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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 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 loop, a ventilation loop, and a thermal loop. One of the key functions of the ventilation loop is to remove and control the carbon dioxide (CO_2) delivered to the crew member. CO_2 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 to provide a lower cost and more controlled alternative to human testing while providing a one to one match with the suit and manikin geometry used in CO_2 washout analytical models. The dynamics of the breathing gas helmet ventilation and astronaut breathing are also captured. The CO_2 removal function is performed by the regenerative Rapid Cycle Amine within the PLSS ventilation loop, and its performance is evaluated within the integrated SMTA and Ventilation Test Loop 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
CO_2	=	carbon dioxide
COTS	=	commercial off-the-shelf
EMU	=	Extravehicular Mobility Unit
EVA	=	extravehicular activity
ft	=	feet
GAC	=	Gas Analyzer Console
H_2O	=	water vapor
HUT	=	hard upper torso
hr	=	hour
IOS	=	Intelligent Optical Systems, Inc.
ISS	=	International Space Station
IVTS	=	Integrated Ventilation Test System
JSC	=	Johnson Space Center
min	=	minute
mmHg	=	millimeters of mercury
O_2	=	oxygen
N_2	=	nitrogen
PLSS	=	portable life support subsystem
$ppCO_2$	=	partial pressure of carbon dioxide
psia	=	pounds per square inch absolute
PUMA	=	Portable Unit for Metabolic Analysis
REI	=	Rear Entry I-Suit
RCA	=	Rapid Cycle Amine
SMTA	=	suited manikin test apparatus
TCC	=	Trace Contaminant Control
VCFG	=	ventilation configuration

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. Microgravity extravehicular activity (EVA) and planetary surface operations necessitate reliable, robust, right-sized, and efficient space suit life support systems. EVAs (i.e., 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 the ISS and the repair the Hubble telescope. The space suit, in all its complexity, provides a safe haven for the spacewalker. Space suits used for EVAs performed in the vacuum of space must meet tremendous and unique technical challenges.

NASA is 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 loop for crew member metabolic heat rejection. For exploration missions, the APLSS will also need to be robust, lightweight, and low-power, and will need to contain durable hardware for maintaining and monitoring critical life support constituents in the suit.

As part of the environmental control, the ventilation loop 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, it also enables the breathing function of the suited crew member. An important aspect is that the flow of O_2 must be adequate to convectively remove or "washout" CO_2 in the helmet and aid in the prevention of fogging in the helmet. Adequate flow to effectively remove CO_2 from the oronasal region within 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, many 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 and time consuming, and such trials involve human test subjects, which include additional safety protocols for testing. Also, there is intrinsic variability across human subjects that is difficult to control during testing. Therefore, research is currently under way 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) that includes a breathing manikin, as shown in Figure 1 during NASA 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, validate CO_2 washout computational fluid dynamics (CFD) models, evaluate space suit nitrogen (N_2) 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 loop 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.

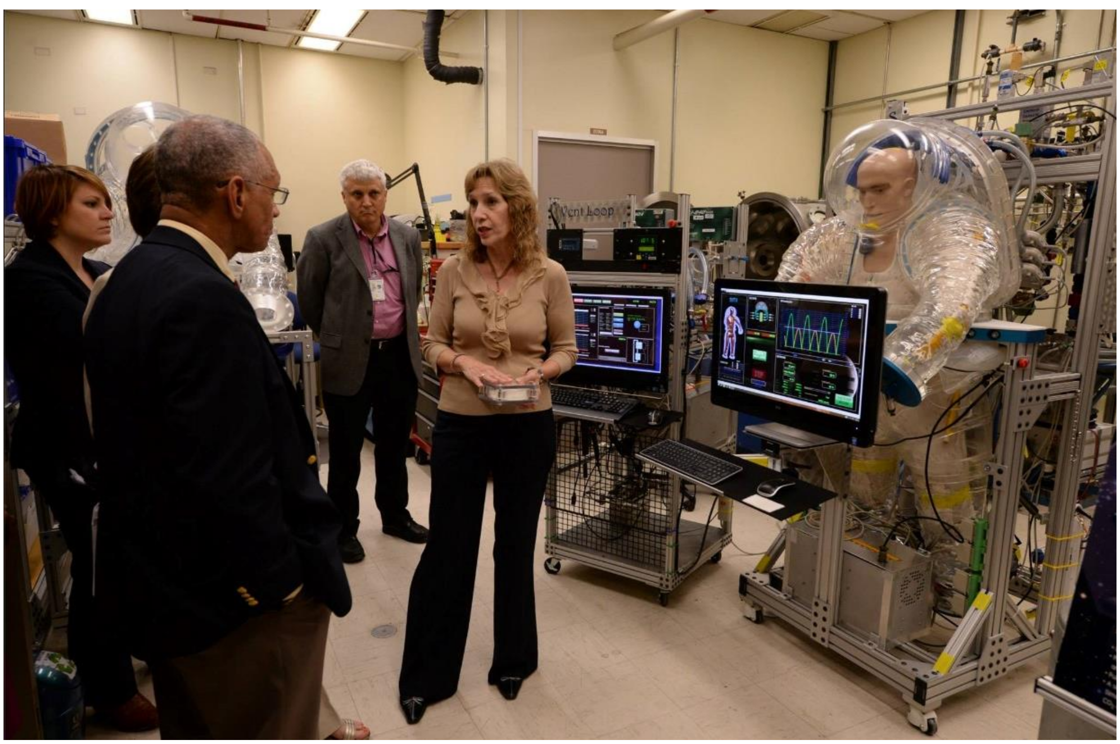

Figure 1. **The IVTS allows NASA at JSC to realistically simulate the complicated geometry of the spacesuit, astronaut anatomy, and dynamics of the life support system in ways never before realized in life support technology development.**

II. Importance of Carbon Dioxide Washout

Whenever a person is enclosed within a suit, too much of the exhaled CO_2 can accumulate and be re-inhaled, causing hypercapnia (CO_2 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 the amount of re-inhaled metabolically produced CO_2 within a space suit can be challenging. Extensive measures are necessary in the ventilation loop to ensure that CO_2 is not only monitored and removed, but adequately transported away from the oronasal region and 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.

CO_2 washout performance is one of the most critical parameters needed to ensure proper and sufficient suit design for a new APLSS. CO_2 washout is not only important in a space suit, but in vehicle applications 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.

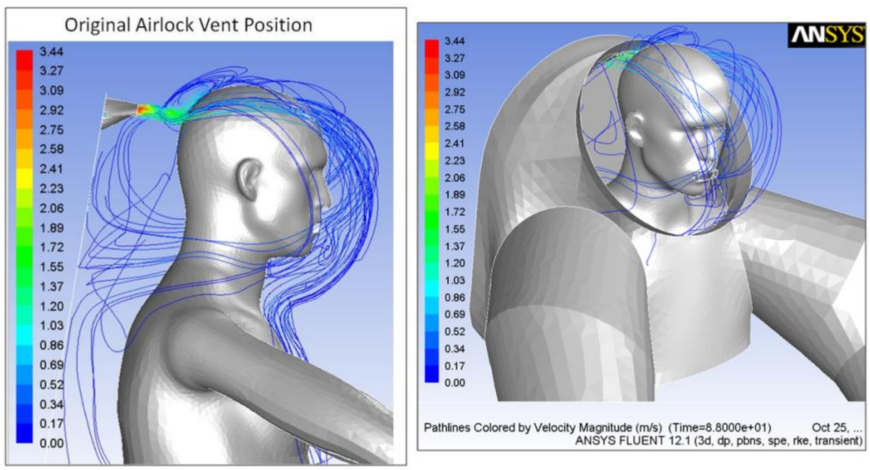

Figure 2. Example flow patterns within a helmet and space suit.

A breathing capability within the SMTA combined with the Ventilation Test Loop provides a safe, lower-cost, stable, easily modeled alternative to human CO_2 washout testing. This configuration provides 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 necessary to set more stringent criteria for CO_2 levels for exposure limits than are 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) (current AEMU average EVA metabolic rate is defined as 1200 BTU/hr) 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] In addition, 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] to maintain 3.8 mmHg inhaled in the helmet. Additional testing and investigation of the CO_2 goals are recommended to determine if they are reasonable and achievable.

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 integration of the SMTA with the Ventilation Test Loop provides an effectual systematic way to test the ability of the system to meet the stringent CO_2 level requirements in the advanced suit. The primary parameters and design features that the IVTS monitors and evaluates include the following:

1. Concentration of CO_2 returning from the APLSS 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 IVTS is currently the only nonhuman system that can physically simulate and assess CO_2 washout within a space suit attached to the APLSS ventilation loop. The system combines the RCA in the ventilation loop with 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 APLSS 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 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 along with any gas leakage in the ventilation system. 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 lost to ambient in a demand regulator system) is large relative to the amount of metabolic O_2 consumed during the breathing process assuming that the system leakage rate is low. The trade between rebreathers versus demand regulator systems is whether the additional size of the CO_2 removal system, gas transport power and equipment (fan and battery), and trace contaminant removal equipment needed in the rebreather system 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. An additional factor to be considered is that demand regulator systems require the crew person's breathing action to drive gas flow in the system which increases fatigue and may affect work rate capability.

The launch and entry suits worn during the Space Shuttle and ISS eras (Launch Entry Suit and Advanced Crew Escape Suit) have used a demand regulator approach since the design duration of the system is short and the metabolic rates typically encountered during launch and reentry are low relative to those typically experienced during EVA.[7] The APLSS, however, uses 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, using CO_2 removal units that were either discarded or regenerated after each EVA. The APLSS ventilation loop contains the following key components:

RCA: The APLSS uses 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 was minimized to help keep the APLSS volume within limits. The fan currently has the capacity to provide 6 actual cubic feet per minute (acfm) to the helmet 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.

Trace Contaminant Control (TCC): The TCC unit is placed inside the hatch (pressurized volume) of the space suit 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 N_2 instead of O_2 as the test gas. Metabolic O_2 usage in the SMTA is accomplished by "exhaling" less gas than was "inhaled" by the appropriate amount similar to the actual human breathing function. The PLSS 2.0 is shown in Figure 4.

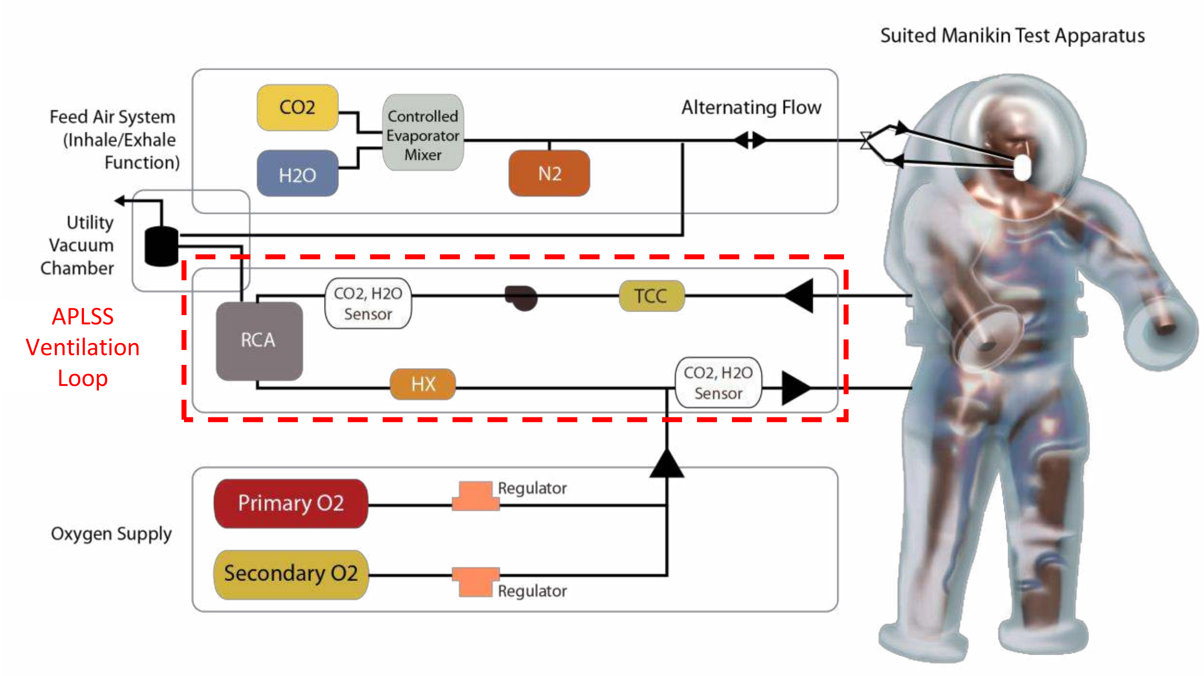

Figure 3. PLSS 2.0 Laboratory SMTA test schematic with APLSS ventilation loop highlighted.

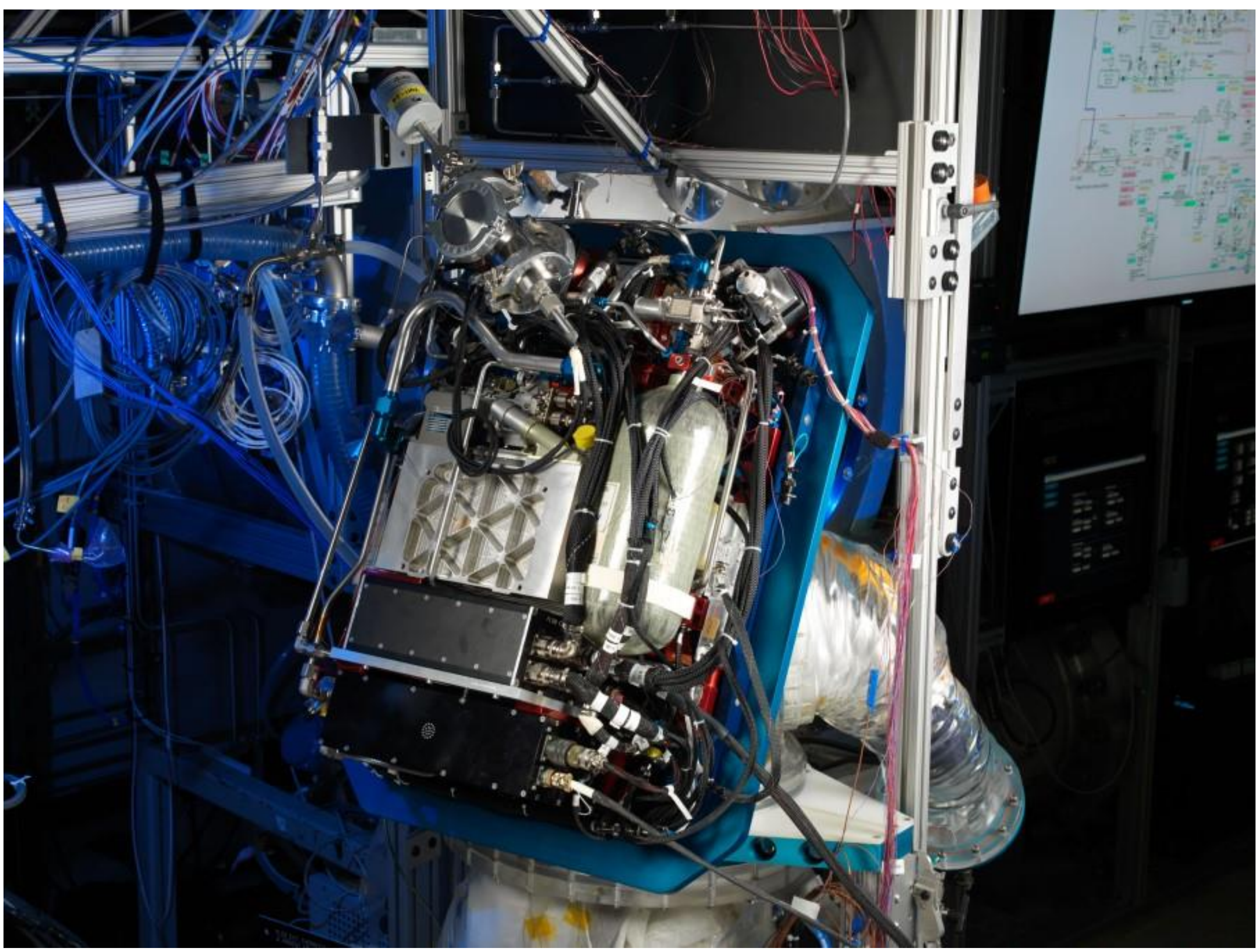

Figure 4. PLSS 2.0 within the NASA JSC PLSS Laboratory.

IV. Ventilation Test Loop and the Suited Manikin Test Apparatus

CO_2 washout and a number of other test trials will be accomplished using an IVTS. The IVTS was recently completed after 2 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 designed to emulate the human in the loop with breathing capability. The Ventilation Test Loop was primarily designed to replicate the ventilation loop in the APLSS. The main function of the ventilation loop 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 APLSS ventilation loop 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.

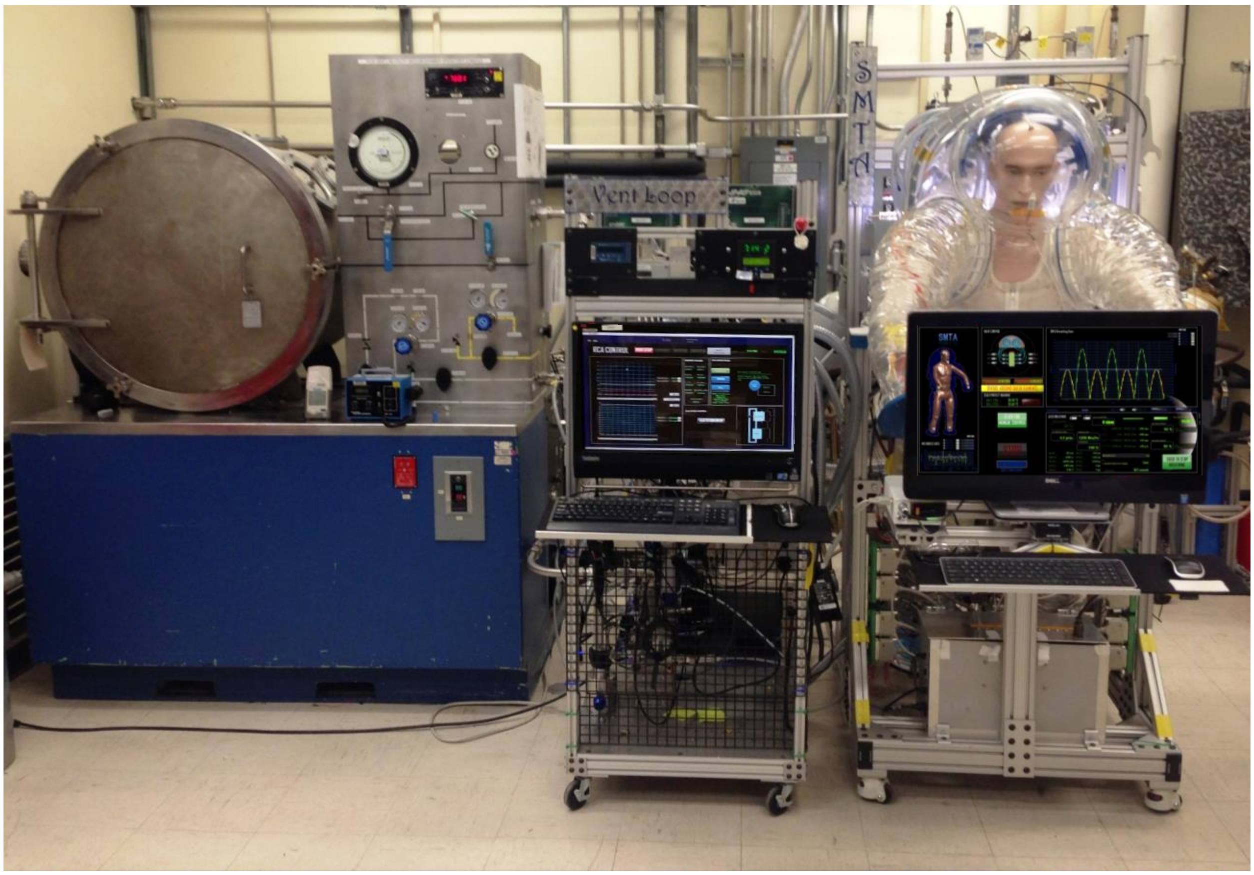

Figure 5. Integrated Ventilation Test System: Ventilation Test Loop (left) and SMTA (right).

A. Ventilation Test Loop

The Ventilation Test Loop design simulates portions of the APLSS ventilation loop previously shown in Figure 3. The Ventilation Test Loop was 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 Ventilation Test Loop maintains the desired ventilation loop flow rate using a commercial off-the-shelf (COTS) fan and maintains the system pressure using a COTS regulator. The Ventilation Test 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 Ventilation Test Loop interfaces with facility vacuum resources that are used to remove CO_2 and humidity from the desorbing RCA bed. The Ventilation Test Loop combined with the SMTA as the IVTS also interfaces to facility N2 that supplies the test loop with dry N2 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 APLSS. The TCC function is not currently simulated within the Ventilation Test Loop, which is shown in Figure 6.

Figure 6. Ventilation Test Loop.

B. Suited Manikin Test Apparatus

The SMTA was developed to augment testing of the APLSS ventilation loop by simulating the ventilation parameters associated with a suited crew member. 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. Correlation of space suit ventilation 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 APLSS ventilation loop 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.[9]

The SMTA has the ability to simulate various 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 operates with a human breathing profile, however, the SMTA is not O_2 rated, and N_2 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 liquid 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 H_2O injected in the breathing gas stream.

The breathing exhale system of the SMTA mixes the CO_2 and H_2O 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 H_2O to the manikin. A real time algorithm adjusts the exhale flow rate to properly simulate metabolic O_2 consumed. 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 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 are installed in the inhale and exhale lines to monitor and record CO_2 levels. A Portable Unit for Metabolic Analysis (PUMA) CO_2 sensor[10] is installed within the mouth of the manikin to monitor and record the inhaled and exhaled CO_2 concentration levels. Five additional CO_2 sensors are 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 draws the system pressure down to the desired operating pressure for sub-ambient testing. 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.

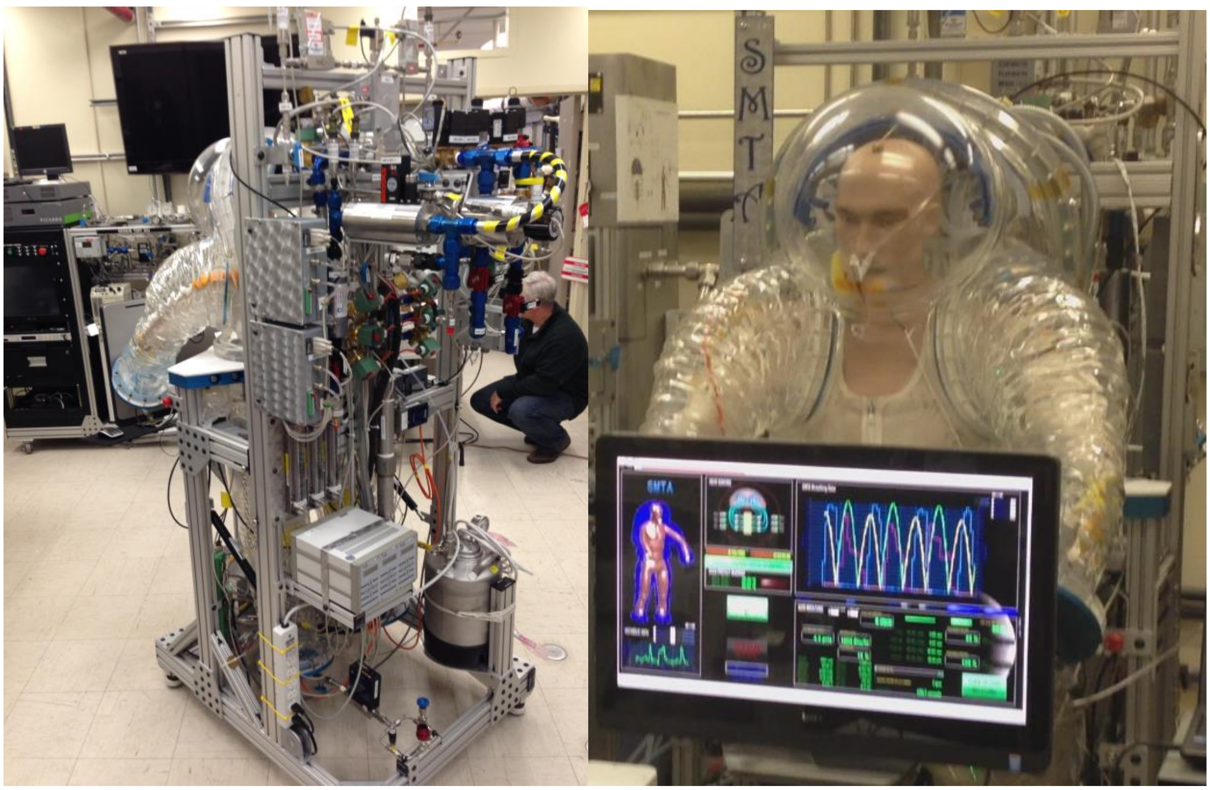

Figure 7. SMTA.

V. Testing and Analysis

The SMTA and Ventilation Test Loop test stands have been used 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 to evaluate CO_2 washout performance with the PLSS 2.0 ventilation loop, which includes the RCA 2.0 unit. Within this paper, "cases" refer to analytical model simulations and "test points" refer to physical testing with direct measurement of parameters of interest.

A. Intelligent Optical Systems Carbon Dioxide 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 constituent being measured. Prisms and optical cables, on the outside of the transparent helmet surface, transmit 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 2 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.[11]

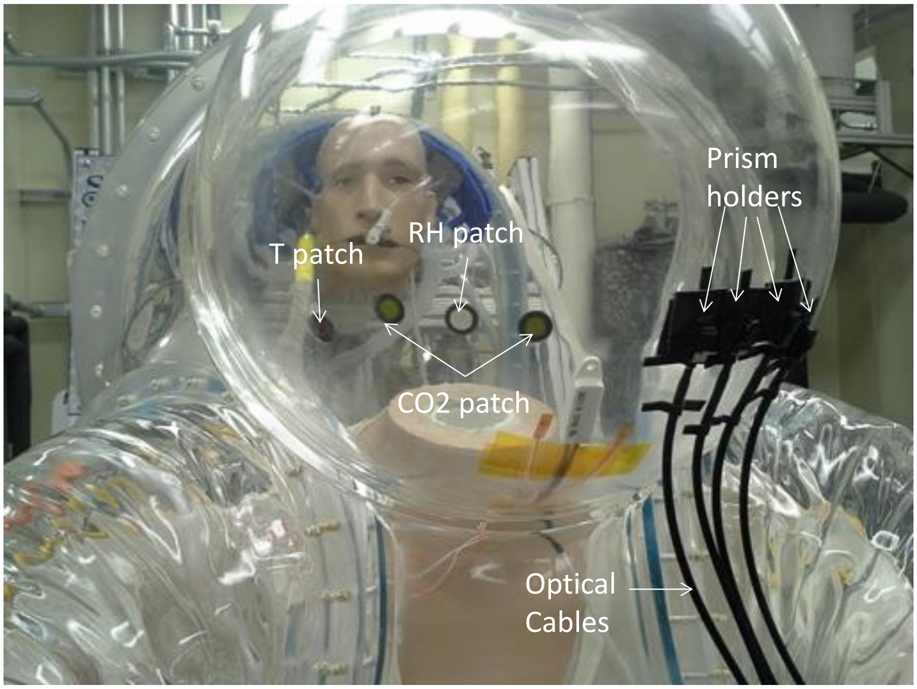

Figure 8. CO_2, relative humidity, and temperature patch sensors installed on SMTA helmet.

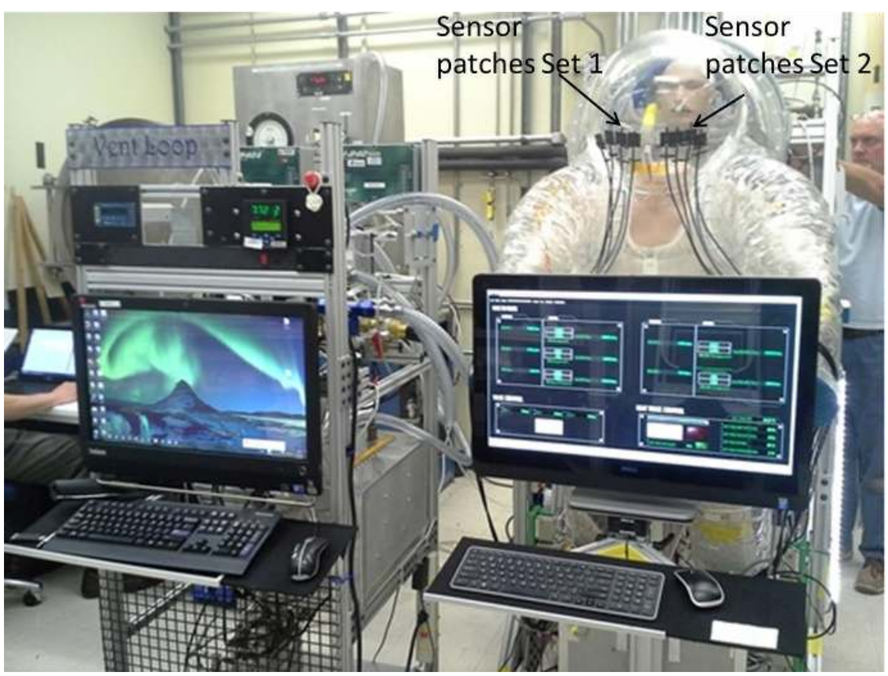

Figure 9. Ventilation Test Loop (left) and SMTA (right) setup for patch sensor testing.

B. Gas Analyzer Console Testing

During February and March of 2015, the SMTA was used 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 AEI Technologies CD-3A CO_2 sensor used with the GAC in this test operates at ambient pressure but cannot operate at the sub-ambient pressures to be experienced during the Z-2 Chamber B testing sequence. It was envisioned that the GAC would compress the breathing gas samples from 4.3 psia to above 14.7 psia and then flow the sample gas to the CD-3A 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). In this SMTA test, a continuous sample stream of breathing gas coming from the blue and white mask on the SMTA manikin shown in Figure 10 was transported through the GAC via the GAC compressor to the CD-3A CO_2 sensor.

Results of the testing indicated that the GAC caused mixing within the sample breath stream and unfortunately smoothed out the sinusoidal variation of CO_2 concentration as shown in Figure 11 below. The plots in Figure 11 show CO_2 levels as measured by the PUMA sensor within the mouth of the SMTA manikin compared to the CD-3A CO_2 sensor measurements with and without the GAC. It is believed that the mixing phenomenon occurs within the GAC compressor, causing the dynamic variations of CO_2 levels during breathing to be smoothed to essentially become a time-weighted average of the CO_2 levels. This test was performed by two test operators during a majority of the test duration and demonstrates the utility of the SMTA in providing human-like breathing performance at various suit pressures with fewer resources required than those required for human testing (which would have required higher staffing levels). 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 to provide measurements that indicate the full range of CO_2 concentrations associated with breathing. The GAC unit works well for steady state conditions, but is not a recommended solution for measuring the dynamic CO_2 transients experienced during breathing. A task to investigate and develop the alternate approach has been initiated.

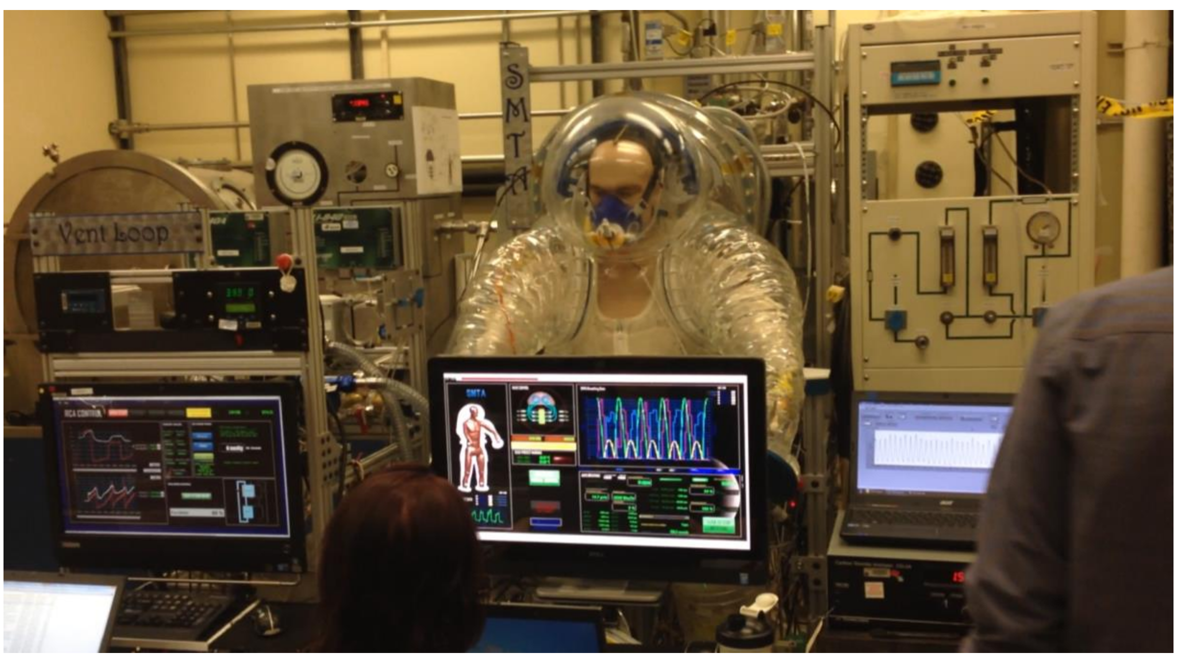

Figure 10. GAC test setup—Ventilation Test Loop (left), SMTA (middle), and GAC (right).

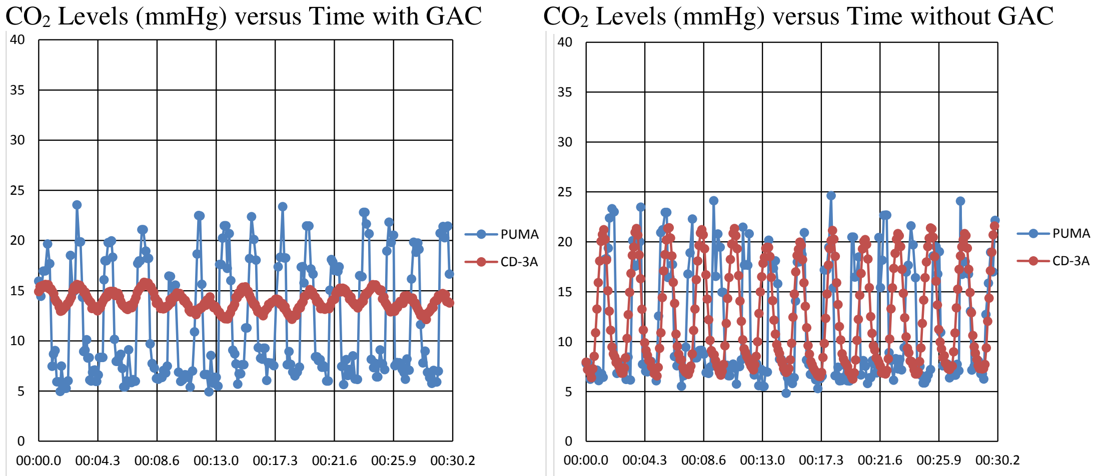

Figure 11. Example CO_2 partial pressure (mmHg) test results from SMTA GAC test at approximately 13.5 psia space suit pressure show poor agreement with the GAC but good agreement without the GAC (note that time syncronization between PUMA and CD-3A measurements has not been performed).

C. Carbon Dioxide Washout Test Plans

The IVTS 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 IVTS CO_2 washout test are as follows:

1) Use the SMTA breathing manikin to simulate 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 configurations (VCFG) A through F (refer to Figures 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 VCFG's (A-F) shown in Figures 12 through 17 based on previous CFD analyses.[12] 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.[13,14] The other metabolic rates listed in Table 1 are included in the Priority 5 group of test points. Currently, 315 test points are planned, and they have been grouped into the following priorities:

Priority 1: Evaluation of VCFG's A-F at 4, 5, and 6 acfm at 15.6 psia and 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

Test results from priority 1 and priority 2 test results will be analyzed to determine the three best-performing VCFGs. Test points for priorities 3 through 7 will only evaluate these three best-performing VCFDs to reduce the total number of required test points.

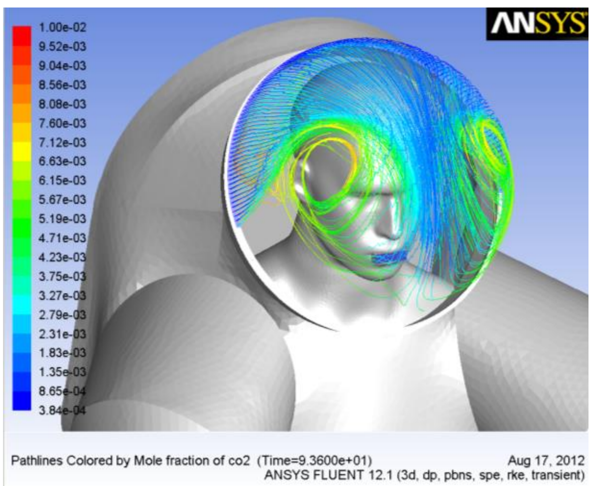

Figure 12. VCFG A - "All Vents Open."

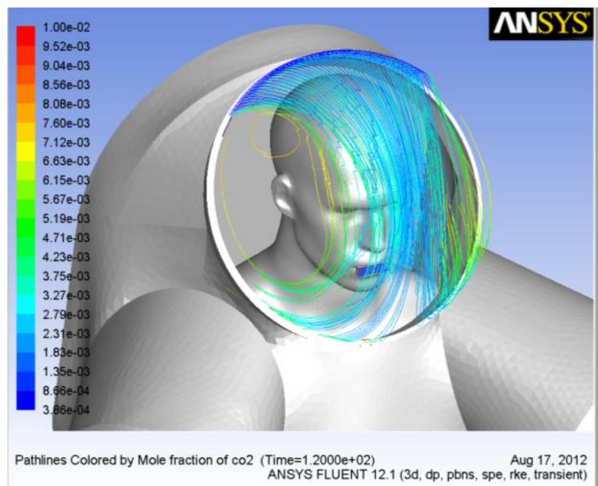

Figure 13. VCFG B - “Y” + "Center Configuration."

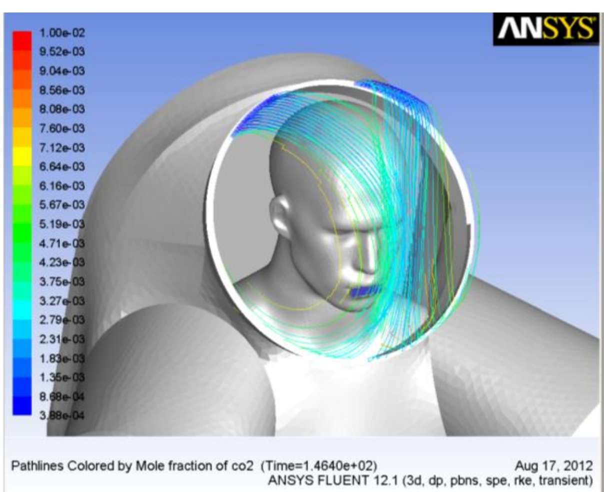

Figure 14. VCFG C - “Y Configuration.”

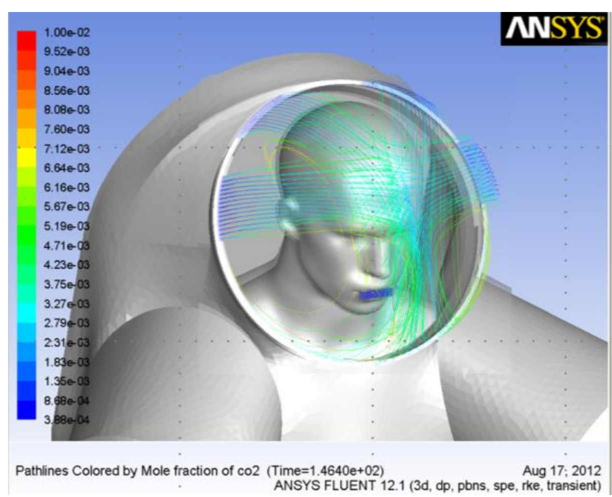

Figure 15. VCFG D - "Y + Ear Configuration."

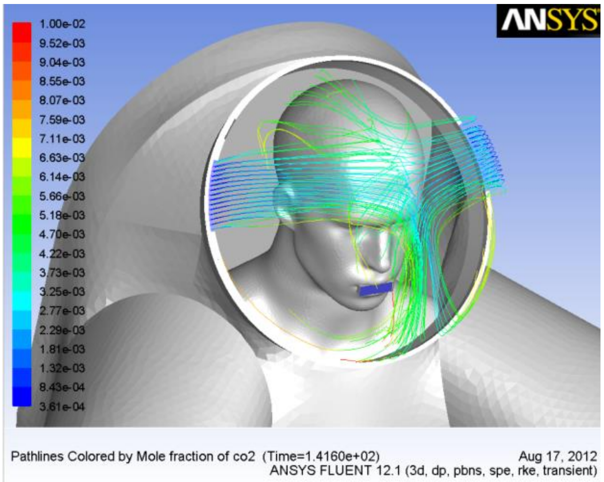

Figure 16. VCFG E - "Ear Configuration."

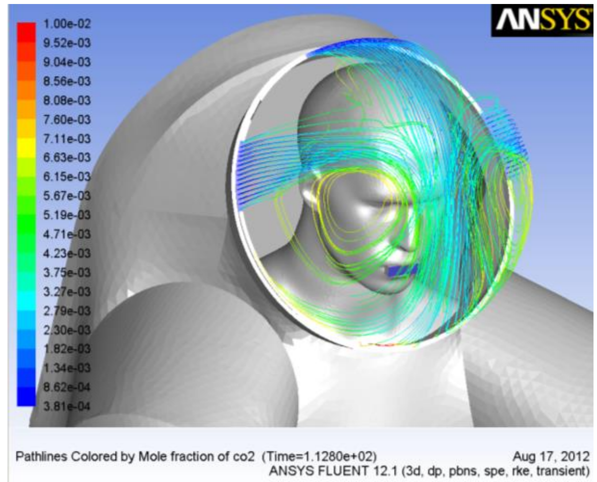

Figure 17. VCFG F - "Ear + Center Configuration."

D. Suited Manikin Test Apparatus Pre-test Computational Fluid Dynamics Evaluations

A CFD analysis was performed using ANSYS Fluent™ to provide pre-test predictions for the testing to be performed with the IVTS. The purpose of this analysis task was to determine the inhaled CO_2 levels for a suited crew inside the Mark-III suit configuration, similar to what is being used during SMTA testing. Due to time constraints, only two of the VCFGs were evaluated with this CFD modeling effort (VCFG C and VCFG F).

A number of human space suit CO_2 washout tests have been performed using an oronasal mask and there are concerns that the mask changes the behavior of CO_2 washout in the helmet. Therefore CFD modeling was performed to evaluate these concerns. Numerous variables involved in the human testing that affect the boundary conditions for the flow may cause differences in the simulation results. The human testing variables that have not been accounted for in the CFD simulations include the following:

- Test subject head position relative to flow
  - Partially blocking the flow in the rear
  - Movement of the oronasal 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, which can vary the back-pressure down a particular flow path
- Physiological differences between subjects and the assumed model
  - Tidal volume and tidal rate
  - Percentage of breathing through mouth versus nose

CFD modeling was performed to simulate the characteristics of planned SMTA testing including the following:

- Use the mask modeled in CFD using the manikin head and the Mark-III Suit volume matching the SMTA geometries
- Use the SMTA to execute the breathing pattern chosen for the model

The case matrix for CFD simulations performed is listed Table 2. A series of transient breathing cases using the SMTA CFD model were analyzed as follows:

- Two CFD configurations (see Figure 18)
  - Without a mask
  - With a mask
- Two vent flow configurations were modeled, based on the best performing VCFGs in the Mark III CO_2 washout test series.[14]
  - VCFG C
  - VCFG F

- Two flow rates
    - 4 acfm
    - 6 acfm
- Two metabolic rates
    - 2000 BTU/hr
    - 3000 BTU/hr

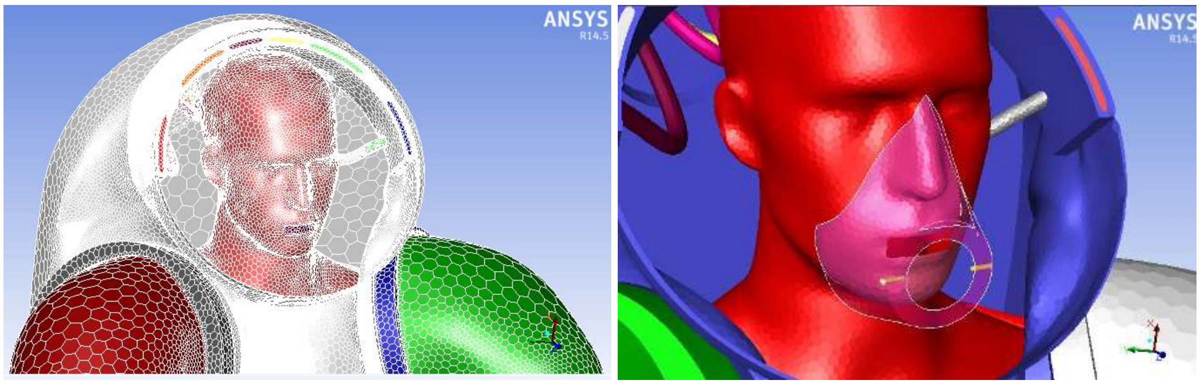

Figure 18. No-mask geometry (left) and mask geometry (right).

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

- CFD modeling notes and assumptions
  - Inhale and exhale transient sinusoidal breathing pattern using a user-defined function with mouth flow only
  - Four gas species (N_2, O_2, carbon dioxide, H_2O) for all cases, though N_2 gas is near zero concentration for all cases
  - Mask cases included 500 milliliter/minute flow exiting the domain through each of the two 0.125-inch-diameter sampling tubes
  - All cases simulated at a suit pressure of 4.3 psia
  - No heat transfer between inner suit wall and human (breath outlet temperature was specified)
  - Transient simulation run until inhaled CO_2 concentration reaches cyclic steady state
  - No buoyancy effects were modeled (zero-gravity assumption)

Summarized results of the CFD simulations are shown in Table 3. 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. Note that the CO_2 goal previously stated was to maintained inhaled CO_2 levels at or below 3.8 mmHg at 1200 BTU/hr. The results in Table 3 are for 2000 and 3000 BTU/hr and do not indicate whether or not the goal is met. These results are intended to provide comparisons for the CO_2 washout efficiencies of VCFG C and VCFG F and to also provide pre-test predictions for upcoming SMTA testing.

Table 3. Velocity-Weighted Average CO_2 Level during Inhale at the Mouth from CFD Runs, 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

Table 4 below includes volume-average CO_2 levels and ventilation flow velocities in the helmet and suit hard upper torso (HUT) volumes. 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 VCFG C vent versus the VCFG F, in the no mask cases, the VCFG C inhaled CO_2 is less than the average value in the HUT and helmet in three out of four cases, while for the VCFG F 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. Also, for the "no mask" cases, the average velocity in the HUT/helmet is higher for all of the VCFG C cases compared to the VCFG F cases. This is also true when comparing the "mask" cases, the VCFG C cases are higher than their respective VCFG F cases.

The trends of CFD results can also be seen in Figure 19 that shows that the "no mask" cases performs better than the "mask" cases in seven out of eight flow rate/metabolic rate combinations. The 4 acfm, 3000 BTU/hr results show slightly better CO_2 washout performance for the no mask case as compared to the case with the mask.

Table 4. Volume Average CO_2 Levels and Velocities from CFD Evaluations

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

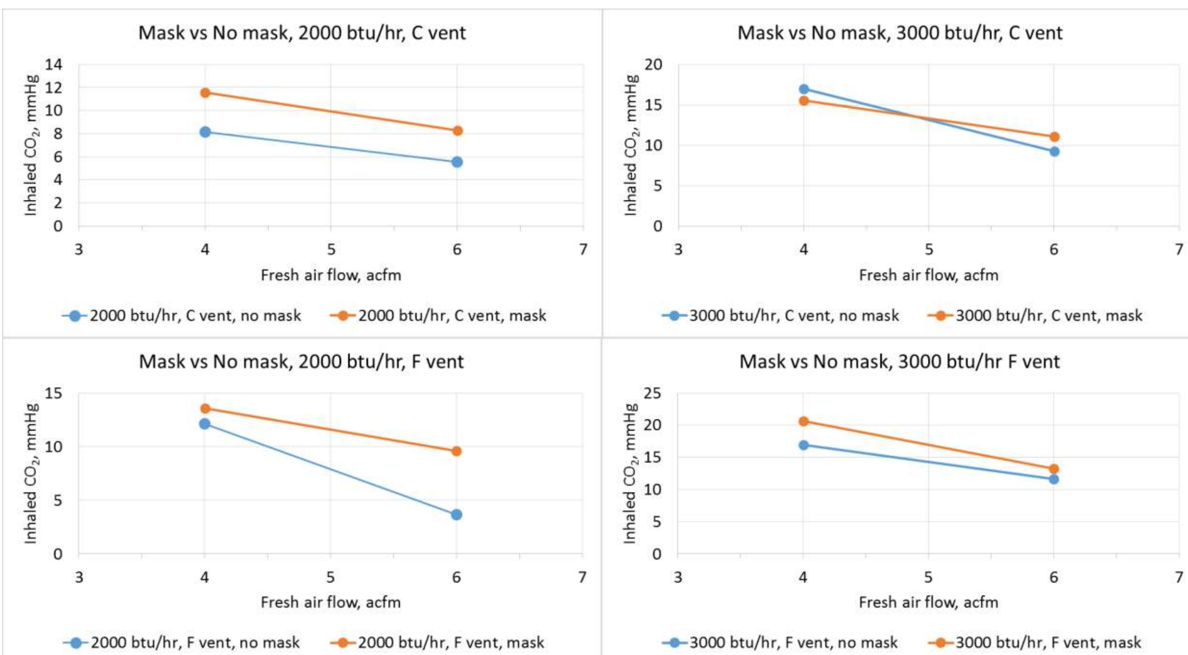

Figure 19. Inhaled CO_2 trends for flow rates, metabolic rates and mask versus no mask from CFD runs.

A few unexpected trends have been identified within the results (the unexpected low inhaled CO_2 value in Case 4, for example). 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
- Inhaled CO_2 decreases going from 4 acfm to 6 acfm for all cases
- 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 versus no mask observations include the following (higher inhaled CO_2 levels are considered worse CO_2 washout performance):

- At 2000 BTU/hr metabolic rate, higher inhaled CO_2 for all cases with mask
- At 3000 BTU/hr, results are inconclusive since results are generally closer for "mask" versus "no mask" and the "mask" results are better at the 4 acfm for VCFG C

As shown in Table 4, inhaled CO_2 for VCFG C was equal or better (lower) than the inhaled CO_2 for VCFG F in all metabolic rate and mask/no mask configurations except one (inhaled CO_2 for the 2000 BTU/hr at 6 acfm, with no mask for VCFG F was better than for the same VCFG C).

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 combination of testing and analysis should help understand differences that have been experienced with prior 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.

The potential benefits from optimizing CO_2 washout performance include:

- Reduced APLSS/space suit ventilation flow rate requirements that could reduce power and fan performance requirements.
- Reduced efficiency requirements for the APLSS 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 APLSS.
- More robust helmet/ducting designs that are less sensitive to head position, head size, hair/communications hardware configurations.
- More predictable CO_2 washout performance that reduces the risk of elevated CO_2 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. These investigations should include human testing, SMTA testing and CFD simulations of corresponding conditions and configurations. A few configurations have been investigated, but many potential configurations exist that may provide better CO_2 washout performance for the Advanced Extravehicular Mobility Unit (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, and 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 Test Loop 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 the AEMU. These efforts are targeted to provide robust, safe, and efficient space suit designs.

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