Flow-Through and Closed-Loop Recirculating Swing Beds for Carbon Dioxide Adsorbent Evaluation Within a Rapid Cycle Amine System

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Advances in Rapid Cycle Amine (RCA) technology, utilized as the carbon dioxide and humidity control technology within the Extravehicular Mobility Unit (xEMU) spacesuit, require ground-level testing to facilitate system optimization, adsorbent selection, flight hardware certification, and RCA service-life viability for planned operational missions. XploSafe has developed a flow-through swing bed and a closed-loop recirculating swing bed to facilitate the required ground-level testing of these new RCA technologies. With a recent focus on regenerable materials to extend the Extravehicular Activity (EVA) duration, the flow-through swing bed is capable of both in-situ positive pressure and vacuum regeneration of adsorbents. The swing beds facilitate comprehensive testing of both subscale (~50–75 g) and operational-scale (>750 g) materials using a calibrated dosing source over time. Experimental parameters include CO_2 injection rates of 8 mmHg, flow rates up to 2 L/min, relative humidity of 50 percent (~11.1–14.8 °C dew point), and 2 min adsorption/desorption cycles for the flow-through swing bed. The closed-loop recirculating swing bed is capable of adjustment to flow rates (1–30.6 cfm), relative humidity levels (0–95 percent), adsorption/desorption swing cycles, bed size (> 1 kg of material), vacuum regeneration, adjustable injection rates, sub-atmospheric pressure (~4.3 psia), and adjustable system volume (~2 ft^3), representative of the xEMU. The closed-loop recirculating system enables sensing across two unique positions, simulating the monitoring of CO_2 and ammonia concentrations in both the spacesuit and the helmet. Additionally, data logging also includes real-time pressure differential across the beds, system flow rate, internal pressure, relative humidity, and temperature. The closed-loop recirculating bed also features a heat exchanger capable of maintaining ambient-, high-, and low-temperature conditions. Using both the flow-through and closed-loop recirculating swing beds, several materials, including Xplo-SA9T, MMPA-sorbent, and commercial soda lime material of similar sieved particle ranges, were screened and compared at 0.5–2 minute half-cycles.

Acronyms and Nomenclature

acfm	=	actual cubic feet per minute
ASTM	=	American Society for Testing and Materials
BTU	=	British Thermal Units
CAMRAS	=	CO_2 And Moisture Removal Amine Swing-bed
cfm	=	cubic feet per minute
CO_2	=	carbon dioxide
EVA	=	Extravehicular Activity
GUI	=	graphical user interface

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HUT	=	Hard Upper Torso
ISS	=	International Space Station
JSC	=	Johnson Space Center
kPa	=	kilopascal
METOX	=	metal-oxide
MMPA	=	methyl methacrylate tetraethylenepentamine
mm	=	millimeter
mmHg	=	millimeters of mercury, unit of pressure
NASA	=	National Aeronautics and Space Administration
N_2	=	nitrogen gas
NH_3	=	ammonia
O_2	=	oxygen gas
PID	=	proportional-integral-derivative
PLSS	=	Portable Life Support System
ppm	=	parts per million, unit of concentration
RCA	=	Rapid Cycle Amine
RH	=	relative humidity
SA9T	=	solid amine adsorbent (proprietary adsorbent)
SBIR	=	Small Business Innovation Research
SBS	=	Swing Bed Scrubber
T	=	temperature
SS	=	stainless steel
TD	=	thermal desorption
UHP	=	ultra-high purity
VTL2	=	Ventilation Test Loop 2.0
xEMU	=	Exploration Extravehicular Mobility Unit
Xplo-SA9T	=	XploSafe's proprietary solid amine adsorbent (SA9T variant)

I. Introduction

Advancement in RCA technology to facilitate full integration into the xEMU requires substantial testing across various metabolic profiles and test conditions. Material development for the preferred amine/adsorbent choice to replace the LiOH and METOX systems has continued to be an ongoing effort to both reduce mass and allow in-situ regeneration.[1–3] SA9T, originally developed by Hamilton Sundstrand, has been continuously tested as the preferred replacement choice, and various alternative options have been explored.[4] Beyond adsorbent material development, the adsorbent cartridge, or RCA unit, is a point of continued evolution.[5–7] Currently, RCA units 1.0 through 4.0 exist and have each featured numerous design improvements. RCA 3.0 has been tested at the component level, and the integrated xEMU PLSS level; however, the design advancements are limited to using requirements and assumptions based on the current limitations of the PLSS.[8] Initial swing bed scale testing of SA9T adsorbent occurred in 2006 with the CAMRAS system, where prior efforts mainly focused on open-loop and subscale testing.[9, 10] This system, designed for the ISS and operating at a flow rate of 10–26 cfm (283–736 L/min) has been tested with simulated metabolic loads of four to six people at atmospheric and sub-atmospheric conditions. The first launch of a CAMRAS system to the ISS occurred in January 2011 and has since completed over 1,000 hours of testing in space.[11] Post-2015, ground testing included SBS testing that was conducted at NASA Johnson Space Center within the VTL2 to compare directly to RCA 3.0.[12] With over 30 years of development on specific amine adsorbent technology, it is necessary to fabricate an xEMU condition-simulating swing bed to accommodate the testing of any newly synthesized SA9T alternatives as well as any commercially viable replacement options. Multiple metabolic profiles have been theorized, computed, and assessed, which require extensive experimental use case data collection, including swing bed testing, to ensure any new materials or prototype designs can be screened accordingly.[7, 13] Furthermore, these tests require hardware longevity tests, material degradation studies, temperature screening, environmental exposure tests, toxicological tests, and substantial software development.[14–19] In 2020, a helmet-HUT ANSYS model analysis along with the JSC Chief Medical Officer indicates that if the partial pressure of CO_2 is at or below 4.0 mmHg then the human duration of exposure can last an unlimited amount of time.[20] However, if the partial pressure of CO_2 is between 4–7 mmHg, a human should not be exposed for more than 7 hours.[20] With this information in mind, the development of swing bed

test equipment to further optimize CO_2 removal and humidity control is vital and allows the exploration of nominal and contingency scenarios.

II. Background

After initial testing of XploSafe-developed adsorbents for carbon dioxide removal, humidity control, and vacuum regeneration at a small scale (~60–110 mg), the need for larger RCA swing bed testing arose.[21] XploSafe carbon dioxide and humidity control adsorbents (Xplo-SA9T and MMPA-Sorbent) synthetic batch size was scaled to multiple kilograms (**Figure 1**, Xplo-SA9T), and xEMU viability testing followed. In a parallel effort, XploSafe previously fabricated several versions of a trace contaminant control test rig to explore vacuum-regenerable absorbents for TCC prototyping at the xEMU scale.[22, 23] This acquired knowledge was utilized to develop the swing bed test equipment. The first swing bed test rig was built to accommodate <100 g of adsorbent per bed and featured positive pressure regeneration capability only. The detailed custom software development, along with in-depth vetting and testing of commercial sensors, allowed the creation of a second, more advanced swing bed comprised of stainless steel components. This system is capable of vacuum regeneration and has the ability to continuously run and monitor bed output CO_2, NH_3, RH, and T at the output of each bed. This design, challenges, and evolution of these systems paved the way for further swing bed test rig designs and evolved the dual-purpose vacuum regeneration or positive pressure regeneration flow-through swing bed design detailed below. The following system was used to evaluate a metabolic

Figure 1. Multiple-kilogram bottled batch of Xplo-SA9T (600–1000 μm) for CO_2 and humidity control.

profile based on the respiratory quotient of 0.85 and a metabolic rate of 1650 BTU/h. These values consist of the generation of 1.17 kilograms of CO_2 and 0.73 kilograms of H_2O over an 8-hour EVA.

III. Equipment Design

To efficiently screen materials for carbon dioxide adsorption and humidity control, two unique test rigs are utilized to balance subscale regenerative testing and xEMU-simulating RCA scale testing. High-throughput and subscale bed design (<100 g per bed), Subscale Swing Bed (Swing Bed v3.0), can be accommodated by an open-loop test bed to monitor new and developing materials at realistic CO_2 and H_2O vapor dosing rates. The open-loop design, when regenerating with positive pressure as opposed to a vacuum, affords the ability to readily monitor CO_2 and RH at the regeneration flow path, further supporting the classification of the material as a regenerable adsorbent. The closed-loop design, RCA-Scale Swing Bed (Swing Bed v4.0), offers more realistic xEMU condition testing, including the ability to run at sub-atmospheric pressure and higher flow rates. The recirculating nature of the closed-loop design also benefits from running the beds at increased scale (~300–500 g per bed), and subsequently, more realistic metabolic profile dosing conditions can be tested while simultaneously affording simulations of both RCA bed outlet sensing and helmet inlet sensing.

1. Flow-Through Swing Bed Test Rig Design

The flow-through aspect of the Subscale Swing Bed was chosen to facilitate high-throughput testing without the requirement of large-scale synthetic batches of adsorbents. In this test rig, the non-thermally linked beds are ~128 mL internal volume each and made of aluminum with stainless steel fittings (**Figure 2**). These beds could be changed for size as needed by extending the length of the swing bed as necessary.

A traditional swing bed setup consists of a dual adsorbent bed system, a dosing system, a regeneration system, and an analyte sensing system. The design in **Figure 2** utilizes four different mass flow controllers to form a dosing system to deliver calibrated gas into the inlet of each bed. The mass flow controllers are calibrated within a range of $0-50$ mL/min for carbon dioxide (Dakota 6AGC1SL5-03CA), 0–1000 mL/min for the balance gas (Dakota 6AGC1SL5-07NC), 0–1000 mL/min for the humidity source (Dakota 6AGC1SL5-07NC), and 0–5000 mL/min (Dakota 6AGC1AL44-09AB2) for the optional positive pressure regeneration source. Humidity is generated by bubbling the carrier gas and metered via a mass flow controller into a washing bottle filled with water. All tubes connecting the mass flow controllers to the test rig are stainless steel and ¼" in diameter, along with all tubing
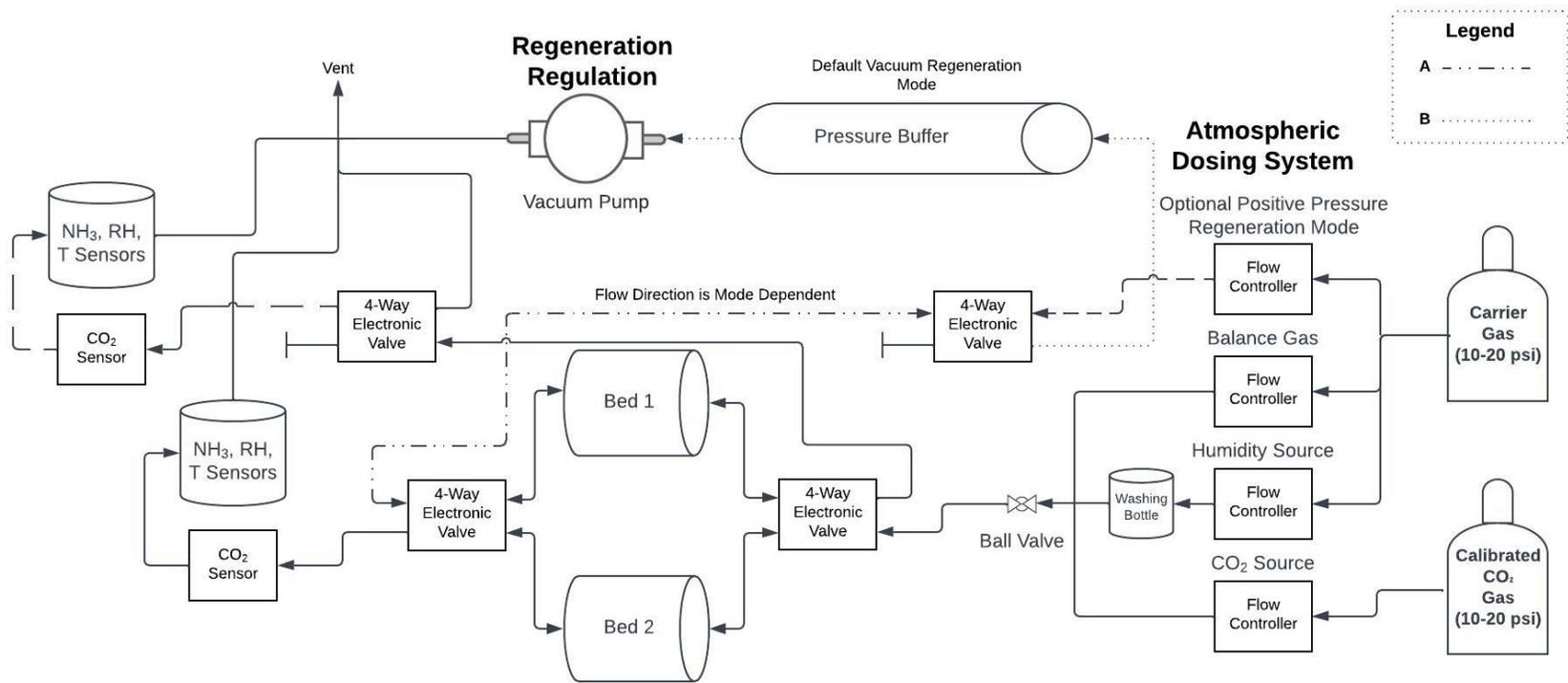
Figure 2.   Schematic of the flow-through swing bed offering vacuum or positive pressure regeneration.
Legend: A indicates flow direction can change depending on vacuum regeneration vs positive pressure regeneration; B indicates vacuum source line that is adjustable by the regeneration regulation source.

found within the test rig components, including the vacuum regeneration system. All tubing connecting the gas cylinders to their respective mass flow controllers and all exhaust vent tubing is polyethylene with stainless steel fittings.

The Subscale Swing Bed utilizes four electronic cross-valves (MAC 45A-AA1-DDBA-1BA) to direct the calibrated gas stream across the test rig in the correct direction. As one bed is active and flowing through to the sensor set, the other bed is regenerating. This operational control and data logging is facilitated by a microcontroller with XploSafe-developed software to afford variable half-cycle timing, regeneration modes, and detailed logging of all sensor output and control circuits. The microcontroller output to a computer is time-stamped and includes, for each bed, its status (active or undergoing regeneration), regeneration mode type, bed output carbon dioxide concentration, bed output ammonia concentration, bed output humidity, and bed output temperature.

When in the vacuum regeneration mode, the removed adsorbates are directed from the bed output of the bed undergoing regeneration to the vacuum source line. The vacuum source line uses a pressure buffer chamber that is approximately two times the bed volume to compensate for slower-pumping speeds through the ¼" lines and affords greater stability. The vacuum source is controlled via two sub-atmospheric GO regulators (SPR-1A11AHA111 and SBPR-1E11K5A111) connected to an Edwards RV3 vacuum pump. A setpoint of 1 torr was used for vacuum regeneration. Subscale Swing Bed (**Figure 3**) features two Telaire T6615-50KF dual-channel flow-cell carbon dioxide sensors, two Sensirion SHT75 temperature and humidity sensors, and two SEN0469 Gravity ammonia sensors. The second set of sensors was utilized if the optional positive pressure regeneration mode was selected. During this operational mode, the fourth mass flow controller directs the carrier gas of choice across the beds while they are undergoing regeneration instead of a supplied vacuum source. The carrier gas pushes any adsorbate out of the bed inlet and across the 2nd sensor set, where it can be monitored.
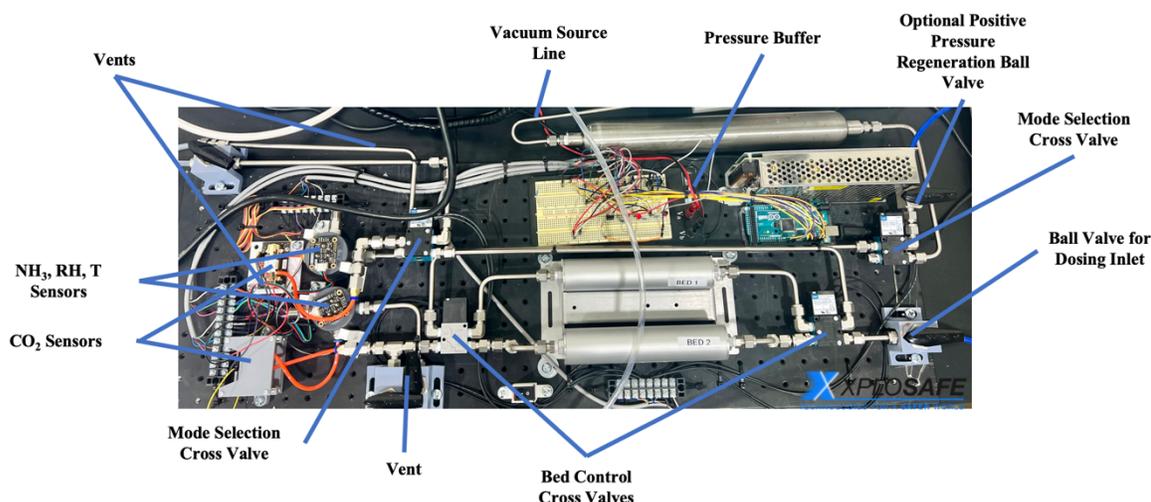
Figure 3.   Subscale Swing Bed (Swing Bed v3.0) with a flow-through design (top view).

2.   Closed-Loop Recirculating Swing Bed Test Rig Design

Next, a closed-loop test rig was designed to accommodate adsorbent screening at the current xEMU RCA scale. The RCA-Scale Swing Bed schematic is shown in **Figure 4**. The entire system (**Figures 5–6**) is constructed using stainless steel tubes and SS KF-25 fittings, except for the bed spacers within each bed and the sensors and their mounts. The entire system volume is ~2 ft^3 (~0.0566 m^3) to simulate the approximate suit/vent loop volume, accomplished by the loop and three SS tanks. The system utilizes two isolated vacuum systems, one for regeneration and one for sub-atmospheric control. The sub-atmospheric control is accomplished with an Alcatel 2012A vacuum pump and two sub-atmospheric GO regulators (SPR-1A11AHA111 and SBPR-1E11K5A111) set to 4.3 psia (~30 kPa). If the system falls below the desired pressure, the system is refilled through the sub-atmospheric regulator via a zero-grade air cylinder with flow regulated through a Swagelok SS-20VS4 valve. The regeneration vacuum source is controlled by an Edwards nXDS10Ci scroll pump. The two vacuum sources are monitored by ConvecTech CVT-275-101 convection gauges with a Granville-Phillips 316 vacuum gauge controller.
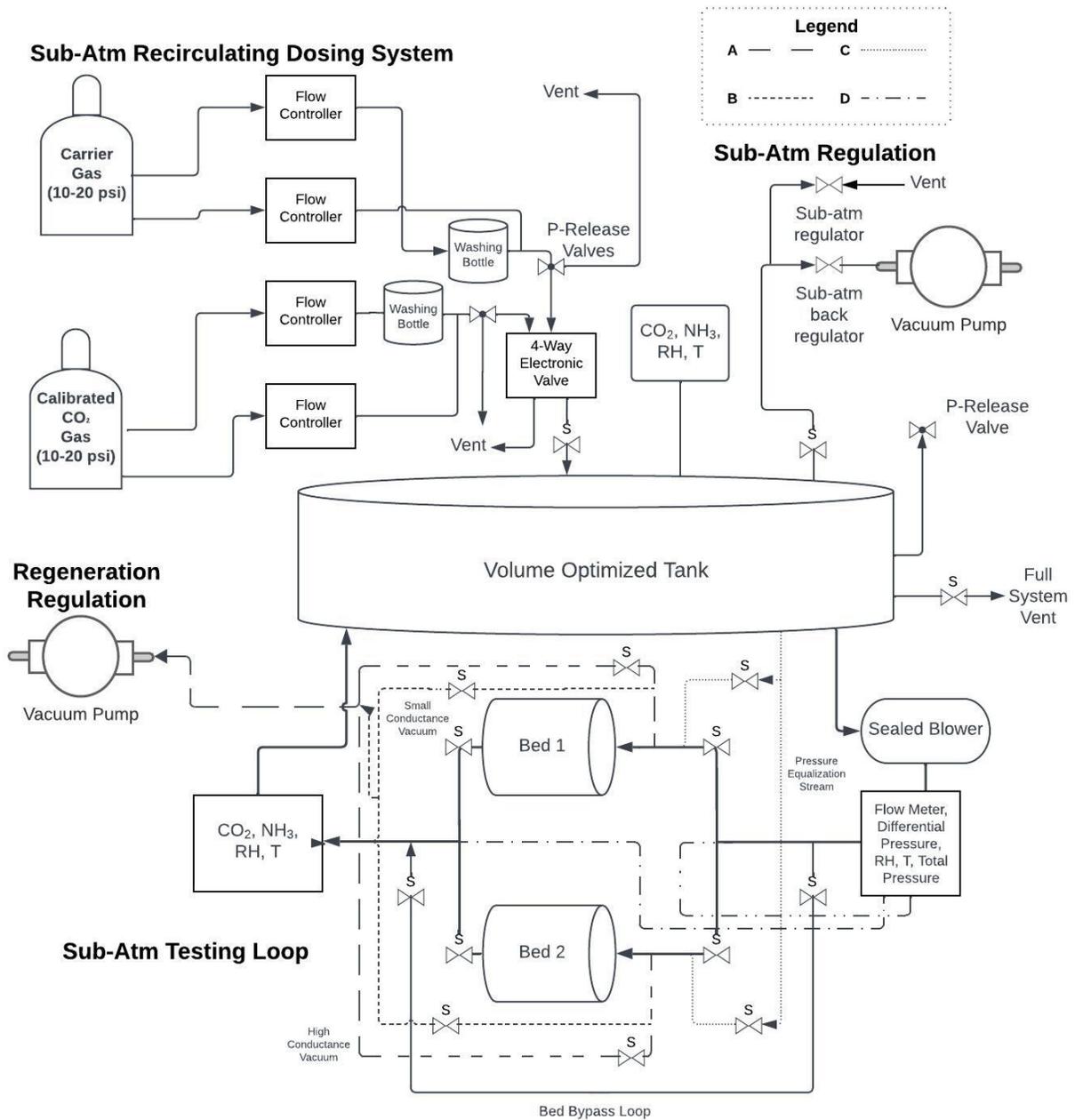
Figure 4. Schematic of the closed-loop recirculating RCA-Scale Swing Bed.
Legend: A illustrates high conductance, and B illustrates low conductance vacuum routing; C illustrates the repressurization stream that connects to the system; D illustrates the differential pressure monitoring locations.

A. *Valves, Solenoids, and Flow Control*

The regeneration vacuum source offers both high and low-conductance vacuum paths. The low conductance vacuum path is routed through ¼" (6.35 mm) SS tubing and controlled by two Gem B3316-S62 solenoid valves with a 1/8" × 5/64" (3.175 × 1.984 mm) orifice per adsorbent bed. Thus, this system provides a much higher conductivity channel between the bed and the regeneration pump. The high-conductance vacuum is routed through KF-25 convoluted SS tubing and controlled by two Ideal Vacuum Super-Seal KF-25 right-angle pneumatic valves (P103979).

The directional control system for flow between beds also utilizes four Ideal Vacuum Super-Seal KF-25 right-angle pneumatic valves (P103979). The bypass loop was integrated into the design to allow the system to pre-humidify and reach sub-atmospheric pressure within the recirculating system without affecting the adsorbent beds. The bypass loop is controlled by one Ideal Vacuum Super-Seal KF-25 in-line pneumatic valve (P105354) and one Kurt Lesker equivalent (SY0100PVQF). The pneumatics are controlled by five Fonray 4V210-08-FDC24V pneumatic valves utilizing ¼" polyethylene tubing. The air supply for the pneumatics is generated via a California Air Tools 15020C air compressor. The RCA-Scale Swing Bed also incorporates five additional Gem B3316-S62 solenoid valves with a 1/8" × 5/64" orifice to refill each adsorbent bed during swing cycles (refills from the closed-loop tank set), sub-atmospheric control, system vent control, and dosing control. All of these five valves are connected with ¼" SS tubing. The test rig affords programmable flow rates via a Micronel radial sealed blower (U100HL-024KA-4), and the system temperature is controlled with a retrofitted SS heat exchanger (365052665702) connected to a Fisher Scientific Isotemp 3031P chiller. Each bed is comprised of one Kurt Lesker QF160-600-N nipple, two Kurt Lesker centering rings (QF160-SAVR), two Ideal Vacuum ISO160-K to KF-25 reducers (P108751), and the required clamps (Ideal Vacuum P104067). Both the bed outlet sensor flow cell connection location and the helmet simulating final sensor flow cell connection location are controlled by four manual ¼" Swagelok ball valves (SS-43GS4) that allow for up to two sets of sensors to be tested while the system operates. Two sets of calibrated mass flow controllers are utilized for dosing. The first set was previously utilized to dose the Subscale Swing Bed and is used to pre-humidify the RCA-Scale Swing Bed without CO_2. The second set uses two calibrated CO_2 mass flow controllers to deliver a preferred metabolic profile where one mass flow controller, 0–10 mL/min (Dakota 6AGC1SL5-01CA), delivers humidity by bubbling CO_2 gas, which exits the mass flow controller into a washing bottle filled with water and then routes back into the dosing stream. The second CO_2 mass flow controller has a flow rate range of 0–2000 mL/min (Dakota 6AGC1SL5-08CA) that delivers the remaining known carbon dioxide source rate. Both of these mass flow controllers can be exchanged with the preferred calibrated mass flow controller range to deliver higher or lower metabolic rate profiles as needed. All of the RCA-Scale Swing Bed components can be observed in the labeled **Figures 5 and 6**.
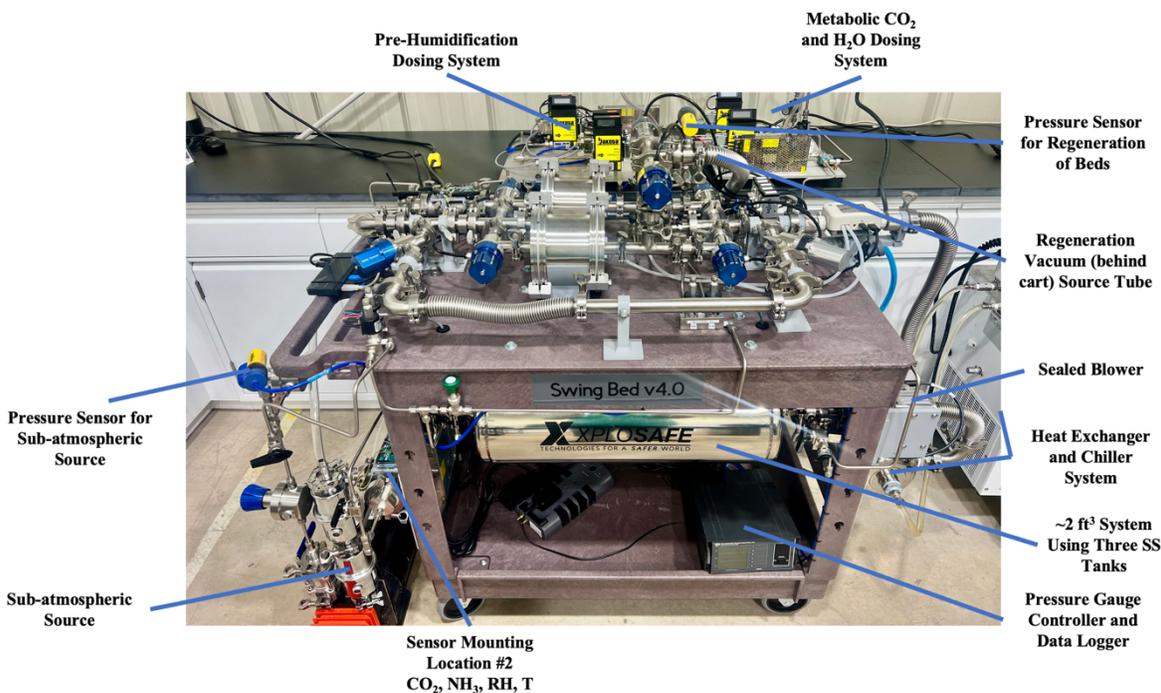

Figure 5.   RCA-Scale Swing Bed (Swing Bed v4.0) with a closed-loop recirculating design (front view).
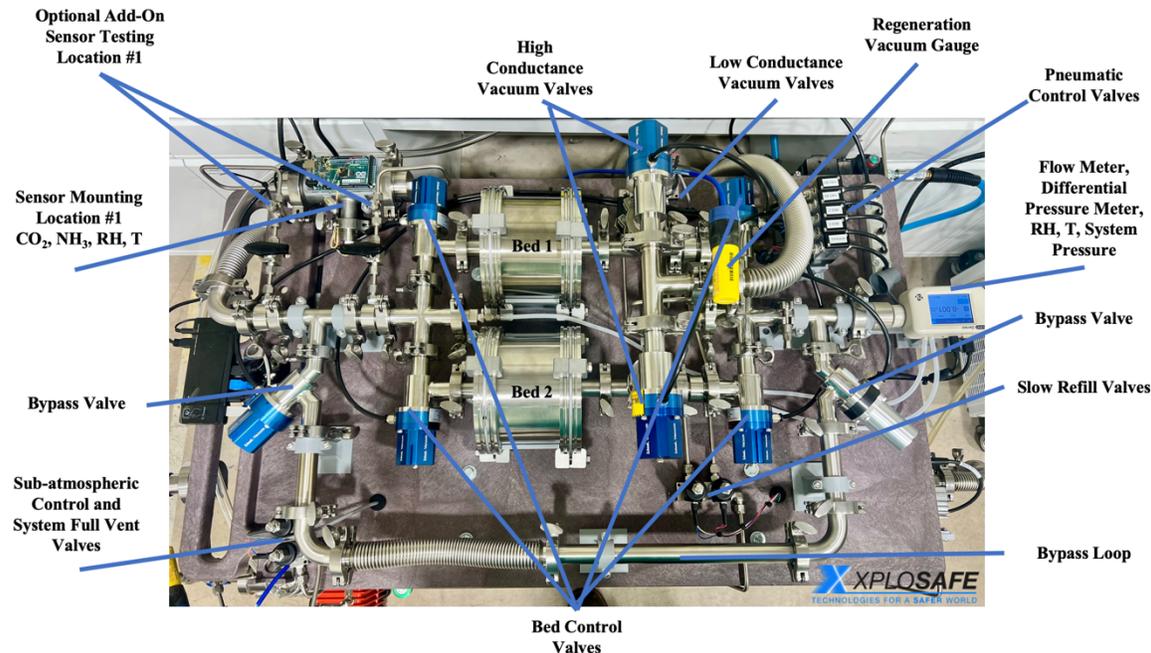
Figure 6. RCA-Scale Swing Bed (top view).

B. Adsorbent Bed Housing and Internal Configurations

The RCA-Scale Swing Bed test rig utilizes large ISO160-K SS beds to accommodate multiple adsorbent cartridge configurations and adsorbent quantities; however, any RCA prototype bed can be fitted in this position with appropriate KF-25 adapters, including thermally linked designs. The adaptability of KF-25 flanges in the design allows different adsorbent cartridge holders and bed sizes to be explored. **Figure 7, A** displays the design utilized for the experiments within this manuscript and a SolidWorks 2019 flow simulation at 6 acfm (~170 L/min), 4.3 psia (~30 kPa), and 25ºC with air velocity across the y-axis. The flow simulation suggests adequate flow across enough of the packed adsorbent area for material screening. The design contains two bed spacers that are 3D printed from ABS using FDM that are fitted with 80 Mesh SS screens that are affixed with Loctite Aero EA 9321 epoxy. These spacers allow the ~1992 mL internal volume of the beds to be reduced down to any desired sorbent volume; for example, 788 mL for RCA 3.0 or 1050 mL for RCA 2.0.[5] For the experiments below, two bed spacers were chosen with an internal adsorbent volume of ~948 mL to match with known and ongoing RCA designs by commercial space suit vendors. The use of SS mesh affixed to the spacers allows all contact points of the adsorbent material to be stainless steel, preventing any direct contact with the ABS 3D-printed material. At the inlet and outlet of each bed is one 210 μm KF-25 SS mesh screen to protect the test rig in the event of any adsorbent escape due to housing failure. **Figure 7, B** illustrates the flexibility of the swing bed to accommodate different filter modules. This alternative design introduces a gas stream from the center of the filter to potentially increase the residence time across the adsorbent, which may potentially increase the adsorption rate and efficiency of carbon dioxide removal.
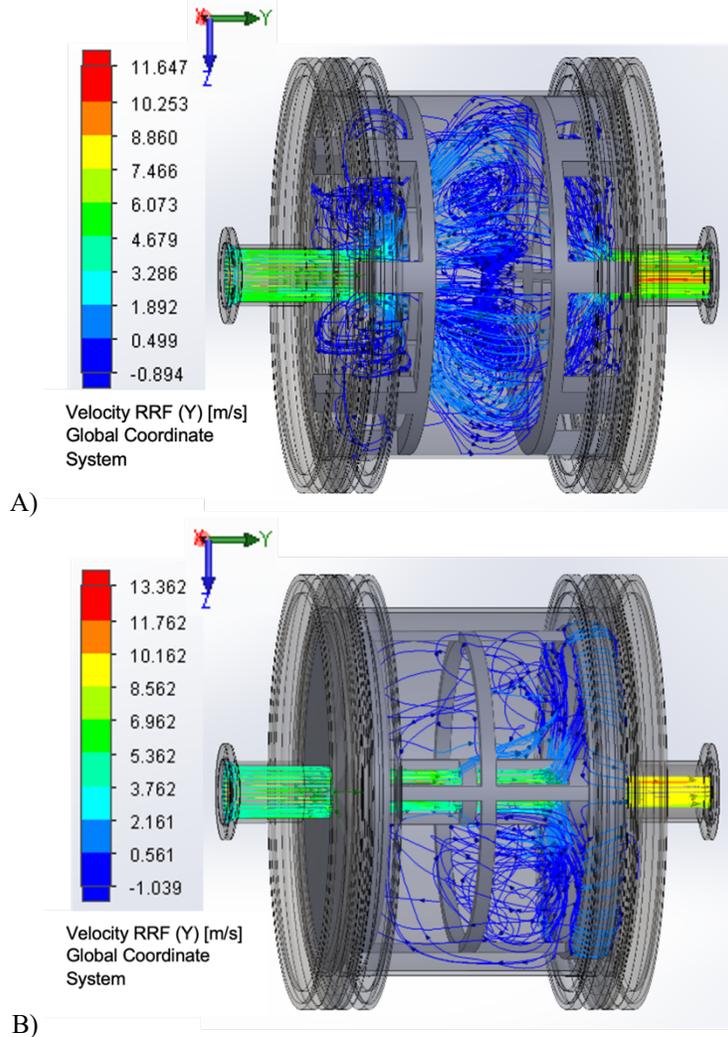
Figure 7. Flow simulations of internal adsorbent cartridge types within the SS ISO160-K housing. Design A uses a set of bed spacers to accommodate specific direct bed volume sizes, and design B employs a removable adsorbent cartridge with an outward flow from the center to potentially increase residence time across the adsorbent material.

C. Sensors

The CO_2, NH_3, RH, and T sensors are housed within specific sections of the RCA-Scale Swing Bed and are used to continuously measure concentrations within the system. One set is mounted in a flow cell that diverts the gas stream for sampling at the output of the adsorbent beds. The second flow cell samples between the second and third SS tanks to simulate the helmet location. The CO_2 sensors within the RCA-Scale Swing bed, as observed in **Figure 8,** are diffusion-based (Telaire T6615-50K) instead of a flow cell type found within the Subscale Swing Bed. The temperature and humidity sensors utilized are Sensirion SHT85. The ammonia sensors are identical to the Subscale Swing Bed (SEN0469 Gravity). The sensors, unlike the Subscale Swing Bed, are mounted within a KF-50–KF-25–KF-50 tee on an FMD-printed ABS holder (**Figure 8**). The wiring is routed through a feedthrough on the KF-25 tee port. This tee eliminates additional plumbing and allows the sensors to be contained fully within the flow cell gas stream, thus reducing the possibility of system leaks.

Figure 8. RCA-Scale Swing Bed flow-cell sensor assemblies. Two are mounted within the test rig.

Beyond the two flow cells to measure CO_2, NH_3, RH, and T (**Figure 8**) at the bed outlet and simulated helmet inlet, a TSI 531002 flow meter is fitted on the inlet side of the beds (**Figure 6**). This flow meter measures RH, T, system pressure, flow rate, and differential pressure. The flow meter is connected for differential pressure across the main tee on each side of the bed to read pressure deltas across an actively flowing bed (**Figure 6**). This meter also allows the measurement of both temperature and relative humidity pre- and post-bed. The operational control of RCA-Scale Swing Bed and data logging is facilitated by XploSafe-developed software GUI that manages three microcontrollers. The software enables variable half-cycle timing, run modes, and experimental conditions. One microcontroller is dedicated to each sensor set at bed output and helmet inlet. The third contains analog-to-digital controls, a high-precision digital-to-analog converter and tachometer for controlling the blower, and the drivers for the various valves. The single computer controls all pneumatic valve and solenoid activity and collects the carbon dioxide concentration, ammonia concentration, humidity, and temperature at both the bed and helmet locations. The computer also logs differential pressure across the active bed, flow rate, system pressure, bed inlet humidity, bed inlet temperature, regeneration vacuum pressure, and sub-atmospheric vacuum pressure from the TSI flow meter. The blower speed, blower temperature, and swing cycle counter are also logged. Finally, the software is tolerant of any loss of communication or sensor failure if it were to occur during operation. The system has variable data logging frequency and has been tested at five-second logging intervals where the only restriction for faster logging is the sensor sampling/update rate. The software utilizes several different timer threads to ensure uninterrupted flow between beds and consistent logging times. The system has been evaluated to log up to four data points per second, logging any stimulation of any valve, solenoid, or controller.

IV. Results and Discussion

A. Flow-Through Test Rig: Subscale Swing Bed

The setup on the Subscale Swing Bed consists of three blanks that were run at a pre-specified humidity and known CO_2 dosing concentration. The blanks allow for full system operational tests as well as ensure the sensors are within the manufacturer's listed accuracy of the calibrated dosing rates. The carrier gas utilized was UHP nitrogen (99.999 percent) to supply the humidity source and balance gas with a maximum allowable impurity concentration of 1 ppm O_2, 1 ppm H_2O, 0.5 ppm total hydrocarbons, 1 ppm CO, and 1 ppm CO_2. The carbon dioxide source was a calibrated gas cylinder (99.99 percent) with a maximum allowable impurity concentration of 10 ppm H_2O, 10 ppm total hydrocarbons, 70 ppm N_2, and 20 ppm O_2. The adsorbent materials were not pretreated and were loaded directly within the adsorbent beds with glass wool at each end to ensure minimal, if any, bead movement at a flow rate of 2 L/min. The comparison between Xplo-SA9T and MMPA-Sorbent during a simulated 8-hour EVA using the Subscale Swing Bed can be observed in **Figure 9**.
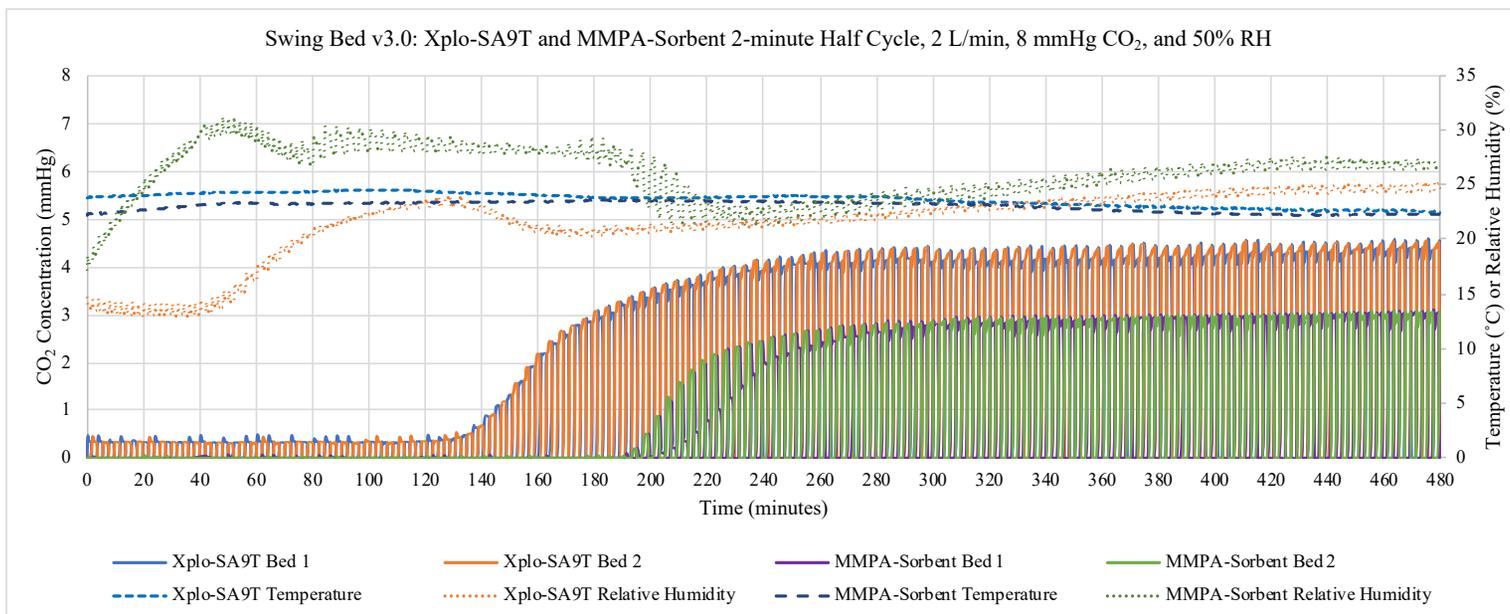
Figure 9. Subscale Swing Bed (Swing Bed v3.0) CO₂, RH, and T measurements with Xplo-SA9T and MMPA-Sorbent as a function of time.
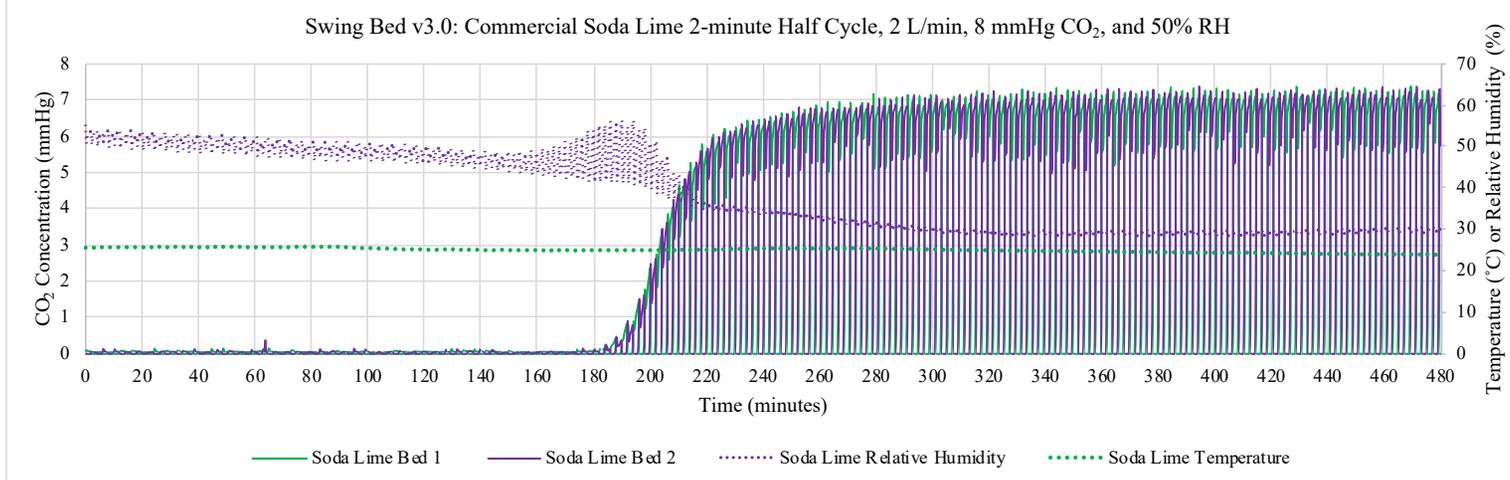

Figure 10. Subscale Swing Bed (Swing Bed v3.0) CO₂, RH, and T measurements for Soda Lime as a function of time.
(note the change in relative humidity scale compared to Figure 9 due to the lack of initial humidity control by commercial soda lime)

Both Xplo-SA9T and MMPA-Sorbent were sieved between 600–1000 µm, and the dosing rate of 50 percent relative humidity and 8 mmHg CO_2 were held consistent between experiments. Bed volume remained consistent between materials, and accordingly, an average mass of adsorbent per bed was measured (Xplo-SA9T: 64.76 g and MMPA-Sorbent: 60.79 g). In this experiment, vacuum regeneration was chosen as the running mode, where the vacuum source was set at 1 torr (0.133 kPa). In using the manufacturer's CO_2 sensor accuracy of 10 percent of the measured value, the time required to hit the NASA helmet limit was determined for each material as a range. Xplo-SA9T hit the 2.2 mmHg helmet limit after 176–196 minutes, and MMPA-Sorbent hit the limit after 218–238 minutes. The average dew point exiting the bed (temperature corrected) was 2.6ºC for Xplo-SA9T and 1.5ºC for MMPA-Sorbent. The average temperature across the 8-hour EVA was 23.1ºC for Xplo-SA9T vs 21.6ºC for MMPA-Sorbent. The CO_2 steady state, as observed within the graph (**Figure 9**), was significantly lower with MMPA-Sorbent than Xplo-SA9T, consistent with the previous breakthrough capacity tests.[21]

Further testing with commercial soda lime (Sodasorb 6/12 IND H: calcium hydroxide, potassium hydroxide, and sodium hydroxide) was conducted where the material was first mechanically broken apart and sieved to match the same particle size range of 600–1000 µm then an average of 60.3 g was loaded per bed. The material was run under the same conditions: 2-minute half-cycle, 2 L/min, 8 mmHg CO_2, and 50 percent RH to compare directly, even though soda lime is non-regenerable. The soda lime material hit the 2.2 mmHg helmet limit after 199–200 minutes. The average dew point exiting the bed (temperature corrected) was 6.5ºC, and the average temperature was 24.4ºC. Once the helmet limit was hit, the material continued to break through (**Figure 10**) at a constant rate until the bed outlet CO_2 concentration matched the inlet dosing concentration at ~315 minutes, and no further detectable adsorption occurred.

A comparison image of all three materials (Xplo-SA9T, MMPA-Sorbent, and commercial soda lime) is included in **Figure 11** utilizing an AmScope T390B biological trinocular compound microscope and AmScope MU300 3.1 megapixel camera. A 1 ± 0.01 mm Microyn calibration slide was used as a reference, illustrating all three materials are between 600 and 1000 µm. This size constraint limits the experimental variability and affords equal pressure drop between all adsorbents.
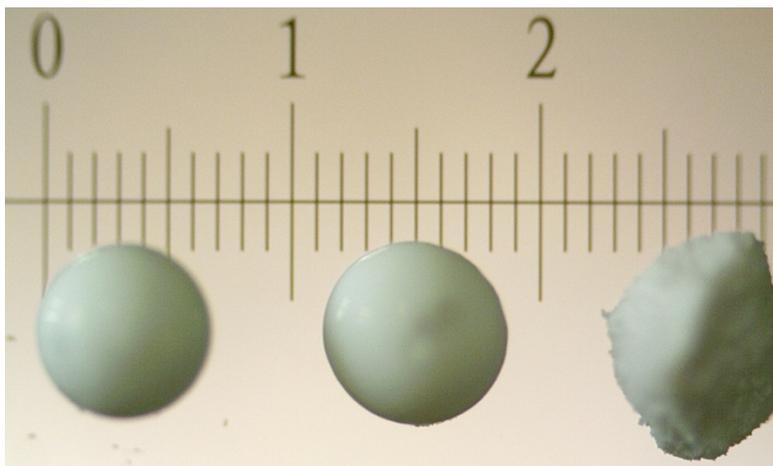

Figure 11.   Microscope image comparing Xplo-SA9T (left), MMPA-Sorbent (middle), and commercial soda lime (right). A 1 ± 0.01 mm scale was used as a reference.

B. Closed-loop Reicirculating Test Rig: RCA-Scale Swing Bed

An initial test of the RCA-Scale Swing Bed was conducted to test for any leaks; the system was brought to sub-atmospheric pressure of 4.3 psia (~30 kPa) and a flow rate of 6 acfm (~170 L/min), maintained, and PID-controlled with the XploSafe-developed GUI software. The system was isolated from the sub-atmospheric source, and it held system pressure for the normal 8-hour EVA. A system blank was run where the swing bed spacers were installed, the pressure was set to 4.3 psia (~30 Pa), and the swing cycle was started and run for a full 24 hours. This resulted in a baseline performance data set of pressure drop across the unfilled adsorbent beds for times exceeding the 8-hour EVA requirement. System dosing was verified by installing a 0–2000 mL/min calibrated mass flow meter (Dakota 6AGM1SL5-08NC) in line between the metabolic profile dosing rig and the swing bed while actively dosing the RCA-

Scale Swing Bed with 2.44 g/min CO_2 at 4.3 psia (~30 kPa) pressure. The metabolic dosing profile was based on the respiratory quotient of 0.85 and a metabolic rate of 1650 BTU/h, while injecting 2.44 g/min CO_2 and 1.51 g/min H_2O vapor. Currently, the system is set to switch beds based on half-cycle time and not by concentration. Two experiments were run where Xplo-SA9T sieved between 600 and 1000 μm was exposed to constant 2.44 g/min CO_2 (same source used in the Subscale Swing Bed) and 1.51 g/min H_2O (carrier gas switched to Zero-Grade Air, 78–80 percent N_2, 20–22 percent O_2, and a maximum allowable impurity concentration of 2 ppm H_2O, 0.1 ppm total hydrocarbons, 1 ppm CO_2, 1 ppm CO). One experiment was set at a 1-minute half-cycle, whereas the other used a 0.5-minute half-cycle. The Xplo-SA9T material loaded within the ~948 mL internal cavity had an average mass of 423.6 g. This material was previously tested within RCA-Scale Swing Bed for five additional experiments not included in this manuscript, displaying excellent reuse capability. To pre-condition the material, each bed was evacuated for 10–30 minutes to reach the same starting vacuum threshold of ~0.333 torr (44 Pa). During this pre-conditioning time, the test rig was brought to 4.3 psia (~30 kPa) and pre-humidified using a dosing stream of ~80 percent RH and a dosing rate of 1.356 L/min. The system reached a maximum of ~ 24.5 percent RH at ~25°C before the runs were started. The system temperature was maintained at 25°C throughout the 8-hour EVA tests. The results can be observed in **Figure 12**, wherein, in each half-cycle test case, a steady state was reached for the target dosing metabolic profile.
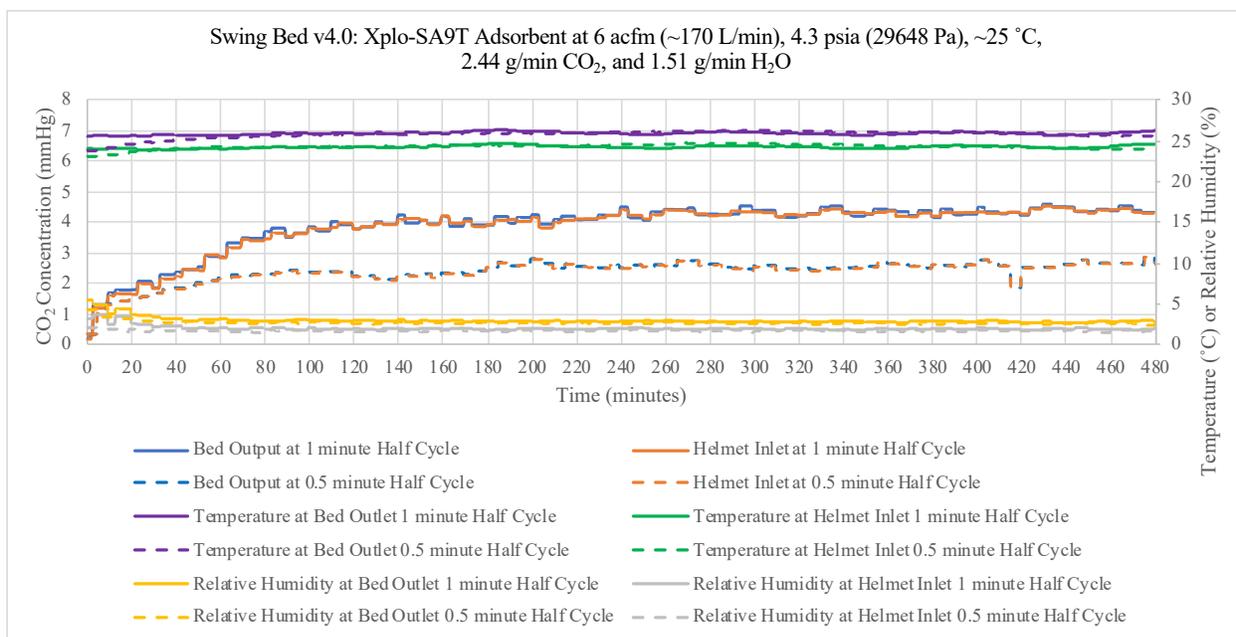
Figure 12. RCA-Scale Swing Bed (Swing Bed v4.0) CO_2, RH, and T measurements with Xplo-SA9T as a function of time.

The data suggest an average helmet inlet CO_2 concentration of 3.89 ± 0.39 mmHg for the 1-minute half cycle and an average of 2.37 ± 0.24 mmHg for the 0.5-minute half cycle across the 8-hour EVA simulation. A maximum helmet inlet CO_2 concentration spike of 4.54 ± 0.45 mmHg for the 1-minute half cycle and a maximum of 2.86 ± 0.29 mmHg for the 0.5-minute half cycle across the 8-hour EVA simulation were observed. All of these results are without residence time or bed optimization, which is beyond the scope of this manuscript. This testing is meant to serve as a base comparison between materials that can be easily expanded for high-throughput testing at the RCA scale. All reported statistical deviations reflect the analytical uncertainty based on equipment specifications as reported by the corresponding equipment manufacturer.

During the 8-hour blank run (no adsorbent), an average pressure differential across the system beds was recorded at 3.14 ± 0.06 inH$_2$O (7.98 ± 0.15 cmH$_2$O), attributed mostly to the 210 μm KF-25 mesh screens at each end of the beds. After the pressure drop correction from the blank run, the average pressure differential across Xplo-SA9T sieved 600–1000 μm during the 1-minute half-cycle was 2.57 ± 0.06 inH$_2$O (6.53 ± 0.15 cmH$_2$O) and 2.04 ± 0.06 inH$_2$O (5.18 ± 0.15 cmH$_2$O) during the 0.5-minute half-cycle. Neither the ammonia sensor at the bed output nor the helmet inlet sensor detected ammonia during the 8-hour EVA simulations, with the limit of detection of each ammonia sensor being at least 1 ppm. The average system pressures during the EVA experiments were 4.61 ± 0.15 psia (~31.8 ± 1.03

kPa) for the 1-minute half-cycle and 4.23 ± 0.15 psia (~29.2 ± 1.03 kPa) for the 0.5-minute half-cycle. The average flow rates during the EVA simulations were 5.94 ± 0.12 acfm (168 ± 3.4 L/min) for the 1-minute half-cycle and 5.97 ± 0.12 acfm (169 ± 3.4 L/min) for the 0.5-minute half-cycle. All of these values indicate the target system pressure, flow rate, and dosing requirements align with NASA's 2022 solicitation requirements and indicate material viability within the sub-atmospheric test case scenario. The temperatures and humidity values across the three sampled locations are listed in **Table 1**.

Table 1. Experimental averages were collected from the 1- and 0.5-minute half-cycle tests of Xplo-SA9T on the RCA-Scale Swing Bed.

	1-minute Half-Cycle	0.5-minute Half-Cycle
Temperature at Bed Inlet	23 ± 1ºC	23 ± 1ºC
Temperature at Bed Outlet	25.9 ± 0.1ºC	25.8 ± 0.1ºC
Temperature at Helmet Inlet	24.3 ± 0.1ºC	24.3 ± 0.1ºC
Humidity at Bed Inlet	7.7 ± 0.2%	7.4 ± 0.2%
Humidity at Bed Outlet	2.97 ± 0.04%	2.70 ± 0.04%
Humidity at Helmet Inlet	2.02 ± 0.03%	1.72 ± 0.03%

V. Conclusion

The design, construction, and experimental capability for the flow-through and closed-loop recirculating swing bed test rigs provide a realistic RCA technology assessment of the developed adsorbent technologies for carbon dioxide and humidity control. Two adsorbents previously developed, Xplo-SA9T and MMPA-Sorbent,[21] were evaluated on the flow-through Subscale Swing Bed along with soda lime independently. All three materials (~60-64 g per bed) were evaluated at 2 L/min, 8 mmHg CO_2, 50 percent RH, and reached a steady state within a simulated 8-hour EVA. Xplo-SA9T was further evaluated in the closed-loop recirculating RCA-Scale Swing Bed under more representative xEMU conditions. These conditions include 6 acfm (~170 L/min), 4.3 psia (~30 kPa), 2.44 g/min CO_2 injection rate, 1.51 g/min H_2O vapor injection rate, and at 25ºC controlled temperature. An array of sensors were used to actively monitor the differential pressure across the material, flow rates, CO_2, NH_3, RH, T, and system pressure.

The RCA-Scale Swing Bed results indicate that even without cartridge flow optimization, residence time consideration, or aluminum foam to mitigate heat transfer around the material, the ideal helmet inlet CO_2 concentration of 2.2 mmHg or below can be met with Xplo-SA9T at 0.5-minute half-cycles while dosing at a simulated metabolic profile of 1650 BTU/h. The implementation of this test equipment affords variability for future testing in both hardware and EVA scenario-specific applications. The developed hardware can be used to test and optimize residence time, adsorbent bed design, adsorbents, system volumes, sensors, alternative sorbents, and RCA prototype designs. The RCA-Scale Swing Bed test rig can also be adapted to potentially explore RCA/TCC integration. The scenario-specific application testing options include flow rates, metabolic profiles, sub-atmospheric or atmospheric pressures, half-cycle timing, bed switching on concentration triggers, and operational ambient temperatures.

Acknowledgments

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