Swing Bed Scrubber Design and Test Integration Results for Carbon Dioxide Removal in the Ventilation Test Loop 2.0

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NASA is developing an advanced portable life support system (PLSS) to meet the needs of a new NASA advanced space suit. The PLSS provides the necessary oxygen, ventilation, and thermal protection for an astronaut performing a spacewalk. The PLSS ventilation subsystem is responsible for providing adequate carbon dioxide (CO_2) and water vapor removal. To experimentally validate the performance of CO_2 removal and advanced CO_2 sensing systems, NASA Johnson Space Center developed the Ventilation Test Loop 2.0 (VTL2) and tested the Oceaneering Swing Bed Scrubber (SBS) that was fabricated and delivered under the Constellation Space Suit System Contract in 2015. The SBS was designed to continuously remove CO_2 and water vapor from a space suit ventilation loop with a pair of thermally integrated amine beds that alternately adsorb and desorb water vapor and CO_2. The SBS hardware was recently resurrected and reassembled to support a full battery of performance testing in the VTL2. This paper describes the design and development of the SBS and the VTL2 along with the performance test results of the SBS.

Nomenclature

acfm	= actual cubic feet per minute
BTU/hr	= British Thermal Units per Hour
CSSS	= Constellation Space Suit System
SBS	= Swing Bed Scrubber
sccm	= standard cubic centimeters per minute
Update	

I. Introduction

PEFORMING an Extra-Vehicular Activity (EVA) or spacewalk continues to be one of the most critical aspects of human space flight due to the hazardous environment of space. An EVA suit must provide a life sustaining environment that is safe and protects the astronaut under these extreme space conditions. The current space suit, the Extravehicular Mobility Unit (EMU), is expected to be operational to at least the year 2024. To enable an EMU

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replacement or a deep-space exploration EVA space suit or both, the National Aeronautics and Space Administration (NASA) is developing an exploration Extra-Vehicular Activity (EVA) space suit in-house at the Lyndon B. Johnson Space Center in Houston, Texas. To facilitate this exploration EVA (xEVA) project, NASA intends to transition from technology development and systems maturation to a focused flight delivery milestone for an advanced space suit to be demonstrated on the International Space Station (ISS) in the mid-2020s. The xEVA project leveraged a decade of technology investments and system maturation through support from programs such as Constellation, the NASA Office of Chief Technologist's Game Changing Development Program, and the Advanced Exploration Systems (AES) program. Whether designed for orbital operations or planetary surface explorations systems, a future EVA space suit, must continue to be safe and reliable, and must provide a high degree of performance capabilities.[1]

The Portable Life Support Subsystem (PLSS) within the xEVA suit will attach to the space suit pressure garment subsystem and provide for the life sustaining environment. The ISS EMU PLSS currently uses state-of-the-art technologies which are not regenerable in situ during EVA, and therefore require consumables and additional crew time to manage. These include the lithium hydroxide (LiOH) and regenerative metal oxide (MetOx) sorbent technologies. The LiOH canister is a consumable that can only be used once. The MetOx can be used repeatedly. However, the MetOx canister requires a 14-hour post-EVA regeneration bake-out cycle. In situ regenerative technologies such as Swing Bed Scrubber (SBS) and Rapid Cycle Amine (RCA)[2] are of great interest to the xEVA suit project for CO_2 removal and humidity control as these technologies will reduce consumables, logistics, and crew time for the suit, and they may reduce weight and volume of the Exploration system as a whole.

This paper describes the design and development of the SBS and the Ventilation Test Loop 2.0 (VTL2) along with the performance test results of the SBS. The SBS continuously removes CO_2 and water vapor from a space suit PLSS ventilation loop with a pair of thermally integrated amine beds that alternately adsorb and desorb water vapor and CO_2. The SBS was designed, fabricated and delivered under the Constellation Space Suit System (CSSS) Contract in 2015 by Oceaneering Space Systems (OSS). It was resurrected and reassembled in 2017 to support a full battery of performance testing in the VTL2. The VTL2 was designed and built by NASA JSC to experimentally validate the performance of in situ regenerative CO_2 removal and humidity control systems and to evaluate advanced CO_2 sensing systems.

II. Background & Development

The need for EVAs in space was evident over many decades in programs such as Gemini, Apollo, Skylab, Space Shuttle, and ISS programs. The current EMU was originally developed in the 1970s for the Space Shuttle and was then enhanced for operation with ISS. It remains the the last developed pressurized flight suit that includes both a life support system and a spacesuit assembly to enable spacewalks in zero gravity.[3]

The technology development for a new space suit originated under the Constellation Program's (CxP) over a decade ago with a vision of returning to the moon and it transitioned to a microgravity application. The development progression was based on published Technology Roadmaps with content including EVA. The technology advancements considered included increased component life, protection from radiation events, mobility in a partial gravity environment, dust mitigation, interfaces with rovers and habitations, high-data-rate-network-based communication, innovative life support systems that minimize consumables or take advantage of in-situ resources, smart caution and warning capabilities, and advanced information systems that enable crew autonomy. Besides CxP, many of these advancements were facilitated by numerous programs such as NASA Office of Chief Technologist's Game Changing Development Program, and the Advanced Exploration Systems (AES) program.[4] The maturity investment success has led to the ISS program desiring to pursue further development of a new suit.

NASA plans to pursue a phased approach to explore EVA capability from Low Earth Orbit (LEO) through cislunar space to the surface of Mars. The reference Exploration EVA Architecture is shown in Figure 1. The Advanced EVA Development project is planning for three separate hardware configuration phases referred to as Lite-Configuration (xEMU Lite), X-Configuration (xEMU), and M-Configuration (mEMU).

The xEMU Lite configuration will be an exploration class space suit hardware system integrated with legacy EMU components for use in LEO on ISS. The xEMU-Lite focuses on critical life support and pressure garment capabilities. It will include a means for upgrading to a full xEMU. It will consist of the Exploration Portable Life Support System-

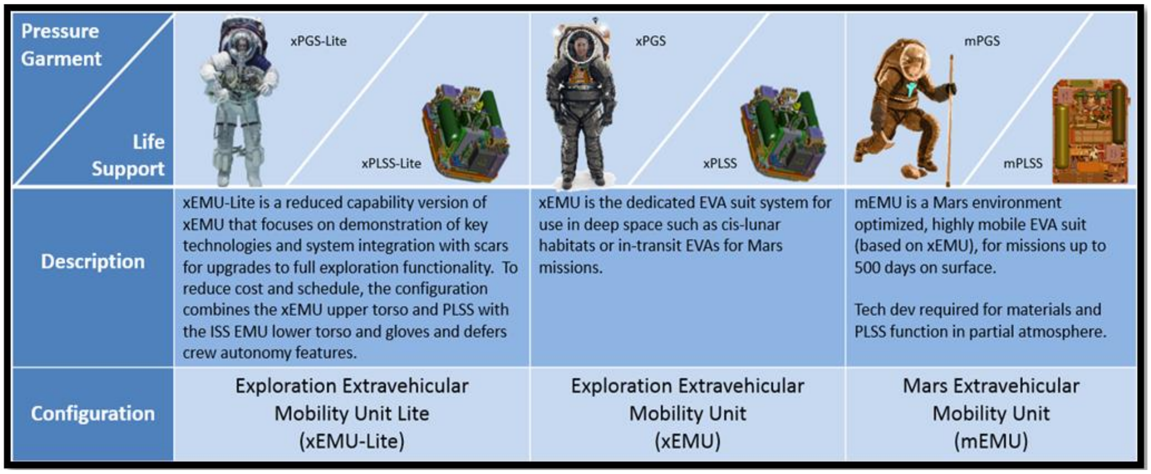

Figure 1. NASA's Exploration EVA Architecture, Phased Approach

Lite (xPLSS-Lite) and the Exploration Pressure Garment System-Lite (xPGS-Lite) with existing ISS EMU lower torso and gloves. This configuration is planned for a flight demonstration in a Detailed Demonstration Test Objective (DTO) on the ISS by 2024. NASA plans to lead the development, perform the integration activities in-house, manufacture a single flight demonstration unit, and qualify the xEMU-Lite for testing on the ISS.

The xEMU will be a fully outfitted exploration space suit for deep space missions. The mEMU is a Mars environment suit optimized for missions for up to 500 days. This suit is planned to be highly mobile and based on the xEMU design. However, there will be technology development required for materials and PLSS functions.

Within the xEMU resides the xPLSS-lite or referred to in this paper as PLSS. The PLSS will provide for 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 astronaut metabolic heat rejection. The PLSS will 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.

The SBS was designed and fabricated as a regenerative technology which performs CO_2 removal and humidity control. This work was accomplished under the CSSS contract with OSS. NASA remains interested in the SBS due to its potential for reduce consumables, logistics, and crew time for the suit. The SBS was functionally testing under the CSSS contract. However, performance testing was not. The SBS was delivered to NASA in 2015 just prior to CSSS contract end. The hardware was reassembled by OSS via the JSC Engineering, Technology, and Science (JETS) contract in 2017 to support testing on VTL2. The SBS was integrated into the VTL2 in the NASA JSC PLSS laboratory for testing. The SBS is described in detail in Section III below. The VTL2 is described in Section IV. The SBS test results are described in Section V and Section VI compares the development goals and observed performance for the SBS and RCA 3.0.

III. Swing Bed Scrubber Development

A. Test Item Description

The SBS is comprised of two separated subcomponents connected with hoses: the sorbent bed assembly and the linear valve with motor. The sorbent bed assembly, shown in Figure 2, is comprised of anodized aluminum panels held together with fasteners, sealed with Viton® gaskets, and filled with a commercially available sorbent.

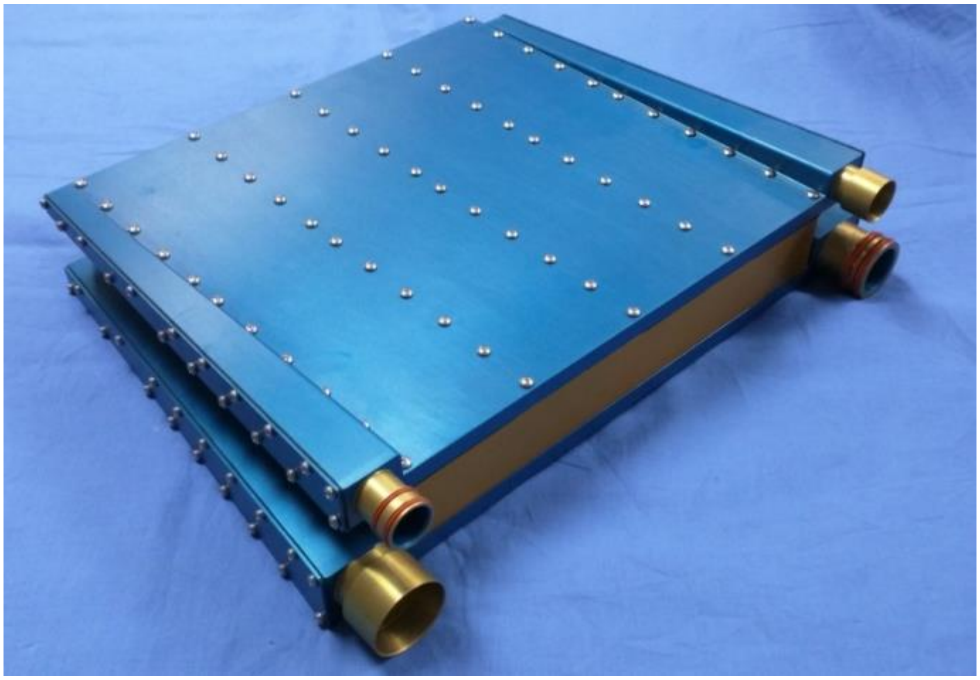

Figure 2. Swing Bed Scrubber Sorbent Bed Assembly

The assembly is configured as a thermally integrated two-bed design. Ventilation gas containing oxygen (O_2), carbon dioxide (CO_2), and water (H_2O) enters the beds from the suit through the linear valve. The CO_2 and H_2O in the gas stream are adsorbed by the sorbent while the O_2 passes through and is returned to the suit through the linear valve. The linear valve is used to alternate the beds between scrubbing and vacuum regeneration. The ports and hoses leading to vacuum are larger than the ventilation flow hoses in order to achieve a very low vacuum for regeneration, which in turn results in better adsorption.

The sorbent bed was sized using two key design parameters:

1) Contain sufficient sorbent in a swing bed configuration to provide a 4 minute cycle time on each bed when exposed to the CO_2 and water output from an average metabolic rate of 300 Watts. This operating point was derived from a NASA requirement and goal for the development of the RCA[y]. However, the RCA 3.0 was developed to a different specification.
2) Keep pressure drop below 1" H_2O while flowing 4.5 Actual Cubic Feet per Minute (ACFM) of flow through the bed at a pressure of 4.3 psia. This requirement resulted from the SBS' allocation of pressure drop for the CSSS ventilation loop.[5]

The linear valve, shown in Figure 3 and 4, is used to direct the flow from the PLSS vent loop through alternate scrubber beds while simultaneously venting the other bed to vacuum. It accomplishes this through a series of seals and passages that redirect the vent flow as the spool portion of the valve is driven back and forth by the motor. There are two seals between the ventilation loop and vacuum in all valve positions in order to meet a NASA structural design standard for large diameter critical seal redundancy.[6] The linear valve incorporates features to allow the ventilation flow to bypass the beds during cycling to provide consistent and uninterrupted flow of gas to the crew. This eliminates potentially distracting pressure pulses when the flow starts and stops, eliminates disconcerting flow stoppages during each half cycle, and eliminates the possibility of the valve failing in a no flow position. While the valve is in the bypass position, the beds are isolated from the ventilation flow and the valve connects the evacuated, regenerated bed to the pressurized, saturated bed, thus equalizing bed pressures and reducing the amount of ullage gas lost to vacuum during each half cycle.

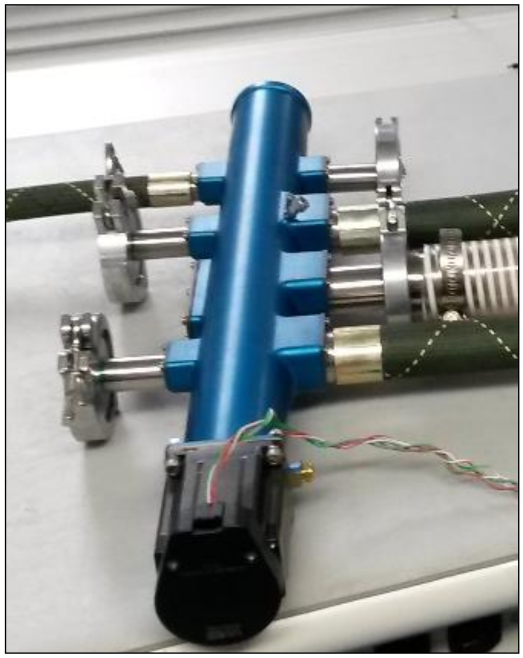

Figure 3. Swing Bed Scrubber Linear Valve

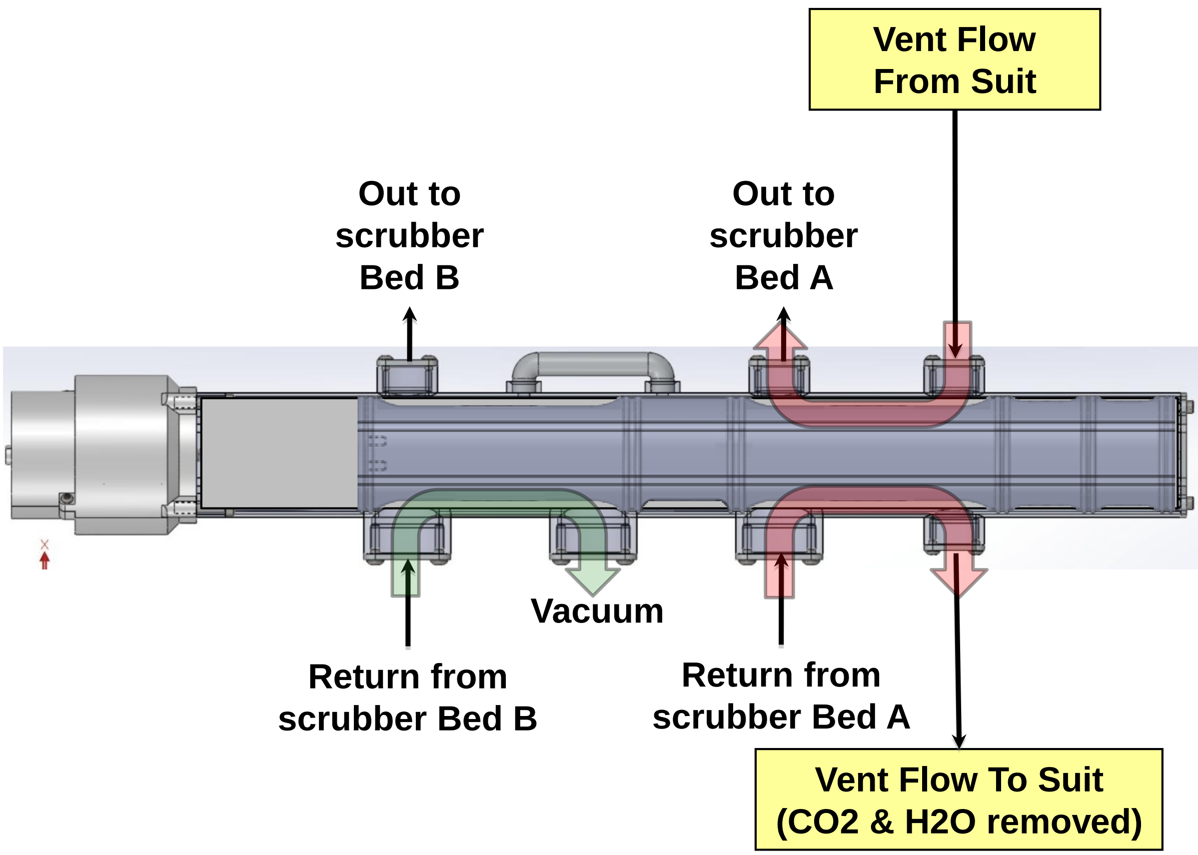

Figure 4. Illustration showing SBS valve spool driven to right for ventilation flow through Bed A and vacuum regeneration of Bed B. When valve is driven to left, ventilation flow is through Bed B and Bed A is regenerated.

The linear valve design was driven by three key parameters:

1) Smooth flow transitions when switching beds and performing bed pressure equalization to minimize pressure drop and eliminate flow interruption in the ventilation loop and suit.
2) Low pressure drop for both ventilation flow and vacuum vent. Low pressure drop for ventilation flow allows for a smaller motor with less power consumption. Low pressure drop for vacuum vent is critical to achieve adequate desorption which in turn allows better adsorption during the subsequent half-cycle.
3) Low actuation force (minimize friction from the seals). Friction corresponds directly to power, so less friction requires less power to cycle the valve.

Figure 5 illustrates a Computer Aided Design (CAD) model of the SBS beds, valve, and connecting hoses as packaged within the CSSS PLSS. The flat configuration of the beds and the separated valve allow for a variety of packaging options as opposed to a single monolithic scrubber that commands the rest of the PLSS to be packaged around it.

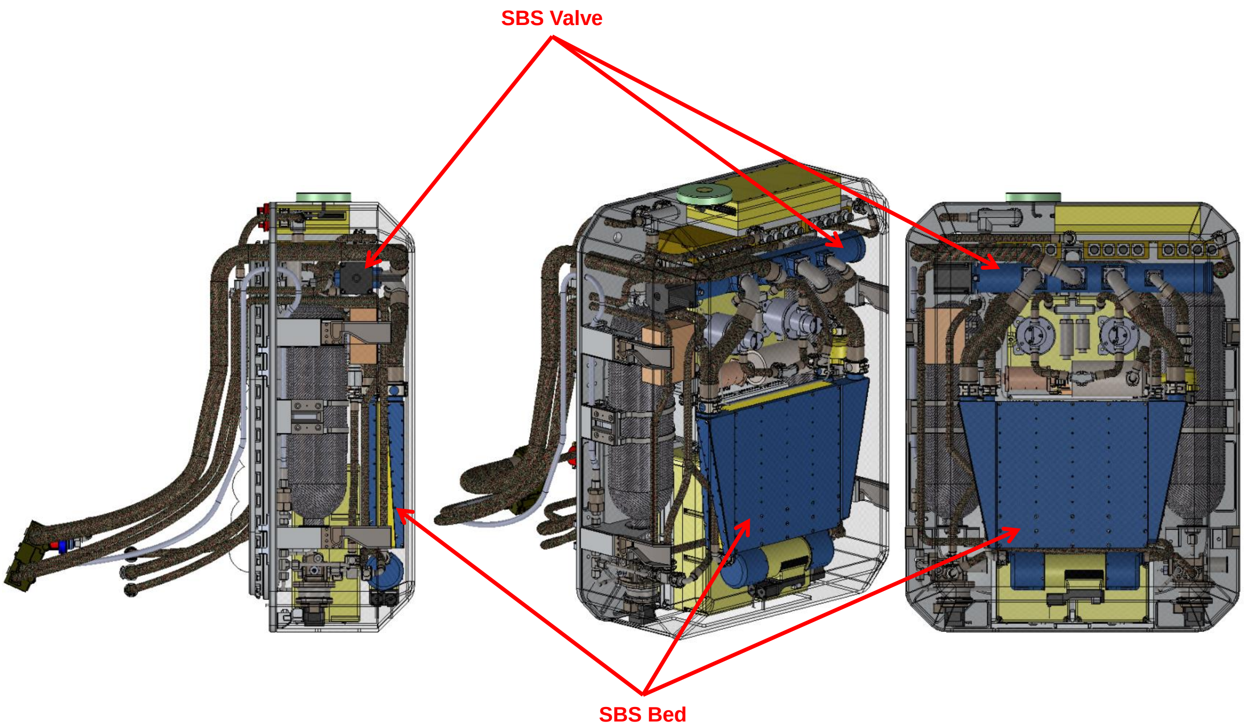

Figure 5. CAD Model of SBS beds, valve, and hoses packaged in the CSSS PLSS

Performance of the projected SBS at the design set point of 1020 BTU/hr, 6 acfm, and 3 mmHg ppCO_2 exiting the scrubber is shown in Table 1. Additional SBS characteristics are shown later in Table 4.

Table 1. Swing Bed Scrubber Goals and Characteristics

	Swing Bed Scrubber
CO_2 Removal (3 mmHg Outlet)	1020 Btu/hr average*, can do more or less by changing frequency of swings
H_2O Removal (Outlet RH)	10-20%*
Enveloping Volume (in^3)	Valve: 139 (2.2" x 3.3" x 19.2") Bed: 452 (2.8" x 11.8" x 13.7")
Average Power (W)	0.2
Leakage (sccm)	0.3**

* Expected performance based on preliminary testing or analyses

** Bed leakage only, valve has not been tested

B. Previous Tests

1. Sorbent Bed Proof Pressure Testing

The empty sorbent bed was placed inside a Lexan™ blast chamber. It was pressurized for proof pressure testing, then isolated and monitored for 5 minutes to record pressure decay. This process was performed for a variety of bed combinations: Bed A only, Bed B only, Bed A and B simultaneously, Bed A at pressure and Bed B at vacuum, and Bed B at pressure and Bed A at vacuum. The sorbent bed successfully passed all proof pressure testing with no signs of deformation. Pressure decay rates were essentially 0 psig/minute after pressurizing to 17±1 psig and monitoring for 5 minutes.

2. Sorbent Bed Vacuum Leakage Testing

The empty sorbent bed was placed on a vacuum manifold and pumped down to ~40 torr, isolated from the vacuum source, and the Rate of Rise (ROR) was monitored for at least 5 minutes. Vacuum leakage tested was performed on Bed A only, Bed B only, and Bed A and B combined. The empty sorbent bed successfully passed vacuum leakage testing. The sorbent bed was placed on a vacuum manifold and pumped down to ~40 torr, isolated from the vacuum source, and the ROR was measured using a 100 torr Baratron® head for at least 5 minutes. The measured leakage rate on both beds was less than 0.05 torr/minute, which is approximately 0.1 sccm (volume calculation included the sorbent bed headers as well as the test apparatus manifolds).

3. Sorbent Bed Pressure Drop Testing

Pressure drop in Bed A and B were measured at a variety of flow rates at 14.7 psia (Figure 5). At 6 acfm, the pressure drop values through Bed A and B were approximately 2.4" H_2O each. At 4.3 psia, the pressure drop through the bed would be 0.7" H_2O each. These values do not include the pressure drop through the SBS valve.

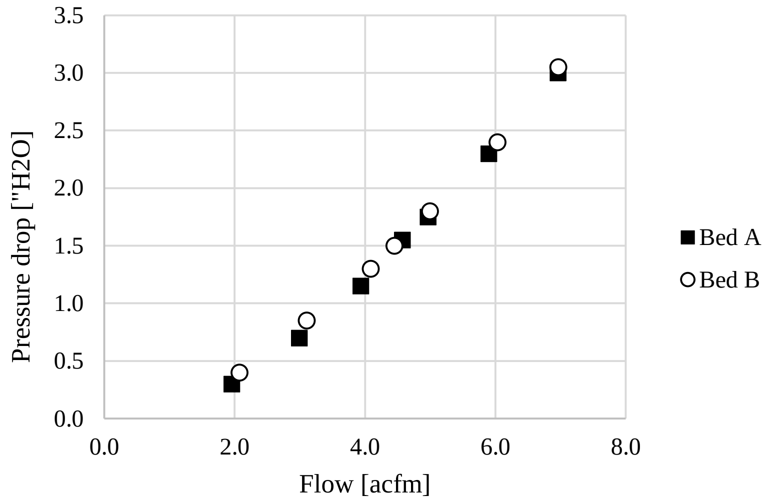

Figure 5. Pressure drop in Bed A and B at ambient pressure

4. Linear Valve Proof Pressure

The linear valve was placed inside a Lexan™ blast chamber. It was pressurized and isolated for proof pressure testing. The proof pressure was 17.0 ± 0.7 psig and the vacuum level was 40 ± 1 torr. The test article did not show any structural deformation. The shuttle portion of the valve was placed in all expected operating conditions for the various proof .

5. Motor Testing

Valve cycle time testing was performed at a variety of speeds. Cycle times were captured with a hand held stop watch and LabVIEW was used to control the motor speed. The motor performed nominally in the loaded configuration. The motor moved the linear valve spool smoothly at all commanded speeds and the hard-stop feature of the valve functioned as designed. The relationship between the motor speed and the valve travel times was characterized, as was the relationship between the motor positions and the spool positions within the linear valve. The cycle times showed that the linear valve could be actuated fully in less than 2 seconds while drawing 20 Watts. One cycle per four minutes provides an average power draw of 0.2 W over an 8 hour EVA. Longer cycle times may be acceptable or desireable given the bypass and gas recovery features built into the linear valve.

6. Sorbent Outgassing Testing

Amines are known to outgas contaminants, with ammonia being the most concerning for space suit applications. To reduce these contaminants, the SBS sorbent was washed to remove unbound ammonia and contaminants from the bulk sorbent. A sample of the washed sorbent was sealed in a container so that the ratio of sorbent to free volume was equivalent to the ratio found in a PLSS and suit. After three days, the container was sampled with an ammonia gas detector tube and found to contain 29 ppm ammonia, which is below the OSHA 8 hour limit of 50 ppm[7]. After four days, the container was sampled using gas chromatography and gas chromotography/mass spectrometry by NASA JSC's Toxicology group. With contaminants in the parts per billion range, they found no comainants at levels of concern for human health.[8]

IV. Ventilation Test Loop 2.0

The VTL2 is a computer-controlled system designed to simulate the ventilation subsystem of the next generation PLSS. The VTL2 is designed to provide a controlled flow of CO_2 and water vapor in a base gas of Nitrogen (GN2) to a PLSS sized CO_2 and H_2O removal system for the purpose of testing and characterizing under variable conditions of gas temperature, system pressure, process flow rate, and CO_2 and water vapor molar concentrations.

Several solid amine-based systems have been designed to continuously remove CO_2 and H_2O vapor from a flowing ventilation stream through the use of a two-bed amine-based, vacuum-swing adsorption system. The CO_2 and H_2O removal performance criteria are based on meeting or exceeding the expected CO_2 and H_2O vapor generation rates over the range of anticipated metabolic rates for EVA operations. Additionally, the system outlet CO_2 partial pressure were maintained at or below the allowable helmet inlet (inhaled) limits established by current requirements (4 mmHg).

As a secondary objective, the VTL2 was designed with manifolds to provide a controlled flow of CO_2 and H_2O vapor in a base gas of GN2 to test developmental gas sensors delivered under small business innovation and research (SBIR) contracts. The VTL2 can be used for the purpose of testing and characterizing gas sensor performance under variable conditions of gas temperature, pressure, and CO_2 and water vapor molar concentrations.

A. **Ventilation Test Loop 2.0 Description**

The VTL2 was designed to accommodate any RCA or CO_2 scrubber testing with the required instrumentation. The ventilation loop maintains the desired simulated metabolic rate, flow rate, and pressure to interface with the RCA or SBS. The ventilation test loop interfaces to facility gaseous nitrogen (GN2), facility CO_2, and a vacuum pump. The facility GN2 supplies the test loop with dry GN2 and provides any ullage lost from the RCA, or SBS, actuation. The facility CO_2 supplies the test loop with the required simulated metabolic CO_2. The vacuum pump connected to the test loop draws the system pressure down to the desired operating pressure for all test cases. A back pressure regulator controls the system pressure at all times. The utility vacuum chamber (UVC) is connected to the RCA, or SBS, vacuum port to represent the space vacuum that is required to desorb the amine. The system flow rate was evaluated between 4 to 6 actual cubic feet per minute (acfm) at various system pressures: 4.3 and 14.7 psia.

B. **Ventilation Test Loop 2.0 Design**

The ventilation test loop rig is based on a rounded design for a re-circulating closed loop to minimize pressure drops and unnecessary bends within the test stand. The system was designed to integrate all required sensors to analyze the performance of the RCA and SBS test articles while providing the proper volumetric flow rate and CO_2 and H_2O injection rates, as shown in Figure 6. The system allows for the collection of CO_2 concentration and relative humidity (RH) data immediately before and after the test article, allowing for analysis of each constituent to be calculated based on the effect of the test article.

The ventilation loop was constructed with 25.4 millimeters (mm) [1-inch (in.)] stainless-steel piping configured in a recirculated loop with a total loop volume of approximately 59.5 liters (L) [(2.1 cubic feet (ft3)]. A 56.6 L (2.0 ft3) mixing volume was integrated into the test loop to simulate the empty volume of the spacesuit. The ventilation loop was configured with minimal fittings and connectors to reduce leak paths and to ensure maximum flow rate through the test article.

There are two mechanical operational modes of the VTL2: test and bypass mode. The test mode configuration provides the entire system flow rate through the test article and can be adjusted by two three-way valves upstream of the test article. Adjusting the three-way valves in the opposite configuration allow the VTL2 to be operated in a bypass mode, thus supplying the entire system flow rate to bypass the test article. The bypass mode allows for sensor evaluation while maintaining the integrity of the test article.

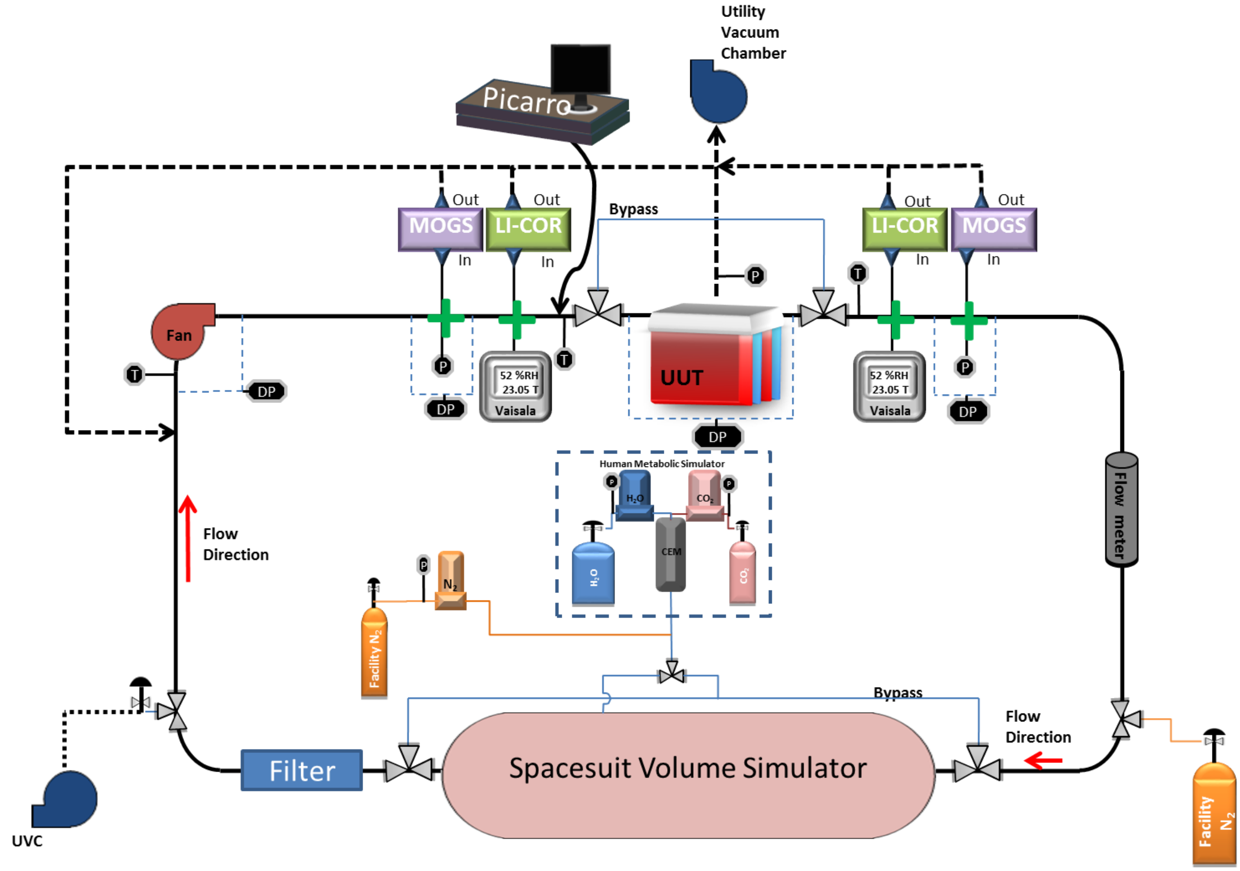

Figure 6. Illustration of the ventilation test loop 2.0

A controlled evaporation and mixing (CEM) system is an advanced liquid delivery system (LDS) that can be applied for atmospheric or vacuum processes to simulate human metabolic flow (Bronkhorst High-Tech B.V.). The vapor generation system consists of a liquid flow controller, a mass flow controller (MFC) for carrier gas and a temperature-controlled mixing and evaporation device. The CO_2 flow rate is controlled through a mass flow controller and directed into the CEM where the CO_2 is heated and mixed with the water injection. The water injection rate is controlled with a LIQUI-FLOW mass flow meter upstream of the CEM to allow for precise water injection rates to be attained. A temperature-controlled heat exchanger was designed within the CEM system to add heat to the mixture to ensure complete vaporization. Two CO_2 sensors were installed in the inlet and outlet lines to monitor and to record the CO_2 levels.

The utility vacuum chamber (UVC) was connected to the VTL2 to draw the system pressure down to the desired operating pressure for all test cases. A back pressure regulator was used to control the system pressure at all times. The UVC was connected to the unit under test (UUT) vacuum port to represent the space vacuum that is required to desorb the amine packed beds.

A picture of the actual VTL2 is shown in Figure 7.

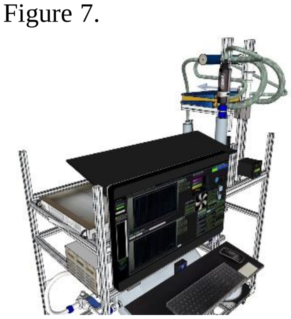

Figure 7. SBS integrated into VTL2 (Placeholder)

V. Swing Bed Scrubber Test Results

(Placeholder test data and discussion follow in this section that do not represent actual SBS performance and will be replaced once actual data is collected – this section will be fully rewritten for the final version of this paper)

A. Data Collection and Processing

Test data were collected using a variety of instruments connected to the LabVIEW data acquisition system and through a secondary computer system associated with the Picarro cavity ring-down spectroscopy unit. The Picarro data was exported as a generic data file. The LabVIEW data was exported in the National Instruments TDMS format which is a proprietary hierarchical format optimized for high-speed data acquisition and for minimizing hard drive disk usage.

Microsoft Excel, with the National Instruments TDMS file viewer add-in, was used to initially import the data and write it out as a comma separated values format file. The entire process was automated with Visual Basic for Applications. Though Excel provides basic plotting features, it is limited in terms of functionality since 'for', 'while' and 'switch' constructs were not available. Also, the plotting of multiple large data sets can be cumbersome and memory-intensive. To overcome these issues, the Python 3.0 programming language was used to script a file to import data, perform necessary conversions, and plot out resulting data. In addition, the Python script also performed a system mass balance. The mass balance results were used to ensure data quality and to aid in identifying and correcting any faulty instruments. The entire automated process resulted in a consistent application of analysis techniques while enabling a rapid means to re-evaluate data as new findings focus attention on different aspects of the data.

In addition, the Python community has developed a number of highly specialized modules for advanced data analysis. In this investigation, the SciPy Statistical module was used to compute the Pearson correlation coefficient for each column of data compared individually to all other columns of data. The resulting Pearson correlation coefficient matrix varies from 1 (perfect positive correlation) to -1 (perfect negative correlation) where a value of 0 is regarded as uncorrelated. Some data are expected to be positively correlated. For example, a high water mass flow controller set point should be positively correlated with test article inlet relative humidity. However, this method allows the team to identify other non-obvious correlations or any anomalous data indicating instrumentation issues.

B. Test Results

Carbon dioxide removal performance has traditionally been quantified by evaluating the "half-cycle time" of the swingbed as a function of metabolic rate. Before analyzing test data, it is first worth understanding the chemical process through which carbon dioxide is captured in the sorbent. The swing beds analyzed herein rely on covalent bond formation between carbon dioxide which interacts with a finite number of sites associated with sorbent molecule. Such processes have a higher heat of adsorption than do physisorptive processes (*e.g.,* condensation) and typically follow a Type III isotherm[9]. For a packed bed with Type III isotherm behavior, a constant input of adsorbate will produce a breakthrough curve as in Figure 8 (A) where the concentration of the adsorbate is monitored at the bed mid-point for a dimensionless time (with time = 1.0 as the breakthrough time at the outlet of the bed). Adsorbate loads the bed from front to back with a distinct region of active mass transfer which is referred to as the mass transfer zone (annotated with dashed lines in Figure 8 (A)). The steepness of the breakthrough curve is dictated by the bed packing. High void fraction beds with low flow rates have less mechanical dispersion and the shape of the curve is dictated by molecular diffusion. Alternatively, for lower void fraction beds or for higher flow rates, mechanical dispersion becomes important which serves to broaden the mass transfer zone. Finally, the capacity of a bed is determined by integration of the breakthrough curve. All in all, the higher the mass of sorbent, the higher the bed capacity which leads to longer use of a bed prior to regeneration.

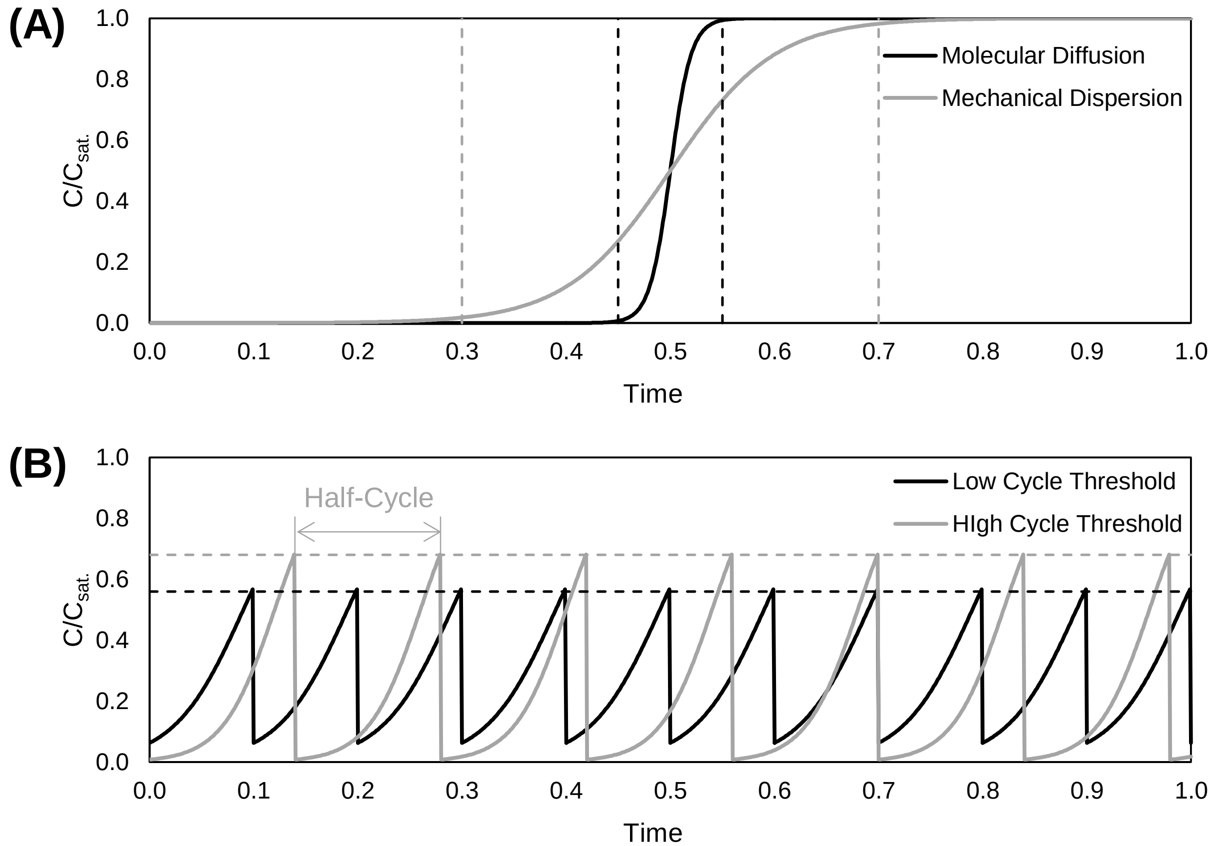

Figure 8. Illustration of carbon dioxide removal performance. (A) Adsorbent bed breakthrough curves with varying degrees of dispersion where dashed lines indicate the mass transfer zone. (B) Demonstration of cyclic steady-state performance for two-bed systems with both high and low cycle thresholds.

In practice, it is not desirable to allow a bed to become fully saturated as this can lead to substantial CO_2 accumulation. Instead, the bed outlet CO_2 concentration is monitored and a cycle-threshold is set as the criteria to switch adsorbing/desorbing beds. Figure(B) illustrates the outlet carbon dioxide concentration as a function of time for various CO_2 cycle thresholds. The half-cycle time is the time requirement between subsequent valve cycles when the adsorb bed is exposed to vacuum for desorb (and vice versa). Traditionally, swingbed testing has chosen cycle criteria ranging between 3.0-6.0 mm Hg. In general, when a higher threshold is set, half-cycle times are longer. The result is that the bed undergoing vacuum desorb has a longer time for regeneration. Therefore, for higher thresholds, the cyclic steady-state profile generates a saw-tooth pattern that bounds the maximum and minimums for lower cycle thresholds which result in shorter half-cycles times. The downside of higher CO_2 thresholds is that the mean CO_2 concentration the crewmember is exposed to is higher. The results in Figure(B) are illustrative herein though actual curves for test data have been reported in previous results.[9-11]

Finally, water sorption behavior is much different than CO_2 capture which follows an isotherm of Type I category.[9] This means that although there is a distinct mass transfer zone for CO_2, water loading breaks through much faster and loading continues to occur throughout the bed. As a result, lower half-cycles can lead to higher mean outlet dew point temperatures.

For performance characterization at JSC, swingbeds were exposed to a variety of metabolic rate challenges summarized in Table 2. These data are based on regression models to experimental results from human metabolic testing.[12-13]

$$r_c(lb_m/hr) = \frac{44}{32} MR \cdot RQ \left[1.708 \times 10^{-4} - 1.23 \times 10^{-5} \frac{(RQ - 0.707)}{0.293}\right]$$

$$r_w(lb_m/hr) = -9.874 \times 10^{-8} MR_{max}^2 + 2.791 \times 10^{-4} MR_{max} + 1.730 \times 10^{-3}$$

Carbon dioxide production rate, r_c (lb_m/hr), varies linearly with metabolic rate, *MR* (Btu/hr), and also depends on respiratory quotient, *RQ* (unitless), which is associated with the crewmembers diet (a value of 0.90 was used herein).[12] Water production rate, r_w (lb_m/hr), varies linearly as well but the liquid cooling ventilation garment has been found to act as a condenser at high metabolic activity where the crew member typically compensates for overheating by diverting more cooling water flow through the garment.[13] As a result, test data show a non-monotonic water vapor production rate as a function of metabolic rate. The experimental data for r_w was collected up to 2000 Btu/hr. Therefore, use outside of that range involve extrapolation which is not advised. Concordantly, the variable MR_{max} was used where MR_{max}=max(*MR*,2000) where *MR* is in Btu/hr which prevents erroneous results associated with extrapolation.

Table 2. Metabolic rate challenges used to evaluate half-cycle time at cyclic steady-state.[9]

Simulated Metabolic Rate [BTU/hr]	CO_2 Production Rate [slm]	H_2O Production Rate [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

Figure 9 shows half-cycle and mean outlet dew point temperature results for various metabolic rates at a ventilation flow rate of 6 acfm at ambient pressure (14.7 psia). The half-cycle results show an exponential decay from X-Y minutes as metabolic rate increases which is expected for a material characterized with a Type III isotherm. The mean outlet dew point varied between X-Y°F. As previously mentioned, water breakthrough is fast meaning the dew point increases rapidly at lower metabolic rate. However, water production rates are higher in the middle of the metabolic rate. As a result, we see peak dew point temperatures were half-cycles are moderately high and water production rate peaks near 1000-1250 Btu/hr.

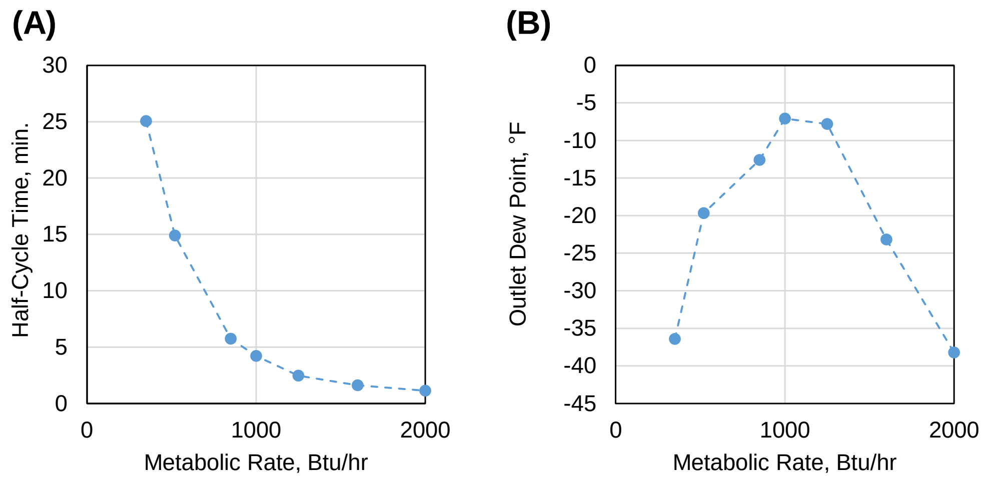

Figure 9. Multiple metabolic rate test at 6.0 acfm and 14.7 psia (ambient).

Similar results are shown in Figure 10 except the ventilation flow rate was varied. Since the overall carbon dioxide flow rate dictates how fast a bed can load, all of the half-cycle time results are essentially independent of ventilation loop flow rate. For a fixed CO_2 introduction rate, lower ventilation flow rates lead to increased CO_2 concentration. However, this is inconsequential as breakthrough is dictated by bed capacity (*i.e.*, the overall mass of sorbent within the bed). The dew point results should show a similar trend although more scatter is observed which could be associated with water condensation and re-evaporation during testing.

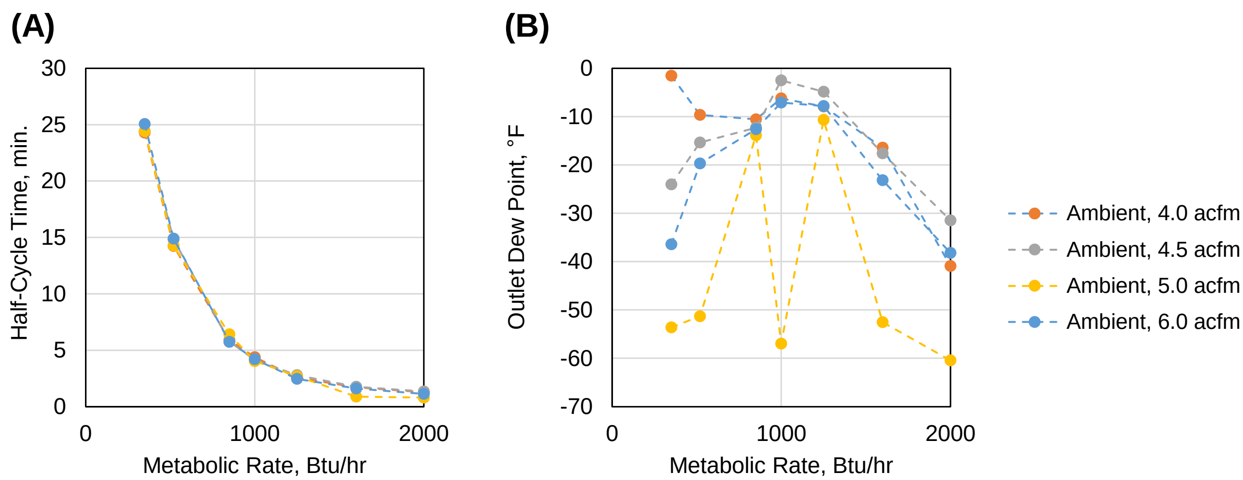

Figure 10. Multiple metabolic rate test at 14.7 psia (ambient) with various ventilation system flow rates.

Finally, the SBS was tested at both ambient pressure (14.7 psia) and at a sub-ambient condition (4.3 psia) for flow rates from 4-6 acfm. At reduced pressure, the gas density has been decreased by approximately 71% (one minus the ratio of 4.3 psia/14.7 psia multiplied by 100%). So even though volumetric flow rates were unchanged, the diluent gas mass flow rate is substantially less. Again, similar results are observed where half-cycle times and dew point temperatures do not substantially change since both factors are essentially governed by the total mass flow rates of CO_2 and H_2O which are set by the simulated metabolic rates.

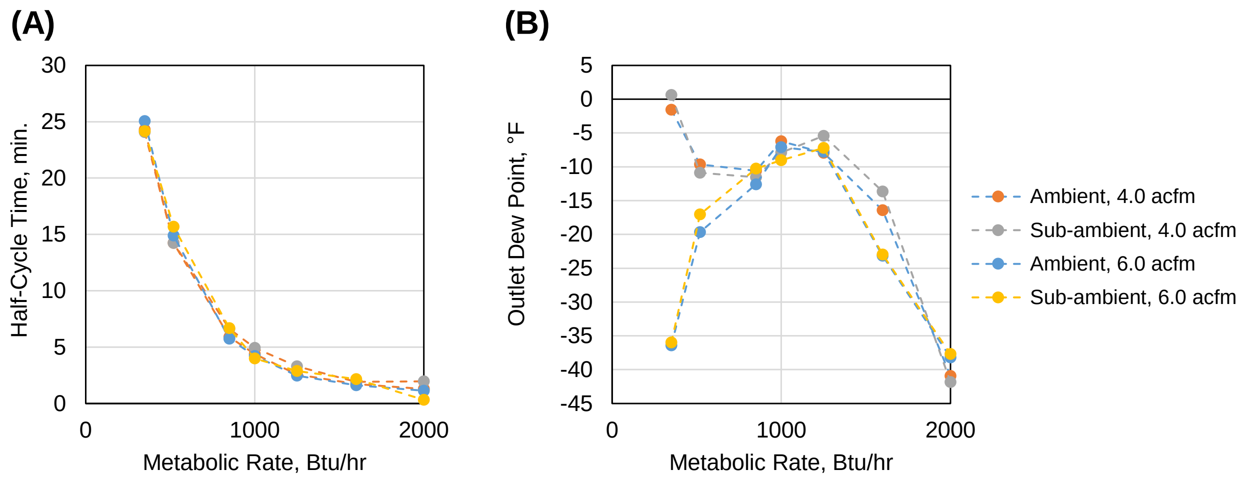

Figure 11. Multiple metabolic rate test at various ventilation system flow rates at 14.7 psia (ambient) and 4.3 psia (sub-ambient).

Finally, all previous results have focused on cyclic steady-state performance. However, EVAs never occur at a fixed metabolic rate and instead have portions of high activity followed by durations of prolonged sedentary behavior. During such transitions, metabolic rates vary leading to a non-constant CO_2 and H_2O challenge. A simulated variable metabolic challenge was imposed on the SBS to evaluate its ability to keep up with more realistic challenges. Table 3 provides the test variable metabolic rate challenge which involves a sequence of 12 step changes in metabolic rate from 273-2493 Btu/hr.

Table 3. Variable metabolic rate challenge for evaluating dynamic behavior of the SBS with an average metabolic rate of 1230 Btu/hr.

Seq. No.	Simulated Met Rate [BTU/hr]	Flow Rate [acfm]	CO_2 Flow Rate [slm]	H_2O Flow Rate [g/min]	System Pressure [psia]	Duration [min]
1	1025	6	0.793	1.39	14.7	30
2	1332	6	1.031	1.50	14.7	60
3	273	6	0.211	0.53	14.7	50
4	2493	6	1.929	1.25	14.7	15
5	1332	6	1.031	1.50	14.7	55
6	2049	6	1.586	1.25	14.7	30
7	1025	6	0.793	1.39	14.7	30
8	1332	6	1.031	1.50	14.7	60
9	2493	6	1.929	1.25	14.7	15
10	273	6	0.211	0.53	14.7	45
11	1332	6	1.031	1.50	14.7	70
12	1981	6	1.533	1.27	14.7	20

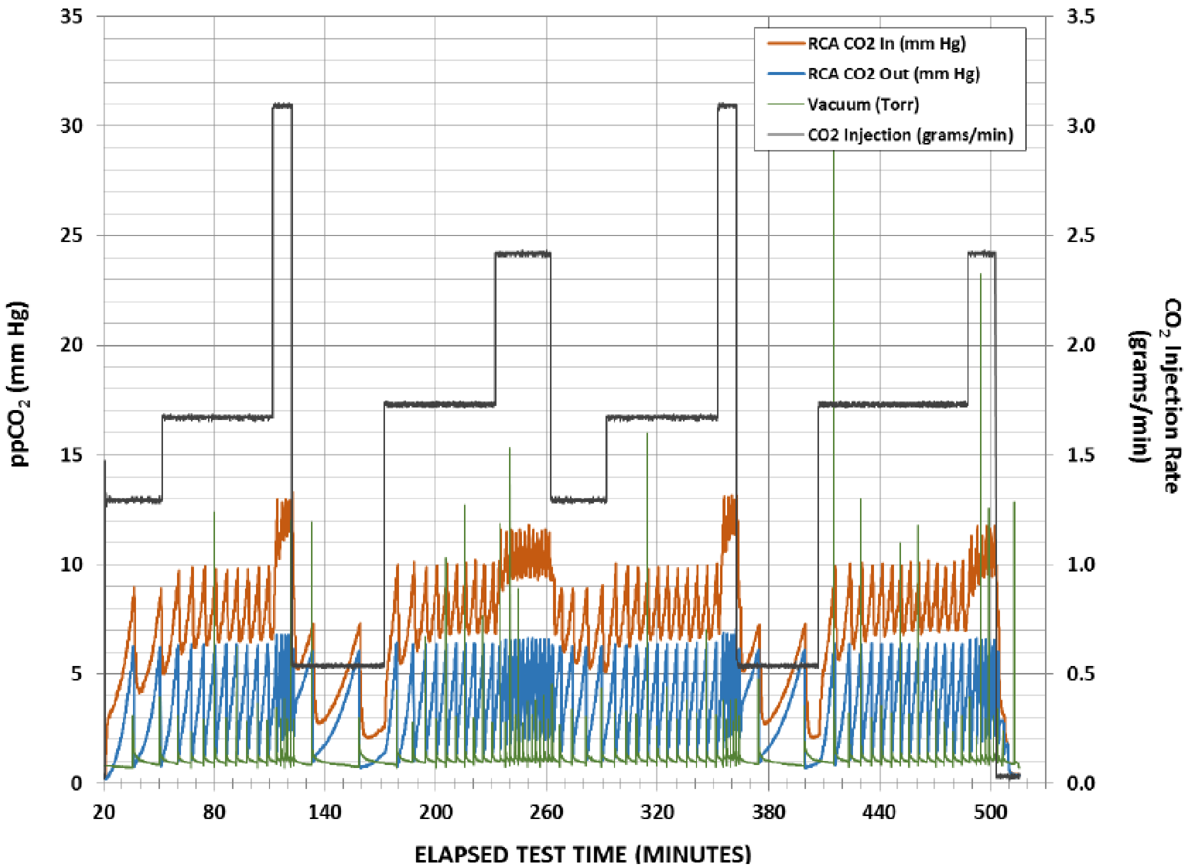

Figure 12. Variable metabolic rate challenge for the SBS.

Figure demonstrates the results for the variable metabolic rate challenge. The outlet c^y^cle threshold was set to 3.0 mm Hg of CO_2 which sets the maximum outlet concentration. The inlet concentration responds based on this cycling threshold. High metabolic activity decreases the half-cycle time while lower metabolic activity increases half-cycle time. Transitions from low to high metabolic activity lead to a transient decrease in half-cycle times until cyclic steady-state is achieved (and conversely, for transitions from high to low). Even though half-cycle is shorter for high metabolic activity, the high CO_2 generation rates lead to rapid accumulation in the suit volume simulator leading to higher overall CO_2 partial pressure into the RCA. In aggregate though, the SBS was able to keep up with the dynamic challenge which is an encouraging result with respect to application for an actual EVA.

VI. Comparison of Swing Bed Scrubber to Rapid Cycle Amine 3.0

(Placeholder test data and discussion follow in this section that do not represent actual SBS performance and will be replaced once actual data is collected – this section will be fully rewritten for the final version of this paper)

A. Development Goals and Observed Performance Comparison

Selected development goals and observed performance characteristics for the SBS and RCA 3.0 are shown in Table 4. The SBS and the RCA 3.0 units are at different stages of the development cycle and a direct comparison of all aspects of these two units is not recommended. The SBS unit is the first prototype representing its approach whereas the RCA development effort includes two development units prior to RCA 3.0 and lessons learned from the prior units were incorporated into the RCA 3.0 unit as resources allowed. Also, some of the RCA development information was available when the SBS unit was conceptualized. Some characteristics that were significantly driven by the magnitude of the prior development effort are not included here since this table is meant to compare some of the high level aspects of these two technologies.

Table 4. Development Goals and Observed Performance for the SBS and RCA 3.0

	SBS		RCA 3.0	
	Goal	**Actual**	**Goal**	**Actual**
TRL	6	☑	6	☑
Mass - kg (lbm)*	Minimize	6.35 (14)	< 10 (22)	6.38 (14.1)
Volume - liter (ft^3)	Minimize	9.7 (0.34)**	Minimize	11.3 (0.40)
Sorbent Volume per Bed - cm^3 (in^3)	N/A	775 (47.3)	N/A	788 (48.1)
Valve Design		Motorized linear spool valve		Motorized ball valve
Pressure Drop	1 in H_2O @ 6 ACFM, 4.3 psia	2.6 in H_2O @ 6 ACFM, 4.3 psia	2.5 in H_2O @ 6 ACFM, 4.3 psia	☑
Bed equalization during actuation	Required	☑	Required	☑
Valve actuation time	< 5 seconds	~2 seconds***	< 3 seconds	~3.5 seconds
Ullage Volume - liter (in^3)	Minimize	0.8 (48.8)****	Minimize	1.3 (79)

* Masses do not include controller, SBS mass includes hoses

** SBS volume does not include hoses as hose length will be packaging dependent

*** Bed equalization not evaluated to date

**** Ullage volume does not include hoses

B. Performance Comparison

NASA at Johnson Space Center and United Technologies Corporation Aerospace Systems (formerly, Hamilton Sundstrand), have spent many years developing a swing bed system that relies on a low-volatility amine absorbent coated on a porous substrate[14] referred to as the Rapid Cycle Amine (RCA). Concordantly, SBS test results are presented in the context of previous results generated with several prototypes of the two-bed Rapid Cycle Amine swingbed summarized elsewhere[9-11] with a comprehensive historical summary of development efforts recently presented.[2] The first generation of the Rapid Cycle Amine (RCA 1.0) had a sorbent volume of 715 cm^3per bed. The sorbent volume was increased for the second generation to 1050 cm^3 per bed for RCA 2.0 to attempt to meet more stringent CO_2 control requirements. Generation 3 (RCA 3.0) reduced the sorbent volume to 788 cm^3 per bed. The valving and flow manifolds/headers were also altered substantially between the three prototypes. In comparison, the volume of sorbent in the SBS is 775 cm^3 per bed and an amine-based sorbent similar to that within the RCA.

The pressure-flow characteristics for the swing bed are critical to PLSS design as it drives the ventilation fan specifications and, as a result, affects PLSS power requirements. The design point for the RCA is 2.5 inches H_2O at 6 acfm and 4.3 psia which is the anticipated nominal EVA suit pressure.[2] The results for pressure drop characteriziation are presented in Figure.

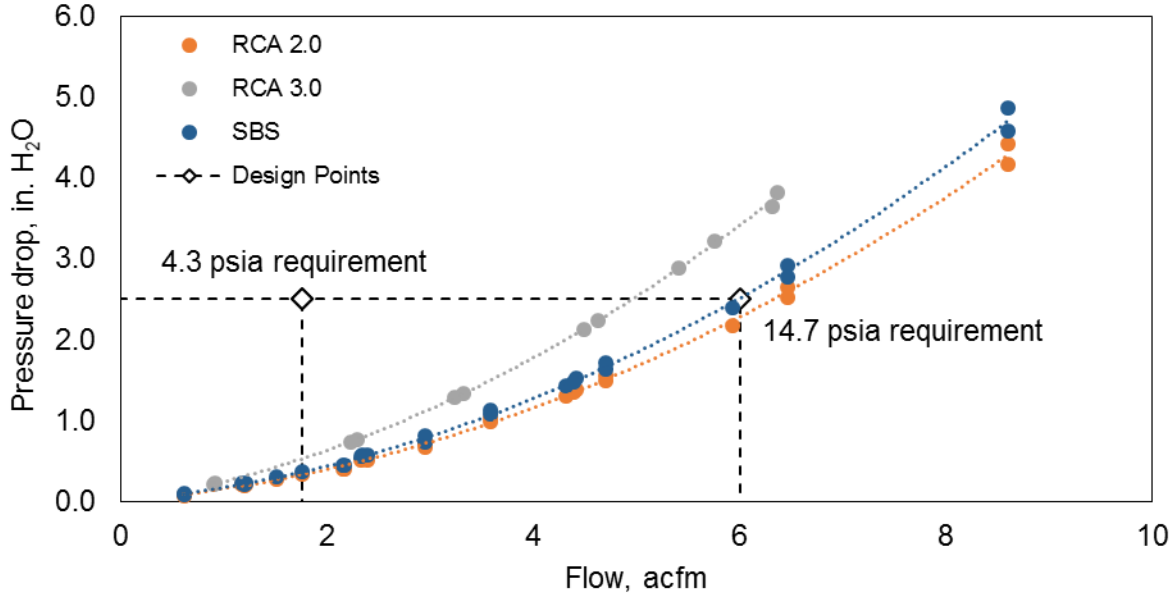

Figure 13. Pressure-flow characteristics for the SBS compared against previous RCA prototypes.

As demonstrated in Figure, the pressure-flow curves for RCA 2.0 and the SBS are very close to the pressure drop requirement at 14.7 psia with the SBS having a slightly higher/lower pressure drop. RCA 3.0 exceeds the pressure drop requirement at 14.7 psia though the pressure drop for all three swingbeds is well beneath the requirement set based on the EVA pressure of 4.3 psia.

Figure shows the half-cycle time as a function of metabolic rate for CO_2 partial pressure thresholds of (A) 6.0 mm Hg and (B) 3.0 mm Hg. The RCA half-cycle data presented here comes from United Technologies Corporation Aerospace Systems[15] testing while the SBS data was collected at Johnson Space Center. These data indicate, that as expected, half-cycle time is longer for the higher partial pressure threshold of 6.0 mm Hg. Moreover, it is clear from the figures that the SBS performs similarly to RCA 2.0. This was suspected given the similarities between the sorbents used as well as the comparable volumes of total sorbent.

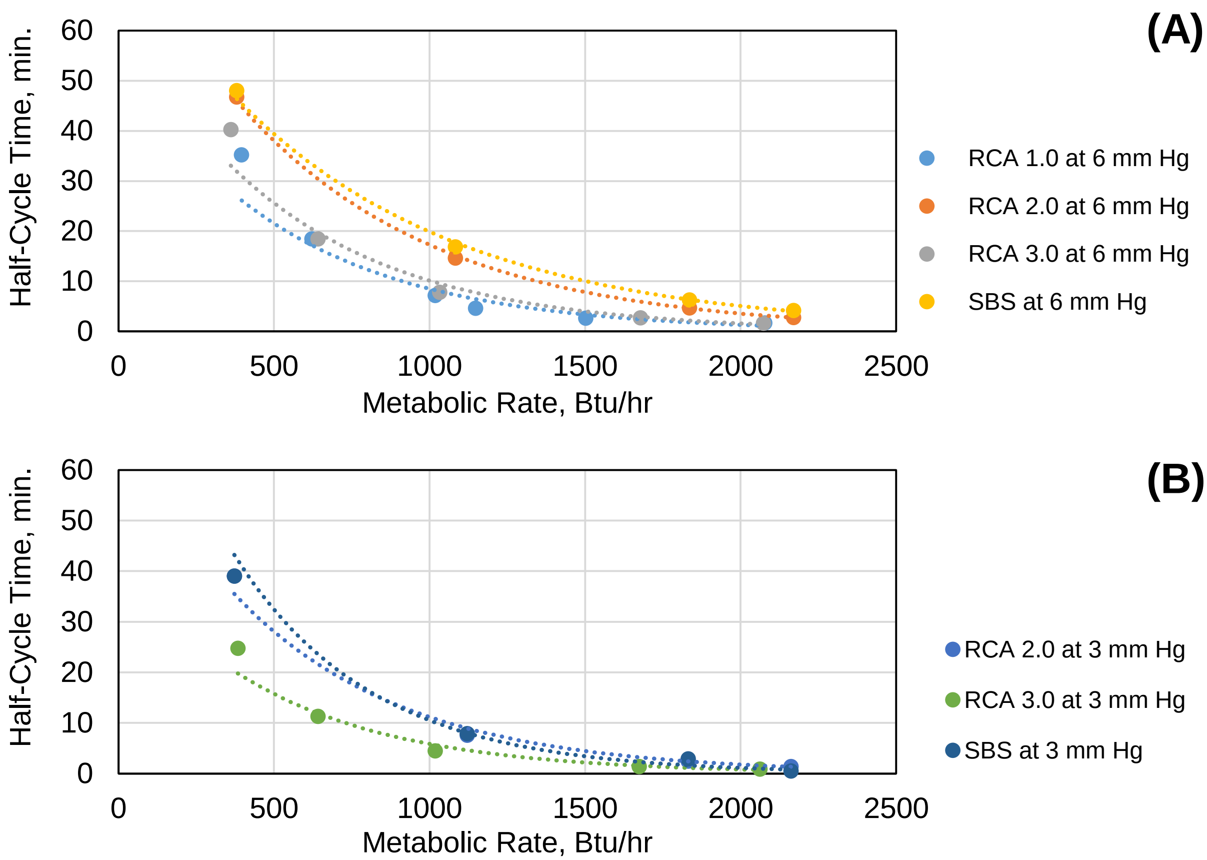

Figure 14. Half-cycle times as a function of metabolic rate and cycle threshold (A) for a cycle threshold of 6.0 mm Hg CO_2 and (B) for 3.0 mm Hg CO_2.

Figure 14 shows the half-cycle time at cyclic steady-state. In reality, the half-cycle time varies for several cycles before achieving a steady-state condition. In addition, actual EVAs involve transient metabolic activity as the crewmember performs various tasks with intermittent rest scattered throughout. Therefore, it is necessary to understand the transients associated with the swing bed. To evaluate these transients, a variable metabolic rate profile was generated as indicated in Table 3 3.

In previous testing at United Technologies Corporation Aerospace Systems[15], inlet and outlet relative humidity were found to vary linearly with the water input challenge normalized by the total sorbent mass. These data are compared to the SBS in Figure 15. As indicated in Figure SBS performance is commensurate with RCA 2.0 which had a higher overall band of humidity ranges encompassed across the range of water input rates normalized by sorbent mass.

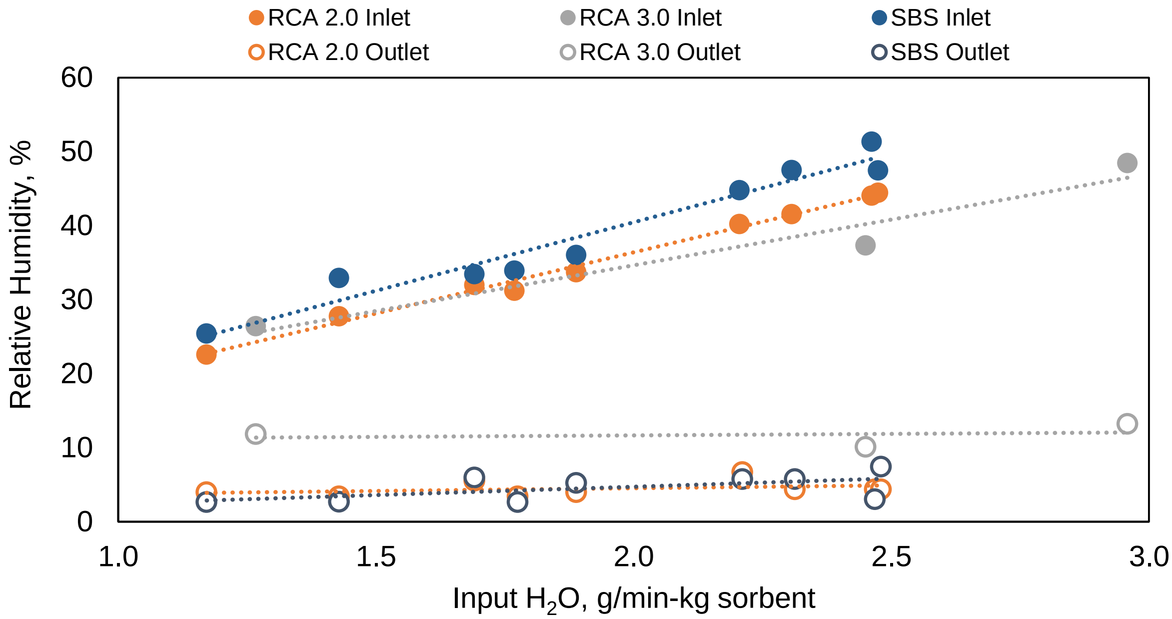

Figure 15. Inlet and outlet humidity as a function of water introduction rate normalized by sorbent mass.

These data in aggregate indicate the SBS performance is similar to other thermally-linked swing bed systems previously tested at Johnson Space Center. This is an encouraging collection of results for a first-of-a-kind alternative to the RCA technology.

VII. Conclusion and Future Work

The physical and performance characteristics of the SBS have been presented in this paper. This SBS technology is a potential CO_2 removal technology that could be used in the exploration PLSS being developed at JSC. Testing has been performed at JSC to evaluate the CO_2 and humidity removal performance of the SBS. The SBS test results have been presented and compared to the performance of the RCA 3.0 unit which is the CO_2 and humidity removal unit currently incorporated into the current exploration PLSS design. The results indicate… (testing is currently underway and results will be provided and discussed in the final version of this paper. This section of the paper will be updated after testing and included into the final version of this paper.)

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