Integrated Setup for a Typical Spacesuit [From CTSD-ADV-2127]

The purpose of this system is to provide measurements of suited CO_2 exposures and an analysis method focused on the inspiration portion of the breath waveform. New and updated hardware improve the measurement of suit atmospheric conditions (pressure, temperature, humidity) and the metabolic expenditure of the subjects. Additionally, bi-directional flow sensors enable the opportunity to calculate both flow-weighted average and “Baseline” levels of breathed gasses, reducing uncertainty introduced by previous time-weighted calculation methods.

Two sensor configurations, oral and nasal, are provided for subject-interfacing hardware with specific use cases. The NDIR sensor package may be modified for a mouthguard configuration inclusive of breathing gas flow using the moldable bite piece described above, or a nasal cannula configuration without a flow sensor (Figure 2.2). Both configurations sample breathing air at 40 Hz and measure CO_2 from 0-60.8 mmHg [3]. While the mouthguard is appropriate for the expected use case for most EVA systems and is capable of measuring at lower resting metabolic workloads, the nasal cannula is more appropriate for certain IVA systems with expected low metabolic rate use cases and where preserving verbal communication during testing is preferred. In such cases, nasal breathing is generally preferred by human subjects and the mainstream pickup capability of a cannula is expected to increase precision of the inspired CO_2 measurement. During mouthguard usage, a nose clip should be worn to prevent bypassing the sensor, and during cannula usage, the subject should keep a closed mouth for the same reason. Usage of the bi-directional flow sensor is not possible with simultaneous use of the nasal cannula. Usage of the flow sensor with the mouthguard is possible (as used in the NASA setup) but not mandatory given the required overhead for its calibration and usage as the “Baseline” method can also be used for the inspired CO_2 measurement with the mouthguard.

One aspect that should not be overlooked is the integration of instrumentation within the suit. For the ICWTS, the integration is less sensitive per suit as the critical measurements are contained within the suit volume and the ICWTS NDIR unit connections to an external DAQ computer are simpler with a feed-through USB cable. The interface needs to comply with the USB PHY limitations for length, pin-out, and impedance; exceeding these limits will likely result in "brown-out" of the NDIR unit and/or data corruption of the telemetry.

The ICWTS also includes a robust LabVIEW data acquisition software that runs on Windows-enabled operating systems and is available upon request. Screenshots of typical usage are shown below (Figures 2.3 and Figure 2.4). Key features include (but are not limited to) live reporting of metabolic rate, pump controls, component hardware status, live analysis of breath waveforms provided by the flow sensors, and live calculations of various methods of inspired CO_2 measurements. If integrated into testing procedures, these features strengthen the reliability and repeatability of the test. Figure 2.3 depicts the main display window reflecting the system status with respect to fault detection as well as measured parameters. A secondary window can be used for a machine learning algorithm to detect breaths in the suit trained using data collected from multiple in-suit CO2 washout tests (Figure 2.4).



File Name: ICWTS_DAQ_07-28-2025_12-05-25.csv

Software Version: 24.1.1f1

Respiration Rate (bpm): 21

Good Breath Count: 0

PPCO2 (mmHg): 1.45

Cuvette Pressure (psia): 14.27

Flow Rate (mL/min): 298

Target Qmet (BTU/hr): 0

Pump Setpoint: 300 mL/min

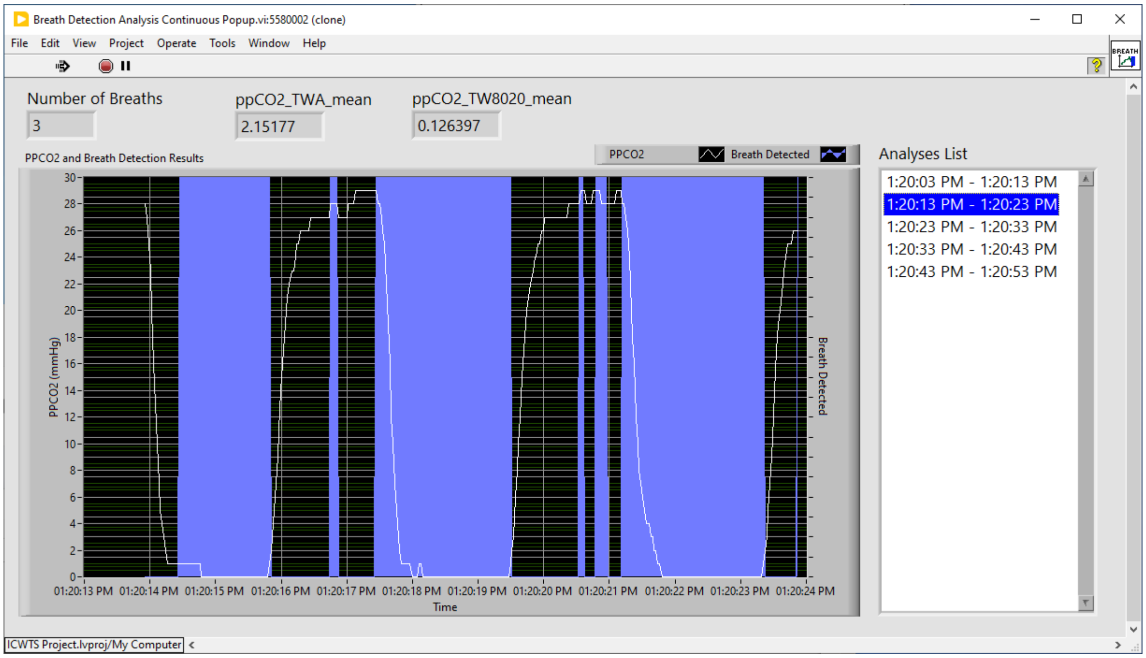
Measured Flow Rate: 295 mL/min

Seconds of History to Show: 15 s

Dead Volume (L): 0.15

```
12:06:03 PM | Warning – Sample flow rate low. The required range is 300.0 - 350.0 mL/min
12:06:02 PM | Warning – Sample flow rate low. The required range is 300.0 - 350.0 mL/min
12:06:00 PM | Warning – Sample flow rate low. The required range is 300.0 - 350.0 mL/min
12:05:59 PM | Warning – Sample flow rate low. The required range is 300.0 - 350.0 mL/min
12:05:57 PM | Warning – Sample flow rate low. The required range is 300.0 - 350.0 mL/min
12:05:54 PM | Warning – Sample flow rate low. The required range is 300.0 - 350.0 mL/min
```

Figure 2.3: Example of ICWTS main display tab.



Number of Breaths: 3

ppCO2_TWA_mean: 2.15177

ppCO2_TW8020_mean: 0.126397

Analyses List
1:20:03 PM - 1:20:13 PM
1:20:13 PM - 1:20:23 PM
1:20:23 PM - 1:20:33 PM
1:20:33 PM - 1:20:43 PM
1:20:43 PM - 1:20:53 PM

Figure 2.4: Example of ICWTS breath detection tab.

2.4 Testing Procedures

2.4.1 PRETEST

Prior to testing, subjects should be queried for adequate sleep and hydration and verified for abstention from caffeinated products within 4 hours of test and abstain from meals during the two hours prior to testing as all of these prevent confounding of the metabolic analysis. Subjects should also disclose any ongoing orthopedic injuries and, should hyperbaric exposure be part of the testing, verify the ability to equalize air pressure in their ears via a Valsalva maneuver.

The ICWTS hardware must be correctly configured prior to testing, and this process can take up to an hour. Section 6.0 of the CTSD-ADV-2127 ICWTS FOMTSC fully details these steps to ensure that the system is correctly interfaced with the suit system hardware and ready for a HITL test. Of note is the importance of recording the serial number of the NDIR mouthguard and test hardware used for each test, as calibrations may vary by serial number and require a post-hoc data correction during analysis.

2.4.2 DEVELOPING TEST PROCEDURES

Each spacesuit system test will require the development of unique HITL testing procedures. To ensure repeatability and comparability of the ppCO$_2$ measurement between tests and suit hardware, certain procedures are expected to be common.

In all cases, test points should be utilized that are representative of the expected and/or required metabolic expenditure rates of crew wearing the suit system on mission. Testing should also include an unsuited, unpressurized, resting test point to represent a control point, and a suited, pressurized, resting, test point to compare the effect of simply wearing the suit and any effects of the change in atmospheric pressure. Only then can the effects of elevated physical activity beyond resting, and its associated increase in measurable metabolic rate and ppCO$_2$, on the suit's ability to "wash out" CO$_2$, be determined. In both instances, a minimum of 10 minutes is the recommended duration for data collection for each test condition. This amount of time ensures the collection of enough breath waveforms for analysis. A minimum of 30 acceptable breaths (see section 3.2.4 on Breath Detections) and a goal of greater than 60 acceptable breaths is recommended. Depending on the suit system, it may be possible to reach target elevated metabolic rates with unassisted limb movements, though the use of external hardware such as an arm ergometer may be needed to elicit very high metabolic rates expected in certain EVA contingency scenarios. Care should be taken during testing to consider the suit design and minimize movements that alter the suit volume, thereby presenting pressure fluctuations that adversely impact the stability of the measurement; for example, squatting in a soft suit or similar may produce poor measurement waveforms. Subjects should be regularly monitored and coached to achieve the desired metabolic rates. Operators should also be aware of an expected hardware lag time between the onset of a subject's movement designed to elicit a specific metabolic rate and when the measurement of their expired gasses can occur- about 30-60 seconds for the produced CO_2 to reach the sensor, owing to the system's architecture. This further emphasizes the importance of continuous monitoring, and data may reflect an oscillatory behavior of metabolic rate about the target. In previous testing, a margin of 10% about the target metabolic rate has been deemed acceptable due to this hysteresis.

For the purposes of data analysis, it is critical to use the "Add Note" feature in the DAQ software (as seen in Figure 2.3) to demarcate the moment of attainment of target metabolic rates by the subject. The breath detection display window of the software provides an estimation in the number of collected breath waveforms (upper left, Figure 2.4) and is a useful tool for determining the attainment of a target number of breaths needed for the analysis and any desired margin for measurement error (which may increase the target number to 60 or more). It must be emphasized that this "number of breaths" reported by the software is an algorithmically-derived *estimation* (see CTSD-ADV-2127 section 5.7.35) and therefore a conservative number should be chosen and modified based on preliminary engineering dry-runs.

In the case of iteratively increasing metabolic rate targets, it is recommended to transition directly from demarcating the end of one test point into the attempt to reach the next targeted test point's metabolic rate. Allowing the subject to return to baseline resting rates between test points only increases the total time at pressure within the suit system, potentially increasing fatigue and confounding metabolic rate measurements, and should therefore be minimized if possible.

2.4.3 TEST TERMINATION CRITERIA

To ensure subject safety, conservative criteria are utilized based on continuous measurements of heart rate, inspired CO_2, and subjective reporting of symptoms. Example test termination criteria references for testing can be found in Appendix 5.3.

3 HUMAN-IN-THE-LOOP VERIFICATION WITH THE EXTRAVEHICULAR MOBILITY UNIT

3.1 Purpose

Following development of the ICWTS, verification of the test system was completed through comparison with previous CO_2 washout data collected in a 2017 EMU test series and a pilot 2024 EMU test series using the same test points and analysis methods as well as the new flow-weighted average analysis. The full details of the 2017 test series are published [10] [11], and the 2024 pilot test series results are published as part of a bulletin released by the Office of the Chief Health and Medical Officer [20].

3.2 Methodology

3.2.1 SUBJECT SELECTION

20 subjects (16M/4F) were recruited to participate in the 2025 test series which was deemed non-human subject research by the NASA IRB (Study #00000660). All subjects had been cleared for suited testing by the Test Subject Screening facility at the Johnson Space Center Clinic. Aggregate subject characteristics are conveyed on Table 3.1.

Table 3.1: Subject Characteristics provided as group mean ± standard deviation. HUT = Hard Upper Torso.

Age *(yrs)*	**VO_{2Peak}** *(ml/kg/min)*	**Height** *(cm)*	**Weight** *(kg)*	**EMU HUT Size**
37.3 ± 7.5	39.97 ± 7.14	179.8 ± 7.3	82.3 ± 8.6	4M/12L/4XL

3.2.2 PROCEDURE

CO_2 washout performance of the EMU using the ICWTS was assessed at up to five conditions depending on the sensor configuration, as shown in Table 3.2. For both the nasal and mouthguard configurations, performance was first assessed in an unsuited, seated resting condition; then a suited, pressurized, standing resting condition; followed by metabolic workloads of 1000 British Thermal Units (BTU) per hour, 2000 BTU/hr, and in the case of the mouthguard sensor configuration only, 3000 BTU/hr if the subject was able to attain this level of effort without triggering test termination criteria. Suit pressure was maintained at 4.3 psi differential from ambient sea level with a helmet breathing air flow rate of 6 absolute cubic feet per minute, both nominal in-flight values for EMU operation. The A7LB helmet bubble was used as it provides feedthrough ports on either side of the face, necessary for the ICWTS wiring configuration. Weight relief was provided by a test stand which allowed foot contact with the ground but not bodyweight-bearing properties. Metabolic workloads were accomplished via body motions only, such as leg flexes, arm flexes, and/or marching in place. A suit leak check was performed to verify pressure and flow rates prior to each test and nominal sensor ranges were verified continuously throughout each test via the ICWTS software.

Table 3.2: Test points completed using the ICWTS NDIR sensor package. *Denotes optional condition.

Test Point	**Metabolic Rate (BTU/hr | Watts)**
1A – Unsuited	Resting (seated)
1B – Suited	Resting (standing)
1C – Suited	1000 | 300
1D – Suited	2000 | 600
1E* - Suited	3000 | 900

3.2.3 ICWTS AND EMU CONFIGURATION

ICWTS software was configured for unpressurized data collections to support test point 1A resting baseline measurements (Figure 3.1). The resting baseline data collection provided a verification of the ICWTS NDIR sensor measurement at ambient levels of inspired CO_2. Once verified, the ICWTS software was configured for suited data collections.

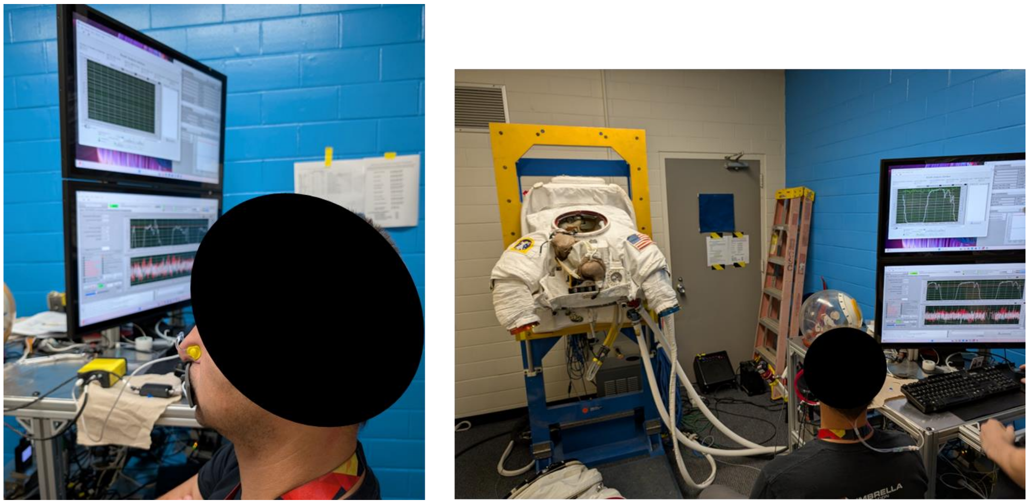


Figure 3.1: Unsuited resting baseline data collection test points with ICWTS NDIR sensor.

Prior to suit donning, the NDIR sensor package along with an integrated peripheral circuit (I2C) adapter module were positioned in the EMU HUT (Figure 3.2). The NDIR sensor package was located on the subject's left side behind the upper left shoulder blade and beneath the EMU shoulder bearing. No subjects reported discomfort or interference of hardware. The I2C adapter module was positioned opposite, on the subject's right.

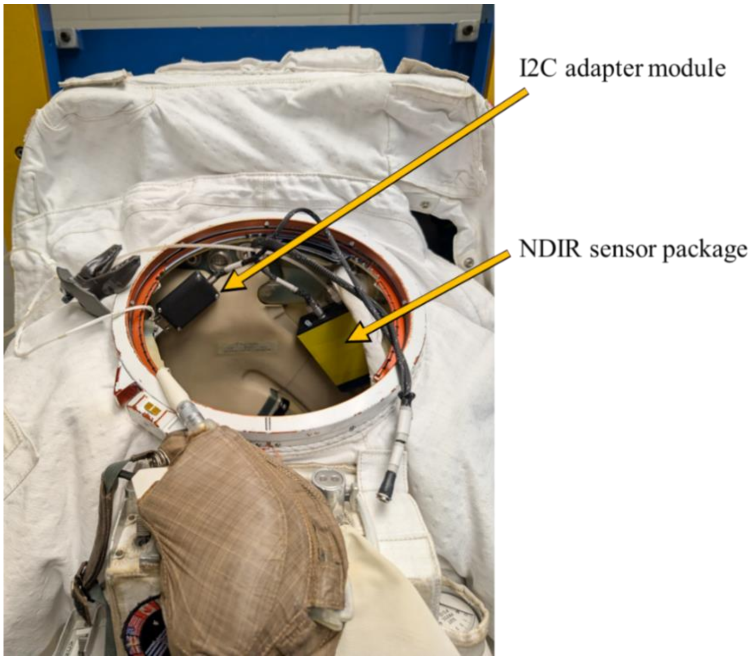


Figure 3.2: ICWTS NDIR sensor package placement within the EMU for suited pressurized operations.

Subjects then donned the EMU liquid cooling and ventilation garment (LCVG), lower torso assembly (LTA), and HUT. The suit test stand flowed cooled water continuously through the LCVG throughout the test at the subject's request/discretion. Suit breathing gas inlet and outlet were also provided by and controlled via the EMU test stand, permitting the control of pressure and atmosphere drawn from ambient air. Prior to positioning the helmet, the test team assisted the subject in placement of the nose clip, mouthguard, and mating connections for the sensor package (Figure 3.3). The mouthguard side sample line and flow meter electrical lines were routed to the subject's right and connected to the NDIR sensor package. Electricals were routed from the NDIR sensor package through the EMU A7LB helmet feedport to the ICWTS test stand.

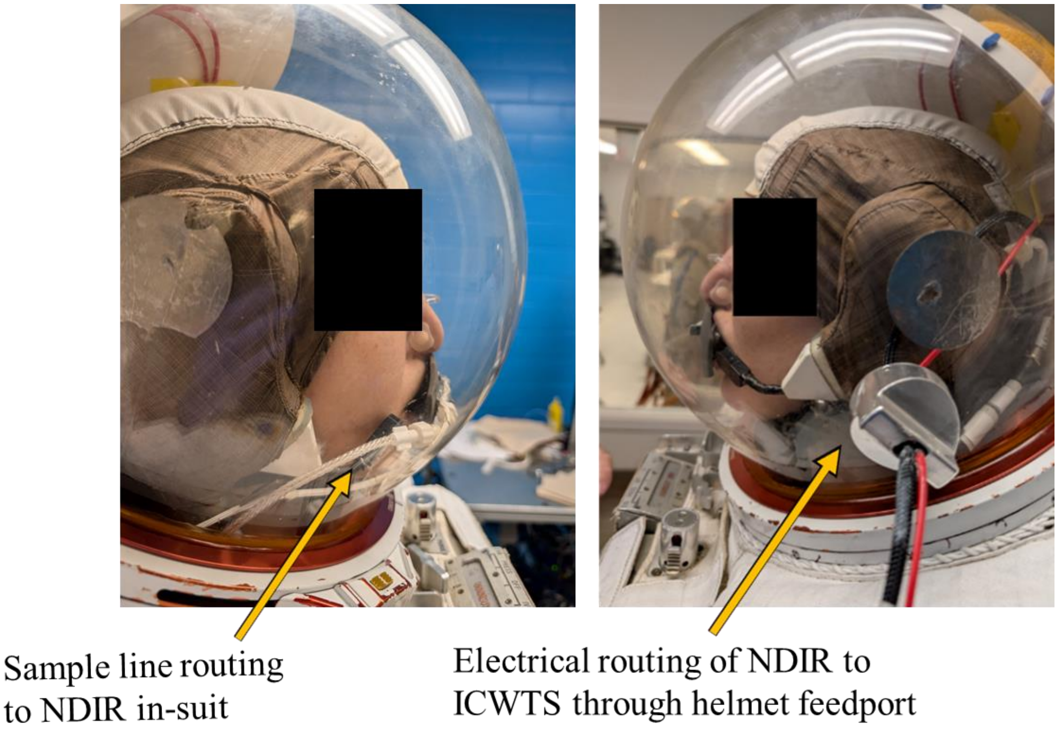

[redacted]
[redacted]

Figure 3.3: Mouthguard side sample and flow meter configuration route to NDIR.

(A) Electrical routing of the NDIR sensor package through helmet feedport to the ICWTS test stand. (B) Mouthguard side sample line connects a Nafion line to in-suit NDIR sensor package on subject right.

3.2.4 BREATH DETECTIONS

A perfect capnograph tracing would be described as a square wave with inflections of the waveform marking the start and end of each exhale and inhale. In reality, mixing effects related to the anatomical dead space, measurement hardware, unsteady breathing flow rates common to humans, and poor CO_2 washout via suit ventilation can create less than ideal breath waveforms. This necessitates a subjective judgement of "acceptable" breath waveforms, as well as uncertainty regarding the actual beginnings and ends of breath periods.

Work by Kim et. al. was previously leveraged as an algorithmically-derived approach to determine measurable breath waveforms to reduce uncertainty arising from the subjectivity of manual breath selections (Figure 3.4) [14] (Appendix, section 5.4). This methodology can be used in breath detection when no flow meter is present; however, for the 2025 EMU test series, the ICWTS flow meter was used to better identify start and end of breath transitions. Additionally, to aid in training a machine learning model to evaluate the algorithm, manual breath evaluations were used.

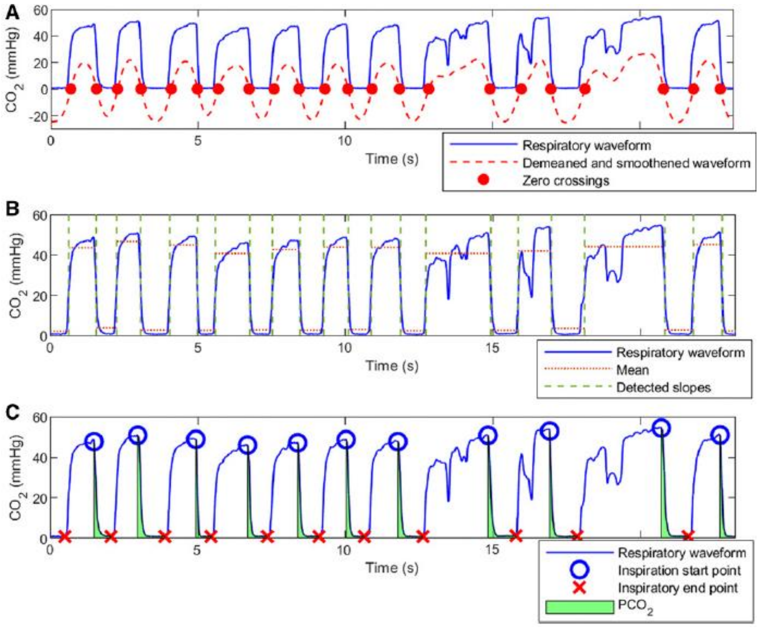


Figure 3.4: [Reproduced from Kim et. al. (2020)] Procedure for calculating ppCO$_2$: (a) A simple method for counting the number of change points, (b) Detected slopes, (c) ppCO$_2$ inspiration start and end points.

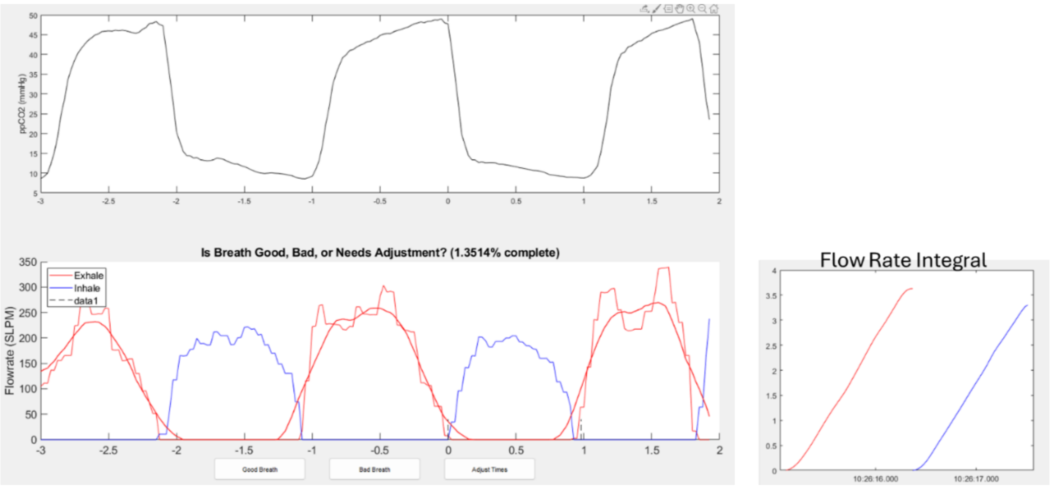


Figure 3.5: Flow characteristics for exhale and inhale outputs of the ICWTS flow meter. The flow rate integral is used to determine consistent acceptable breaths improving breath detection by excluding erroneous noise or false breaths.

From here, the duration of the inspiratory period for each breath can be determined, and a method for calculating the inspired CO$_2$ is applied to these periods. There are three such calculations that were used during this verification test series, and they are each described below.

3.2.5 INSPIRED CO$_2$ CALCULATIONS

3.2.5.1 TIME-WEIGHTED AVERAGE

Using the breath selection algorithm described above with manual breath verifications, an integration of the ppCO$_2$ across the determined period of inspiration was performed. This TWA method is understood to be the least precise of the three as the previously described uncertainty arising from the measurement itself is retained. Inhalation start time (t_0), end time (t_e), sampling period (Δt), and total inspiration period (t_{breath}, which $t_{breath} = t_e - t_0$) are used in eq. 1. The TWA calculation in the context of this document is only used to assess hardware configurations and uncertainty as a comparison of hardware across previous testing campaigns (i.e., the 2017 EMU test series). It is not the recommended method to use for future test data reductions.

$$\boldsymbol{TWA}\,[\boldsymbol{mmHg}] = \frac{\sum_{i=t_0}^{t_e} \boldsymbol{pCO_{2,i}} \cdot \boldsymbol{\Delta t}}{\boldsymbol{t_{breath}}} \qquad \textbf{eq 1.}$$

3.2.5.2 BASELINE

To eliminate the uncertainty regarding the precise start and end time points of inspiration, the initial and final 20% of the inspiration period are ignored entirely in the “Baseline” calculation. These ignored periods are understood to have some amount of intrinsic error which would be variable with each breath. While less precise than the flow-weighted average (FWA) and still burdened with some remaining uncertainty in flow characteristics, the results of the Baseline calculation are nevertheless comparable to FWA while requiring less hardware (eq. 2).

$$\boldsymbol{Baseline}\,[\boldsymbol{mmHg}] = \frac{\sum_{i=t_0+0.2t_{breath}}^{t_e-0.2t_{breath}} \boldsymbol{pCO_{2,i}} \cdot \boldsymbol{\Delta t}}{\boldsymbol{0.6} \cdot \boldsymbol{t_{breath}}} \qquad \textbf{eq. 2}$$

3.2.5.3 FLOW-WEIGHTED AVERAGE

The inclusion of a pressure-compensated, bi-directional flow sensor to the ICWTS represents the most novel update to the methodology. It permits the inclusion of flow rate measurements (V) and the data logging frequency (*f*) of the sensor, seen in eq. 3. A time delay between the flow sensor’s reading and the CO_2 sensor must be incorporated (δt) due to the time required for gas to pass through the side stream sample port to the CO_2 sensor. Calculating this delay is a critical step in the nominal ICWTS procedures (see Appendix 5.2) for the inclusion of FWA. Once calculated, an adjustment to this value may be performed to account for water vapor saturation in the exhaled gas, seen in eq 4.

$$\boldsymbol{FWA}\,[\boldsymbol{mmHg}] = \frac{\sum_{i=t_0}^{t_e} \boldsymbol{pCO_{2,i+\delta t \cdot f}} \cdot \boldsymbol{\dot{V}_i} \cdot \boldsymbol{\Delta t}}{\sum_{i=t_0}^{t_e} \boldsymbol{\dot{V}_i} \cdot \boldsymbol{\Delta t}} \qquad \textbf{eq. 3}$$

$$\boldsymbol{FWA_{hum}}[\boldsymbol{mmHg}] = (\boldsymbol{P}\,[\boldsymbol{mmHg}] - \boldsymbol{47\ mmHg}) \cdot \frac{\boldsymbol{FWA}\,[\boldsymbol{mmHg}]}{\boldsymbol{P}\,[\boldsymbol{mmHg}]} \qquad \textbf{eq. 4}$$

3.2.6 COMPARISON TO PRIOR TEST SERIES AND STATISTICAL ANALYSIS

A 2017 test series with the previous CO2 washout test methodology was performed in the EMU suit with 19 subjects [11], [13], [14]. In 2024, an interim updated co2 washout methodology was pilot tested with n=3 subjects in the same suit [20]. These tests introduced analysis methodology using breath detections and time weighted average (TWA) techniques.

Following these test series and to compare against the ICWTS, analysis was performed to compare the 2025 test series with the ICWTS described herein with the 2017 and 2024 tests.

Regression analysis of mean $ppCO_2$ responses were compared across hardware test series (2017, 2024, and 2025) and calculation method (TWA, Baseline, FWA) using an analysis of covariance (ANCOVA) and mixed models approach to assess and compare between the CO_2 washout test series. The output equation sets of the ANCOVA analysis are below.

1) ANCOVA relationship of TWA Max comparison across testing campaigns and associated variable hypothesis for analysis (eq. 5) (Table 3.3):

$$ppCO_2 = \beta_o + \beta_1 \cdot MR + \beta_2 \cdot x_1 + \beta_3 \cdot x_2 + \beta_4 \cdot MR \cdot x_1 + \beta_5 \cdot MR \cdot x_2 \qquad \textbf{eq. 5}$$

$$x_1 = \begin{cases} 1 & 2017\,data \\ 0 & other \end{cases} \qquad x_2 = \begin{cases} 1 & 2024\,data \\ 0 & other \end{cases}$$

Table 3.3: ANCOVA hypotheses of comparison across testing campaigns.

Variable	Hypothesis
β_o	Y-int of 2025 data is zero
β_1	Slope of 2025 data is zero
β_2	Y-int of 2017 data is same as 2025
β_3	Y-int of 2024 data is same as 2025
β_4	Slope of 2017 data is same as 2025
β_5	Slope of 2024 data is same as 2025

2) ANCOVA relationship of TWA Max comparison to Baseline and FWA and associated variable hypothesis for analysis (eq. 6):

$$ppCO_2 = \beta_o + \beta_1 \cdot MR + \beta_2 \cdot x_1 + \beta_3 \cdot x_2 + \beta_4 \cdot MR \cdot x_1 + \beta_5 \cdot MR \cdot x_2 \qquad \textbf{eq. 6}$$

$$x_1 = \begin{cases} 1 & Baseline \\ 0 & other \end{cases} \qquad x_2 = \begin{cases} 1 & FWA \\ 0 & other \end{cases}$$

Table 3.4: ANCOVA hypotheses of ICWTS ppCO2 calculation measures TWA Max, Baseline, and FWA.

Variable	Hypothesis
β_o	Y-int of TWA Max is zero
β_1	Slope of TWA Max is zero
β_2	Y-int of TWA Max is same as Baseline
β_3	Y-int of TWA Max is same as FWA
β_4	Slope of TWA Max is same as Baseline
β_5	Slope of TWA Max is same as FWA

System uncertainty was investigated on a breath-by-breath basis. This uncertainty analysis was performed to characterize the intrinsic error of the NDIR CO_2 sensor and ICWTS flow meter. A Monte Carlo simulation was performed on each breath using established variability in these properties and averaged across each test point to reveal the overall uncertainty associated with the TWA, Baseline, and FWA measurements.

Additionally, CO_2 washout data were analyzed by mixed models including year within subject-specific random effects to address the repeated measures. Robust standard errors allowed non-homogenous variance across combinations. Models were defined in terms of the interaction of linear fixed effects over metabolic rate for each year of data. Expected marginal means were used to produce estimates of the mean response, as well as conduct contrasts comparing 2017 and 2024 to 2025 data sets across the TWA, Baseline, and FWA calculation methods.

3.3 Results

3.3.1 TWA AND BASELINE MEASURES ACROSS TEST CAMPAIGNS:

When comparing the TWA Max and baseline measures, the original 2017 test system appears to give higher TWA Max and baseline inspired CO_2 values compared to the 2025 updated system (ICWTS; Figure 3.6). This is likely due to the 2017 system having pressure compensation offsets, humidity displacement, and uncompensated sensor drift [15], [20]. The 2024 Interim ppCO_2 Test System (IPTS) test system is more comparable to ICWTS 2025. Variance analysis shows that the fit for the ICWTS 2025 data is statistically different from the original 2017 data for TWA Max and baseline measures. Variance analysis shows no evidence of difference between IPTS 2024 and ICWTS 2025 fit.

Table 3.5: ANCOVA outputs comparing TWA Max and Baseline analysis outputs of the 2017, 2024, and 2025 test series.

Variable	P-value (TWA Max)	P-Value (Baseline)	Hypothesis
β_o	0.075	0.86	Y-int of 2025 data is zero
β_1	0.00	0.00	Slope of 2025 data is zero
β_2	0.00	0.30	Y-int of 2017 data is same as 2025
β_3	0.49	0.80	Y-int of 2024 data is same as 2025
β_4	0.37	0.03	Slope of 2017 data is same as 2025
β_5	0.79	0.86	Slope of 2024 data is same as 2025

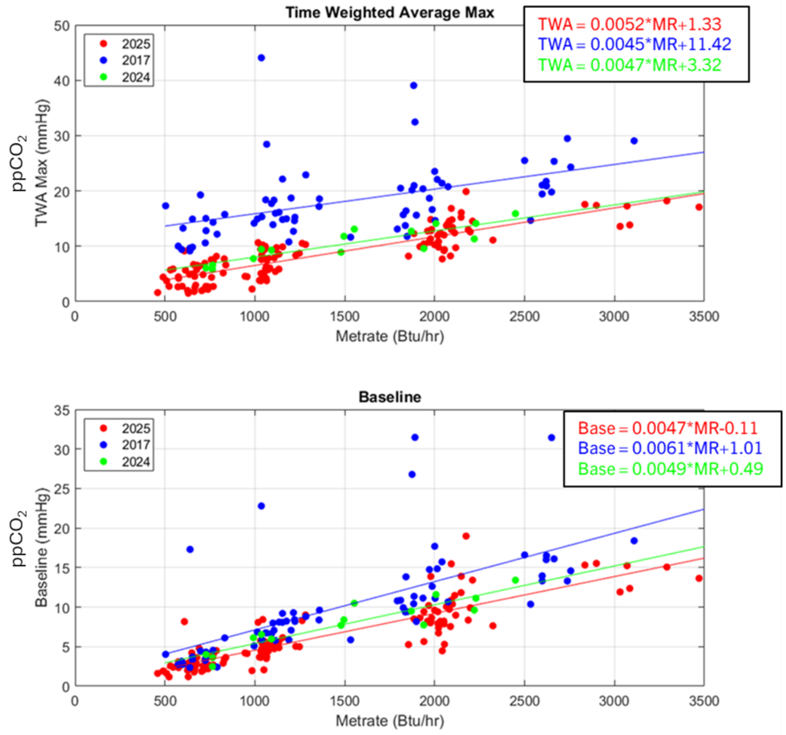


Figure 3.6: ppCO2 as a function of metabolic rate with the time weighted average analysis method (top) and baseline method (bottom) for the 2017, 2024, and 2025 test series. The original 2017 series is statistically different and resulted in higher CO₂ estimates than the 2025 ICWTS and 2024 IPTS hardware configurations.

3.3.2 FWA COMPARISON TO TWA AND BASELINE MEASURES IN ICWTS 2025:

Statistical assessment showed no difference between the three computations for the ICWTS 2025 dataset, likely due to the large variance between test subjects. Results are compared on Table 3.6 and Figure 3.7.

Table 3.6: ANCOVA outputs comparing FWA, TWA Max, and Baseline analysis method outputs from the ICWTS 2025 test series.

Variable	P-value	Hypothesis
β_o	0.6576	Y-int of TWA Max is zero
β_1	0.00	Slope of TWA Max is zero
β_2	0.8097	Y-int of TWA Max is same as Baseline
β_3	0.9103	Y-int of TWA Max is same as FWA
β_4	0.5379	Slope of TWA Max is same as Baseline
β_5	0.3052	Slope of TWA Max is same as FWA

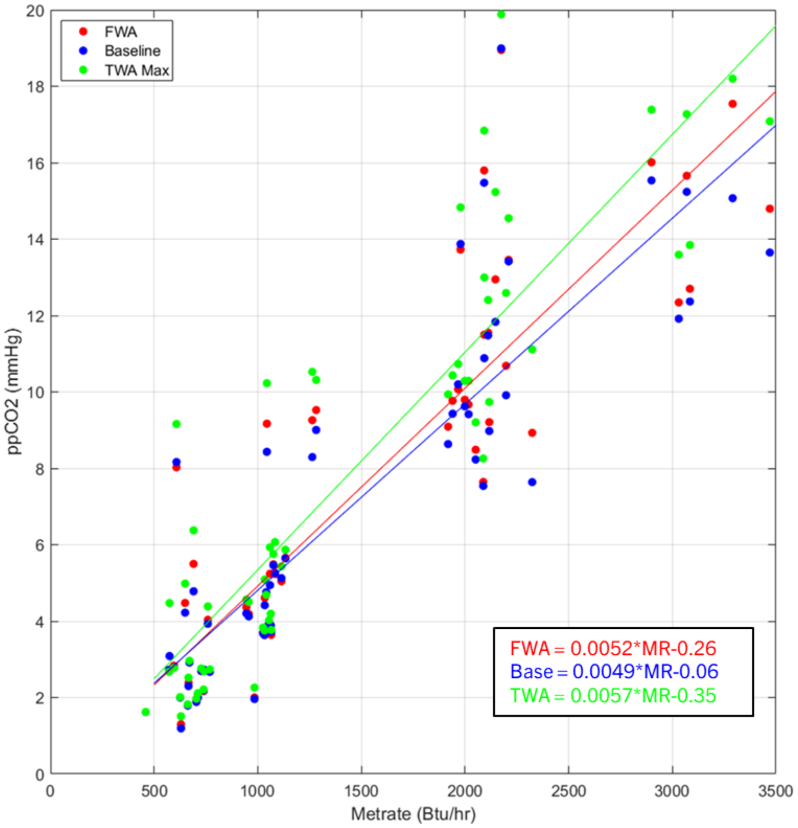


Figure 3.7: Linear fit of resultant ANCOVA analysis comparing FWA, TWA Max, and Baseline analysis methods of the 2025 ICWTS test series. No statistical difference was found between the outputs of the three analysis methods.

3.4 Discussion

The development of suited CO_2 washout test systems is a process that has evolved since the Apollo program; however, uncertainty existed within these early test systems due to sampling position, hardware calibrations, hardware configurations, and environmental conditions. No standard methodology in collecting or assessing CO_2 washout characteristics within a spacesuit existed until 2020 with the first publication of a standard approach [12]. The 2025 ICWTS hardware configuration described in this report lowered uncertainty of the suited CO2 washout test system by measuring temperature, humidity, and pressure which enabled test teams to monitor each test point within allowable suited and sensor ranges. These reductions of uncertainty were shown in comparisons to TWA Max measurements to the original 2017 test series. Additionally, as seen in Figure 3.6, the ICWTS NDIR sensor produced reliable $ppCO_2$ measurement outputs consistent with hardware development campaigns from 2017 to 2024 and 2025.

The TWA analysis method has been shown to be susceptible to breath selection criteria, environmental conditions, and flow condition uncertainty. Through the verifications of ICWTS, it was also confirmed that TWA proved to be less reliable based on uncertainty regarding breath waveform characteristics and flow dynamics; however, as seen in Table 3.6, $ppCO_2$ trends compared between methodologies were shown to have no statistically significant differences. As a result of this, FWA and Baseline outputs provide improved reliability output for future usage. Both Baseline and FWA have been shown to be less susceptible to breath selections. As seen in

Figure 3.7, Baseline and FWA estimates are nearly identical in the outputs calculated within the EMU with Baseline being the simplest method to implement. **Due to this testing simplicity, the Baseline methodology described in section 3.2.5.2 is recommended for use as the reference standard approach for space suit hardware ppCO$_2$ washout characterizations.** The additions of a flow meter and associated FWA can further improve characterizations if desired at a cost of increased operational and analytical complexity.

4 RECOMMENDATIONS / LIMITATIONS

4.1 Recommendations:

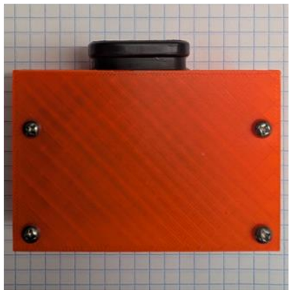
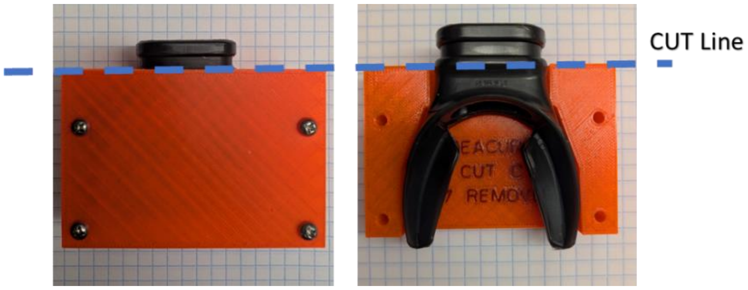
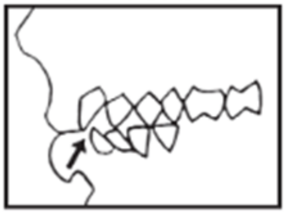
1) The ICWTS configuration or an equivalent system is recommended for future suit qualifications and CO$_2$ washout characterizations using the established hardware and operating procedures which can be found in Appendix 5.2 and CTSD-ADV-2127. Further recommendations are provided when developing the hardware's configuration:
    a. Utilize a standard suit inlet and outlet characteristics measurements (e.g., pressure, humidity, temperature, and system CO$_2$ plus flow rates from suit for metabolic rate calculations) per the ICWTS configuration.
    b. Utilize the in-suit NDIR sensor system.
    c. Utilize at-the-mouth side-sampling with mouthguard and small line-length to in-suit NDIR sensor.
        i. Nasal cannula may be sufficient at metabolic rates less than 1200 BTU/hr. Above 1200 BTU/hr, the mouthguard side sampling should be used.
    d. Utilize an at-the-mouth flow meter to improve breath-by-breath flow sampling if the flow-weighted average methodology is preferred.
    e. Utilize a nose clip to limit mouth breathing across the sampling position.
2) It is recommended to use the Baseline Method Analysis (described in Section 3.2.5.2) approach when calculating the inspired CO$_2$ values.
    a. A goal of 60 acceptable breaths is recommended for analysis.
    b. The usage of breath detection algorithms is acceptable, though it is recommended to verify selections (Appendix 5.4).
3) It is recommended to perform unsuited data collection to establish and verify sensor readings at ambient atmosphere (i.e., room equivalent inspired CO$_2$).
4) All instruments require calibration to ensure accuracy. For ICWTS specific sensors, it is recommended to calibrate NDIR sensors per CTSD-ADV-2127.

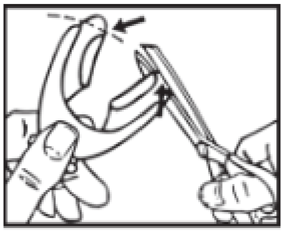
4.2 Limitations:

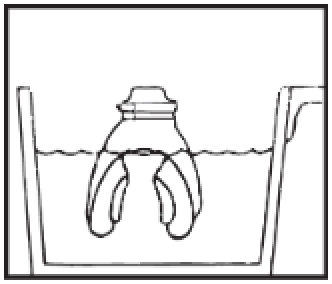
1) Side sampling is susceptible to sensor position in flow path. Sampling must be performed in the core flow.
2) Flow meter conditions at the mouth during operational suit test points can yield higher uncertainty if the sampling line is not placed correctly near the mouth or breathing stream.
    a. Addressed per usage of CTSD-ADV-2127 for proper setup and install of hardware.
    b. Baseline ppCO$_2$ methodology is less susceptible than FWA analysis methodology.

5 APPENDIX

5.1 Bite Guard Fit and Assembly

Step	Procedure Steps
1.	Assemble mouthguard cutting fixture – Open fixture and place mouthguard with bite wings inside of fixture. Follow images 1 through 3 below: 1  2  3 
2.	Cut mouthguard with precision cutting tool across the flat surface of the cutting fixture. 
3.	Once cut identify if subject has an overbite or under bite. A: Overbite  B: Underbite 

Step	Procedure Steps
4.	If the subject has an Overbite as seen in A above the “SeaCure” logo should be facing downward when shaping/placing in the mouth. If the subject has an Underbite as seen in B above. The “SeaCure” logo should be facing upward when shaping/placing in the mouth. 
5.	Have the subject place the mouthguard in their mouth to get a feel for how it is placed. **Note:** To the subject it will feel uncomfortable to get a feel of where the bite wings are to trim if needed prior to shaping. If the bite wing tips touch the back of the subject’s mouth behind the last teeth to the point of discomfort, take a sharp pair of scissors and trim off a small portion of each bite wing tip (see figure below).  **Note: Cut off only ~1/8th inch of the tips at a time. Retry the mouthpiece in the mouth before trimming more. Trim only enough to clear the back of your mouth.**

Step	Procedure Steps
6.	**Note: This step has hot boiling water use caution.** - **Use a kettle or a three-quart saucepan to bring water to a vigorous or rolling boil. Remove from heat and let water sit a few moments until the bubbling stops.** - **Pour water into a bowl or cup with enough water to submerge mouthguard bite wings.** - **Holding the mouthpiece using the yellow plug insert that comes with the COTs item, submerge the bite wing portion into the hot water up to the top of the bite piece area. Hold the mouthpiece in this immersed position for 15 seconds.**  - **Remove from water. SHAKE THREE TIMES TO REMOVE EXCESS HOT WATER.** - **Immediately have the subject place the mouthguard in the mouth with the word “SeaCure” properly positioned (Overbite or Underbite) and perform the following three steps together:** o **Bite down firmly but try to prevent over closure.** o **While setting teeth, press the inner portion of the bite wings against the inside of your teeth with your tongue.** o **At the same time, press the outer edges of the bite wings against your teeth and gums by pressing your fingers against your cheeks.** 

Step	Procedure Steps
7.	**Note: Some people have a very strong gag reflex that can be triggered by touching the back or sides of the tongue. If the subject has this discomfort take a sharp pair of scissors and carefully remove some of the material from the mouthguard, cutting on an angle as shown:** 
8.	**Note: This step has hot boiling water use caution.** Once the mouthguard has been shaped have the subject hold the top end (regulator side) into the hot water for 10 seconds. When removed assist the subject in friction fitting the bottom of the lip guard (shown below) to the mouthguard (regulator side) following 1 through 3 below. Top  Bottom  1  2  3 
9.	Have subject test for comfort.

5.2 CTSD-2127 Familiarization, Operation, Maintenance, Test, Service, and Calibration (FOMTSC) Procedures for the In-suit CO2 Washout Test System (ICWTS)

Given that the ICWTS is an instrumentation system that works in tandem with an active suit which is the Unit Under Test (UUT), this section merely offers templates for inclusion in specific usage procedures with the ICWTS as the full set will include the contributions of the host suit system and supporting ancillary hardware.

5.2.1 STANDARD CO2 WASHOUT TEST PROCEDURE (NDIR)

NOTE: This section provides a template or example procedure for using the NDIR configurations to perform a suited test. It does not consider tailoring to meet specific test objectives or address constraints for a specific suit. It is expected that a test specific procedure will be generated to meet given test objectives and suit interface considerations informed by this procedure that is based on exemplifying how this hardware may be used.

Refer to CTSD-ADV-2127 section 6 to begin hardware setup and start procedures using the table below.

5.2.1.1 CTSD-ADV-2127 SECTION 6.2 – ICWTS SET-UP PROCEDURE

_____TE 1) Setup ICWTS with space suit/facility per test set up diagram (SIZ36162361)

CAUTION:

ENSURE THAT THE PRESSURE CONTROLLER/REGULATOR IS LOCATED ON THE OUTLET SIDE OF THE ICWTS-100 SUCH THAT THE ICWTS-100 IS OPERATING AT SUIT PRESSURE. THIS PREVENTS OVER-RANGE DAMAGE TO DP-141 MEASURING THE DIFFERENTIAL PRESSURE ACROSS THE SUIT VENTILATION FLOW PATH.

1.1. Verify/connect facility breathing air to ICWTS-100 connections
1.2. Verify/connect suit to ICWTS-100 connections

_____TE 2. Inspect the MG-220 (mouthguard flow meter)
2.1. NDIR: Verify that the pickup line and flow sensor are connected and secure.

_____TE 3. Verify access for engineers and technicians to suit pressure controls.

_____TE 4. If ICWTS-100 connections not clean bagged:
4.1. Perform open loop blow-through using facility supplied breathing air for 10 min.
4.2. Perform cleanliness inspection to GC specs

_____TE 5. Velcro NDIR box and I2C interface box into appropriate location in HUT per test set up.

NOTE:

I2C INTERFACE BOX IS NOT REQUIRED IF THE MG-220 BI-DIRECTIONAL FLOW SENSOR IS NOT BEING USED IN THE MOUTHGUARD.

_____TE 6. Take inventory for the ICWTS Hardware Configuration and record the S/N information:

Item	P/N	S/N
FM-110	MW-500SLPM-D-485-AS8-ALM/1V	
FM-111	MW-500SLPM-D-485-AS8-ALM/1V	
PPCO2-120	GMP251C4B5N1	
PPCO2-121	GMP251C4B5N1	
PPO2-150	FD02	
PPO2-151	FD02	
RH-130	PC52-4-SX-T1-CCF27	
RH-131	PC52-4-SX-T1-CCF27	
PT-140	3000A400160APT1	
DP-141	MMDWU015V5P1J5T3A3S	
PC-149	2501P	NA
MG-220		
PT-223	MS580305BA01-00	
ICWTS-200 NDIR		

_____TE 7. Verify/Place UPS = ON

_____TE 8. Verify/Place Power supply = ON and Verify/set channels as shown:
Verify channel 1: set to 5V OVP: 6V OCP: 3A Output: Enable
Verify channel 2: set to 24V OVP: 24.5V OCP: 1A Output: Enable
Verify channel 3: set to 5.5V OVP: 6V OCP: 3A Output: Enable
Verify channel 4: set to 0V OVP: 5.5V OCP: 3A Output: Disable

_____TE 9. Boot the DAQ computer
_____TE 10. Open ICWTS_DAQ Settings Utility
_____TE 11. On the Analog Inputs tab, Verify/correct calibration information
_____TE 12. On the Analysis tab, verify/correct the python script and breath detection model versions selected are correct for the test being performed

NOTE:

SOFTWARE CAN BE FOUND: PC > C:DRIVE > REPOSITORIES > BUILDS > ICWTS PROJECT > ICWTS DAQ/ SETTINGS UTILITIES

_____TE 13. Pressure test and record leak rate of System unmanned and record leak rate __________

5.2.1.2 CTSD-ADV-2127 SECTION 6.3.1 – HARDWARE AND SOFTWARE START UP

NOTE:

STEPS ARE IN REFERENCE TO THE START UP OF ICWTS HARDWARE. STEPS PERTAINING TO INTEGRATED SYSTEMS WILL BE CALLED OUT FOR ORDER PURPOSES BUT WILL BE

PERFORMED FROM THEIR PERTINENT PROCEDURES AND SHALL BE CALLED OUT ON THE ASSOCIATED WAD.

_____TE 1. Verify/connect suit to the ICWTS-100 per SIZ36162361.

_____TE 2. Verify/connect the ICWTS-100 UPS to a 120V/60Hz lab outlet.

_____TE 3. Take UPS – ON.

_____TE 4. Power on ICWTS-100 DAQ CPU.

_____TE 5. Open ICWTS_DAQ by shortcut or by EXE location
(C:/Program Files/ICWTS Project/ICWTS_DAQ.EXE
(Software can be found: PC > C:drive > Repositories > Builds > ICWTS Project > ICWTS DAQ/ICWTS_DAQ.exe)

_____TE 6. Analog inputs will automatically connect. If an error pops up, inform the test director before proceeding. Otherwise, verify that "Analog Input" light is illuminated.

_____TE 7. Verify / Connect external-suit instrument connections per test diagram, SIZ36162361 (NDIR SUIT INTERFACE CONNECTIONS).

_____TE 8. Perform suit specific donning procedure steps up to helmet donning.

_____TE 9. Verify/Connect internal-suit instrument connections per test diagram, SIZ36162361 (NDIR SUIT INTERFACE CONNECTIONS).

_____TE 10. Connect the side-stream sample line to the MG-220 mouthguard or nasal cannula (circle one) and provide to the subject.

_____TE 11. Verify/Place Power supply = ON and Verify/set channels as shown:

Verify channel 1: set to 5V	OVP: 6V	OCP: 3A	Output: Enable
Verify channel 2: set to 24V	OVP: 24.5V	OCP: 1A	Output: Enable
Verify channel 3: set to 5.5V	OVP: 6V	OCP: 3A	Output: Enable
Verify channel 4: set to 0V	OVP: 5.5V	OCP: 3A	Output: Disable

_____TE 12. Configure ICWTS_DAQ software for NDIR configuration.
If any error popups present themselves, inform the test director before proceeding.
Verify the connected status lights are illuminated.

_____TE 13. Complete helmet donning steps or proceed at ambient pressure.

_____TE 14. ICWTS_DAQ Software Startup for NDIR mode:

NOTE:

FOR THE SOFTWARE PROCEDURE REFERENCES BELOW, “NDIR UNIT” AND “CAP-201” ARE INTERCHANGEABLE.

14.1. Verify that the CAP-201 is connected by checking the connected status light.

14.2. Enter the Dead Volume in liters for the test subject into the “Dead Volume” field.

14.3. Leave the "Pump On" checkbox unchecked. This checkbox is for the CAP-201 COTS unit internal pump which is not present on the COTS+ unit.

14.4. Click the "Start CAP-201 and Logging" button. This will start the CAP-201 and data logging. The CAP-201 has a short warm-up time indicated by the "Device Warming Up" light under the CAP-201 status section. Once warmup is complete, the CAP-201 is ready.

14.5. Click the "Live Breath Analysis" button to display the live analysis user interface window.

14.6. Verify that the CAP-201 unit has started.

_____TE 15. ICWTS_DAQ Software Data delay setup for NDIR mode:

NOTE:

THE CAP-201 (AKA NDIR) HAS A DELAY BETWEEN A BREATH OCCURRING AND THE CO2 READING BEING MEASURED. THIS IS THE TIME DELAY IS VARIABLE BASED ON SIDE-STREAM SAMPLE LINE, SUIT PRESSURE, AND SAMPLE FLOW RATE. THE CO2 DATA DELAY ACCOUNTS FOR THIS DELAY FOR ANALYSIS PURPOSES, BUT IT DOES NOT AFFECT THE LOGGED DATA OR DATA SHOWN ON THE LIVE DISPLAYS.

15.1. Click the "Set CO2 Data Delay" button to launch the CAP-201 CO2 Data and Velocity Data Alignment Tool.

15.2. Prepare the test subject to take a few breaths into the mouthpiece.

15.3. When test subject is ready, click the "Start Data Collect" button. This will start populating CO2 and flow sensor data into the graph. Record 3-5 breaths and then click the "Stop Data Collect" button.

15.4. Adjust the slider on the bottom of the window until the CO2 plot aligns with the exhale velocity plot.

15.5. Click the "Set Data Delay" button to save this delay in memory.

15.6. Close the CAP-201 CO2 Data and Velocity Data Alignment Tool.

_____TE 16. Perform “Continuous Analysis” with CAP-201:

16.1. On the Breath Analysis Interface, check the "Continuous" checkbox

16.2. Enter the number of seconds for each analysis in the "Data Chunk Size" input box.

16.3. Verify that the CO2 Data Delay has been set

16.4. When the test subject is ready to breath into the mouthpiece, click the "Start Data Collect" button to begin collecting data for analysis. The "Collecting Data" light will illuminate and the "Breath Data Array Size" will increase and reset to 0 each time the Data Chunk Size time limit is met.

16.5. Analyses will begin to populate in the "Analyses List" as they are available to view. Click on a time range to view the analysis results.

16.6. To view live data, set the slider on the lower left to "Live"

16.7. When finished collecting data for analysis, click the "Stop Data Collect" button.

_____TE 17. Perform “on-demand” breath analysis

17.1. On the Breath Analysis Interface, uncheck the "Continuous" checkbox

17.2. Verify that the CO2 Data Delay has been set

17.3. When the test subject is ready to breath into the mouthpiece, click the "Start Data Collect" button to begin collecting data for analysis. The "Collecting Data" light will illuminate and the "Breath Data Array Size" will increase.

17.4. Once enough data has been collected, click the "Stop Data Collect" button.

17.5. Click the "Analyze on Demand" button to begin the analysis on the collected data. The Breath Data Array Size will be reset to 0 as the buffered data is sent to the script for analysis. The analysis will occur in the background, and a new entry will appear on the "Analyses List" when it is ready.

17.6. To view live data, set the slider on the lower left to "Live"

NOTE:

ANALYSES WILL REMAIN IN MEMORY UNTIL THE SOFTWARE IS CLOSED. TO REMOVE THESE ANALYSIS FROM MEMORY, CLICK THE "CLEAR ALL ANALYSES" BUTTON.

5.2.1.3 STANDARD TEST POINT PROCEDURES TEMPLATE

Test Point 1: Unsuited Resting Non-dispersive Infrared Sensor (NDIR) with Mouthguard

Initials	OPERATION	Remarks
	Connect NDIR sensor package nafion line to mouthguard.	
	Verify that LabView VI “ICWTS_DAQ.exe” is configured for data collection and running nominally comparing the Digital Display to Table 24, Appendix E in CTSD-ADV-2127. Verify Data Delay is Enabled and Mouth Flow and Pressure Sensor is connected and powered on.	
	Have subject don NDIR sensor package with mouthguard and nose clip.	
	If it’s not already open, click “Live Data Analysis” button in lower-right of Labview UI.	
	Once subject and team are ready: Enter “Start 1A” into the Notes section of the Labview UI and click “Start Data Collection” in the Live Data Analysis Window. Record Start Time: _____________	
	Record inspired CO2 data until the 60 breath minimum threshold is reached.	
	Enter “Stop 1A” into the Notes section of Labview UI and click “Stop Data Collection” in the Live Data Analysis Window. Record Stop Time: ________	
	Poll subject for CO2 symptoms	__ Headache __ Dizziness __ Short of Breath __ Tingling __ Numbness __ Nausea

		__ NONE If symptoms present, consent subject to continue.
	Click the "Stop CAP-201 and Logging" button	
	Doff NDIR mouthguard and nose clip. Stage nearby.	
	Power off Bidirectional flow sensor (Channel 3) and NDIR Pump (Channel 4)	
	Verify previous step, **then** disconnect NDIR from helmet bubble	

Test Point 2: Suited Non-dispersive Infrared Sensor (NDIR) with Mouthguard at Rest

Initials	OPERATION	Remarks
	While subject is donning EMU LTA, mount NDIR package to Velcro strips in rear left scapula area of HUT. Affix tubing and wires to neck dam using tape to prevent interference with HUT and helmet donning.	
	Once subject is ready for helmet bubble, connect sensor package to helmet bubble (Test engineer will need to hold it.) and don mouthguard and nose clip. Record suit don Start time: ____________________	
	Verify previous step, **then** power on bidirectional flow sensor (Ch 3) and NDIR pump (Ch 4). Verify pump is on in Labview software.	
	Verify that LabView VI "ICWTS_DAQ.exe" is configured for data collection and running nominally comparing the Digital Display to Table 24, Appendix E in CTSD-ADV-2127. Verify Data Delay is Enabled	
	Click the "Start CAP-201 and Logging" button Record file name: _______________________________________	Note: File name is not expected to change between Test Points 1B, 1C, 1D, and 1E.
	Begin pressurization. Record Start Time at 19 psia:___________________	
	Using the Graph button in the upper-right, open a new graph and choose the Mercaldo MET rate value to plot. Leave this window running throughout this test point to verify metabolic rates.	.

	Met Rate should generally not deviate from the target by more than 100 BTU/hr.	
	Once subject and team are ready: Enter “Start 1B” into the Notes section of the Labview UI and click “Start Data Collection” in the Live Data Analysis Window. Record Start Time: _____________	
	Provide feedback to subject to maintain target Met Rate. Target: **Resting**	HR:
	Record inspired CO2 data until the 60 breath minimum threshold is reached.	
	Enter “Stop 1B” into the Notes section of Labview UI and click “Stop Data Collection” in the Live Data Analysis Window. Record Stop Time: ________	
	Poll subject on CO2 symptoms	__ Headache __ Dizziness __ Short of Breath __ Tingling __ Numbness __ Nausea __ NONE If symptoms present, consent subject to continue.

Test Point 3: Suited Non-dispersive Infrared Sensor (NDIR) with Mouthguard at 1000 BTU/hr

Initials	OPERATION	Remarks
	Provide feedback to subject to reach target Met Rate. Target: **1000 BTU/HR**	
	Once subject and team are ready: Enter “Start 1C” into the Notes section of the Labview UI and click “Start Data Collection” in the Live Data Analysis Window. Record Start Time: _____________	
	Provide feedback to subject to maintain target Met Rate. Target: **1000 BTU/HR**	HR:

	Record inspired CO2 data until the 60 breath minimum threshold is reached.	
	Enter “Stop 1C” into the Notes section of Labview UI and click “Stop Data Collection” in the Live Data Analysis Window. Record Stop Time: ________	
	Poll subject on CO2 symptoms	__ Headache __ Dizziness __ Short of Breath __ Tingling __ Numbness __ Nausea __ NONE If symptoms present, consent subject to continue.

Test Point 4: Suited Non-dispersive Infrared Sensor (NDIR) with Mouthguard at 2000 BTU/hr

Initials	OPERATION	Remarks
	Provide feedback to subject to reach target Met Rate. Target: **2000 BTU/HR**	
	Once subject and team are ready: Enter “Start 1D” into the Notes section of the Labview UI and click “Start Data Collection” in the Live Data Analysis Window. Record Start Time: ______________	
	Provide feedback to subject to maintain target Met Rate. Target: **2000 BTU/HR**	HR:
	Record inspired CO2 data until the 60 breath minimum threshold is reached.	
	Enter “Stop 1D” into the Notes section of Labview UI and click “Stop Data Collection” in the Live Data Analysis Window. Record Stop Time: ________	
	Poll subject on CO2 symptoms	__ Headache __ Dizziness

		__ Short of Breath __ Tingling __ Numbness __ Nausea __ NONE If symptoms present, consent subject to continue.

Sensor Stop and Suit Doff

Initials	OPERATION	Remarks
	Click the "Stop CAP-201 and Logging" button	
	Inform TD when ready to depress EMU. Record depress time: ________________________	
	After suit is open to ambient, turn off power to NDIR pump and turn off power to sensors at the controls.	
	Perform suit doffing procedures Record Time:___________________________	

5.2.1.4 CTSD-ADV-2127 SECTION 6.4 – NOMINAL SHUT-DOWN PROCEDURE

NOTE:

STEPS ARE IN REFERENCE TO THE SHUTDOWN OF ICWTS HARDWARE. STEPS PERTAINING TO INTEGRATED SYSTEMS WILL BE CALLED OUT FOR ORDER PURPOSES BUT WILL BE PERFORMED FROM THEIR PERTINENT PROCEDURES AND SHALL BE CALLED OUT ON THE ASSOCIATED WAD.

_____TE 1. Perform depressurization steps of suit specific procedure.

_____TE 2. Disable ICWTS-100 Power Supply, Channel 3.

_____TE 3. Perform helmet doffing steps of suit specific procedure.

_____TE 4. Disconnect in-suit wiring from passthrough, as well as from NDIR and circuit interface box if present.

_____TE 5. Perform Suit Doffing steps of suit specific procedure.

_____TE 6. Transfer acquired test data to secure folder.

_____TE 7. Verify/Disable all channels on the ICWTS-100 Power Supply.

_____TE 8. Take ICWTS-100 Power Supply to OFF.

_____TE 9. Disconnect suit interface lines and stow.

_____TE 10. Select Shutdown on ICWTS_DAQ software.

_____TE 11. Take ICWTS-100 DAQ CPU to OFF.

5.3 Test Rules

The test rules provided below are included for reference, as they will be combined and assessed for each specific integrated test setup with the ICWTS; however, they serve as a starting point.

Table 5.1 – Test Rules Reference

Condition	Response
Subject presents with confusion, convulsions, loss of consciousness, muscle twitches, hand flaps	<u>TERMINATE TEST.</u>
At direction of test subject or test conductor	<u>TERMINATE TEST.</u>
Presentation of symptoms potentially indicative of acute hypercapnia **nausea, vomiting, dizziness, vertigo, light-headedness, headache that is felt not to be normal, rapid breathing or difficulty breathing that is uncomfortable or painful, heart palpitations or feelings of irregular heartbeats, flushed feeling (monitor for flushed feeling symptom progression)**	<u>TERMINATE TEST.</u>
Severe discomfort experienced by test subject	<u>TERMINATE TEST.</u>
PPCO2 Exceedance	<u>HOLD and EVALUATE:</u> Terminate if PPCO2 reading from the ICWTS indicates >30 mmHg for more than 10 seconds continuously or > 23 mmHg for more than 2 minutes continuously.
Heart Rate Exceedance	<u>HOLD and EVALUATE:</u> If the test subject's heart rate >85% of VO2 Max derived heart rate maximum for more than 2 minutes continuously, terminate the test. 1. If subject is approaching 85% of VO2 Max derived heart rate maximum, they will be asked to slow down or pause/rest. 2. Operator will monitor heart rate for rapid jumps in heart rate (e.g., >20-30 BPM sustained for >1min)

Condition	Response
	not directly following a change in posture or exercise effort and the subject will be queried for CO2 symptomology. 3. Operator will monitor heart rate for sustained elevated heart rate (>140 BPM) and query subject for CO2 symptomology.
Heart Rate Signal Lost	HOLD and EVALUATE. If signal cannot be regained, terminate test.
Mouth trauma/pain due to mouthpiece	HOLD and EVALUATE. If subject continues to express pain due to mouthpiece, terminate test.
Fire	TERMINATE TEST. Extract subject and evacuate facility per the defined evacuation routes.
Water Leak or Spill	HOLD and EVALUATE. If leakage cannot be resolved, terminate test.
Loss of Facility Power and/or Facility/Lab Lighting	HOLD and EVALUATE. If power and/or facility lighting loss lasts longer than ~15 seconds, terminate test.
Loss of Test Instrumentation Data or Indication of Instrumentation Faults	HOLD and EVALUATE. If problem cannot be resolved in a reasonable amount of time test conductor, terminate test.

5.4 Determination of Acceptable and Unacceptable Breaths

Identification of acceptable breath traces from within a dataset is essential for accurate calculation of the in-suit ppCO2. Due to the variability associated with HITL testing (e.g., subject size, suit fit, physiology, etc.), ventilation designs, suit configuration, there is no single method that can be applied across all suit configurations and tests. Considering this, guidelines for determining acceptable traces for analysis have been established to provide a consistent framework by which analysis can be completed. The following are descriptions of acceptability criteria along the breath waveform (Figure 5.1):

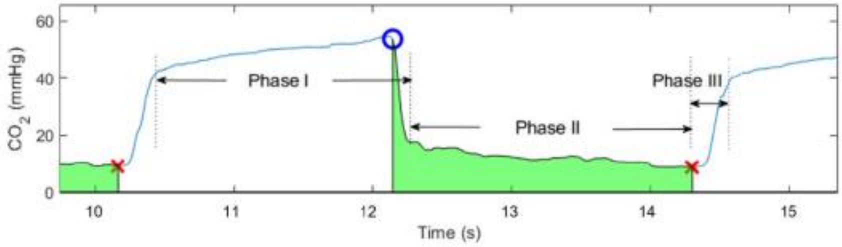


Figure 5.1 Breath cycle trace.

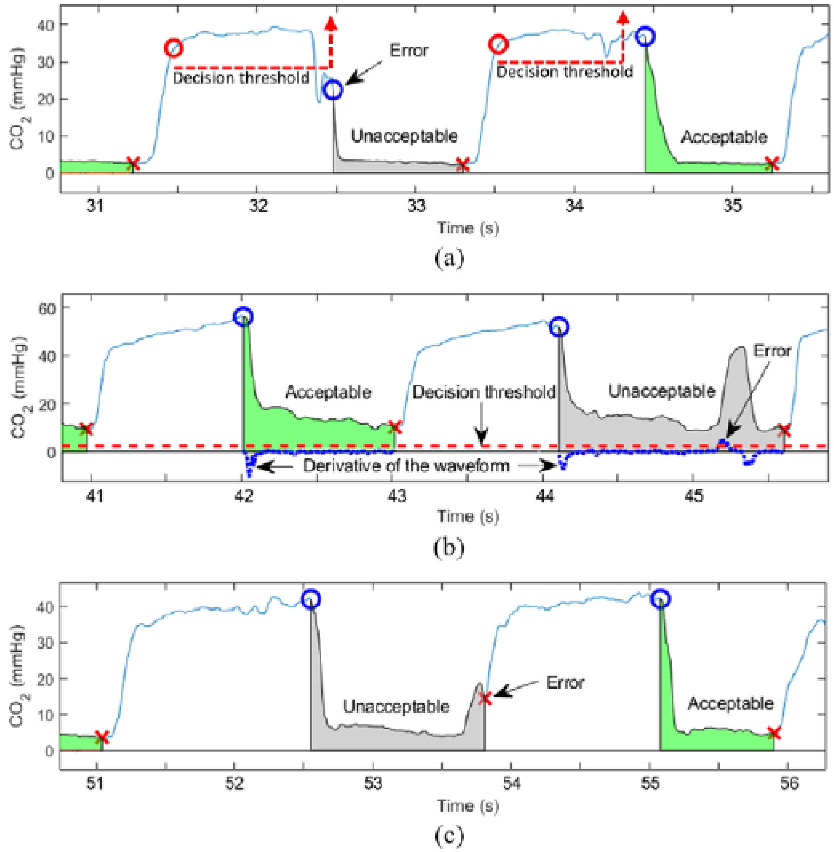


Figure 5.2 Examples of acceptable and unacceptable breaths.

(1) Step 1 (plateau during the expiration phase and sloped decrease after inspiration start): Breath is acceptable if the amplitude of inspiration start (blue circle: **O**) is greater than 90% of the amplitude of the starting point in the plateau period (red circle: **O**) as shown in Figure 5.2a. The knee point detection algorithm provides the point of maximum curvature (red circle: **O**) after the inspiration end (red

cross: **X**) which is a mathematical measure of how much a function differs from a straight line [21]. If the amplitude of inspiration start (blue circle: **O**) is less than 90% of the amplitude of the starting point in the plateau period (red circle: **O**) (Figure 5.2a), the breath is unacceptable. The shape of the plateau between the inspiration end and the next inspiration start is variable depending on the type of suit. This guideline provides a consistent and mathematically justifiable answer regardless of the shape of the plateau.

(2) Step 2 (plateau during the inspiration phase): Breath is acceptable if the plateau during Phase II is maintained flat without an error in measurement. To detect unexpected error, a decision threshold derived from the first derivative of the waveform of Phase II is set (Figure 5.2b). If the amplitude of the first derivative of the waveform is greater than 3 (mmHg/s), the breath is unacceptable.

(3) Step 3 (Sloped increase after inspiration end): Breath is acceptable if the inspiration slope is continuously increasing without an error in measurement. During the process to find an inspiration end point from a sloped increase (Figure 6.1), this unwanted peak (Figure 5.2c) can be detected as a fake inspiration end point before reaching to the start point of the next waveform. The inspiration end point is therefore a wrong choice and the breath unacceptable if 90% of the amplitude at the inspiration end point is greater than the average of adjacent inspiration end points.

(4) Step 4 (Manual breath verifications): It is recommended to conduct regular manual breath verifications as a final step when using an automated breath detection algorithm to ensure acceptable breath criteria are met.

5.5 Defining Inspired CO2 (PiCO2)

Below in Table 6.2 is an example of the same $PiCO_2$ of 15mmHg under hyperbaric, normobaric, and hypobaric tests of a spacesuit.

Table 5.2 Examples of $IsoPiCO_2$ Conditions

P_B Psia, mmHg	Sensor dry-gas FiCO2	(1) $ppCO_2$ mmHg	(4) $PiCO_2$ mmHg	Condition
19.0, 982	0.016	15.7	15.0	Suit tested at 1 ATA with 4.3 psid
14.7, 760	0.021	16.0	15.0	Suit tested at 1 ATA with 0 psid
4.3, 222	0.085	19.0	15.0	Suit tested at vacuum with 4.3 psid

$IsoPiCO_2$ is the same $PiCO_2$ over a range of P_B.

(1) ppCO2 = $P_B \times FiCO_2$ or if a target $PiCO_2$ is desired, then compute the required $ppCO_2$ as:

(2) ppCO2 = $P_B \times [PiCO_2 / (P_B - 47)]$ with mm Hg unit, where 47 is the partial pressure of water vapor (PH_2O) in mm Hg at 37°C body core temperature.

Also,

(3) $FiCO_2 = PiCO_2 / (P_B - 47)$ or $FiCO_2 = ppCO_2 / P_B$ with mm Hg unit, and

(4) $PiCO_2 = (P_B - 47) \times$ FICO2 with mm Hg unit.

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