Dynamic Regulation of Sub-Atmospheric Pressure for Constant and Cyclic Gas Loads During Testing of Spacesuit Components

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New iterations of the various subsystems within the spacesuit will benefit from a new sorbent technology. For example, sorbents used in the Trace Contaminant Control (TCC) and the Rapid Cycle Amine (RCA) systems within the Exploration Portable Life Support System (xPLSS), part of the Extra-Vehicular Mobility Unit (xEMU). For proper validation, the sub-atmospheric pressure needs to be maintained within a simulated 2 ft^3 spacesuit volume. The traditional approach, which involves placing the entire vent loop within a hypobaric chamber, is not practical for the widespread testing of components and prototypes, as these specialized chambers are costly and not widely available. A two-stage regulator based sub-atmospheric pressure system is presented in this work. The method regulates the pressure based on pressure differentials between the pressure regulation pump, the test system, and the ambient environment. The performance of this system is demonstrated using data collected during a 150+ hour non-regenerative TCC sorbent evaluation, several 24-hour regenerative TCC sorbent evaluations with different regeneration cycles, and an 8-hour RCA sorbent evaluation, all under xEMU operating conditions. For regulation, the inlet regulator was set to propagate a small leak to increase the stability of the system as the gas load from the testing system changes. It was also found that controlling the input flow rate that replaces the material lost during regeneration is critical for ensuring the stability of the system. This system provided excellent pressure regulation, without adjustments, for constant loads during shorter time evaluations (hours), while longer time evaluations (days) are easily obtainable with periodic regulator adjustments. A second method is under development to address longer-term stability and to automate pressure regulation. It will incorporate flow and pressure measurements to dynamically control a set of electronically controlled proportional valves for adjusting the pumping speed and air bleed supply.

Acronyms and Nomenclature

acfm	=	actual cubic feet per minute
Airosorb	=	XploSafe's proprietary nanoporous silica-based sorbent
BTU	=	British Thermal Unit
CO_2	=	carbon dioxide
EVA	=	Extravehicular Activity
HITL	=	Human in the Loop
h	=	hour
kg	=	kilogram

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kPa	=	kilo pascals
lpm	=	liters per minute
NASA	=	National Aeronautics and Space Administration
mL	=	milliliter
mmHg	=	millimeters of mercury, unit of pressure
psia	=	pounds per square inch absolute
RCA	=	Rapid Cycle Amine
RH	=	relative humidity
TCC	=	Trace Contaminant Control
torr	=	unit of pressure
xEMU	=	Exploration Extravehicular Mobility Unit
Xplo-SA9T	=	XploSafe's proprietary solid amine adsorbent (SA9T variant)
xPLSS	=	Exploration Portable Life Support System

I. Introduction

NASA's directive on humanity's return to space with sights set on lunar, Mars, and deep-space exploration has driven significant changes to the Extra-Vehicular Mobility Unit (xEMU) spacesuit [1, 2]. Within the xEMU, the Exploration Portable Life Support System (xPLSS) houses vital functions including oxygen regulation, carbon dioxide (CO_2) removal, and air filtration [1, 3]. New iterations of the Trace Contaminant Control (TCC) and the Rapid Cycle Amine (RCA) systems are benefiting from new sorbent technologies [4–6]. For example, XploSafe has reported a new regenerable nanoporous silica sorbent for TCC applications [7–9] and amine based absorbents for the RCA system [10], [11]. As NASA and other commercial manufacturers create new sorbents and develop new iterations of TCC and RCA systems within the xPLSS, rigorous testing is required to ensure functionality and safety.

Material development (sorbent, system, and/or analytical technique) requires a combination of new materials and extensive testing under realistic xEMU conditions, including a spacesuit pressure of 29.6 kPa (4.3 psia) and a gas flow rate of 170 lpm (6 acfm) for lunar missions [12–15]. Furthermore, many earlier studies rely on flow-through testing [8, 16–19], which, among other complications, neglects concentration accumulation over time when the sorbent is close to its capacity. The accumulation of ammonia during recirculation was noted in a 2025 study of a Microlith substrate [20]. For the current xEMU spacesuit, the traditional testing approach involves placing the entire test bed within a hypobaric chamber [21], [22]. Since these specialized chambers are costly and not widely available, they are impractical for the widespread testing of components and prototypes. Consequently, sub-atmospheric testing incorporating both recirculation and swing beds is uncommon. To address this limitation, XploSafe has developed two sub-atmospheric test rigs [7], [9], [23] capable of directly comparing the trace contaminant removal performance of both regenerable and non-regenerable sorbents as well as to test adsorbents for the RCA system under operational xPLSS conditions [10]. This paper discusses the methodology used to maintain sub-atmospheric pressure within a 2 ft^3 (56 L) spacesuit volume while achieving a realistic 6 acfm flow rate and continuous bed swings at preset half-cycles.

II. System Overview

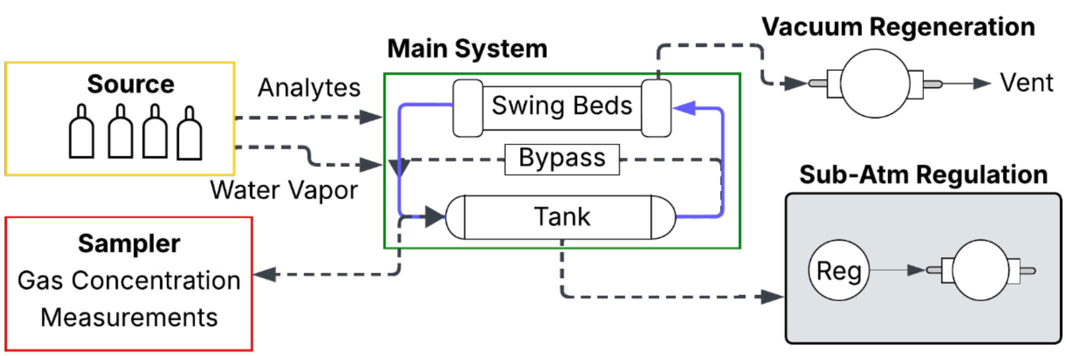

Figure 1. Outline of the TCC and RCA test-bed apparatus. The operation, performance and future developments for the shaded sub-atmospheric regulation sub-system is the subject of this paper.

Figure 1 presents a simplified schematic of XploSafe's test system for TCC and RCA sorbent performance evaluations [24], [25]. This system has evolved from a simple single-bed apparatus for non-regenerable TCC sorbents to a fully automatic swing bed capable of testing RCA sorbents. With simulated high metabolic rates (at and exceeding 3000 BTU/h, corresponding to 2.42 L/min CO_2 and 2.50 mL/min water) and concentration-controlled bed cycles while maintaining a gas flow rate of 6 acfm and sub-atmospheric pressure of 4.3 psia. System details have been published [7, 9, 10, 23], with the most advanced swing-bed design described in our 2025 publication [10]. Referencing Figure 1, the central system (Main System, dark green) contains two or three stainless-steel tanks (Tank), depending on the iteration, with a total volume of approximately 56 L to match the xPLSS volume of ~2 ft^3 (~0.0566 m^3). It also holds the sorbent beds (Swing Beds) which house a sorbent cartridge with the material to be tested. Each sorbent bed consists of a stainless-steel KF-160 vacuum nipple, which holds the sorbent cartridge. The sorbent cartridge allows the ~1992 mL combined internal volume to be adjusted to any desired volume. For example, 788 mL is required for the RCA 3.0 design and 1050 mL for the RCA 2.0 design [26]. The sorbent bed(s) within each recirculation loop can be electronically initiated or flow can be directed through a bypass loop. The recirculation loop also contains a calibrated TSI flow meter (5300 series) to monitor the gas temperature, relative humidity, pressure, flow rate, and pressure drop across the sorbent beds, a Micronel blower (U100HL-024KA-4) to maintain the airflow at 6 acfm, and a heat exchanger to maintain a constant gas temperature. On the left in Figure 1, the Source (Dark Yellow) contains an array of calibrated mass flow controllers for injecting multiple gases precisely into the ventilation loop, a humidified air source, and in the latest revisions, a water vapor source. The Sampler (Dark Red) is an analytical sub-system to collect and quantify analytes in-situ during operation. On the right side of Figure 1, there is a large vacuum pump (Vacuum Regeneration) that can evacuate each Swing Bed during the time the bed is switched out of the ventilation loop. Additional sensors are placed in the ventilation loop depending on the sorbent testing procedure. The shaded sub-atmospheric regulation sub-system is the focus of this paper. This sub-system maintains the pressure in the ventilation loop at 4.3 psia, independent of the gas injection rate and gas loss during regeneration.

Figure 2 shows the regulation system for the test-bed apparatus. The gray box represents a small volume (a few cm^3 including tubing) that serves to connect the various components. Pressure can be monitored for checking the pump operation and regulation using the pressure gauge (a ConvecTech CVT-275-101convectron gauge or, in later iterations, a 0–1000 torr Terranova Model 808 Silicon Diaphragm Sensor). All the reported pressures below are measured by the integrated pressure sensor within the TSI 5300 flow meter to directly monitor the pressure within the ventilation loop and remain most representative of the Spacesuit. This pressure is identical to that measured before the blower. The 6 acfm flow in the loop increases the pressure before the sorbent's beds by approximately 5 torr. The regulated gas source is independent of the dosing system.

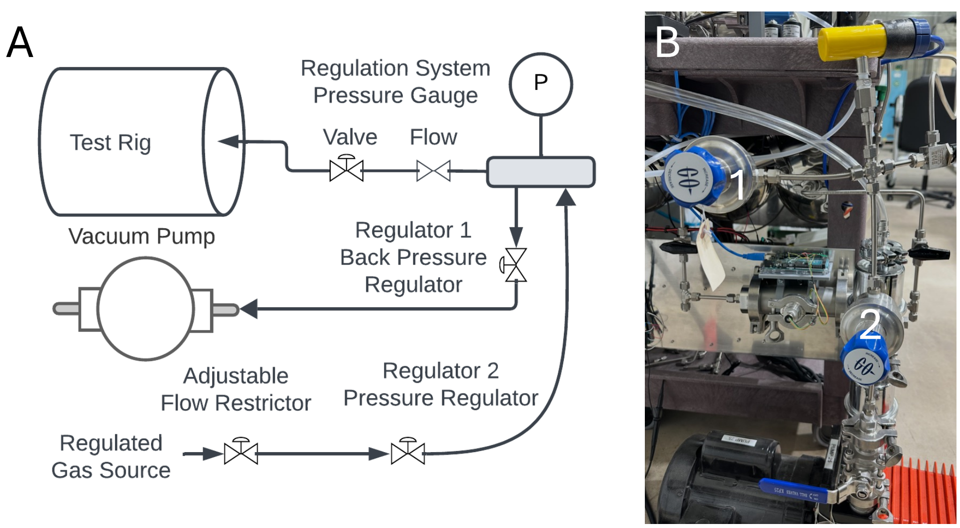

Figure 2. (A) Sub-atmospheric regulation system for the test-bed apparatus. (B) Picture of the sub-atmospheric regulation system showing its location with respect to the test-bed apparatus (Test Rig).

Figure 2 shows the initial schematic for the sub-atmospheric control system. The regulation is accomplished with an Alcatel 2012A vacuum pump (11 cfm) and two sub-atmospheric GO Regulators (SBPR-1E11K5A111 and SPR-1A11AHA111). The GO SBPR (Regulator 1) is a back pressure regulator placed between the sub-atmospheric system and the pump. This regulator is used to decrease the pressure to the setpoint by removing gas from the test-bed apparatus via the vacuum pump. The other regulator is a GO SPR regulator (Regulator 2) designed for flowing low vapor-pressure reactive or purge gases into a sub-atmospheric environment. It is used to increase the pressure in the test-bed apparatus if the pressure drops below the setpoint, by allowing the gas from the gas source into the test-bed apparatus. A Swagelok SS-20VS4 (Adjustable Flow Restrictor) needle valve was placed between the inlet of this regulator and a zero-grade air cylinder. This valve is required to limit the flow when testing sorbents that require vacuum regeneration. Importantly, these are single-stage regulators with a large diameter diaphragm designed to provide quick responses to pressure changes as required for the test-bed apparatus. If the system's pressure increases above the setpoint, Regulator 1 opens, and the vacuum pump restores the pressure. If the apparatus falls below the desired pressure of 4.3 psia or ~30 kPa, the system is refilled through Regulator 2. In general, a stable system requires either a hysteresis or a small difference between setpoints to prevent oscillations. Zafer and colleagues published a comprehensive overview of the design considerations and trade-offs that determine the stability of gas regulators [27]. Thus, performance of this system is determined by the spring loading of the diaphragm in the regulators, pressure-dependent flow rate through the regulators, physical temperature of the regulators, and slow increase in the leak rate versus pressure around the setpoint. Although it is implied that the setpoint corresponds to the absolute pressure at the inlet, this assumption is not true. Regulator setpoint is not pressure, but the response to the pressure difference between the inlet and outlet of the regular, as set by the loading on the internal diaphragm. Finally, the pumping speed of the mechanical pump is a function of the flow through the back pressure regulator.

The flow-through test rig depends on the half-cycle times, the rate of contaminant injection for TCC testing, and the rate of CO_2 and water vapor injection for RCA testing. Given that the base pressure of the mechanical pump varies with pumping speed, different input flows result in slightly different base pressures at the inlet of the mechanical pump. Larger flows increase the pressure at the pump inlet, changing absolute pressure at the inlet of the pump and, thus, the required setpoint for the differential pressure across Regulator 1. The response time of the spring loading of the diaphragm also means that the setpoint for Regulator 2 needs to be such that there is a slow leak through this regulator at pressures below its setpoint to allow it to respond quickly once the pressure in the chamber exceeds the desired pressure. The slow leak also changes the base pressure at the entrance of the mechanical pump. Thus, the combination of the two regulator setpoints is not unique. The addition of a flow meter (Dakota GM1 Series) before the valve to the Test Rig (see Figure 2) was found to be helpful in initially setting the setpoint of the regulator to balance the input with the output flows. The flow meter worked surprisingly well and provided an accurate reading considering that both the inlet and outlet were both at sub-atmospheric pressures.

The following discussion introduces the hierarchy of increasing the regulation complexity based on the results of sorbent evaluations conducted under different test conditions. For non-regenerative TCC sorbent evaluations, the contaminant input flow is balanced exclusively by the flow through the sub-atmospheric pressure regulator. In regenerative testing configurations, an additional volumetric loss occurs during the vacuum regeneration cycle. This lost volume is initially replenished by the suit volume (Tank) and then subsequently replaced by the sub-atmospheric pressure regulation system, thereby increasing the complexity of the overall flow balance. RCA sorbent testing represents the most demanding operating conditions. At elevated metabolic rates, there is a substantial input flow of CO_2, reaching up to approximately 3 L/min, in conjunction with the outward flow associated with the regeneration process. Furthermore, the swing time is not fixed and varies as a function of the metabolic rate and system usage (see References [28] and [10]). Half-cycle times can range from as fast as 15 seconds to near 5 minutes within the same simulated EVA. This change occurs as a CO_2 sensing system allows the active bed to continue scrubbing the gas stream until a pre-determined CO_2 concentration set point is reached, and thus a bed switch occurs. This rationale is indicative of Human In the Loop (HITL) testing from the literature using an RCA system to scrub the recirculation loop and maintain CO_2 within a safe level (bed switch at 3 mmHg) [28].

III. Pressure Regulation

A. Pressure Regulation for Non-Regenerative TCC Sorbent Testing

Non-regenerative TCC sorbent testing required an input flow of trace analytes (XploSafe uses 200 mL/min [7], [9], including a zero-air carrier gas), which must be balanced by the flow through the vacuum pump. To maintain 4.3 psia, one only requires that the flow in is equal to the flow out. In a minute, the injected volume becomes less than 1% of the total volume (56 L). The timescale of potential pressure changes is slow compared to the response time of the pressure regulators. Thus, the sub-atmospheric regulator (Figure 2, Regulator 1) provides a leak rate to remove the injected gases and maintain the pressure. Regulator 2 allows the system to be refilled, from ambient air in this case, if the pressure drops below the setpoint. In the non-regenerative testing, this second regulator does not play a significant role once the pressure is set. In this experiment, a small added flow was provided by Regulator 2 to ensure stability.

The flow meter between the tank and the sub-atmospheric regulation setup helps to ensure that the outlet flow is equal to the input flow while adjusting Regulator 1.

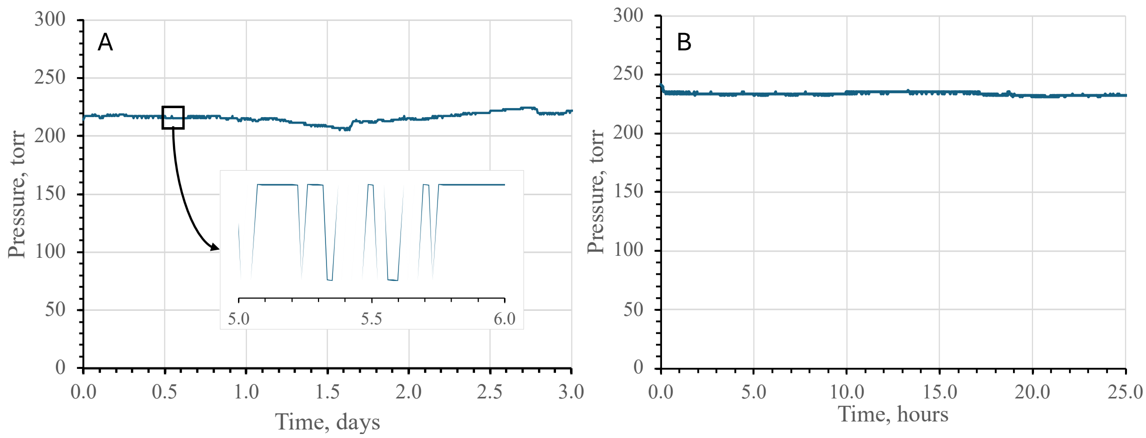

Figure 3. (A) A 25-hour run with a one-hour expanded view of the pressure versus time plot and (B) a longer three-day pressure versus time plot during the non-regenerative TCC sorbent testing of Ammonasorb II.

For the non-regenerative pressure regulation testing, a single bed with 125 g of sieved Ammonasorb II sorbent in a 230-mL sorbent cartridge was used. The experiment run for 180 hours with a 200 mL/min injection of nine priority contaminants [7]. As discussed above, the calibrated TSI flow meter was located before the sorbent bed and used to record the pressure. As shown in Figure 3A, the pressure was maintained at 234 ± 1 torr over 25 hours. The resolution of the TSI flow meter was 0.2 torr with a stated accuracy of 8 torr. The insert shows a 1-hour expanded plot that better illustrates the short-term stability. The one-hour variation was within the reading precision (0.2 torr) of the TSI flow meter. Thus, the short-term stability of the sub-atmospheric pressure regulation is excellent. Changes in temperature and differential pressures between the system and the environment do impact the performance, as a typical long-duration experiment for non-regenerative TCC sorbent testing required over 150 hours (150 hours is the operational service life of the current non-regenerative TCC sorbent) [29]. Figure 3B shows the pressure measured before the sorbent beds for three days (72 hours) during the non-regenerative TCC sorbent breakthrough experiment with Ammonasorb II, which is an activated carbon sorbent made from coconut shells and impregnated with phosphoric acid to enhance ammonia sorption [7]. The longer-time fluctuations can clearly be seen in the data plot. Over 3 days, the pressure averaged 220 ± 4 torr. Referring to Figure 3B, the observed variation at just after the 1.5-day timepoint is due to the small adjustments of the sub-atmospheric pressure regulation. Some changes in the setpoint for the back pressure regulator (Figure 2, Regulator 1) restored the normal pressure in the system to 220 torr. Another small adjustment occurs after the 2.5-day timepoint. Thus, manual monitoring and small adjustments at daily intervals can eliminate the pressure drift. Several experimental changes, such as moving the location of the sub-atmospheric regulation system closer to the tank and an improved heat exchanger for the temperature regulation of the recirculating gas, have led to additional improvements. Nevertheless, the stability of the dual-regulator system is sufficient (standard deviation of ± 4 torr) to provide the necessary sub-atmospheric pressure regulation for non-regenerative sorbent testing.

B. Pressure Regulation for Regenerative TCC Sorbent Testing

The sub-atmospheric regulation also was used during TCC sorbent evaluations with vacuum regeneration for XploSafe's nanoporous silica-based sorbent beads (Airosorb) [7]. In more recent experiments, the data were collected from experiment trials with a sorbent cartridge size of 230 mL containing 72 g of nanoporous silica-based beads (Airosorb). The half-cycle time is the active time for a given bed to be scrubbing contaminants in the ventilation loop before being switched for regeneration. Thus, a 1-minute half-cycle time means one minute of working as a filter to remove contamination from the ventilation loop and one minute of vacuum regeneration. During regeneration, the second bed is switched into the ventilation loop. As in the case of non-regenerative sorbent testing, the inlet of the NASA priority contaminants in a zero-air carrier gas was 200 mL. After each vacuum swing, the beds must be refilled from the simulated spacesuit volume and not from an external source before switching back into the ventilation loop. Thus, there is a gas loss of approximately 1 L per half-cycle calculated from the dead space surrounding the sorbent within the bed. For the 1-min half-cycle, this additional outward flow corresponds to a rate of 1000 mL/min. Thus, the sub-atmospheric system must use an external zero-air gas source to counteract this volume lost, and return the pressure quickly to prevent pressure fluctuations. Therefore, Regulator 2, which is connected to an external zero-air gas source (see Figure 2), becomes important to maintain the pressure at 4.3 psia. As in the case above, the setpoint of this pressure differential was set so that there was always a small flow rate through the regulator. This flow not only helps stabilize the regulation but also allows the regulator to respond quickly to the pressure drop. The inlet to this regulator was connected to a zero-grade air cylinder with the flow regulated through a Swagelok SS-20VS4 valve. This additional valve limits the input flow of gas when the regulator opens, preventing an uncontrollable inrush of gas. Damping this inrush caused by a hard opening of the regulator was critical for pressure regulation during the swing cycles. The stability of the pressure with varying the half-cycle timing is a critical test of the sub-atmospheric regulation system.

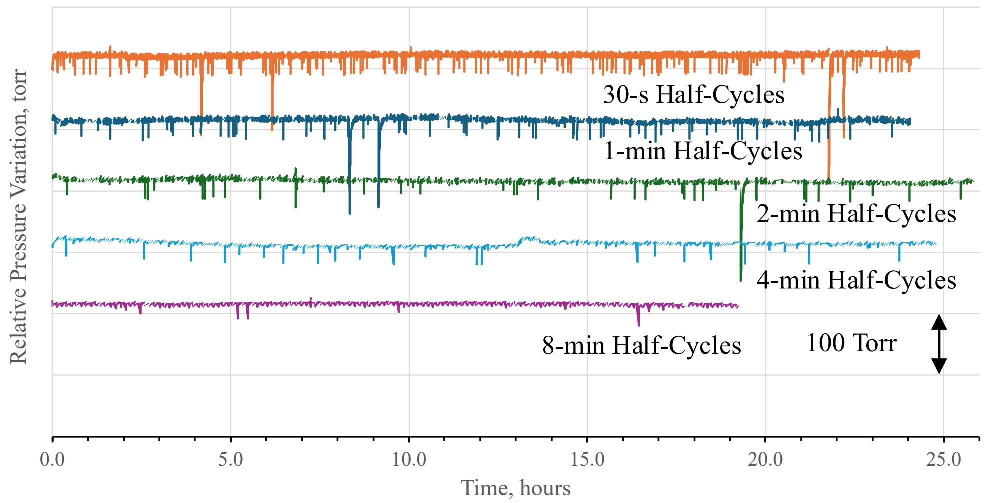

Figure 4. Sub-atmospheric pressure regulation during regenerative TCC sorbent testing at different half-cycle times. To visualize the relative changes, experimental runs have been offset. The y-axis corresponds to the relative pressure change from the average of each experimental run. The y-axis grid spacing is 100 torr.

Table 1. Average measured pressure and its variation (standard deviation) as functions of the half-cycle time during regenerative TCC sorbent evaluations.

Half-Cycle	Pressure (torr)	Variation (torr)	Run Time
30 sec	222	9	24 hours
1 min	217	7	24 hours
2 min	218	6	26 hours
4 min	215	4	24 hours
6 min	220	3	8 hours
8 min	217	3	19 hours

Figure 5 shows the pressure plotted as a function of time and the half-cycle time for several tests of a regenerative TCC sorbent. The plotted data from each run is offset to help visualize the relative changes from the setpoint (220 torr) in Table 1. Thus, the y-axis corresponds to the relative pressure change with respect to average pressure, noted in Table 1, for each half-cycle run. The y-axis grid spacing is 100 torr. Table 1 summarizes the average pressure and standard deviation as functions of the half-cycle time during regenerative TCC sorbent evaluations with different half-cycles. The average pressure and standard deviation were calculated from the whole data set without filtering or excluding any points. For these experiments, the pressure was set nominally to 220 torr (4.3 psia) and monitored during regenerative TCC sorbent evaluations for 24 hours, except for the 6-min half-cycle sorbent evaluation, which was for 8 hours. An 8-hour evaluation is the minimum required to simulate a typical EVA, specified as 8 hours [29]. The longer times were performed to show the stable performance of XploSafe's nanoporous silica-based sorbent beads over multiple back-to-back simulated EVAs. As mentioned above, the resolution of the TSI flow meter was 0.2 torr, significantly smaller than its stated accuracy of 8 torr. The downward spikes in the raw data, more pronounced with the shorter cycle times, are further discussed below. Ignoring the spikes in the graphs (Figure 5), the pressure drops visibly appears to be approximately 5 to 8 torr depending on the selected half-cycle. Longer-term fluctuations are not pronounced in this data set as the experiments were significantly shorter than that required for a non-regenerative TCC sorbent evaluation.

The periodic pressure variation can be clearly seen in the 8-min half-cycle time pressure plot. For the shorter half-cycle times, these variations look like noise. For the longer half-cycle times (≥ 4 min), the standard deviation is consistent with the non-regenerative data above. With shorter swing times, the regulators are stressed to their design limits as the system must handle more frequent bed refills and the resulting pressure fluctuation. For the 30-s half-cycle, the outlet flow due to the vacuum regeneration is 2000 mL/min, is 10 times that of the input flow of contaminants. However, the pressure variations were still less than 10 torr, indicating that the performance of the sub-atmospheric regulation system is acceptable.

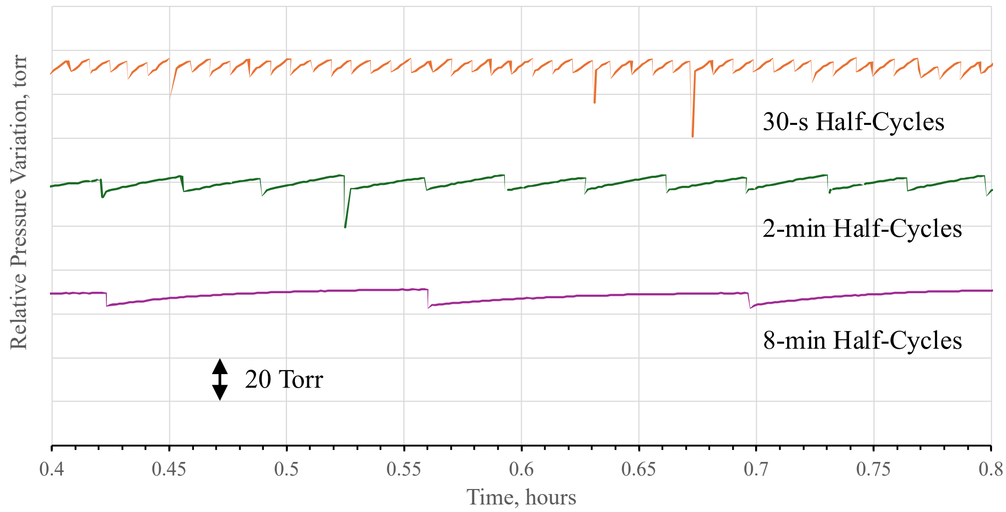

Figure 5. A plot of an arbitrary half-hour section of the relative sub-atmospheric pressure versus time data shown in Figure 4 for the 30-s, 2-min and 8-min half-cycle times starting 7 hours into the experiment. The experimental runs have been offset, and the y-axis corresponds to relative pressure change with respect to average pressure in Table 1 for each run. The y-axis grid spacing is 20 torr.

Figure 5 plots a half-hour section (starting the 7th hour) of the data shown in Figure 4 for the 30-s, 2-min, and 8-min half-cycle times. The 7th hour was arbitrarily picked, close to the center of the set of runs. The data at this location is representative of the data at different times. The displayed data are offset for visibility, and the y-axis corresponds to the relative pressure change with respect to average pressure noted in Table 1 for each run. The y-axis grid spacing is 20 torr. The downward spikes, seen in both Figures 4 and 5, occur at constant times during each swing cycle. The observed locations correspond with the refilling of the bed, and the downward spikes become more frequent with the faster cycle times. It is suggested that these short downward pressure dips are local pressure drops before the bed which are enhanced by the TSI flow meter, since a quick pressure change for the 56 L volume is not physically possible. Thus, when a bed is switched into the flow and refilled, the resulting pressure drop opens the regulator between the gas source and the sub-atmospheric tank, causing the pressure to return, which stops the refill process. As the pressure gauge is located at the bed inlet, these variations are enhanced compared to the tank, which acts as a ballast. In addition, these periodic pressure drops are inherent in the design as the bed is refilled from the tank and not from an external source, matching the configuration in the current xEMU [28].

The change in pressure after opening the bed to the flow illustrates the importance of the Swagelok SS-20VS4 needle valve, which is in-line with the regulator. Without it, the inlet regulator, by design, opens fully and locally overshoots the setpoint of the back-regulator, which in turn opens, causing stability issues. The Swagelok SS-20VS4 needle valve, combined with a regulated source of zero-grade air, provides a more controlled refill. The longer half-cycle times clearly illustrate this action. For the more rapid cycles, the system just recovers before the next bed switch. Thus, a greater input flow is required, which can be adjusted by the pressure of the dosing system and setting the needle valve appropriately. With this addition, the sub-atmospheric regulator system provides good control, without adjustments, for these time-varying loads over reasonable time periods. In addition, changes in temperature and differential pressures between the system and the environment impact the performance. The shorter experimental time compared to the non-regeneration TCC sorbent testing is also beneficial. However, frequent manual valve adjustment of the sub-atmospheric back-regulator was still important to maintain a constant pressure.

C. Pressure Regulation for RCA Adsorbent Evaluations

For RCA adsorbent evaluations, there is both a loss of gas volume due to the vacuum regeneration swing cycle, as discussed above, and a significant input flow rate (up to 3 L/min) of CO_2 and water vapor at a simulated elevated metabolic rate. In addition, the half-cycle time changes depending on the desired maximum CO_2 concentration, which is set to 3 mmHg [26] for these experiments. For these evaluations, each swing bed contained an average of 431.6 g of Xplo-SA9T adsorbent packed within each ~948 mL sorbent cartridge. The system flow was set to 6 acfm, and the temperature was regulated at 25 ˚C. The back regulator setpoint (Regulator 1), the input flow of zero air controlled by Regulator 2, and the needle valve all need to be optimized for consistent performance. The RCA absorbent evaluation provided a rigorous test for the usability of the sub-atmospheric regulation system.

Figure 6 displays sub-atmospheric pressure regulation during regenerative RCA sorbent testing with a CO_2 pressure-dependent cycle time. The injection rate of CO_2 ranged from 1.16 to 4.36 g/min with 1.06 to 2.50 g/min of water vapor. The total experimental time was at least 8 hours per metabolic profile test, representative of a full EVA. Once a steady-state is reached, or when the rate of CO_2 and water vapor adsorption becomes equal to the desorption rate, the steady-state half-cycle period increases from 39 seconds at 3000 BTU/h to 181 seconds at 800 BTU/h. The half-cycle period shortens with rising metabolic rate as the system needs to increase the CO_2 removal rate due to the elevated amount of CO_2 being injected. For these tests, the pressure range of 205 to 240 torr with a desired set-point of 222 torr. Since this system changes half-cycle times dynamically, the pressure fluctuations can be exacerbated, and both over pressurization and downward dips can become more prevalent. The downward fluctuations are clearly associated with the bed switch. Nevertheless, the average pressures were between 216 and 221 torr with a standard deviation ranging from 6 to 10 torr, similar to that recorded for the non-regenerative TCC sorbent testing.

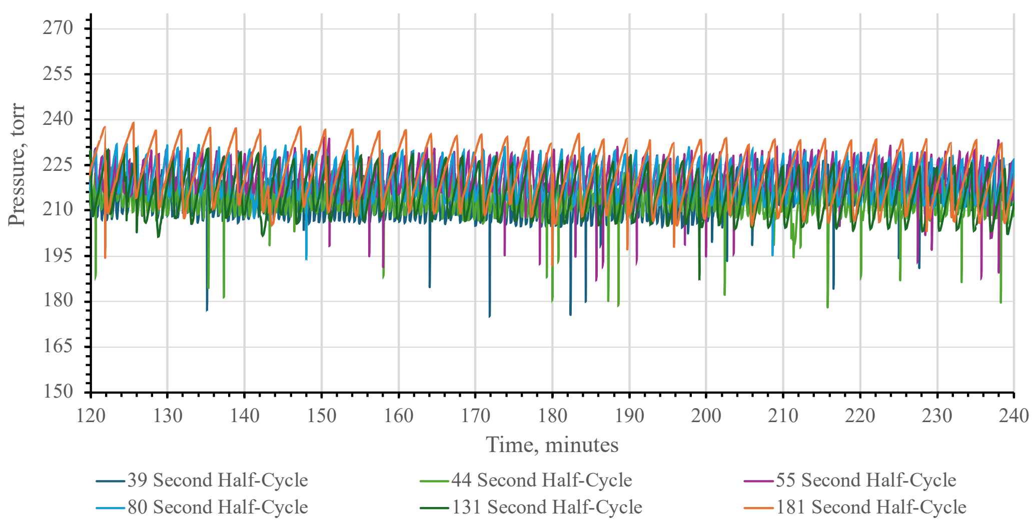

Figure 6. Steady-state sub-atmospheric pressure regulation during an 8-hour simulated EVA with a CO_2 sensing RCA system with different half-cycle times, each one corresponding to a different metabolic rate.

D. Electronic Pressure Regulation for Increased Performance

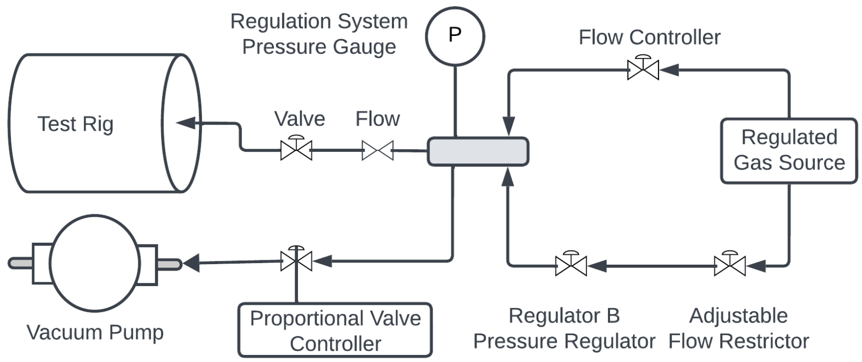

Figure 7. Electronically controlled sub-atmospheric regulation system for the test-bed apparatus. Note the addition of a proportional valve and a flow controller.

The dual regulator system works extremely well under static and dynamic loads. However, the long-term stability and high-metabolic swing bed operations expose some areas for improvement. In another implementation (Figure 7), the back pressure regulator (Regulator 1) is replaced with an electronic proportional valve. In this figure, "controller" refers to a device that is electronically controlled, while "regulator" refers to one that is purely mechanical. When regulating the pressure, the sub-atmospheric pressure is two times greater than that above the pump, and the flow, at a given orifice setting, is proportional to the pressure difference. However, the pressure difference across the valve can change dramatically with a rapid injection of flow, which reduces the pressure across the proportional valve significantly as the valve opens. As the flow region changes from critical-flow (choked-flow) to subcritical-flow, the controller must adjust to a different flow rate at the same valve opening. Adding the change in pumping speed with the pressure, the system control becomes difficult when considering large changes in load. In addition, at the setpoint, there is no restoring "force" to increase the pressure. In the system shown in Figure 2, this was addressed by setting the setpoint of Regulator 2 to allow a slow leak when the system is at the setpoint. In Figure 7, this leak was replaced by a flow controller connected to the regulated gas source which allows the electronic regulator to adjust its flow to maintain a content input flow into the system. This leak compensates for slow changes (several seconds) that occur when the gas injection is turned on.

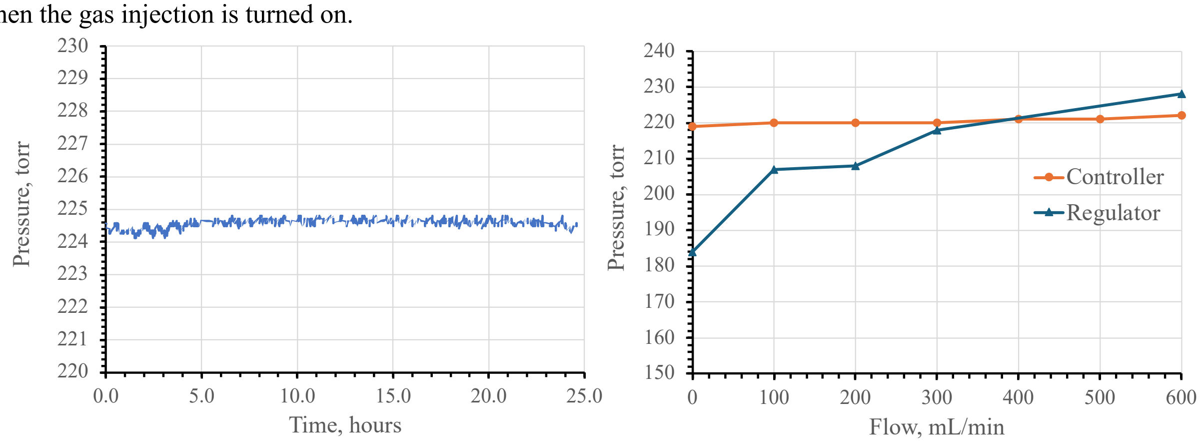

Figure 8. (A) A 25-hour run: the pressure versus time plot with an input flow rate of 200 mL/min to simulate dosing of a non-regenerative TCC sorbent. (B) The regulated sub-atmospheric pressure as a function of the input flow after adjusting the setpoint at an input flow of 200 mL/min.

The pressure control was implemented using a Eurotherm 2404 process controller operating as a proportional controller. The 10-volt output from the Terranova Model 808 Silicon Diaphragm Sensor was converted to torr on the controller. The 10-volt output from the process controller was connected to a programmable Kapco power supply to produce the required input to the proportional valve. The Kapco power supply has an additional operational amplifier at its input that can control the skew rate and scale of the output. This simulates the non-regenerative sorbent TCC experiment that was started using the injection rate of 200 mL/min and gas flow rate of 6 acfm. The flow meter between the test rig and the sub-atmospheric system (labeled "flow" in Figure 7) allowed the flow out of the test rig to be monitored to ensure that the mass flow into the system matches the mass flow out of the system. The 25-hour plot of the pressure is shown in Figure 8A. These are the exact conditions used for the data collected above (see Figure 3). The average pressure was 224.6 ± 0.2 torr, as measured by the TSI flow meter. As variations occur at the level of the TSI resolution, the 10-time improvement is a lower limit. The new system is also more stable to pressure variations with the input flow rate. Figure 8B shows the average pressure plotted at different input flow rates. As expected by the maximum flow limitation of the proportional valve, the new system could not maintain pressure regulation at flows above 700 mL/min. The pressure decrease for the dual-pressure regulator system is reversible with an increased flow and illustrates the need for continued flow to ensure stability.

For a 2-minute swing half-cycle, the vacuum regeneration removes approximately 1 L pre-swing. Assuming an input flow of 200 mL/min, typical for XploSafe's testing of a regenerable TCC sorbent, an additional flow of 300 mL/min is required to keep the pressure constant. Figure 9 shows several 2-min half cycles with an input flow of 600 mL/min, a flow rate of 6 acfm, and a pressure setting of 220 torr. This larger input flow means the system can recover quickly from the loss of material during the regeneration cycle. The measured pressure was 228 torr, due to the location of the blower before the TSI flow meter with a standard deviation of 5 torr. Here, the magnitude of the standard deviation is dominated by the pressure change required to return the system to its nominal pressure after regeneration. After recovery, the pressure levels off and remains relatively flat before the drop generated by the start of a new swing half-cycle.

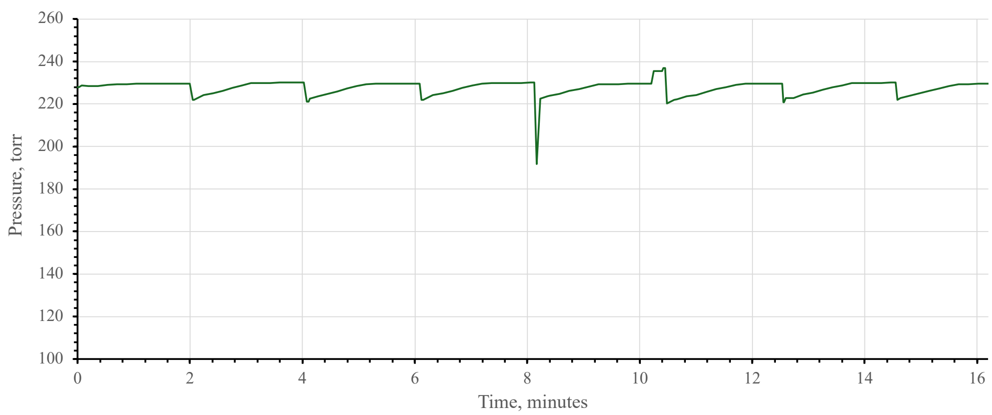

Figure 9. A few 2-min half cycles with the proportional valve regulation system.

There are two downsides in the current proportional valve design. First, in the back pressure regulator (Regulator 1) depicted in Figure 2, the setpoint adjustment is performed at the sub-atmospheric pressure, where the leak rate is set by the spring tension applied to the diaphragm within the regulator. Fast pumping down is possible by fully opening the regulator. With the proportional valve, there is a maximum flow for filling the opened valve of approximately 1 L/min. This speed limited the pump downtime before an experiment and could be avoided by an additional flow path. However, the slow pump downtime ensures the system and the sensors are not damaged by large internal pressure spikes. The second issue is that the proportional valve system has a narrow dynamic range, as the maximum flow rate is a function of the valve. This issue can be compensated by having a selection of valves or the possibility of modifying the valve control voltage circuitry to accept an offset and variable gain input, to allow the proportional valve control signal to be optimized around the setpoint. As XploSafe adds more complexity to the testing apparatus to allow for programmable metabolic rates, higher flows, and possibly, more complex bed setups, the pressure regulation system will further be improved and optimized.

IV. Conclusion

XploSafe is working to further advance a regenerable nanoporous silica sorbent for TCC applications [7–9] and new amine based absorbents for the RCA system [10], [11]. With sorbent development, extensive testing under realistic xEMU conditions, including a spacesuit pressure of 4.3 psia and a gas flow rate of 170 lpm (6 acfm), is critical to ensure functionality and reliability. This paper discussed the methodology used to maintain sub-atmospheric pressure within a 2 ft^3 spacesuit volume while achieving realistic flow rates and bed swinging using a relatively small vacuum pump with active vacuum regulation. Sub-atmospheric control is accomplished using two sub-atmospheric regulators. Pressure stability during a 150+ hour non-regenerative TCC, 24-hour regenerative TCC, and six 8-hour RCA tests (with CO_2 concentration-controlled cycle times) show that the system can maintain the sub-atmospheric pressure within less than 10 torr of the operating pressure at the inlet of the sorbent beds. Some of this variation is inherent in the repressurization method using the reserve volume of the spacesuit. The longer-term stability is dominated by environmental factors, and small periodic adjustments are still required to keep the pressure stable. Future modifications to this basic design were discussed. One modification includes the addition of a flow controller for the input flow to provide a constant leak rate to stabilize pumping speed in the short term and further dampen the variation observed during the bed refill. An electronically controlled proportional valve placed instead of the sub-atmospheric back pressure regulator addressed the longer-term (> 24 hours) stability. Even with these additions, a simple system consisting of two sub-atmospheric regulators was shown to be effective for sorbent testing under realistic xEMU conditions.

Acknowledgments

Financial support for the project was provided by a NASA SBIR program under Contracts No. 80NSSC22PB246, 80NSSC23CA167, 80NSSC21C0579, 80NSSC25C0466, 80NSSC25C0408, and 80NSSC2250461. The authors would like to acknowledge the contributions of Cinda Chullen, Lawrence Barrett, Ryan Ogilvie, Michael Lawandowski, and all other NASA Johnson Space Center employees who have provided wisdom, guidance, and funding for this work.

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