Utilizing a Suited Manikin Test Apparatus and Space Suit Ventilation Loop to Evaluate Carbon Dioxide Washout

Cinda Chullen[1]
NASA Johnson Space Center, Houston, Texas, 77058

Bruce Conger[2], Adam Korona[3], Bryan Kanne[4], Summer McMillin[5], Thomas Paul[6],
Jacobs, Houston, Texas, 77058

Jason Norcross[7]
Wyle, Houston, Texas, 77058

Jesus Delgado Alonso, Ph.D[8]
Intelligent Optical Systems, Inc., Torrance, California 90505

and

Mike Swickrath[9]
Battelle Memorial Institute, Columbus, Ohio, 43201

NASA is pursuing technology development of an Advanced Extravehicular Mobility Unit (AEMU) which is an integrated assembly made up of primarily a pressure garment system and a portable life support subsystem (PLSS). The PLSS is further composed of an oxygen subsystem, a ventilation subsystem, and a thermal subsystem. One of the key functions of the ventilation system is to remove and control the carbon dioxide (CO_2) delivered to the crewmember. Carbon dioxide washout is the mechanism by which CO_2 levels are controlled within the space suit helmet to limit the concentration of CO_2 inhaled by the crew member. CO_2 washout performance is a critical parameter needed to ensure proper and robust designs that are insensitive to human variabilities in a space suit.

A suited manikin test apparatus (SMTA) was developed to augment testing of the PLSS ventilation loop in order to provide a lower cost and more controlled alternative to human testing. The CO_2 removal function is performed by the regenerative Rapid Cycle Amine (RCA) within the PLSS ventilation loop and its performance is evaluated within the integrated SMTA and Ventilation Loop test system. This paper will provide a detailed description of the schematics, test configurations, and hardware components of this integrated system. Results and analysis of testing performed with this integrated system will be presented within this paper.

[1] Project Engineer, Space Suit and Crew Survival Systems Branch/EC5
[2] Engineering Analysis Lead, Thermal and Environmental Analysis, 2224 Bay Area Blvd., Houston, TX 77058
[3] Systems Engineer, Systems Engineering Services, 2224 Bay Area Blvd., Houston, TX 77058
[4] Laboratory Technician, Space Environment Simulation, 2224 Bay Area Blvd., Houston, TX 77058
[5] Project Engineer, Hardware Systems Project Engineering, 2224 Bay Area Blvd., Houston, TX 77058
[6] Engineering Analyst, Thermal and Environmental Analysis, 2224 Bay Area Blvd., Houston, TX 77058
[7] Lead Scientist, Human Adaptation & Countermeasures, 1290 Hercules, Houston, TX 77058
[8] Principal Investigator, 2520 West 237th St, Torrance, California 90505
[9] Principal Research Scientist, 505 King Ave., Columbus, Ohio 43201

Nomenclature

acfm = actual cubic feet per minute
AEMU = Advanced Extravehicular Mobility Unit
APLSS = Advanced Space Suit Portable Life Support Subsystem
Btu = British thermal units
CEM = controlled evaporation mixer
CFD = computational fluid dynamics
CFG = configuration
CO_2 = carbon dioxide
COTS = commercial off-the-shelf
EMU = Extravehicular Mobility Unit
EVA = extravehicular activity
GAC = Gas Analyzer Console
H_2O = water
HUT = hard upper torso
hr = hour
IOS = Intelligent Optical Systems, Inc.
ISS = International Space Station
IVTS = Integrated Ventilation Test System
JSC = Johnson Space Center
mmHg = millimeters of mercury
OSHA = Occupational Safety and Health Administration
O_2 = oxygen
PLSS = portable life support subsystem
psia = pounds per square inch absolute
REI = Rear Entry I-Suit
RCA = Rapid Cycle Amine
SMTA = suited manikin test apparatus
TCC = Trace Contaminant Control

I. Introduction

SPACE suit life support systems are critically necessary for the successful support of the International Space Station (ISS) and future human space exploration missions. Micro-gravity Extravehicular Activity (EVA) and planetary surface operations necessitate reliable, robust, right-sized, and efficient space suit life support systems. EVAs or spacewalks are critical to human space flight. An EVA made it possible for Neil Armstrong to be the first man on the moon. EVAs continued to be a staple in space flight to facilitate the buildup of ISS and repair the Hubble telescope. The space suit in all its complexity provides a safe haven for the spacewalker. Space suits used for EVAs are performed at vacuum which presents tremendous technical challenges that are unique.

NASA is presently developing an advanced suit for exploration missions. A major subsystem of the new space suit that will efficiently adapt to the unique technical challenges is the Advanced Space Suit Portable Life Support Subsystem (APLSS). The APLSS will attach to the space suit pressure garment subsystem and provide approximately an 8 hour supply of oxygen (O_2) for breathing, suit pressurization, ventilation, humidity control, trace contaminant control, carbon dioxide (CO_2) removal, and a thermal control system for crew member metabolic heat rejection. For exploration missions, the APLSS will also need to be robust, lightweight, low-power, and contain durable hardware for maintaining and monitoring critical life support constituents in the suit. Other functions important for space suit include providing mobility to perform required tasks, communications, biomedical data, environment protection, and waste management.

As part of the environmental control, the ventilation system within the APLSS is the only way to provide breathing gas (conditioned O_2) to the astronaut and remove the potentially hazardous CO_2. The O_2 not only provides the pressurization of the suit, but the means in which the astronaut breaths as well. An important aspect is that the flow of O_2 must be adequate enough to remove or "washout" CO_2 in the helmet and aid in the prevention of fogging in the helmet. Adequate flow to disseminate the CO_2 out of the helmet has been referred to as "CO_2 Washout". The effectiveness of the CO_2 washout in a space suit is critical and will be the focus of this paper. The aspects of fogging will not be addressed. The test equipment associated with the CO_2 washout research is not configured to test the cold

case environments that would exacerbate fogging. Prior investigations have determined that there are alternative strategies to reduce fogging.[1] Additional work has also been performed on the effects of helmet geometry and inlet duct configurations.[2,3] The helmet geometry and inlet duct features will be considered in these CO_2 washout optimization studies.

Over the last several years, several human test series have been accomplished to analyze the effects of CO_2 washout with different space suit configurations. These studies are necessary to ensure the crew member receives breathing gas that is safe especially with new space suit configurations. However, human test trials are expensive, time consuming, and involve human test subjects which include additional safety protocols for testing. Therefore, research is currently underway at NASA Johnson Space Center (JSC) in the Portable Life Support Subsystem (PLSS) Laboratory to focus on the CO_2 washout optimization studies using an Integrated Ventilation Test System (IVTS) including a breathing manikin as shown in Figure 1 with NASA's Administrator Charles Bolden's tour of the laboratory.

The IVTS is made up of both a ventilation test loop and a suited manikin test apparatus (SMTA). The purpose of the IVTS is to supplement human testing, optimize CO_2 removal efficiency, to validate CO_2 washout computational fluid dynamics (CFD) models, evaluate space suit nitrogen purge efficiencies, optimize Rapid Cycle Amine (RCA) performance for removing CO_2 and humidity, and reduce the overall cost and logistics of CO_2 washout testing. Other uses of the IVTS include evaluation of instrumentation and test hardware planned to be used during human trials. The ventilation test loop replicates one of the three main loops within the APLSS. The main function of the ventilation subsystem in the space suit is to remove the CO_2 and provide the transport of the breathing gas to the crew member. The SMTA was developed to supplement human testing activities and was uniquely designed for CO_2 washout research. The SMTA contains a manikin that emulates the crew member's position within the space suit and is configured to simulate human breathing.

The focus of this research is to resolve differences that have been experienced between human testing and CFD modeling predictions. The IVTS is envisioned to provide a platform for gaining knowledge of CO_2 washout characteristics and help resolve these differences. This paper describes the IVTS that was built to perform CO_2 washout studies, the importance of CO_2 washout testing, the space suit implementation approach for achieving CO_2 washout, testing and analysis, and a discussion of future plans.

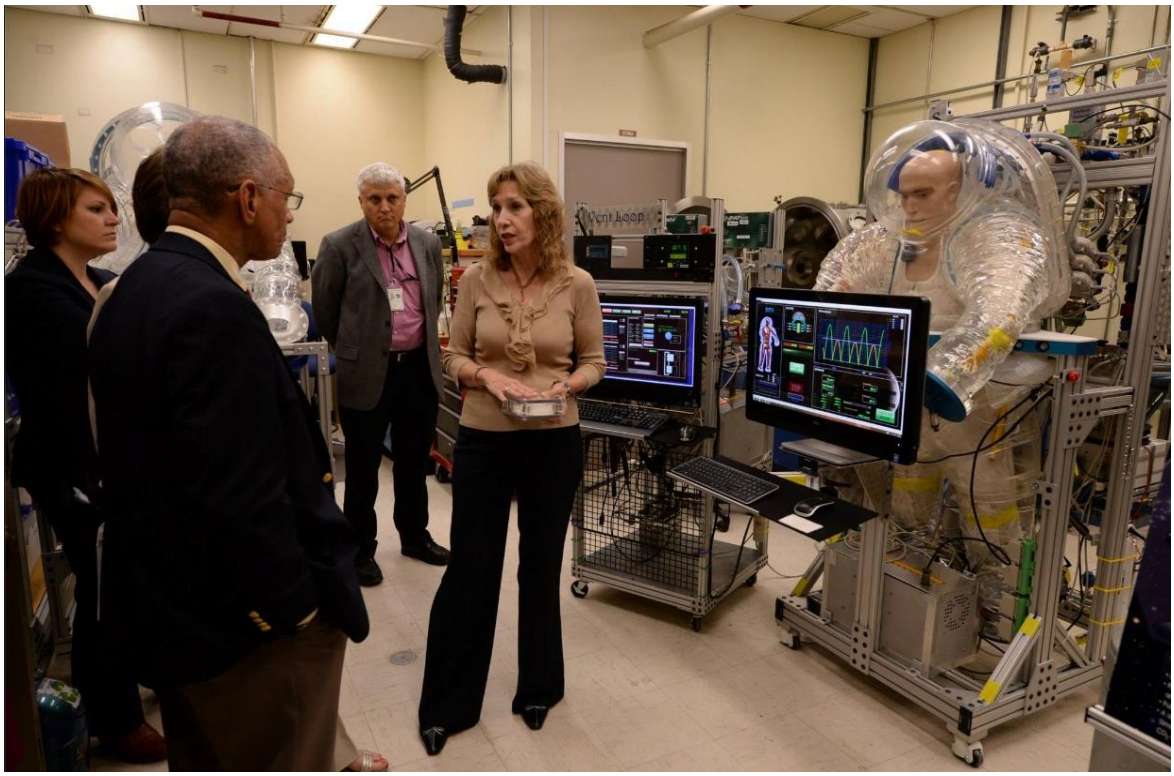

Figure 1. Integrated Ventilation Test System (IVTS)

II. Importance of Carbon Dioxide Washout

Whenever a person is enclosed within a suit, there is a risk that too much of the exhaled CO_2 can accumulate and would be re-inhaled, causing hypercapnia (carbon dioxide toxicity). Hypercapnia may include headache, visual disturbance, impaired mental function, lethargy, dizziness, shortness of breath, and increased heart rate. Higher CO_2 concentrations can cause unconsciousness, convulsions, and ultimately death.[4] Minimizing a suited person from re-inhaling metabolically produced CO_2 can be challenging. Extensive measures are necessary in the APLSS to ensure that CO_2 is not only monitored and removed, but adequately transported out of the suit. In particular, it is extremely important for the CO_2 to be adequately dispersed from the suit helmet and not pocketed in any particular location within the suit. Therefore, this process of moving, monitoring, and eliminating the CO_2 is referred to as CO_2 washout in the space suit.

In designing a new APLSS, CO_2 washout performance has become one of the most critical parameters needed to ensure proper and sufficient suit design. CO_2 washout is not only important in a space suit, but in vehicle applications as well such as sleep stations and hygiene compartments. However, human testing to fully evaluate CO_2 washout is expensive due to the levied safety requirements. Moreover, correlation of math models becomes challenging because of human variability and movement as seen in the complicated patterns that trace CO_2 in the CFD model in Figure 2.

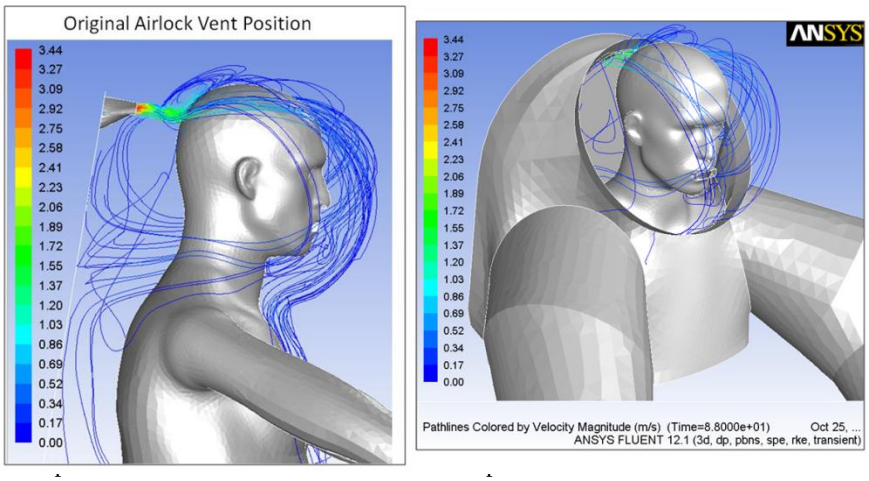

Figure 2.

A breathing capability within the SMTA combined with an APLSS ventilation loop will provide a safe, lower cost, stable, easily modeled alternative to human CO_2 washout testing. This configuration will provide the capability to evaluate CO_2 washout under off-nominal conditions that would otherwise be unsafe for human testing or difficult due to fatigue of a test subject.

Recent research by Law and others suggests that it may be sufficient to set more stringent criteria for CO_2 levels for exposure limits than is currently set by the ISS operations due to certain crew symptoms data.[4] Therefore, the APLSS team has chosen the more stringent criteria of maintaining the average inhaled CO_2 level to an EVA average of 3.8 millimeters of mercury (mmHg) as the challenging target for CO_2 control development and testing efforts as opposed to the previous goal which was to maintain 7.6 mmHg at 1600 Btu/hr.[5] As well, the team is committed to working closely with toxicology experts at JSC to keep abreast of the latest research in CO_2 limits. In addition, it is predicted that the RCA outlet will need to be maintained at 2.2 mmHg[6] in order to maintain 3.8 mmHg inhaled in the helmet.

The CO_2 levels inhaled by a crew member in the space suit are dependent upon multiple parameters and design features in the space suit. The configuration of the SMTA and the APLSS ventilation loop will provide an effectual systematic way to meet the stringent CO_2 levels in the advanced suit. The primary parameters and design features that SMTA and APLSS ventilation loop will monitor and evaluate include the following:

1. Concentration of CO_2 returning from the PLSS and entering the helmet
2. Ventilation duct design in the helmet
3. Head orientation of the simulated crew member
4. Volumetric flow rate in the ventilation loop as driven by the fan design
5. Metabolic rate of the simulated crew member
6. Frequency and flow rates associated with the crew member's breathing cycle

This will be the first time that a system integration test has been performed to assess CO_2 washout with the APLSS ventilation loop and the SMTA in a simulated nonhuman environment. The system combines the RCA in the ventilation loop other design features such as the vent duct assembly. This combination of system level assessments via testing should provide good validation of CO_2 removal efficiency requirements and may provide insight into interactions associated with the RCA and the other parameters mentioned above.

The goal is to obtain increased CO_2 washout effectiveness by assessing a combination of the aforementioned parameters and design features in the APLSS ventilation loop and SMTA. Other potential system benefits might include reductions in the size of the PLSS battery due to reduced fan power demands and reduced O_2 tank mass due to reduced ullage losses associated with the cycling of the RCA. All of these variables will be necessary to have a successful test and verification process to ensure that CO_2 washout is adequately addressed and monitored.

III. Implementation Approach for Achieving Carbon Dioxide Washout

Preventing a suited person from experiencing hypercapnia has been approached using various methods. In recreational scuba applications, for example, a demand regulator is typically used that introduces air into the mouthpiece or mask whenever the person inhales. Firefighters utilize demand regulator systems or rebreather systems depending on the design duration of the breathing system. Demand regulator systems vent the exhaled air to the ambient environment whereas rebreather systems recycle the air, clean out the metabolic CO_2 and introduce a small amount of O_2 to replace the metabolized O_2. Based on an equivalent duration capability, the O_2 tank of a rebreather system is much smaller than the air tank used in a demand regulator system. This is because the amount of air exhaled (and is lost to ambient in a demand regulator system) is large relative to the amount of metabolic O_2 consumed during the breathing process. The trade between rebreathers versus demand regulator systems is whether or not the additional size of the CO_2 removal system needed in the rebreather systems is offset by savings of the rebreather O_2 tank size relative to the air or O_2 tank size of the demand regulator system.

The launch and entry suits used during the shuttle and space station eras (LES and ACES) have utilized a demand regulator approach since the design duration of the system is short and the metabolic rates typically encountered during launch and re-entry are low relative to those typically experienced during EVA.[7] The APLSS, however, utilizes a rebreather approach as did the Apollo and Shuttle/ISS extravehicular mobility units (EMUs) because of the breathing requirements associated with EVA durations and metabolic rates. The rebreather (ventilation loop) designs of the Apollo, Shuttle, and ISS EMUs were similar utilizing CO_2 removal units that were either excessed or regenerated after each EVA. The APLSS ventilation loop contains the following key components:

RCA: The APLSS utilizes the RCA to remove CO_2 and excess humidity. This technology is regenerable throughout the duration of the EVA and does not need the routine maintenance at the end of each EVA that was required by the Apollo and Shuttle/ISS EMU CO_2 removal units.[8]

Fan: The volume of this effective high speed fan has been minimized to help keep the PLSS volume within limits. The fan currently has the capacity to provide 6 actual cubic feet per minute (acfm) to the helmet in order to provide for sufficient CO_2 washout. If the helmet ventilation design becomes more efficient at washing out CO_2, the ventilation rate requirement could be reduced resulting in fan power reduction.

Heat Exchanger: The APLSS ventilation loop includes a small but effective heat exchanger that brings the ventilation gas temperature to within 5 F of the thermal control water loop. Meeting pressure drop requirements is one of the drivers of the heat exchanger sizing. If the ventilation flow rate requirement was reduced due to CO_2 washout efficiency improvements in the helmet, the heat exchanger may be able to be reduced further.

TCC: The Trace Contaminant Control (TCC) unit is placed inside the hatch (pressurized volume) of the space suit in order to allow for convenient periodic change-out of this filter once it becomes saturated. The TCC design may also be able to be reduced in size if the ventilation flow rate requirement was reduced due to CO_2 washout efficiency improvements in the helmet.

Figure 3 shows the simplified layout of the APLSS ventilation loop and SMTA as implemented in the PLSS 2.0 Laboratory test facility. The PLSS 2.0 test facility is not rated for O_2 and uses nitrogen instead of O_2 as the test gas. The PLSS 2.0 is shown in figure 4.

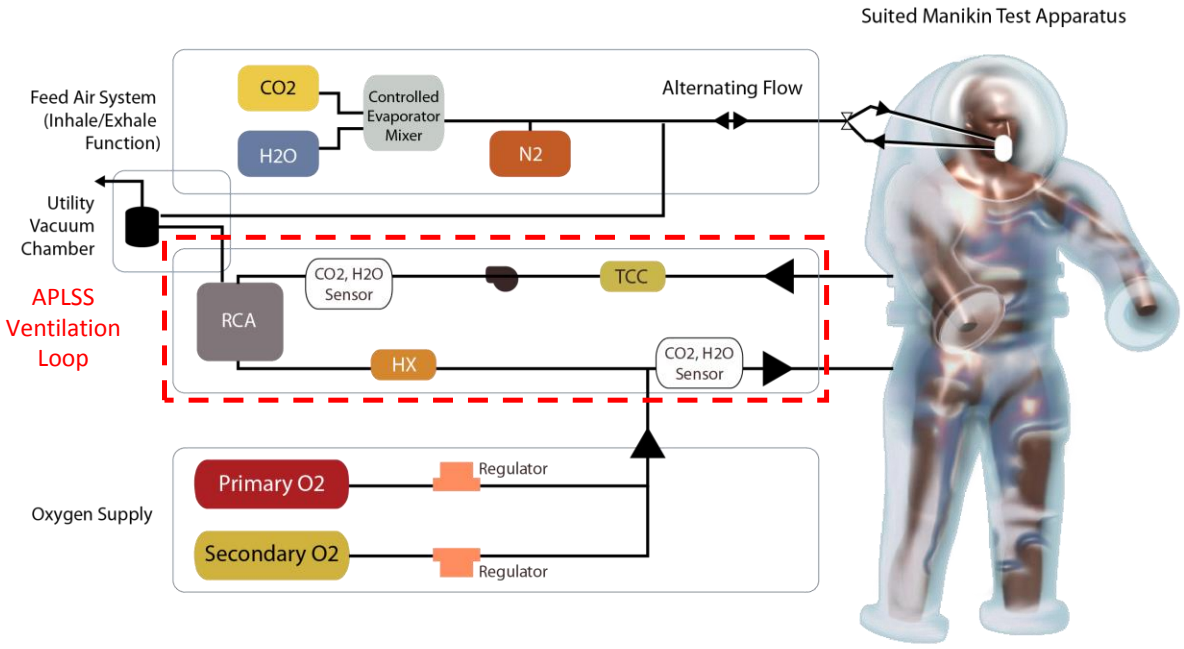

Figure 3. PLSS 2.0 Laboratory SMTA test schematic with APLSS Ventilation Loop Highlighted.

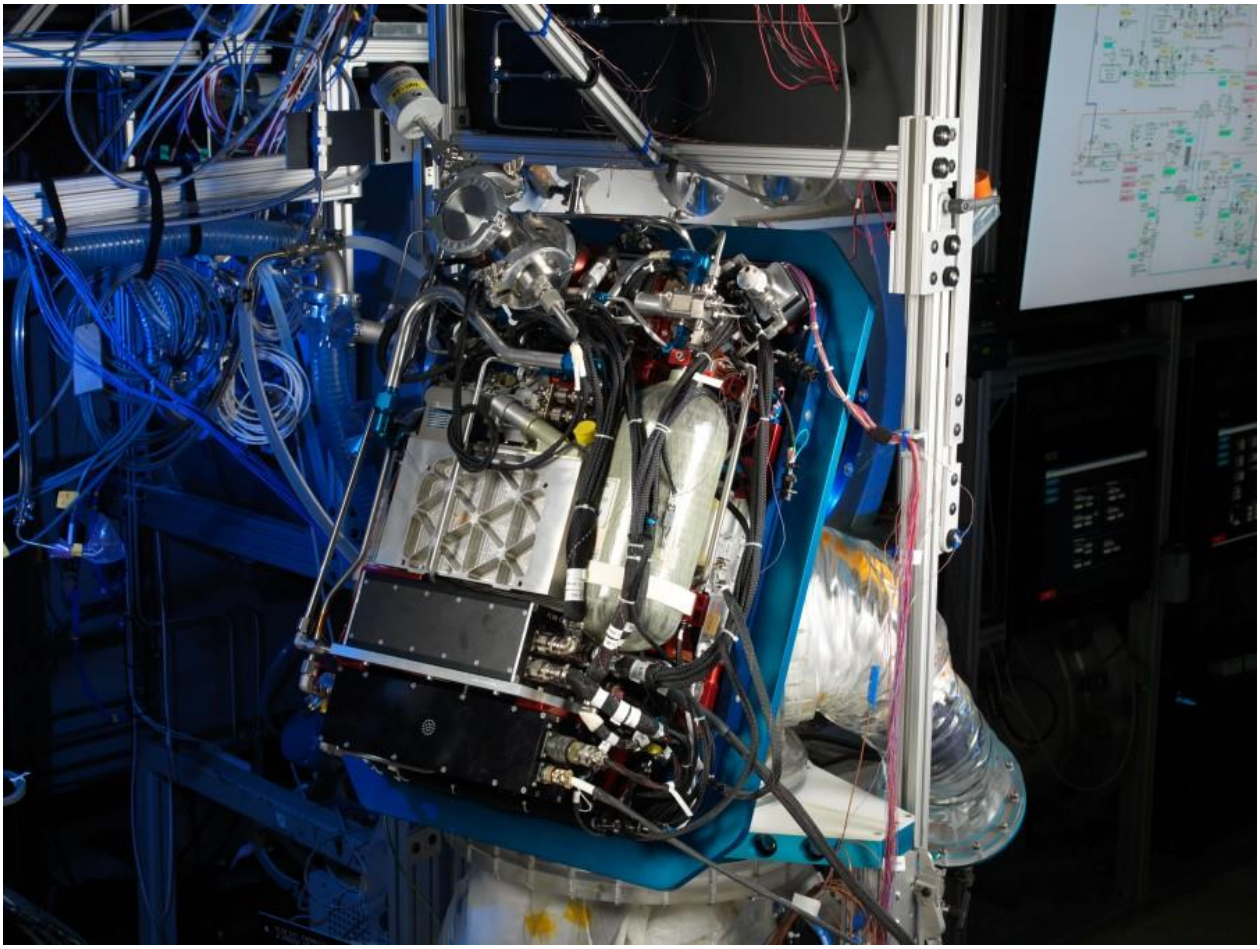

Figure 4. PLSS 2.0 within the NASA JSC PLSS Laboratory.

IV. Ventilation Test Loop and the SMTA

CO_2 washout and a number of other test trials will be accomplished using an IVTS. The IVTS was recently completed after two years of schematic development, component specification, test rig buildup, and system integration. The IVTS is located in the JSC PLSS Laboratory (JSC Building 7, room 2006). The IVTS includes two distinct test rigs, namely the SMTA and the ventilation test loop. The SMTA was design to emulate the human in the loop with breathing capability. The Ventilation Test Loop was primarily designed to replicate the ventilation subsystem in the PLSS. The main function of the ventilation subsystem is to remove the CO_2 in the space suit and provide the transport of the breathing gas to the astronaut. With both the SMTA and the Ventilation Test Loop integrated into the IVTS, the test rig functions as the PLSS ventilation subsystem combined with the simulated astronaut in the loop. A picture of the IVTS showing the Ventilation Test Loop on the left and the SMTA on the right is shown in Figure 5 below.

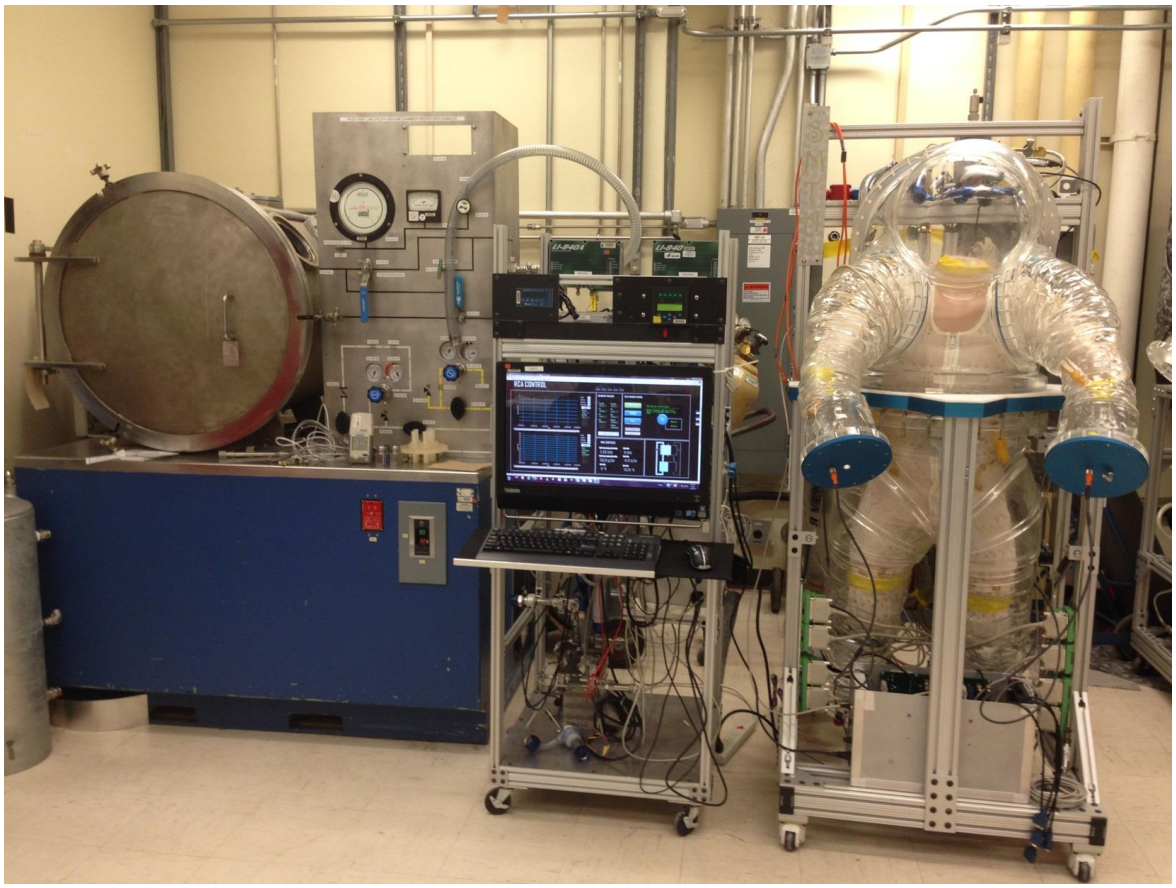

Figure 5. Integrated Ventilation Test System: Ventilation Test Loop (Left) and SMTA (Right)

A. Ventilation Test Loop

The Ventilation Test Loop (Vent Loop) design simulates portions of the APLSS ventilation loop previously shown in figure 3. The Vent Loop has been designed to interface with the SMTA and contains the required instrumentation to evaluate the flow rates, humidity and CO_2 concentrations in the APLSS ventilation loop. The Vent Loop will maintain the desired ventilation loop flow rate using a commercial off-the-shelf (COTS) fan and will maintain the system pressure using a COTS regulator. The Vent Loop also contains a flow meter, CO_2 sensors and humidity sensors at the inlet and outlet of the RCA to evaluate CO_2 and humidity removal performance. The Vent Loop interfaces with facility vacuum resources that are utilized to remove CO_2 and humidity from the desorbing RCA bed. The Vent Loop combined with the SMTA as the IVTS also interfaces to facility gaseous nitrogen that supplies the test loop with dry gaseous nitrogen and provides any ullage lost during the RCA valve cycling operation. This replicates the advanced suit pressure regulation function that provides make-up O_2 to replace any

ventilation gas losses in the suit or PLSS. The TCC function is not currently simulated within the Vent Loop which is shown in figure 6.

Figure 6 Ventilation Test Loop

B. Suited Manikin Test Apparatus

The SMTA has been developed to augment testing of the APLSS ventilation subsystem in order to provide a safer, lower cost and more controlled alternative to human testing. The SMTA includes a transparent urethane suit based on the geometry of the Mark III space suit with a COTS manikin inside that is augmented with breathing capability to emulate the human in the space suit. Human testing to fully evaluate CO_2 washout is expensive due to the levied safety requirements. Moreover, correlation of math models becomes challenging because of human variability and movement. The SMTA can now provide a stable, easily modeled alternative to human CO_2 washout testing. The performance of the RCA in the PLSS ventilation subsystem can be more adequately evaluated using the SMTA. This uniquely designed SMTA with its breathing capability provides NASA the ability to evaluate off-nominal CO_2 washout conditions that would otherwise be unsafe, difficult, and very expensive for human testing due to test subject fatigue. This innovative and unique SMTA is NASA's only breathing manikin test capability. Its first priorities are to validate the advanced CO_2 removal hardware performance and CO_2 washout.

The SMTA will be used to vary metabolic conditions. Total gas pressure within the SMTA can also be varied from 4 psia to 19 psia to simulate a wide range of suit pressures experienced during flight and test scenarios. The SMTA is set up in the PLSS Laboratory at JSC and will be subsequently tested in a configuration merged with the PLSS 2.0 test article in the PLSS 2.0 Laboratory.[9] The SMTA operates with a human breathing profile. However, the SMTA is not O_2 rated and nitrogen is used to simulate O_2.

The SMTA maintains the desired simulated metabolic rate by injecting the proper amounts of CO_2 and water vapor (H_2O) into the breathing stream. A flow controller supplies the proper amount of facility CO_2 to a controlled evaporation mixer (CEM) unit to simulate the desired metabolic load. The CEM controls the amount of water flowing from the SMTA water tank to be mixed with the CO_2 and heats this mixture to vaporize the proper amount of metabolic water injected in the breathing gas stream.

The breathing exhale system of the SMTA mixes the CO_2 and H_2O vapor mixture exiting the CEM with compressed air to create a characteristic breathing profile, ported orally to the manikin's mouth through the back of the manikin's neck. The simulated exhale breath of the manikin is controlled by a mass flow controller, a mass flow

meter, a back pressure regulator and a solenoid valve. These components work together to supply the air stream containing CO_2 and water vapor to the manikin. The simulated inhale breath is controlled by one mass flow meter and two solenoid valves ported to the vacuum system. Each set of mass flow controllers and solenoid valves will alternate to simulate a breathing test subject.

A total of nine CO_2 sensors are used within the SMTA test stand. Two CO_2 sensors is installed in the inhale and exhale lines to monitor and to record the CO_2 levels. A CO_2 sensor will be installed within the mouth of the manikin to monitor and to record the inhaled and exhaled CO_2 concentration levels. Five additional CO_2 sensors will be installed internal to the SMTA suit volume and external to the manikin to monitor and record CO_2 levels at various locations within the suit. Lastly, a CO_2 sensor is installed on the flow stream exiting the suit that returns to the ventilation test loop of the IVTS.

The vacuum system connected to the test loop will draw the system pressure down to the desired operating pressure for sub-ambient test cases. Also, a humidity sensor is installed in the inhale-exhale line just outside of the suit volume of the SMTA to measure the humidity levels during the inhale and the exhale breathing cycles. The SMTA is shown in Figure 7.

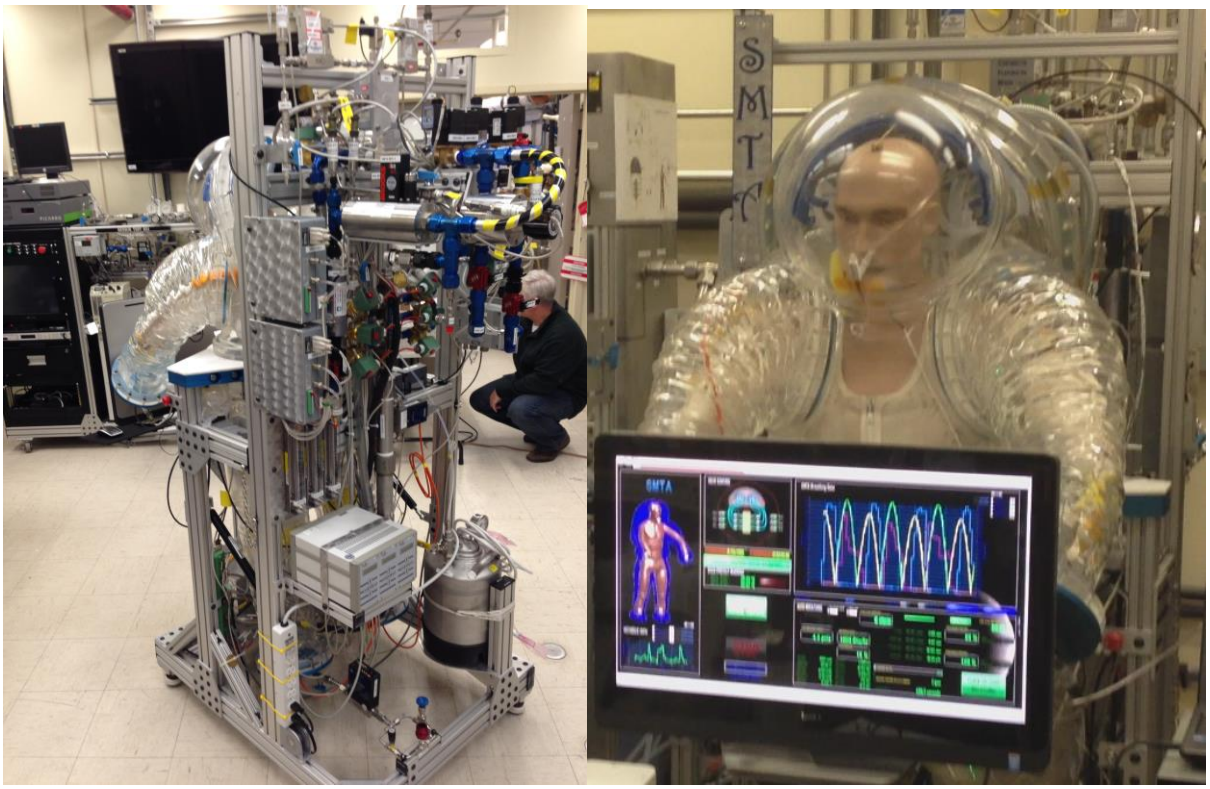

Figure 7. Suited Manikin Test Apparatus

V. Testing and Analysis

The SMTA and Vent Loop test stands have been utilized to perform testing on new sensor technologies as well as demonstration of sub-ambient pressure compatible CO_2 sensor rigs and will be used to evaluate ventilation options for improving CO_2 washout performance. The SMTA is planned to be integrated with PLSS 2.0 in order to evaluate CO_2 washout performance with the PLSS 2.0 ventilation loop which includes the RCA 2.0 unit.

A. Intelligent Optical Systems CO_2 Patch Sensor Validation Testing

Two luminescent demonstrator patch sensor systems developed by Intelligent Optical Systems, Inc. (IOS) with CO_2 and humidity sensing capabilities were tested for validation with the SMTA in December 2014. A test protocol based on steady state conditions of humidity, carbon dioxide, and pressure was generated with the SMTA to compare the SMTA CO_2 and humidity sensor readings to the patch sensor readings.

The luminescence of the patch sensors vary with the concentration of the respective gas property being measured. Prisms and optical cables on the outside of the transparent helmet surface transmitted the luminescence levels to the detector and readout unit. Both sensor sets were placed near the gas outlet in front of the mouth of the manikin: one set at the right side and one set at the left (see figures 8 and 9). All sensor patches were installed in that area to facilitate rapid gas level stabilization so that as many tests as possible could be performed during the two days allocated for testing. Results of this testing indicated good agreement between the SMTA and the IOS patch sensors at various suit pressures and various CO_2 and humidity levels. Additional details and results of this test are detailed in ICES-2015-174.[10]

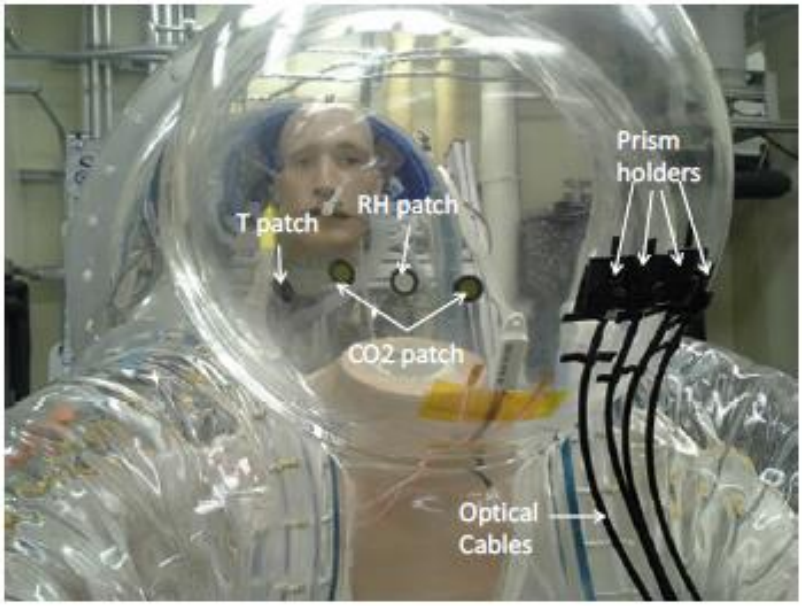

Figure 8. CO_2, Relative Humidity, and Temperature Patch Sensors installed on SMTA Helmet

Figure 9. Vent Loop (left) and SMTA (right) Setup for Patch Sensor Testing

B. Gas Analyzer Console Testing

During February and March of 2015, the SMTA was utilized to evaluate the Gas Analyzer Console (GAC) approach to provide sample breathing gas to a CO_2 sensor to evaluate breath by breath CO_2 concentrations while internal suit pressures ranged from 4.3 to 14.7 psia. This test was an evaluation of the potential methods to be used during upcoming human testing of the Z-2 space suit in Chamber B at JSC. The Z-2 space suit test will include human test subjects within the Z-2 suit at 4.3 psia while the chamber is at near vacuum levels. The CO_2 sensor utilized with the GAC in this test operate at ambient pressure but cannot operate at the subambient pressures to be experienced during the Z-2 Chamber B testing sequence. The GAC compresses the breathing gas samples from 4.3 psia to above 14.7 psia and then the sample gas flows to the CO_2 sensor.

The SMTA simulated the human breathing function during the GAC test including the injection of metabolic CO_2 and humidity with each breath. Figure 10 shows the Ventilation Test Loop (left) SMTA (middle) and the GAC (right). Results of the testing indicated that the GAC mixed the sample breath stream from the mask on the SMTA manikin and unfortunately smoothed out the sinusoidal variation of CO_2 concentration as shown in figure 11 below. This test demonstrates the utility of the SMTA in providing human-like breathing performance at various suit pressures with significantly less resources required than those required for human testing. The results of the GAC testing indicated that an alternate method other than the use of the GAC for measuring breath by breath CO_2 levels is recommended for human testing in order to provide measurements that indicate the full range of CO_2 concentrations associated with breathing. A task to investigate and develop the alternate approach has been initiated.

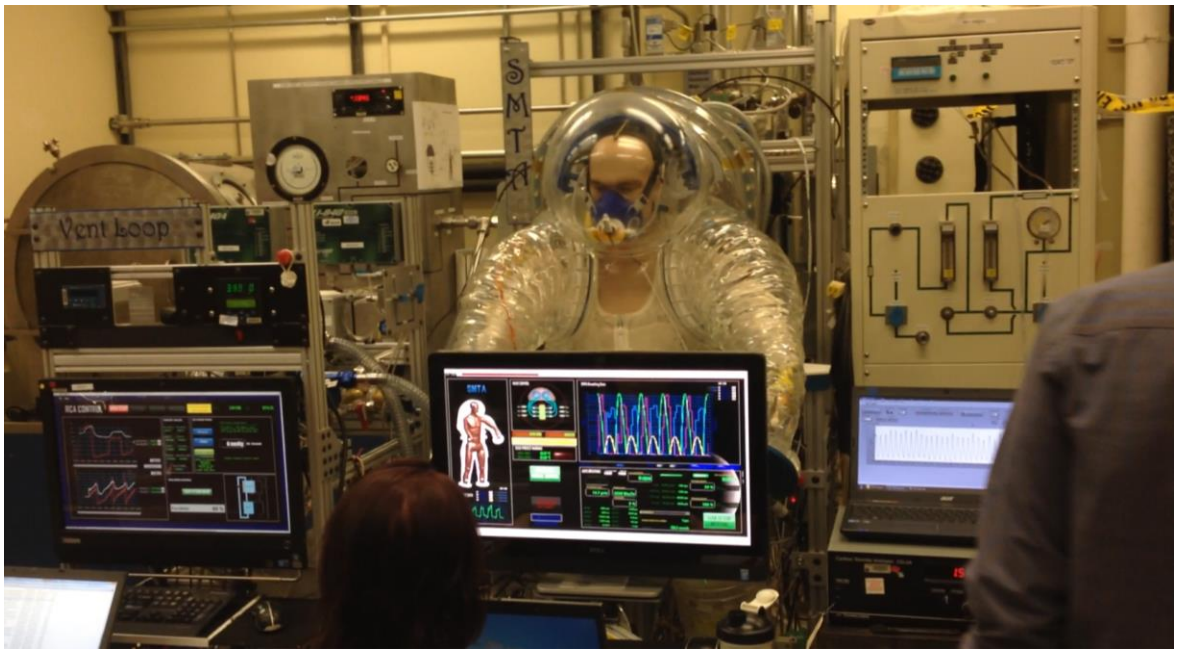

Figure 10. GAC Test Setup - Ventilation Test Loop (left), SMTA (middle), and GAC (right).

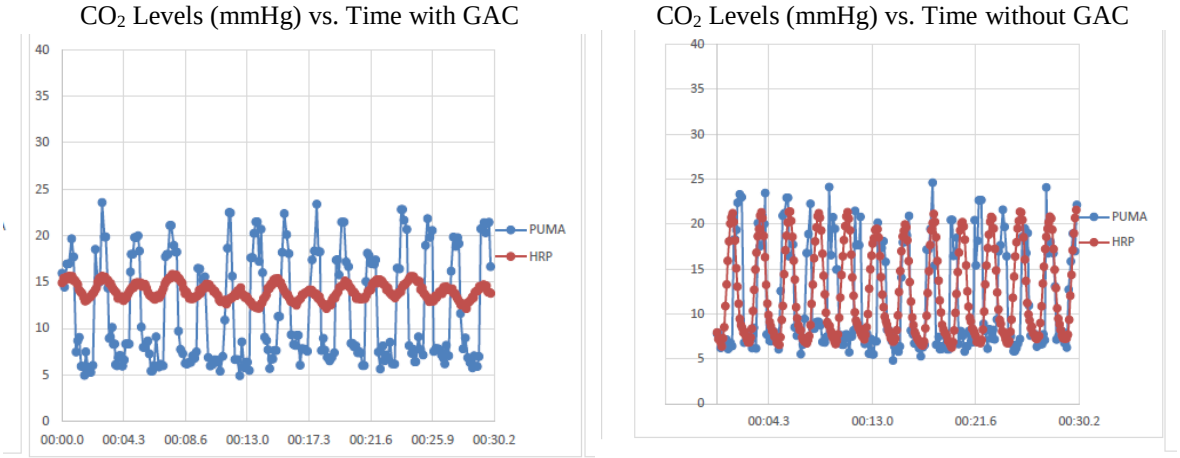

Figure11. Sample CO_2 Partial Pressure (mmHg) Test Results from SMTA GAC Test

C. CO_2 Washout Test Plans

The ventilation loop SMTA CO_2 washout testing will seek to quantify the CO_2 concentration levels within a simulated space suit environment while interfaced to the ventilation loop.

The objectives of ventilation loop SMTA CO_2 washout test are as follows:

1) Utilize the SMTA breathing manikin to simulates breathing profiles with CO_2 and H_2O, metabolic gas consumption, and variation with metabolic rate
2) Assess the uniformity of mixing within the SMTA
3) Validate CFD model predictions and compare results to human CO_2 washout test results
4) Evaluate various helmet ventilation duct configurations (CFG) A through F (refer to **Error! Reference source not found.**12 through 17)

Test points for SMTA CO_2 washout testing will cycle through the metabolic rates listed in Table 1 for each of the ventilation inlet duct CFG's (A-F) shown in Figures 12 through 17 based on previous CFD analyses.[11] The metabolic rates of 1000 Btu/hr, 2000 Btu/hr and 3000 Btu/hr are the highest priority metabolic rates since these are the values that have been tested in previous human CO_2 washout testing.[12,13] The other metabolic rates listed in Table 1 are included in the Priority 5 group of test points. There are currently 315 test points planned and they have been grouped into the following priorities:

Priority 1: Full evaluation of duct CFG's A-F at 15.6 psia with 4 and 6 acfm at 4.3 psia
Priority 2: Add mask to evaluate differences between human testing and CFD results
Priority 3: Turned head position evaluation
Priority 4: Alternate exit port evaluation
Priority 5: Additional metabolic rate performance evaluation
Priority 6: Alternate breathing pattern evaluation
Priority 7: Evaluation of performance at 8.2 psia

Table 1: CO_2 Washout Test Series Metabolic Rates

Simulated Metabolic Rate	CO_2 Production Rate	H_2O Production Rate
BTU/hr	slm	g/min
350	0.271	0.60
520	0.402	1.02
850	0.658	1.13
1000	0.774	1.44
1250	0.967	1.59
1600	1.238	1.36
2000	1.548	1.29
3000	2.322	1.29

Starting with priority 3 test points, only the 3 best performing duct configurations (based on the priority 1 and priority 2 test results) will be tested in order to reduce the total of required test points.

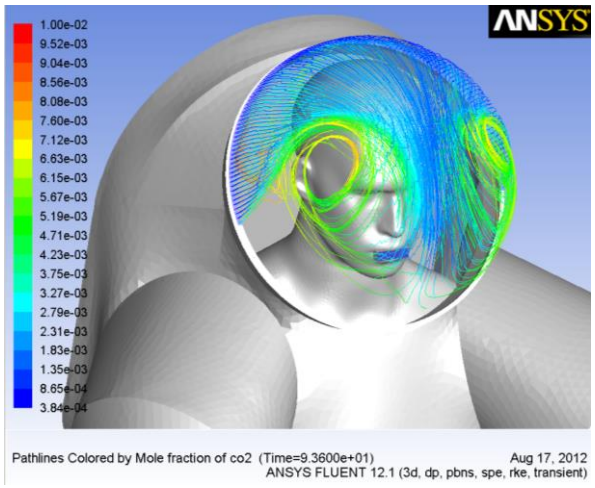

Figure 12. CFG A - "All Vents Open."

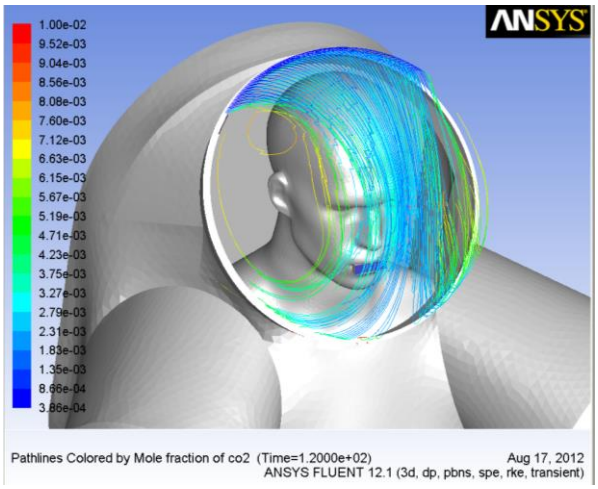

Figure 13. CFG B - "Y" + "Center Configuration."

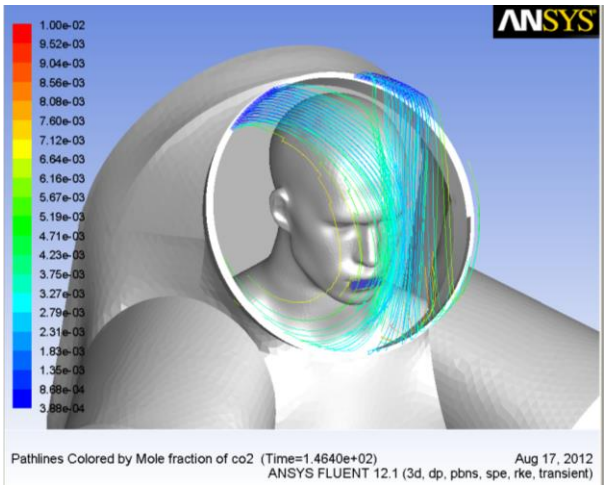

Figure 14. CFG C - "Y Configuration."

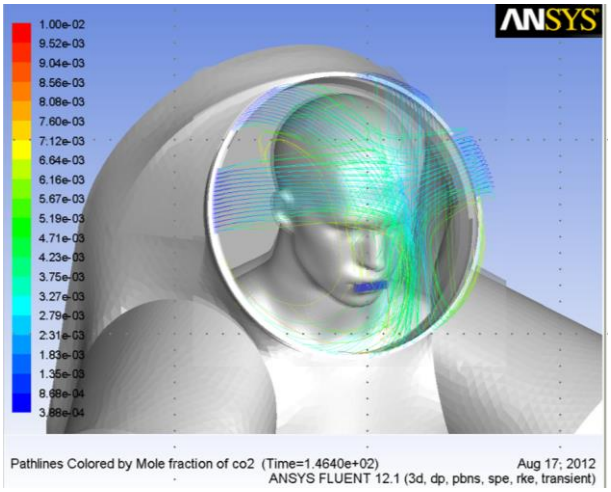

Figure 15. CFG D - "Y + Ear Configuration."

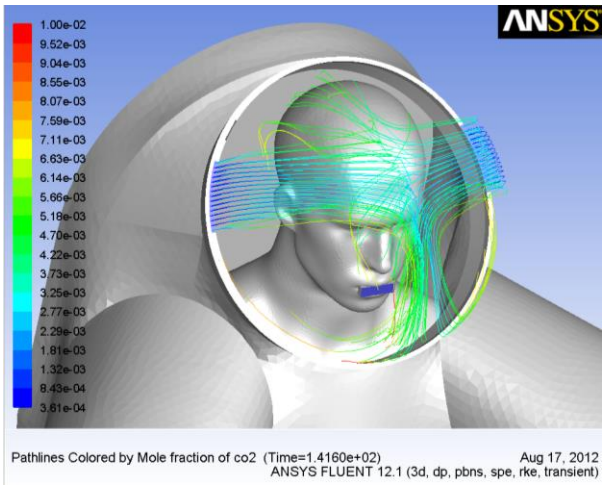

Figure 16. CFG E - "Ear Configuration."

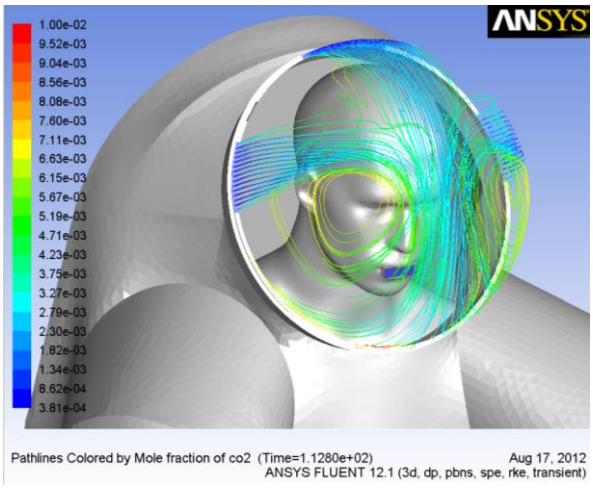

Figure 17. CFG F - "Ear + Center Configuration."

D. SMTA Pre-test Computational Fluid Dynamics Evaluations

A CFD analysis was performed using ANSYS Fluent$_{TM}$ to provide pre-test predictions for the testing to be performed with the SMTA and ventilation loop test stands. The purpose of this task was to determine the inhaled CO_2 levels for a suited crew inside the Mark-III suit configuration, similar to what is being utilized during SMTA testing. In this particular set of cases, comparisons were made between suited crew both with and without an oro-nasal mask. At each "mask" or "no mask" configuration cases were run at metabolic rates of 2000 Btu/hr and 3000 Btu/hr, and with fresh air flow rates of 4 acfm and 6 acfm.

Results showed some expected behaviors, such as higher inhaled CO_2 levels at 3000 Btu/hr versus 2000 Btu/hr for similar configurations and fresh air flow rates, and lower inhaled CO_2 levels at 6 acfm versus 4 acfm for similar configurations. Results showed some definite trends, such as the "C" vent inhaled CO_2 levels were less than the "F" vent inhaled CO_2 cases for all cases except one. Also, the result showed that the "no mask" cases performed better than the "mask" configurations for all cases except one. It is hoped that data from ongoing SMTA testing can be used to improve the predictive ability of this and other CFD transient breathing models.

Characteristics of SMTA testing will include the following:

- It will utilize the mask modeled in CFD using the manikin head and the Mark-III Suit volume in the SMTA.
- The SMTA will be set to execute the breathing pattern chosen for the model.
- Test conditions will be altered to match the model: absolute pressure, ventilation flow rate, etc.

A number of space suit CO_2 washout tests have been performed using an oro-nasal mask. Modeling of the mask with comparison back to manned testing may prove difficult due to the numerous variables involved in the manned test that may affect the boundary conditions for the flow:

- Test subject head position relative to flow
  - Partially blocking the flow in the rear
  - Movement of the oro-nasal area relative to the desired core flow
  - Bobbing in the suit due to ambulation
  - Head turning
- Alteration of the return flow path in the suit/LCVG, which can vary the back-pressure down a particular flow path
- Physiological differences between subjects and the assumed model
  - Tidal volume, tidal rate, etc.
  - Mouth/nose breathing
- A series of cases will be analyzed using the SMTA. Transient breathing cases will be performed using a range of metabolic rates and fresh air flow rates.
  - Two CFD configurations will be analyzed – a configuration without a mask and a configuration with a mask (see figure 18). Two vent flow configurations will be modeled, based upon the CFG's "C" and "F" since these configurations performed well in the Mark III CO_2 washout test series.[13]

The case matrix for CFD simulations performed is listed Table 2:

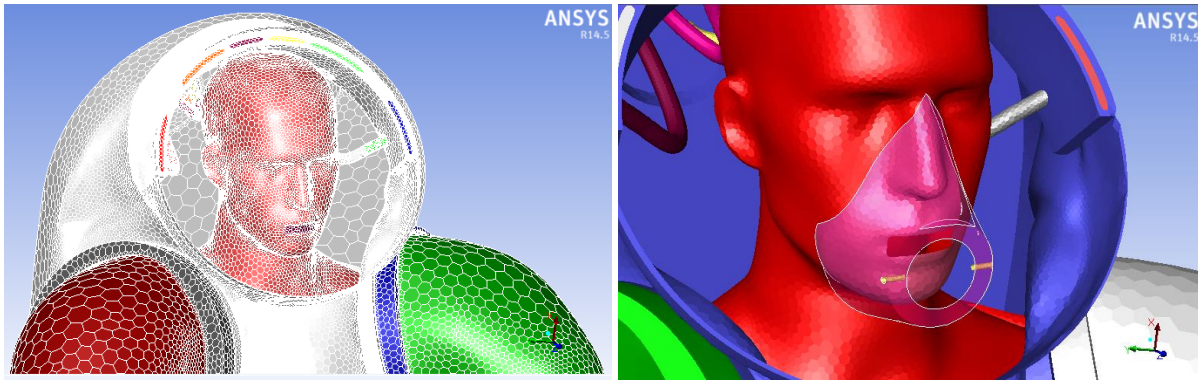

Figure 18. No-Mask Geometry (left) and Mask Geometry (right)

Table 2. Case Matrix for SMTA Pre-Test CFD Evaluations

CASE #	Met rate Btu/hr	Op press psia	Vent flow acfm	Vent config	mask/no mask
1	2000	4.3	4	C	no mask
2	2000	4.3	6	C	no mask
3	2000	4.3	4	F	no mask
4	2000	4.3	6	F	no mask
5	2000	4.3	4	C	mask
6	2000	4.3	6	C	mask
7	2000	4.3	4	F	mask
8	2000	4.3	6	F	mask
9	3000	4.3	4	C	no mask
10	3000	4.3	6	C	no mask
11	3000	4.3	4	F	no mask
12	3000	4.3	6	F	no mask
13	3000	4.3	4	C	mask
14	3000	4.3	6	C	mask
15	3000	4.3	4	F	mask
16	3000	4.3	6	F	mask

- Notes/Assumptions
  - Inhale/exhale transient sinusoidal breathing pattern using a user-defined function with mouth flow only.
  - 4 species (nitrogen, O_2, carbon dioxide, water vapor) for all cases, though nitrogen gas is near zero psi for all cases.
  - Mask cases included 500 ml/min flow exiting the domain through each of the two 0.125 inch diameter sampling tubes.
  - All cases at 4.3 psia.
  - No heat transfer between suit and human currently planned other than specifying breath outlet temperature.
  - Transient simulation run until inhaled CO_2 concentration reaches steady state.

Summarized results of the CFD simulations are shown in Table 3 below. The velocity-weighted CO_2 average during the inhale cycle is the measurement used to indicate CO_2 washout performance. If the helmet and inlet ventilation configuration is efficiently washing the CO_2 away from the face, then the average amount of CO_2 inhaled will be reduced. The average is velocity-weighted to properly account for variations in the velocity over the duration of the inhale portion of the breathing cycle.

Table 3. Velocity-weighted average CO_2 level during inhale at the mouth, mmHg

Metabolic rate, btu/hr	No Mask				Mask			
	4 acfm		6 acfm		4 acfm		6 acfm	
	C vent	F vent	C vent	F vent	C vent	F vent	C vent	F vent
2000	8.2	12.1	5.5	3.7	11.6	13.6	8.3	9.6
3000	17.0	17.0	9.3	11.6	15.5	20.7	11.1	13.3

Observations from looking at the Table 2 results:

1) 3000 Btu/hr inhaled CO_2 higher than 2000 Btu/hr inhaled CO_2 for all cases, as one would expect.
2) Inhaled CO_2 decreases going from 4 acfm to 6 acfm for all cases, as one would expect.
3) Larger variability going from 2000 Btu/hr to 3000 Btu/hr for the "No mask" cases (increase in CO_2 not consistent).
4) Mask cases showed more consistent increase in CO_2 going from 2000 to 3000 Btu/hr (approximately a 50% increase).

Table 4 below includes volume-average CO_2 levels and ventilation flow velocities in the helmet and suit hard upper torso (HUT) volumes. Observations from Table 3 include:

1) One indication of the ventilation effectiveness is whether the inhaled CO_2 level is less than the average value in the surroundings. As an indicator of the slightly better performance of the "C" vent versus the "F" vent, in the no mask cases, the "C" vent inhaled CO_2 is less than the average value in the HUT and helmet in 3 out of 4 cases, while for the "F" vent the inhaled value is less than the average for only one case. (For the mask cases, the inhaled CO_2 level is higher than the surrounding average in all cases).
2) Also, for the "no mask" cases, the average velocity in the HUT/helmet is higher for all of the "C" vent cases compared to the "F" vent cases. This is also true when comparing the "mask" cases, the "C" vent cases are higher than their respective "F" vent cases.

Table 4. Volume Average CO_2 Levels and Velocities

CASE #	Metabolic rate btu/hr	Operating pressure psia	Fresh air flow rate acfm	Vent configuration		Average inhaled $ppCO_2$ at the mouth mmHg	Volume average $ppCO_2$ inside the HUT and helmet volumes mmHG	Volume average velocity magnitude inside the HUT and helmet volumes ft/min
1	2000	4.3	4	C	no mask	8.16	9.51	13.5
2	2000	4.3	6	C	no mask	5.53	6.45	25.0
3	2000	4.3	4	F	no mask	12.14	8.73	9.8
4	2000	4.3	6	F	no mask	3.67	6.06	14.0
5	2000	4.3	4	C	mask	11.56	9.42	16.5
6	2000	4.3	6	C	mask	8.30	6.10	28.6
7	2000	4.3	4	F	mask	13.61	8.84	12.5
8	2000	4.3	6	F	mask	9.62	6.00	17.5
9	3000	4.3	4	C	no mask	17.00	13.51	16.0
10	3000	4.3	6	C	no mask	9.29	9.81	22.5
11	3000	4.3	4	F	no mask	17.00	14.72	14.5
12	3000	4.3	6	F	no mask	11.63	9.51	15.9
13	3000	4.3	4	C	mask	15.54	13.73	16.9
14	3000	4.3	6	C	mask	11.09	9.36	27.5
15	3000	4.3	4	F	mask	20.69	14.80	16.4
16	3000	4.3	6	F	mask	13.28	9.45	20.0

The trends in Figure 19 show that the "No mask" cases performs better than the "mask" cases in 7 out of 8 flow rate/metabolic rate combinations. The 4 acfm, 3000 Btu/hr results show slightly better CO2 washout performance for the no mask case as compared to the case with the mask.

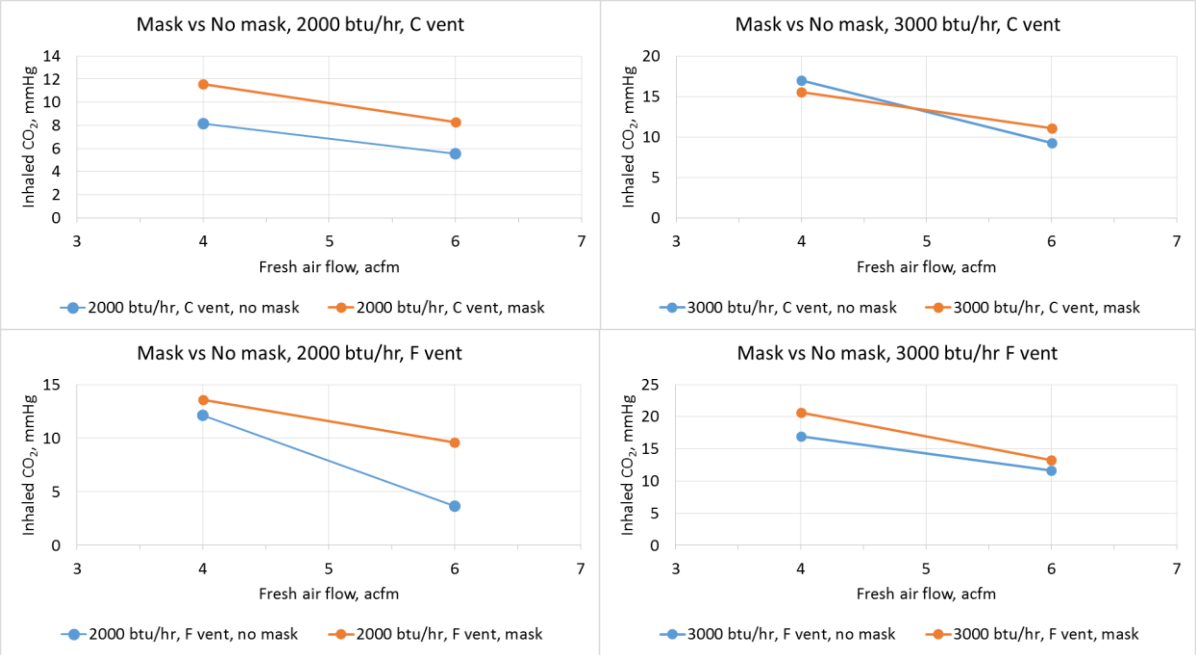

Figure 19. Inhaled CO2 Trends for Flow Rates, Metabolic Rates and Mask vs. no Mask

A few unexpected trends have been identified within the results (the unexpected low inhaled CO2 value in Case 4, for example). Previous analyses might have had the head in a slightly different position and may have been using a different breathing algorithm. It is anticipated that the test results from the ongoing SMTA testing will provide a valuable tool for comparison and eventual improvement of these types of simulations.

A summary of observations from CFD analysis results follows:

- 3000 Btu/hr inhaled CO_2 levels are higher than 2000 Btu/hr inhaled CO_2 for all cases, as one would expect
- Inhaled CO_2 decreases going from 4 acfm to 6 acfm for all cases, as one would expect
- Larger variability going from 2000 Btu/hr to 3000 Btu/hr for the "No mask" cases (increase in CO_2 not consistent)
- Mask cases showed more consistent increase in CO_2 going from 2000 to 3000 Btu/hr (about a 50% increase)

Mask vs. no mask observations include the following:

- At 2000 Btu/hr metabolic rate: higher inhaled CO_2 for all cases with mask
- At 3000 Btu/hr metabolic rate: "No mask" still performs better but difference between "mask" cases is smaller
- "C" vent inhaled CO_2 equal or better than "F" vent inhaled CO_2 in all metabolic rate and mask/no mask configurations except one (inhaled CO_2 for the 2000 Btu/hr at 6 acfm, no mask "F" configuration case was better than that for the same "C" configuration case)

VI. Summary and Future Plans

Initial testing series have been performed with the SMTA and the Ventilation Test Loop demonstrating the capabilities and early benefits that these units can provide. Human testing can be supplemented with SMTP testing to reduce total costs and to provide a stable repeatable configuration to provide a better basis for CFD model correlation efforts and benefits for the testing and evaluation of ventilation loop sensors and components.

The potential benefits from optimizing CO_2 washout performance include:

- Reduced PLSS/space suit ventilation flow rate requirements that could reduce power and fan performance requirements.
- Reduced efficiency requirements for the PLSS CO_2 removal unit (RCA).
- Reduced emergency purge flow rate requirements that would allow for smaller quantities of emergency oxygen to be stored within the PLSS.
- More robust helmet/ducting designs that are less sensitive to head position, head size, hair/communications hardware configurations.
- More predictable CO2 washout performance that reduces the risk of elevated CO2 levels and their effects on human performance.

It is recommended that these investigations continue in order to quantify the risks associated with variations in crew member sizes and positions and to optimize ducting into and out of the helmet/space suit. A few configurations have been investigated, but many potential configurations exist that may provide better CO_2 washout performance for the AEMU and future space suits. Parameters that should continue to be investigated are:

- Breathing patterns (flow rates and frequencies)
- Mouth/nose flow split
- Variations in head sizes and shapes including hair and head gear impacts
- Head orientation within the helmet (height in the suit/turned head variations)
- Communications hardware configurations within the helmet
- Helmet ducting inlet and outlet locations
- Helmet ventilation flow rate variations
- Helmet inlet CO_2 levels
- Helmet design (shape)
- Metabolic rate variations

Additionally, future uses of the SMTA include CO_2 and purge efficiency evaluations of suit geometries other than the current Mark III suit, CO_2 buildup of mask systems that are not dependent on the suit geometries. Evaluations of masks that fit over the head can be accomplished easily with the SMTA because the entire unit can function when the manikin head is tilted back away from the suit volume. Potential mask evaluations could include masks used for aviation, firefighting, and underground mining.

In summary, the SMTA and Ventilation Loop test stands are valuable resources for JSC. Evaluations being conducted show that CO_2 washout may be sensitive to helmet and head configurations. Plans are in place to perform further testing with humans and with the SMTA to provide insight into CO_2 washout variables and to provide guidance for AEMU. These efforts are targeted to provide robust, safe, and efficient space suit designs.

Acknowledgments

The authors of this paper would like to acknowledge the entire Advanced Space Suit team for their concerted efforts toward the design, build up and testing of the Advanced Space Suit subsystems and their components thus far. It has been more than 40 years since a complete space suit of this magnitude has been designed, built, and tested. Also, the authors would like to thank the programs that have contributed to the funding and successes achieved thus far. Finally, the authors would like to thank the leadership of the Crew and Thermal System Division for the dedicated laboratories to accomplish the testing.

References

[1]Navarro, M., Conger, B., and Campbell, C., "Exploration Extravehicular Activity Purge Flow Assessment," *41st International Conference on Environmental Systems*, AIAA 2011-5220, Portland, OR, 17-21 July 2011.

[2]Gilbert, J., and Schentrup, S., "Determination of Residual Carbon Dioxide During Forced Ventilation of a Hemispherical Space Suit Helmet," Johnson Space Center, Houston, TX, 31 July 1991.

[3]Ball, T., and Straus, J., "Space Suit Helmet CFD Analysis Results Utilizing a Sinusoidal Breathing Model," *41st International Conference on Environmental Systems*, AIAA 2011-5054, Portland, OR, 17-21 July 2011.

[4]Law J., Watkins, S., and Alexander, D., "In-Flight Carbon Dioxide Exposures and Related Symptoms: Association, Susceptibility, and Operational Implications," NASA/ TP–2010–216126, June 2010.

[5]"Constellation Program Extravehicular Activity (EVA) Systems Project Office (ESPO) Space Suit Element Requirements Document", Requirement #CSSE3025, CxP 72208, Revision D, September 3, 2010.

[6]Navarro, M., "Evaluation of PLSS Options for Meeting Carbon Dioxide Washout Requirements," Engineering and Science Contract #NNJ05HI05C, Jacobs Technology, ESCG-4470-11-TEAN-DOC-0085, Houston, Tx, 30, September, 2011.

[7]Watson, R., "Modified Advanced Crew Escape Suit Intravehicular Activity Suit for Extravehicular Activity Mobility Evaluations," *44th International Conference on Environmental Systems*, 2014-ICES-194, Tucson, AZ, 13-17 July 2014.

[8]Papale, W., Chullen, C., Campbell, C., Coin, J., Wichowski, R., "Rapid Cycle Amine (RCA 2.0) System Development," *43rd International Conference on Environmental Systems*, AIAA-2013-3309, Vail, CO, July 14-18, 2013.

[9]McMillin, S., "Suited Manikin Test Apparatus (SMTA) Test Plan," NASA CTSD-ADV-1039, Houston, TX, Jan. 2013.

[10]Delgado, J., Phillips, S., Rubtsov, V., Chullen, C., "Non-intrusive, Distributed Gas Sensing Technology for Advanced Spacesuits," *45th International Conference on Environmental Systems*, ICES-2015-174, Bellevue, WA, July 2015.

[11]Chullen, C., Navarro, M., Conger, B., Korona, A., McMillin, S., Norcross, J., Swickrath, M., "Maintaining Adequate Carbon Dioxide Washout for an Advanced Extravehicular Mobility Unit", *43rd International Conference on Environmental Systems*, AIAA-2013-3341, Vail, CO, July 14-18, 2013.

[12]Mitchell K. C., Norcross, J., "CO_2 Washout Testing of the REI and EM-ACES Space Suits," *42nd International Conference on Environmental Systems*, AIAA 2012-3549, San Diego, CA, 15-19 July 2012.

[13]Korona, A., Norcross, J., Conger, B., Navarro, M., "Carbon Dioxide Washout Testing Using Various Inlet Vent Configurations in the Mark-III Space Suit" *44rd International Conference on Environmental Systems* 2014-ICES-55, Tucson, AZ, July 13-17 2014.