Carbon dioxide Control System for a Mars Space Suit Life Support System

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Carbon dioxide (CO_2) control during Extravehicular Activities (EVAs) on Mars will be challenging. Lithium hydroxide (LiOH) canisters have impractical logistics penalties, and regenerable metal oxide (MetOx) canisters weigh too much. Cycling bed systems and permeable membranes that are regenerable in space vacuum cannot vent on Mars due to the high partial pressure of CO_2 in the atmosphere. Although sweep gas regeneration is under investigation, the feasibility, logistics penalties, and failure modes associated with this technique have not been fully determined. TDA Research, Inc. is developing a durable, high-capacity regenerable adsorbent that can remove CO_2 from the space suit ventilation loop. The system design allows sorbent regeneration at or above 6 torr, eliminating the potential for Martian atmosphere to leak into the regeneration bed and into the ventilation loop. Regeneration during EVA minimizes the amount of consumables to be brought from Earth and makes the mission more affordable, while providing great operational flexibility during EVA. The feasibility of the concept has been demonstrated in a series of bench-scale experiments and a preliminary system analysis. This paper presents the latest results from these sorbent and system development efforts.

Nomenclature

P_{CO2}	=	partial pressure of CO_2
$T_{ads. (avg.)}$	=	average adsorption temperature
$T_{des. (avg.)}$	=	average desorption temperature
GHSV	=	gas hourly space velocity
ACFM	=	actual cubic feet per minute

I. Introduction

The extravehicular mobility unit (EMU) is a self-sustained spaceship, equipped with a compact life support system providing oxygen, pressure control, removal of waste heat, and control of carbon dioxide and moisture. Whether designed for orbital operations or planetary surface exploration, the EMU must provide high performance while maintaining safe and reliable operation. The selection of technologies for evolutionary International Space Station or planetary (lunar or Martian) EMU are strongly driven by the system volume and weight as well as life cycle costs.

Early EMU designs relied on a Contaminant Control Cartridge to absorb trace contaminants and the metabolic CO_2 from the astronaut's space suit ventilation loop (Prouty et al., 1991). This sorbent canister used a small amount

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of charcoal along with lithium hydroxide (LiOH) to purify ventilation gases. LiOH has provided reliable CO_2 removal since the Mercury program of the early 1960s, but it cannot be practically regenerated and must be replaced after each EVA. Although this was not considered a major logistics penalty due to relatively short on-orbit stay of the shuttle (7 to 14 days) and the low number of EVAs per mission (3 to 8 contingency and/or planned), it represents an unacceptable consumable burden for planetary explorations.

The regenerable MetOx canister was developed to reduce the logistics burden during ISS operations. The MetOx system practically removes all CO_2 generated during the EVA, is thermally regenerated inside the spacecraft driving off the CO_2 in an oven after each EVA. This system has been successfully used for several years, but it is relatively heavy for high gravity planetary explorations and the use of on-space craft regeneration requirement limits the EVA duration. The advanced space suit design under consideration uses a continuously regenerable CO_2/H_2O removal system based on a rapidly cycling amine swing bed. This system relies on two alternating beds of solid amine beads to remove CO_2 and H_2O from the ventilation loop and will regenerate cyclically during the EVA using space vacuum. Unfortunately, its regeneration capability in environments like Mars is compromised, because the martian atmosphere contains CO_2 at a partial pressure that is near or above the values that are acceptable in the space suit breathing atmosphere.

Mars has a very thin atmosphere made mostly of CO_2. The surface pressure on Mars is only about 0.7% of the average surface pressure at sea level on Earth (7 millibars). Under these conditions, desorption or transport processes which are partial pressure driven will not be capable of stripping adsorbed CO_2 from a sorbent to a level that will produce a breathable atmosphere in the suit. Typical regenerable technologies use pressure swing to collect and then reject the metabolically-produced CO_2, however, an appropriate stripping pressure is not available on Mars since its environment has a CO_2 partial pressure of 3 to 6.8 torr. Temperature swing adsorption processes (TSA) may be used; removing CO_2 at ambient temperatures and then use higher temperature to reject the CO_2. This heat up "cost" makes most of the TSA systems impractical for Portable Life Support System (PLSS) applications. It could be possible to modify TSA operation, and reduce the CO_2 adsorption temperature lower than the standard PLSS operating temperature and use metabolic heat load given at 24 to 31°C for regeneration. The adsorption at low temperature and regeneration at 31°C (max) could provide a viable driving force to remove and concentrate the CO_2, and regenerate the sorbent at relatively high CO_2 partial pressures. This idea was in fact first brought up by Paragon Space Development Corporation; the Metabolic heat regenerated Temperature Swing Adsorption (MTSA) technology is being developed as a solution to address the Martian challenge (Iacomini, 2009).

The Paragon system uses a Molecular Sieve NaX zeolite for reversible CO_2 removal. While the sorbent works well and achieves a high capacity, to remove significant amounts of CO_2, the adsorbent must be cooled to cryogenic temperatures (-79°C). Operating the TSA system over a large temperature differential makes thermal management challenging. The heating and cooling times also impact how fast the beds can be cycled and hence drive the size of the system.

II. TDA's System

TDA is developing a compact, regenerable sorbent-based system to remove CO_2 from the space suit ventilation loop. The system uses two alternating sorbent beds operated in a cyclic manner; one bed absorbs CO_2 from the ventilation loop, while the other regenerates by rejecting CO_2. The regeneration is carried out under vacuum, but above 6 torr to ensure that no Martian atmosphere could diffuse into the regenerating bed or into the ventilation loop. The CO_2 is removed and concentrated on the sorbent at 5°C (41°F) at 3 to 7.6 torr range, while the regeneration is carried out at 22°C (72°F) at high pressure. Upstream of the sorbent bed, the humidity will be removed by a condenser (from 18.5 torr to ~6 torr). The removal of the moisture is not required for operating the sorbent (i.e., the sorbent will not be poisoned), but to prevent water release to the environment (if desired). The sorbent can be modified with specific surface functional groups or an additional sorbent bed could be located upstream if the removal of trace contaminants such as ammonia is desired. The sorbent canister design also includes fine particle filters to prevent any migration of particulate matter away from the bed.

Both the adsorption and regeneration beds are thermally integrated with the cooling water loop circulated in the cooling garment. Figure 1 shows the sorbent beds integrated with the cooling loop and the valve positions that allow coolant flow in the same direction for both beds. In this design we use two pumps to circulate warm and cold water to each sorbent bed to promote regeneration and adsorption, respectively. We use the water from the cooling loop for the garment at 72°F and feed it to the bed under regeneration to increase its temperature. We will use all the water available in the garment (~240 lb/hr). The heat used to warm the sorbent bed and to support the CO_2 release will cool the water temperature to 70.9^{o}F. A small fraction of the water coolant (20.5 lb/hr) is separated and sent to a water or CO_2 evaporator, while the remainder of the coolant is sent back to the garment and then recycled back to

garment temperature control system. Before the evaporator, the small water flow is mixed with the water loop recycled from the cold bed. Following the evaporator, the 260.5 lb/h flow is introduced to the adsorbing bed cooling its temperature to 41°F. As it warms up to 42°F at the bed exit, it is sent back to the evaporator for heat rejection. An additional liquid pump and separate loops are used to ensure the highest comfort to the astronaut.
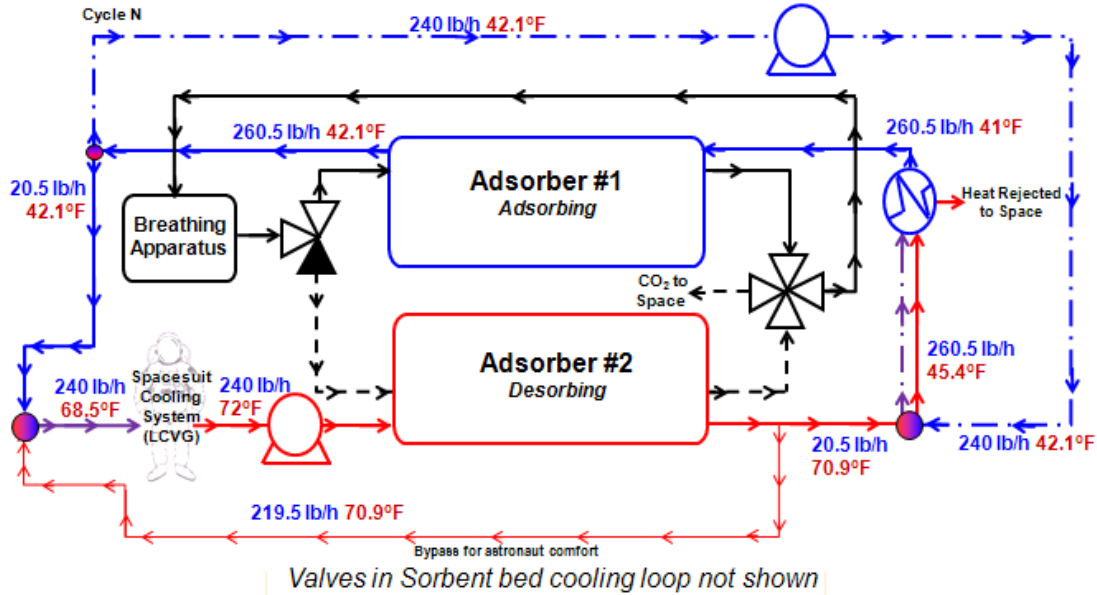

Figure 1. Schematic of TDA's system.

III. TDA's Sorbent

The key to the successful operation of TDA's TSA-based CO_2 removal system is a highly active, high capacity and very durable sorbent. The sorbent for our application (and in fact for any rapidly regenerable CO_2 removal process) must require only a modest heat input for regeneration. TDA's sorbent relies on CO_2 adsorption similar to that of the zeolite sorbents, however, the interaction between our sorbent and CO_2 is much weaker than in the conventional alkali sorbents and zeolites. We measured the heat of CO_2 adsorption on our sorbent in a differential scanning calorimeter (DSC) at different temperatures (Figure 2). The heat of adsorption for CO_2 over the sorbent varied between 4.5 to 5.6 kcal/mol CO_2 adsorbed with the average of heat of adsorption being $-\Delta H_{ads} = 4.9 \pm 0.4$ kcal/mol CO_2. The heat of adsorption remained constant across a large temperature range. The interaction is strong

Figure 2. Heat of adsorption of CO_2 as measured in DSC.

enough to enable CO_2 adsorption on the surface even at 3 torr CO_2. Because no true bond has been formed, the heat input to regenerate our sorbent is low. The energy required to regenerate our sorbent is also only half of the zeolite type adsorbents. This significantly decreases the heat load on the heat integration loop compared to zeolites.
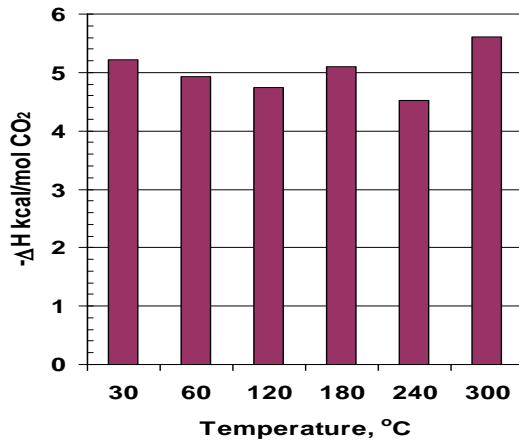
A. Test System

TDA's test system included two jacketed beds that can be cooled down to adsorption temperature (sub ambient conditions) or heated to desorption temperature (close to metabolic temperatures) using two separate circulating baths. The system has valves that direct either the hot fluid or the cold fluid through the bed jackets to maintain the sorbent beds at metabolic temperatures or the sub ambient temperatures. Similarly we have valves on

either side of the two beds to direct either the adsorption gas flow (7.6-16 torr CO_2 in air) through the bed or apply vacuum for desorption.

Foam-Bed Reactors: We used a pancake style reactor assembly (i.e, with L/D ratio less than 1 to minimize the diffusion bed length for the desorbed CO_2). It had reticulated foam from ERG, a commercial supplier as heat transfer medium in the sorbent bed (Figure 3). The sorbent particles were loaded in the voids of the reticulated foam similar to the way Hamilton Sundstrand's solid amine sorbent dispersed into a thermally conductive metal foam.

Thin-walled Aluminum Reactors: Even though the metal foam provided better heat transfer through the sorbent bed, because of the large mass of the foam and the housing that supported it, it took more than 20 minutes to reach the target temperature.

Figure 3. Picture of TDA's reticulated foam reactor.

This will not be a problem in a large unit where mass of the reactor housing mass will be relatively smaller than that of the sorbent. To expedite the cycling time and provide good heat transfer we also carried out bench-scale evaluations in a jacketed aluminum reactor. It had a polyethylene jacket around the thin walled aluminum reactor (wall thickness 0.028") with an aspect ratio (L/D) of 4.65. The outer polyethylene jacket minimized the heat loss to the outside. Thin wall aluminum reactor tube provided high conductivity and low thermal mass relative to sorbent bed to promote rapid thermal cycling. Figure 4 shows the schematics of the thin walled aluminum reactor assembly. Figure 5 compares the temperature profiles during a typical cycle achieved over the jacketed foam bed reactor and the thin walled aluminum reactor at bench scale. The thin walled aluminum reactor reached the target temperature in 10 minutes, which allows us to carry out rapid temperature swing of the sorbent beds.

B. Multiple Cycle Test Results

We carried out a total of 1102 cycles with our sorbent. The cycles 1 through 540 were carried out using the foam bed reactor and for the cycles 541 through 1102 we used the thin walled aluminum reactor. We transferred the same sorbent to a different reactor to continue cycling. During these tests, we varied the operating parameters to study their impact on sorbent performance, and also carried out more than 1,100 cycles to demonstrate its long-term performance and durability. The sorbent maintained a stable capacity of over 1.45% wt. CO_2 over the 1,100+ cycles.

Figure 4. Thin walled Aluminum Reactor.

We cycled our CO_2 sorbent in the two-bed foam reactor system at an adsorption pressure of 212 torr (P_{CO2} = 7.6 to 19 torr) and desorption at vacuum (less than 1.0 torr). We varied the space velocity, temperature and inlet CO_2 concentration. The summary of the results is provided in Figure 6. Even though the two sorbent beds are almost identical, we observed that some slight difference in the CO_2 removal capability of one of the beds was slightly lower, presumably due to the difference in the heat losses from the beds. Our measurements indicate that Bed #2 has better heat transfer (16.8 kW) compared to Bed #1 (12.3 kW); calculations were based on the temperature increase (or decrease) on the coolant supplied to the two reactors. All the CO_2 breakthrough profiles and the capacity calculations were carried out while taking the system dead
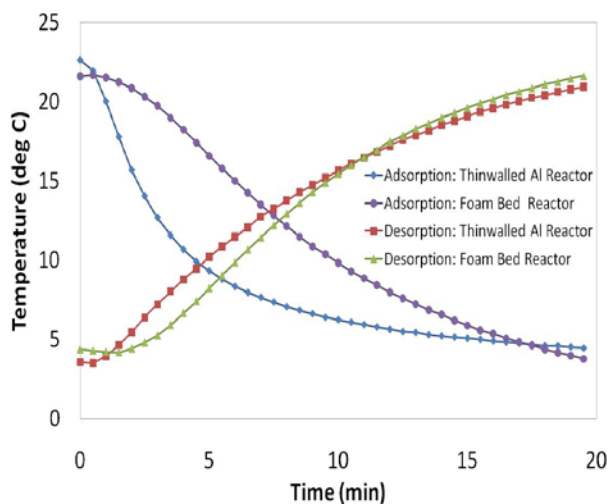

Figure 5. Heat transfer comparison between the two reactors.

volume into account. The system has a dead volume of 400 mL, which takes about 5.7 minutes to sweep through at the baseline flow rate of 70 sccm.

When tested in the foam bed reactors, TDA's CO_2 sorbent showed a stable performance over 540 cycles and achieved capacities in excess of 1.47% wt. CO_2 and reduced the CO_2 concentration from 16 torr to less than 1.0 torr (on average less than 4 torr) with max CO_2 level of 12 torr at the bed exit. Figure 7 shows the CO_2 breakthrough at a CO_2 partial pressure of 7.6 torr. The CO_2 concentration in the gas exiting the sorbent bed was at 0.2 torr at the beginning of the adsorption step and slowly climbed up to 4.2 torr at the end of the adsorption experiment. The average CO_2 concentration in the gas exiting the bed is about 2.0 torr. Figure 8 shows the CO_2 breakthrough at a CO_2 partial pressure of 16 torr. The CO_2 concentration in the gas exiting the sorbent bed was at 0.6 torr at the beginning of the adsorption step and slowly climbed up to 12.0 torr at the end of the adsorption experiment. The average CO_2 concentration in the gas exiting the bed is about 6.0 torr.

After 540 cycles we reloaded the sorbent from the foam bed reactors in the jacketed thin walled aluminum reactor and carried out further cycling experiments under rapid thermal cycles at an adsorption pressure of 212 torr and desorption at vacuum (less than 8 to 27 torr). We varied the cycle time, space velocity, and temperature. The summary of the results are provided in Figure 9. With the aluminum reactors and polyethylene jackets we eliminated the differences between the two beds under rapid cycling conditions.

A typical CO_2 breakthrough profile obtained under rapid cycling conditions with the thin walled aluminum reactor is provided in Figure 10. The CO_2 concentration was reduced from 7.6 torr to less than 1 torr at the beginning of the adsorption step and stayed less than 0.2 torr before breaking through at 8 minutes and increasing to inlet level of 7.6 torr.

Figure 6. Summary of multiple cycle test results on TDA's CO_2 Sorbent in the foam bed reactors. Cycles 1 through 540.

Figure 7. CO_2 breakthrough profiles at inlet CO_2 = 7.6 torr, GHSV = 37 h^{-1}; $T_{ads. (avg.)}$ = 4.2°C, $T_{des. (avg.)}$ = 19.3°C.

Figure 8. CO_2 breakthrough profiles at inlet CO_2 = 16 torr, GHSV = 37 h^{-1}; $T_{ads. (avg.)}$ = 4.2°C, $T_{des. (avg.)}$ = 19.3°C.

The sorbent maintained stable capacity of 1.45% between cycles 640-720 and cycles 1040-1,102 under identical operating conditions as shown in Figure 9. In the cycles between 720 and 1,040 we varied the regeneration pressure, space velocity, cycle time, ΔT and also studied the impact of moisture on the sorbent capacity.
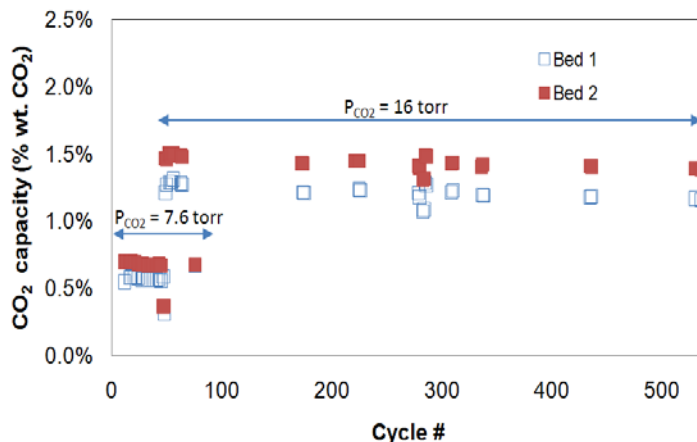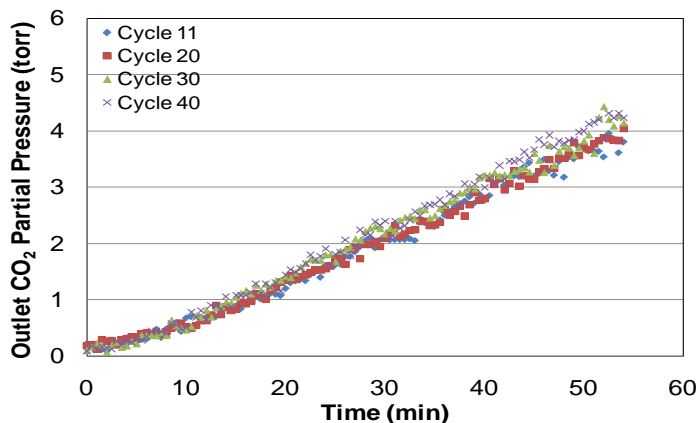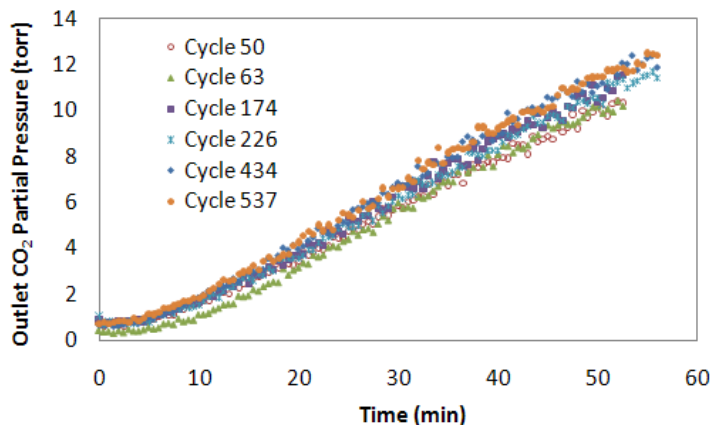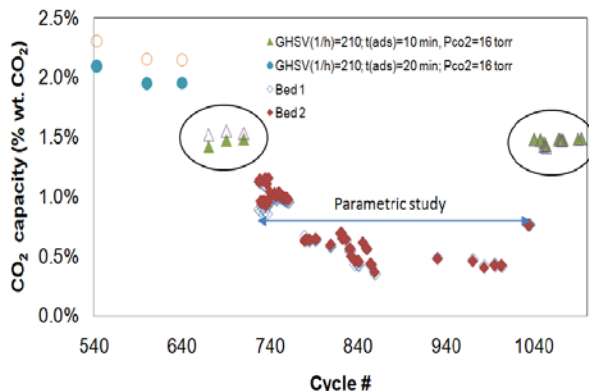
Figure 9. Summary of multiple cycle test results on TDA's CO_2 Sorbent in the thin walled aluminum reactors. Cycles 541 through 1,102.
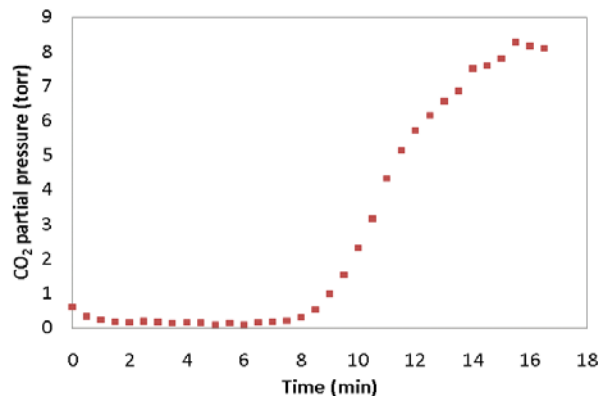

Figure 10. Typical breakthough profile under rapid cycling with thin walled aluminum reactor.

C. Impact of Space Velocity

Figure 11 shows the impact of space velocity on the sorbent performance with the foam bed reactor. The sorbent capacity for CO_2 increased at higher space velocities. This increase was attributed to higher amount of CO_2 provided to the sorbent bed (with presumably high un-utilized capacity). When the space velocity doubled, however, the corresponding capacity increase was less than two times since at lower space velocities the sorbent achieved a much lower CO_2 leakage. The average CO_2 concentration in the exit gas was 0.2 torr and the maximum CO_2 concentration in the exit gas was 1.8 torr. At even higher space velocities (GHSV = 210 h^{-1}) with the thin walled aluminum reactor TDA's CO_2 sorbent achieved higher capacities of 1.48% and 1.95% at half-cycle time of 10 min and 20 min respectively with an average CO_2 leakage of 0.2 torr and maximum CO_2 leakage of 0.9 torr (the space velocity is calculated based on the overall volume of sorbent and the foam).
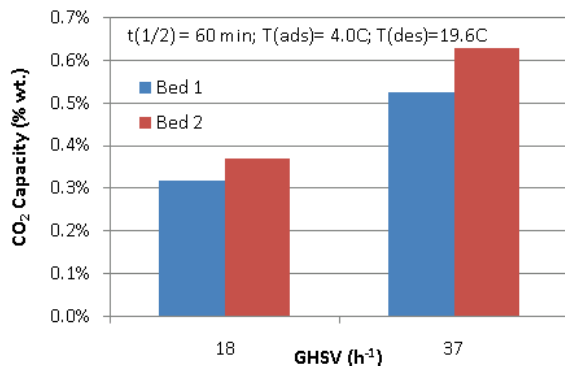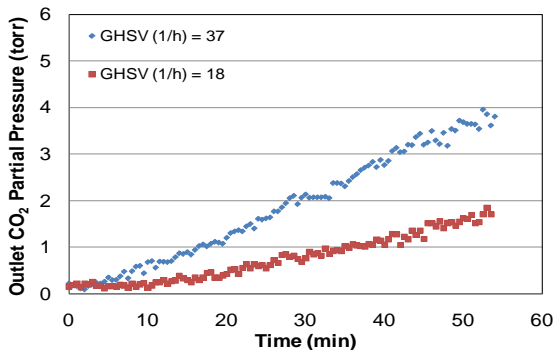

Figure 11. Impact of space velocity on CO_2 breakthrough – foam bed reactor. Inlet CO_2 = 7.6 torr, $T_{ads. (avg.)}$ = 4°C, $T_{des. (avg.)}$ = 19.6°C.

D. Impact of CO_2 Partial Pressure

Figure 12 shows the impact of higher CO_2 partial pressures in the inlet gas on the CO_2 breakthrough. The maximum CO_2 in the exit gas increases from 4.2 torr to 8.8 torr but the sorbent capacity also increases from 0.52% wt. CO_2 to about 1.47% wt. CO_2.

E. Impact of Temperature

Figure 5 shows the typical temperature profile in the bed during adsorption and desorption steps in the foam bed reactor. The bed transitions from the adsorption temperature (about 0°C) to desorption temperature (about 25°C), with average temperature differential of 19.6°C maintained during
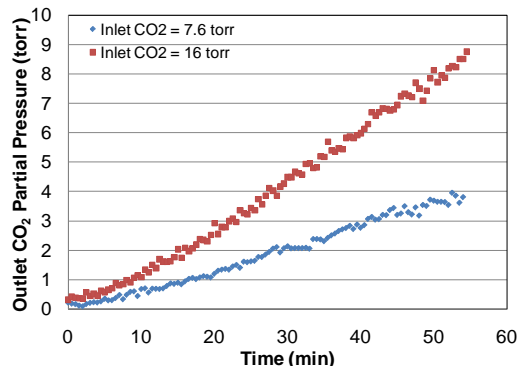

Figure 12. Impact of higher levels of CO_2 in the inlet gas on CO_2 breakthrough. GHSV = 38 h^{-1}, $T_{ads. (avg.)}$ = 4.3°C, $T_{des. (avg.)}$ = 19.5°C.
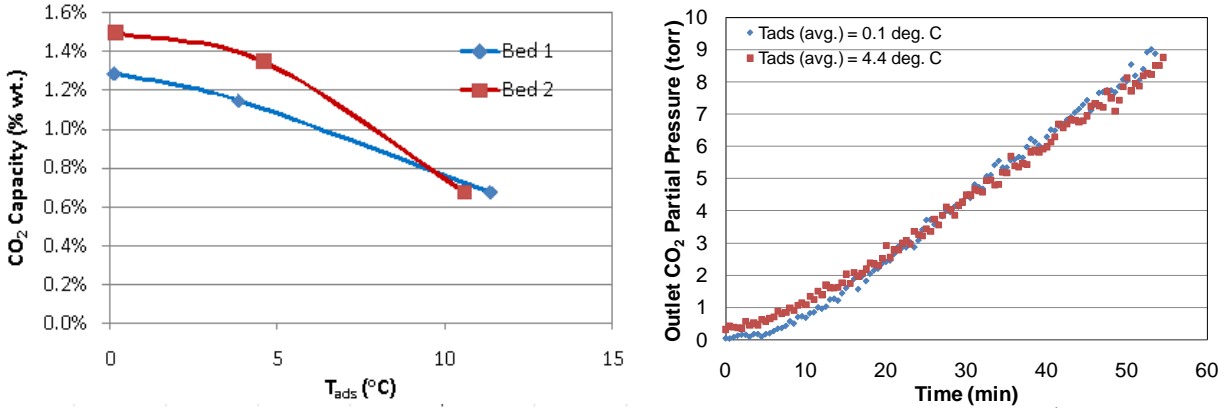
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Figure 13. Impact of adsorption temperature on CO_2 breakthrough. Inlet CO_2=16 torr, GHSV=37 h^{-1}.

regenerations and an average temperature of 4.0°C during adsorptions. This transition took about 40 minutes to get to 95% of the target temperature indicating that the experimental system was heat transfer limited. To overcome this problem we isolated the reactors after adsorption and desorption steps and waited for the temperature to reach target values before starting the adsorption gas flow or the vacuum desorption. Cycles 51 through 56 were carried out in this manner. The sorbent showed better removal efficiency in the initial part of the cycle as shown in Figure 13. The sorbent capacity improved significantly as the adsorption temperature is decreased from 12°C to 4°C but did not improve as much when the adsorption temperature is further decreased to 0°C most probably due to slower diffusion rates at lower temperatures.

F. Impact of Desorption Pressure

We carried out desorption at different pressures to simulate the Martian atmosphere. Figure 14 and Figure 15 shows the impact of desorption pressure on CO_2 breakthrough and the CO_2 capacity at low space velocity (GHSV=11 h^{-1}). We observed that the CO_2 leakage concentration increased and the capacity decreased as the desorption pressure increased due to the reduction in driving force. At higher space velocity the contact time is lower while the linear velocity is higher and the solid (sorbent) diffusion rate increases with contact time while gas phase diffusion rate increases with the linear velocity. We also carried out desorption at 13 torr at high space velocity (GHSV=210 h^{-1}) and observed that the leakage concentration was less than 2 torr while the capacity was increased to 0.96% wt. CO_2. This shows that gas phase diffusion, which will be low at sub ambient temperatures, controls the CO_2 adsorption on our sorbent under the Mars space suit EMU operating conditions. These experiments under high CO_2 partial pressure suggest that we could make a practical device that operates well above the pressure of the Martian atmosphere.

G. Impact of Moisture

We evaluated TDA's CO_2 sorbent using moisture laden air. We carried out experiments at two different moisture levels of 1,750 (dew point of –17.5°) and 13,850 ppmv (dew point of 22°F F).
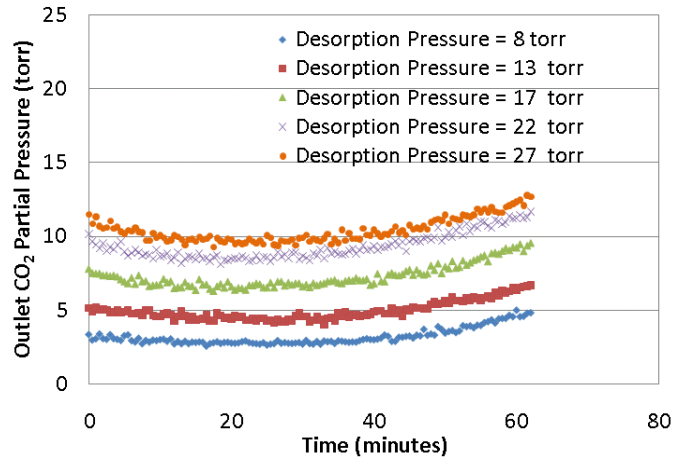

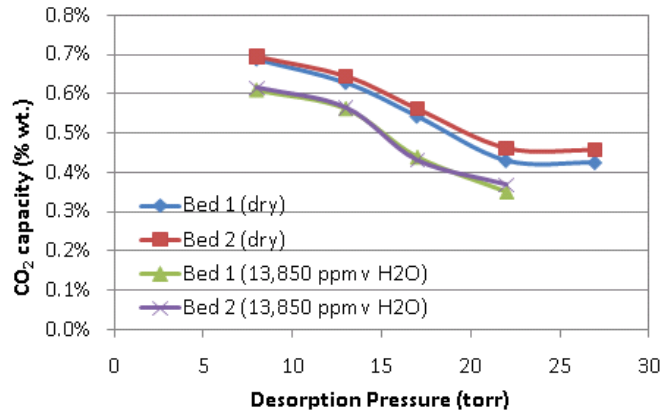Figure 14. Impact of desorption pressure on the CO_2 breakthrough. GHSV = 11 h^{-1}; ΔT = 25°C; P_{CO2} = 19.2 torr.

Figure 15. Impact of desorption pressure on the CO_2 capacity. GHSV = 11 h^{-1}; ΔT = 25°C; P_{CO2} = 19.2 torr.

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We observed that our sorbent has limited capacity for water (Figure 16) but is still selective to CO_2 and retains most of its CO_2 capacity as seen in Figure 16 and Figure 17.

Zeolites on the other hand could interact with water very strongly and needs a larger ΔT of the order of few hundred degrees for desorption. We carried out cycling experiments with moisture laden air (13,850 ppmv) using commercial zeolite – 13X (NaX). Figure 18 shows the impact of moisture on the CO_2 capacity of the zeolite –13X. We see that the sorbent loses much of its capacity on exposure to moisture and does not regain the lost capacity back on returning to cycling under dry conditions. TDA's CO_2 sorbent maintains its selectivity in the presence of moisture, retains more than 90% of its capacity and regains the lost capacity back on returning to cycling under dry conditions. At higher space velocity TDA's CO_2 sorbent had a capacity of 0.96% wt. CO_2 in the presence of moisture at a desorption pressure of 13 torr.
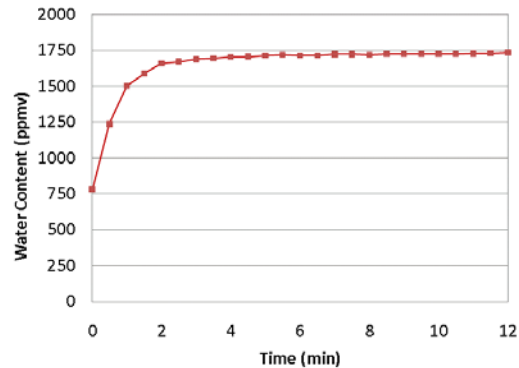

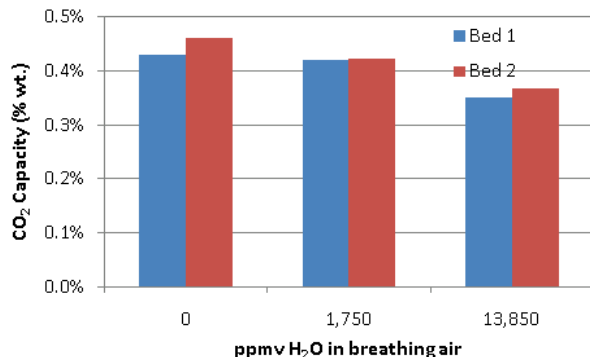Figure 16. Water breakthrough on TDA's Sorbent. H_2O = 13,850 ppmv.

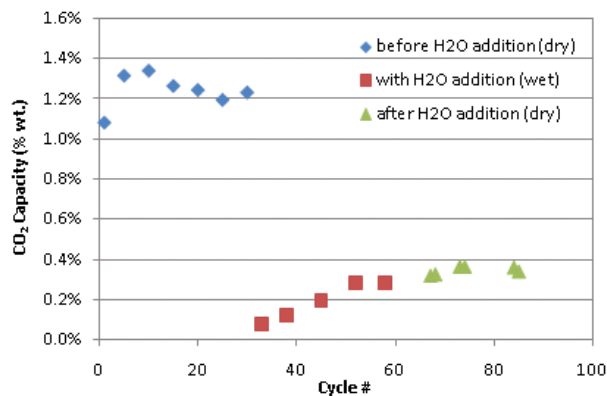Figure 17. Impact of moisture on TDA's Sorbent. P_{des}=22 torr.

Figure 18. Impact of moisture on Zeolite-13X (NaX) Sorbent. P_{des}=17 torr.

IV. System Design

Based on the test data we carried out a preliminary system analysis to estimate the size and weight of the CO_2 control system. Based on sorbent capacity and optimized operating conditions (primarily temperature of adsorption and regeneration) we have estimated the amount of sorbent needed to provide life support. We have then proceeded with the design of the sorbent reactors using three additional operating criteria to minimize:

1. Heat transfer limitations across the sorbent bed
2. Pressure drop across the bed during adsorption (this also helped us with reducing the bed depth that the CO_2 must diffuse through during vacuum regeneration)
3. Oxygen loss (we assumed a 3 bed design to allow pressure equalization and reduce the amount of oxygen loss during vacuum desorption)

The boundary of the system analysis problem and some of the assumptions we used in the system design are summarized in Table 1. We carried out the design for an average metabolic rate of 850 Btu/hr to remove an average 0.17 lb/hr CO_2. As used in the bench-scale experimental tests, we assumed a suit pressure of 4.1 psia with oxygen flow rate in the PLSS circulation loop of 6 ACFM (5.28 ACFM of oxygen flow rate after accounting for 7.6 and 6.5 torr maximum CO_2 and H_2O at the entrance of the CO_2 removal device). For our system, we selected a full cycle time of 15 minutes (with adsorption step time of 5 min for each bed) and a CO_2 capacity of 1% wt. (lb of CO_2 per lb of sorbent). At this capacity, using a 3 bed design (selected for reducing potential oxygen loss during regenerations) we estimated that 1.42 lb of sorbent will be used in each bed, corresponding to an overall carbon sorbent volume of 118 in^3 (1.94 L) in each of the 3 beds. We also estimated the volume of the reticulated aluminum metal foam to support the sorbent as 131.5 in^3 (2.15 L).

The three sorbent beds are incorporated into a single module with proper manifolding for the distribution of the gases to supply the beds with the circulation loop gases and expose the beds to vacuum (e.g., Martian atmosphere

through a proper vent). It has been conceptualized that these beds are all connected to a multi-port flow selection valve to control the bed function similar to the spool valve used in HSC's amine swing bed design. These beds are thermally insulated with minimal thermal linking in between the reactor and with the environment. Each bed is integrated with the liquid cooling garment, with separate inlet and exit streams for water from the LCVG.

Figure 19 provides a schematic of a three-bed sorbent assembly. The valves used for the switch/selection of the gas and water flow is not shown to provide clarity. The beds will have 11.5" x 11.5" cross-sectional area at 1" thickness in the air flow direction to minimize pressure drop across the bed. The overall sorbent module will fit into an envelope of 12"x12"4.3" envelope excluding the external manifolds (but including the internal insulation).

As used in the bench-scale test setup, we selected a 10 ppi aluminum metal foam to house the sorbent and provide a thermal pathway to provide cooling and heating during the adsorption and regeneration steps. In the selection of metal foam properties we used the guidelines provided on the ERG DuoCell website (both for pore volume properties and the thermal properties of the foam). This foam has a 0.1" diameter open cell area.

In order to maximize the heat transfer from the water side to the sorbent material we will use 12 stainless steel tubes that pass through the aluminum foam at 1" spacing. These will be ¼" diameter tubes and manifolded together at each end of the bed. Figure 20 shows a cross-section of the bed design with the water tubing embedded into the metal foam.

Thermal modeling was performed on the heat transfer through the metal foam and sorbent with this design approach using an isothermal model (however, the real conditions will be constant heat flux). We took a section of the foam where a ¼" SS tube passes through a 1" square piece of foam and sliced that section into 1/10" slices. Next, we found a circular section having the same area as the square to be able to treat each slice as a circular fin in the thermal calculations. Since the amount of aluminum and carbon is the same in each of the 1,360 cells in one bed, we can calculate the temperature distribution around each tube. We calculated the fin efficiency of the aluminum to be 88.2% with a nominal 1.7°F temperature difference between the aluminum and carbon. The weighted average temperature difference for the assumed circular cross section is 24.9°F (13.9°C).

The overall volume of the aluminum foam with bed dimensions of 11.5" x 11.5" x 1" is 132 in³. Since this is a 10% density foam this allows a sorbent volume of 118 in³. With a density of aluminum of 0.01 lb/ft³ there is 1.32 lbs aluminum per bed. The carbon sorbent has a density of 20.7 lb/ft³ which allows a sorbent loading of 1.42 lbs/bed. The total heat load can be calculated from the sum of the individual heat

Table 1. Mars CO_2 Removal System Sizing.

|	
Average metabolic Rate (btu/hr)	850
Average CO_2 rate (lb/hr)	0.17
O_2 flow rate (42.4 slpm = lb/h)	8
At 4.3 psia, 41°F	
Air flow rate (with 6.5 torr H_2O & 7.6 torr CO_2 ACFM)	5.28
Full cycle time (min)	15
Adsorption time (min)	5
Sorbent CO_2 loading	1%
Sorbent density (lb/ft³)	20.7
CO_2 flow rate into bed (lb/h)	0.40
CO_2 flow out of bed (lb/h)	0.23
CO_2 out of bed (torr) (with 6.5 torr H2O)	4.45
TDA Sorbent per bed (lb)	1.4167
TDA Sorbent volume (L per bed)	1.94
Al foam volume (L per bed)	2.15
Space Velocity (h⁻¹)	1,312
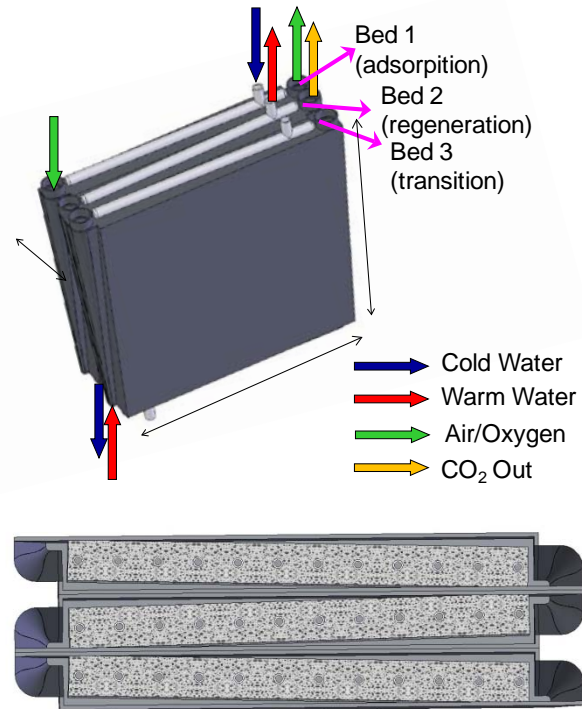
Figure 19. Three bed reactor system showing the gas and cooling water flows.

loads of the sorbent, the heat of reaction, and the aluminum foam. For the sorbent, the heat load is then 6 BTU per ½ cycle, or 72.4 BTU/hr. For the aluminum foam, the heat load is 6.9 BTU per ½ cycle, or 83.2 BTU/hr. The heat of reaction is given as 221 BTU/lb CO_2 therefore requiring 12.5 BTU per ½ cycle, or 75.2 BTU/hr. The total heat load is then 230.8 BTU/hr.

In the preliminary system analysis we estimated that 5.8 L (1.8 kg) of the sorbent must be used in the Martian PLSS. The overall size of the CO_2 control system excluding the external manifolds for a 3-bed system is estimated to be 12" x 12" x 4.3" weighing less than 3.7 kg (8.2 lb). We also estimated that at 6 ACFM gas circulation rate the unit will produce no more that 5.3 inH_2O pressure drop and the parasitic loss associated with the water circulation and overcome the pressure drop in the gas loop will be less than 67.6 W (230.8 BTU/hr). The system uses multiple beds to achieve continuous CO_2 removal. We have selected a 3 bed design to allow proper pressure equalization during the bed transitions to ensure minimal loss of O_2 to space (e.g., the bed just came out of the vacuum is connected to the bed that will be exposed to vacuum to reduce its pressure to half, effectively cutting down the amount of gas to be vented by half). We estimated the oxygen loss to be less than 0.03 lbs for an 8 hr. Although no significant attempts were made to optimize the number of sorbent beds used in the system, we found that a 2 bed design without proper pressure equalization had an oxygen loss below 0.06 lb during an 8 hr EVA. Hence a simple two-bed design may be advantageous in this case since it reduces the system weight and size significantly (12" x 12" x 3.4" envelope weighing less than 2.7 kg (5.3 lbs) compared to oxygen savings.
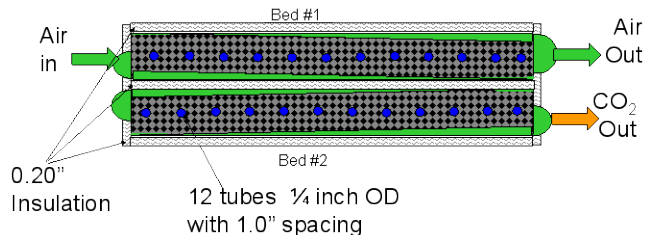

Figure 20. Crosss-section of two beds (third bed is inactive and used for transitions).

V. Conclusion

We demonstrated the feasibility of our concept in a series of bench-scale experiments and by conducting a preliminary system analysis. We carried out extensive evaluations with our CO_2 Sorbent in a bench-scale test setup, simulating the operation of the sorbent beds in the ventilation loop under highly representative conditions (i.e., adsorption and regeneration under sub-atmospheric pressures across the desired temperature differential). We showed that the sorbent regeneration can be accomplished with a temperature swing of just 17°C, while regenerating the sorbent at 13 torr (well above either the pressure of Martian atmosphere or the martian CO_2 partial pressure). We showed that the CO_2 adsorption capacity could exceed 2.1% wt. (lb of CO_2 removed per lb of sorbent) under representative conditions. Although this is lower than that achieved by the molecular sieves adsorbents, the lower temperature differential used for the sorbent regeneration allows rapid cycling of the bed and better utilization of the sorbent. In addition our sorbent is tolerant to moisture, maintaining its cyclic capacity even in the presence of humidified gas with 5°C dew point (under the same conditions the molecular sieve adsorbent degrades within 30 cycles). We explored reactor designs to best integrate the sorbent with engineered structures that allow us rapid heat transfer to achieve short cycles times, demonstrating reasonably high working capacity in full cycle times as short as 10 minutes. We performed 1,100 adsorption/regeneration cycles to demonstrate its life and durability; the sorbent maintained a stable capacity throughout the multiple cycle tests with no signs of degradation in performance.

Finally, we carried out a detailed engineering analysis to assess the technical viability of the concept. We estimated that for a three-bed system 5.8 L (1.8 kg) of the sorbent must be used in the Martian PLSS. The overall size of the CO_2 control system excluding the external manifolds will fit into a 12" x 12" x 4.3" envelope weighing less than 3.7 kg (8.2 lb). We estimate that at 6 ACFM gas circulation rate the unit will produce no more that 5.3 in H_2O pressure drop. The parasitic loss associated with the water circulation and overcome the pressure drop in the gas loop will be less than 67.6 W (230.8 BTU/hr). Although no significant attempts were made to optimize the number of sorbent beds used in the system, we found that a 2 bed design without proper pressure equalization had an oxygen loss below 0.06 lb during an 8 hr EVA. Hence a simple two-bed design may be advantageous in this case since it reduces the system weight and size significantly (12" x 12" x 3.4" envelope weighing less than 2.7 kg (5.3 lbs) compared to oxygen savings.

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