

# RAPID CYCLING CO<sub>2</sub> and H<sub>2</sub>O REMOVAL SYSTEM for EMU

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## ABSTRACT

NASA's planned future missions set stringent demands on the design of the Portable Life Support Systems (PLSS), requiring dramatic reductions in weight, decreased reliance on supplies and greater flexibility on the types of missions. Use of regenerable systems that reduce weight and volume of the EMU is of critical importance to NASA, both for low orbit operations and for long duration manned missions. The CO<sub>2</sub> and humidity control unit in the existing PLSS design is relatively large, since it has to remove 8 hours worth of CO<sub>2</sub>. If the sorbent regeneration can be carried out *during* the extravehicular activity (EVA) with a relatively high regeneration frequency, the size of the sorbent canister and weight can be significantly reduced.

TDA Research, Inc. (TDA) is developing a compact, regenerable sorbent-based system to control CO<sub>2</sub> and humidity in the space suit ventilation loop. The sorbent can be regenerated using space vacuum during the EVA, eliminating all duration-limiting elements in the life support system. This paper summarizes the results of the sorbent development and testing, and evaluation efforts. The results of a preliminary system analysis are also included, showing the size and volume reductions provided by the new system.

## INTRODUCTION

NASA's future missions require dramatic reductions in the weight and volume of the Portable Life Support System (PLSS) (Fullerton, 2001). Existing suit designs include separate CO<sub>2</sub> and H<sub>2</sub>O control units, and are designed to operate for 8 hours or more. The sorbent canister is relatively large since it has to remove 8 hours worth of CO<sub>2</sub>. To minimize the

logistics costs associated with expendable CO<sub>2</sub> removal system, NASA funded the development of a regenerable CO<sub>2</sub> control system that uses a metal oxide sorbent, referred to as "MetOx". The MetOx canister uses a silver oxide-based sorbent to remove practically all CO<sub>2</sub> generated during the EVA. After each EVA, the MetOx canister is thermally regenerated inside the spacecraft driving off the CO<sub>2</sub> in an oven (Butler, 1998). This system has been successfully used for several years, but has two major drawbacks: (1) the canister must contain enough sorbent to capture and stabilize all the CO<sub>2</sub> generated during the EVA, thus, the unit is relatively large and heavy, and (2) the capacity of the CO<sub>2</sub> control unit limits the duration of the EVA, since when the sorbent is saturated, the CO<sub>2</sub> concentration in the suit will rapidly rise to fatal levels. As NASA's missions become more demanding, there is a need to reduce the logistics burden and the weight and volume of the PLSS components. A record 8 hour and 56 minute EVA on STS 102 is already pushing the limits of the system's endurance and capability (NASA STS 102 Post Mission Summary, 2001).

A next generation space suit design is under consideration that uses a regenerable CO<sub>2</sub>/H<sub>2</sub>O removal system; referred to as the Rapid Cycling Amine (RCA) system (Dean, 1998). The RCA will rely on two alternating beds of solid amine sorbent to remove CO<sub>2</sub> and H<sub>2</sub>O from the vent loop and will regenerate cyclically during the EVA. Although the solid amine system is simple, durable and dependable, two major problems still need to be addressed: (1) low CO<sub>2</sub> adsorption capacity both on a mass and volume basis because of the sorbent's high molecular weight (large, low volatility amines are needed to minimize the loss of the amines to space during regeneration), and (2) the presence of a faint ammonia smell in the ventilation loop that

causes discomfort to the crew person (Wilson and Lawson, 1990).

TDA Research, Inc. (TDA) is developing a compact, regenerable long sorbent-based system to control CO<sub>2</sub> and humidity in an advanced space suit. The sorbent is regenerated by pressure swing provided by the space vacuum. The system uses two alternating beds; one bed removes CO<sub>2</sub> and H<sub>2</sub>O from the ventilation loop while the other regenerates under space vacuum (without additional heating).

The system has significantly lower weight and volume than the regenerable CO<sub>2</sub> removal system currently used in the EMU, which uses a silver oxide-based sorbent (i.e., MetOx system). The system weight is reduced by minimizing the amount of sorbent needed for CO<sub>2</sub> control by frequent regenerations using space vacuum. Since the sorbent can control both the CO<sub>2</sub> and water vapor concentrations in the breathing loop, it eliminates the need for the condensing heat exchanger and the rotary water separator for humidity control used in the current EMU design, eliminating the interdependency between the EMU vent and water-cooling loops. This greatly simplifies the life support system, which in turn increases the reliability by eliminating the interface and interaction between subsystems and makes our system simpler and therefore more reliable.

This sorbent has to bind CO<sub>2</sub> just strongly enough to remove it from the breathing gas, but not too strongly, so that the regeneration can be carried without increasing the bed temperature. The sorbent is prepared with TDA's geode technology, which provides high durability through repeated cycling. This paper summarizes the results of our sorbent development efforts.

### **Sorbent Development**

TDA used a proprietary material to remove CO<sub>2</sub> from the gas mixture. The active phase is prepared on commercially available high surface area (550 m<sup>2</sup>/g) silica, which provides favorable support for the active phase and also serves as an excellent sorbent for water vapor removal. The powder was then pelletized using the TDA's proprietary geode technology to form 1/16" or 1/8" cylindrical pellets. This geode structure allows us to combine 80% or

more of active material with an inert binder to provide the mechanical integrity and physical strength needed for the intended application.

The final preparations were pre-screened to identify those that met the physical criteria (i.e., crush strength, surface area, porosity). The sorbents with acceptable physical properties were further tested to measure their activity and capacity, first in a thermogravimetric analyzer and then in a bench-scale reactor. Based upon the screening results, we identified a single-best formulation, which was further tested to evaluate its performance during a multiple-cycle test.

### **Sorbent Testing**

**Preliminary TGA Tests:** The initial capacity screening of the sorbent formulations was carried out using a Shimadzu TGA-50 Thermogravimetric Analyzer. We used gas streams composed of CO<sub>2</sub> only or moisture-laden CO<sub>2</sub> to identify the combined and individual H<sub>2</sub>O and CO<sub>2</sub> sorption capacity of the sorbents. We varied the operating parameters (i.e., adsorption time and temperature, regeneration time) to identify sorbent performance under the conditions of interest. We used the temperature in the 25-35°C and 25-60°C range for adsorption and regeneration, respectively. Although an ideal system should not require any heat input for the regeneration step, we wanted to explore potential capacity improvement that could result from bringing heat to the adsorption side. In these initial TGA tests, we also optimized the adsorption duration. For example, we limited the adsorption duration to where we observed the steepest change in the slope (the slope indicates the rate of CO<sub>2</sub> removal, dW/dt). We usually observed the fastest increase when CO<sub>2</sub> was first introduced in the first 10-15 minute duration. The rate of removal slowed down after this time, and longer CO<sub>2</sub> exposures were determined to be less beneficial. We noticed that lower temperatures promote higher CO<sub>2</sub> capacities. We also observed higher weight gains in those cycles where humidity was introduced, which indicated that the sorbent was simultaneously removing CO<sub>2</sub> and water vapor.

Once we identified the best sorbent, we carried out more extensive testing. With this sample, we observed over 2% CO<sub>2</sub> capacity on saturation basis and 2.8% wt. water vapor capacity. Using the TGA,

we also performed an extended duration test to measure the long-term capacity of the sorbent. We performed a total of 509 cycles (Figure 2 shows the representative cycling details) on the pelletized sorbent. The testing of the best sorbent in the pellet form provides information not only on the capacity of the sorbent but also on the mass transfer limitations (i.e., pore diffusion, external film diffusion). The cycles were conducted isothermally at 25°C with adsorption performed under 1.54% CO<sub>2</sub>/N<sub>2</sub> and regeneration done under 100% N<sub>2</sub>. During the first 130 cycles the sorbent achieved an average of 0.64%wt. CO<sub>2</sub> capacity without showing any signs of degradation (at 4 min adsorption duration). As the sorbent was sufficiently 'aged', we tried to optimize the cycling conditions by varying the time of adsorption and/or regeneration. We noticed an increase in capacity if longer adsorption times were allowed; however, capacity was not significantly affected by a regeneration time increase. Due to its stable performance and high capacity, we selected this sample for larger scale testing in the flow reactor.

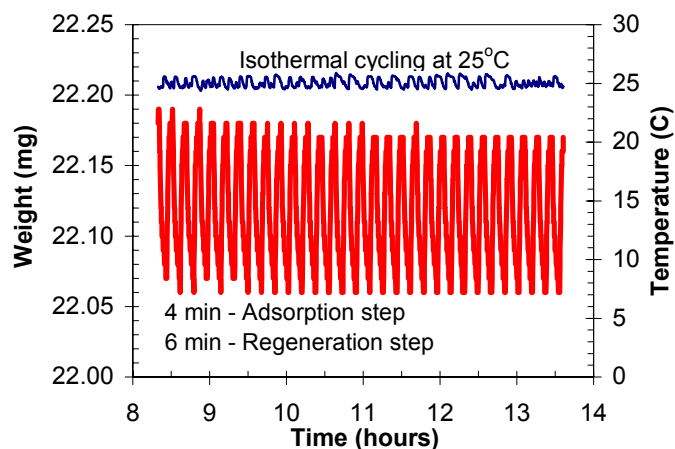


Figure 2. TGA multi-cycle test details.

**Bench-Scale Reactor Design:** The selected formulation was then tested for activity and durability in a bench-scale reactor under simulated reaction conditions to identify pre-breakthrough sorption capacity. Figure 1 presents a picture of the apparatus. In this design, we integrated two vacuum pump assemblies to simulate a 3.65 psia canister pressure during adsorption and a very hard vacuum (less than 0.5 torr) during regeneration (the vacuum was provided by the combination of a mechanical roughing pump and a cryo-pump). In order to

conduct the tests in the presence of water, the CO<sub>2</sub> balanced N<sub>2</sub> gas stream was passed through a saturator where water was mixed into the feed stream by sparging gases in a temperature-controlled humidifier. After mixing in a manifold, the gas stream was maintained above the dew point of water to prevent condensation (heat tapes were used to control the temperature as desired). The sorbent reactor consisted of a 1.0" OD stainless steel tube containing a frit at its mid-point to support from 8.0 to 16.0 g (8-20cc) of pellets. A valve system allowed the gas stream bypass the reactor and flow directly to the analytical system for accurate measurement of the feed gas composition. The CO<sub>2</sub> concentration and relative humidity were measured using an on-line CO<sub>2</sub> analyzer (California Analytical), and a moisture analyzer (Visala), respectively. The apparatus is fully automated and can run without an operator for long periods of time, including overnight. We used Control EG software to control test conditions, log analytical data, and safely shut down the apparatus in case of a malfunction.



Figure 1. Picture of the bench-scale test unit.

**Bench-Scale Test Results:** We conducted some of the initial flow reactor experiments at ambient pressure. We adjusted CO<sub>2</sub> and H<sub>2</sub>O concentrations in our tests so that they matched the same CO<sub>2</sub> and H<sub>2</sub>O partial pressures at the canister inlet. In most of the tests, we maintained an inlet partial pressure of 6.2-7.6 torr and 15.0-21.0 torr for CO<sub>2</sub> and H<sub>2</sub>O, respectively, balanced with oxygen or nitrogen. During the sorbent regenerations, we sometimes used nitrogen to simulate space vacuum.

We ran simulations of a full adsorption/regeneration cycle. We measured the breakthrough times, pre-breakthrough and ultimate sorbent capacity for CO<sub>2</sub>

and H<sub>2</sub>O. Usually in these tests we first observed the breakthrough for CO<sub>2</sub> and then for water vapor. In some tests, after observing the breakthrough, we continued to flow CO<sub>2</sub>/H<sub>2</sub>O to measure the ultimate adsorption capacity of the sorbent. Following adsorption step, the flow of adsorption gases into the reactor was stopped, and the reactor manifolds were purged with 500 sccm of N<sub>2</sub> to flush out the CO<sub>2</sub> and H<sub>2</sub>O remaining in the lines and reactor dead volume. Once a zero baseline in the analyzers was maintained, nitrogen was flown to drive off the CO<sub>2</sub> and H<sub>2</sub>O from the bed. CO<sub>2</sub> and H<sub>2</sub>O were monitored with an on-line CO<sub>2</sub> analyzer and a humidity sensor, and converted into mass units to obtain an overall CO<sub>2</sub> and H<sub>2</sub>O uptake capacity of the sorbent (the current humidity and CO<sub>2</sub> analyzers are not sensitive enough to measure the CO<sub>2</sub> and H<sub>2</sub>O given off during regeneration under vacuum). Next, the reactor was again purged with N<sub>2</sub> until all the CO<sub>2</sub> and H<sub>2</sub>O were removed from the system. After the regeneration step was complete, the reactor was ready for the following cycle.

To demonstrate the long-term cyclic capacity of the sorbent we performed 262 consecutive cycles at conditions simulating the actual operation of the system (temperature of 22°C and GHSV of 2,700 h<sup>-1</sup> were maintained during adsorption). We used an inlet CO<sub>2</sub> concentration of 7.6 torr and a water vapor level of 18.0 torr, simulating the CO<sub>2</sub> and water vapor levels in the breather loop based on average metabolic load. First, we conducted several saturation cycles at the beginning of the test (Figure 3). For all the following cycles we maintained 6 min ½ cycles. Regeneration was carried under nitrogen at GHSV of 2,700 h<sup>-1</sup>. For some of the tests we also used vacuum to regenerate the sorbent without having any nitrogen flow in the loop. The sorbent exhibited an average 0.71% wt. CO<sub>2</sub> adsorption capacity throughout these tests (Figure 4). The constant CO<sub>2</sub> uptake throughout 262 cycles indicates that the sorbent is durable and able to maintain its adsorption capacity through cycling. The water capacity of the sorbent was also unchanged with cycling; the average moisture loading was 1.09% wt. through 262 cycles. During these tests, the inlet dew point was maintained constant at 21-22°C. The material balance for the adsorption and desorption steps for selected cycles indicates a good match suggesting full regeneration potential of the sorbent using pressure swing only. The bench-scale reactor

test results clearly demonstrate that: (1) the sorbent can be used effectively for the combined CO<sub>2</sub> and H<sub>2</sub>O removal; (2) the sorbent can remove and release CO<sub>2</sub> and H<sub>2</sub>O at low temperatures (20°C–25°C); (3) the sorbent is regenerable and maintains its activity for at least 262 cycles.

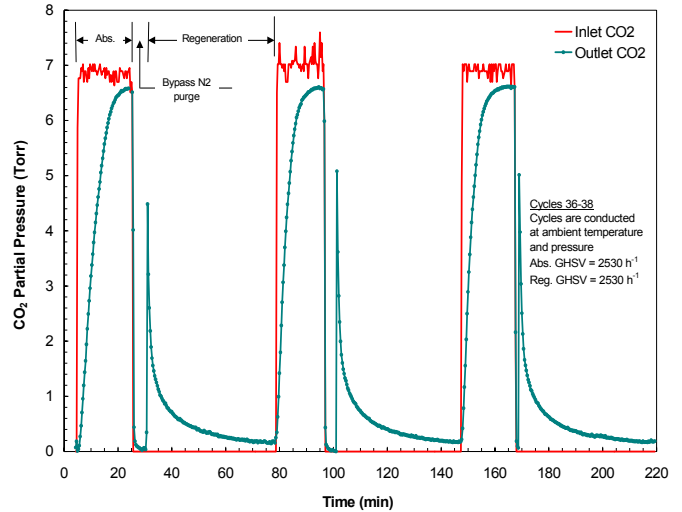


Figure 3. Typical saturation test-profile for multiple-cycle tests.

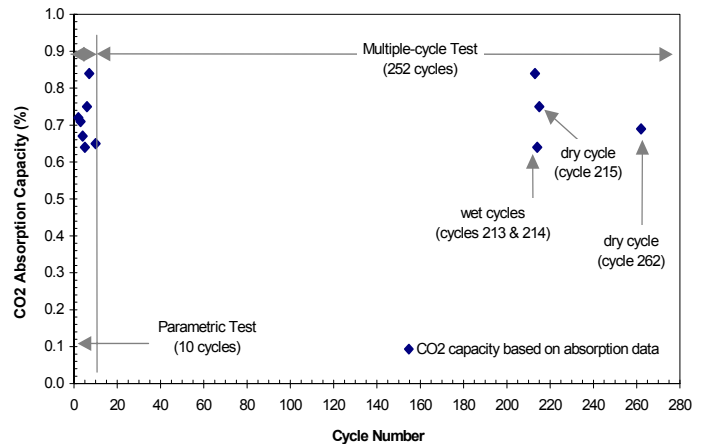


Figure 4. Multiple-cycle tests.

### System Design

The operation of TDA's system is similar to that of the RCA system (Figure 5). Like the RCA system, TDA's system uses two alternating sorbent beds operating in a cyclic manner to simultaneously adsorb the CO<sub>2</sub> and H<sub>2</sub>O from the space suit ventilation loop. The sorbent beds are continuously cycled, alternately adsorbing CO<sub>2</sub> and humidity from

the vent loop and rejecting the adsorbed material into the environment (i.e., space vacuum) without requiring any heating of the sorbent bed. Periodically, a series of valves are activated to switch the bed functions.

Upstream of the sorbent bed, either a carbon-based expendable or a silicalite-based regenerable trace contaminant cartridge is used to remove trace contaminants produced by the metabolism. The removal of the impurities is not required for operating the sorbent (i.e., the sorbent will not be poisoned), but for the comfort of the crew person. The sorbent canister design also includes fine particle filters to prevent any migration of particulate matter away from the bed.

The successful operation the sorbent requires effective heat management. The adsorption of CO<sub>2</sub> and H<sub>2</sub>O over the sorbent is an exothermic process, which will cause an increase in the bed temperature. If the temperature rise is not properly controlled, high temperatures will not only reduce the sorption capacity of the sorbent, but also require that the ventilation gas be cooled before it is sent to the suit requiring additional system components that increase the weight of the system. Similarly, during the regeneration, heat needs to be provided to the sorbent to desorb the CO<sub>2</sub> from the bed. The issue of heat management is addressed first by relying on the sensible heat capacity of the sorbent bed and the reactor components, and the heat released during the adsorption only slightly increases the bed temperature. During the regeneration, the

endothermic desorption of CO<sub>2</sub> and H<sub>2</sub>O cools the bed temperature. At an approximately 1% capacity for both CO<sub>2</sub> and H<sub>2</sub>O, such heat effects is relatively low. In addition, we will use an intelligent reactor design to transfer the heat where it is given off (the adsorption bed) to where it is needed (the bed under regeneration) using a similar approach introduced by Hamilton Sundstrand in their RCA design.

TDA's system requires re-circulation of the gases, as in the case of every closed-loop or low-venting life support system. This can be achieved either with an electric fan or an ejector driven by high-pressure stored oxygen (Goldfarb and Hodgson, 2001). The technology for the valve used to change the bed function (adsorption or regeneration) has also been developed. The Four Bed Molecular Sieve (4BMS) system of the ISS uses similar valves that allow vacuum regeneration of the CO<sub>2</sub> absorbent while providing sufficient sealing and safe operation. The linear motion spool valve design developed for the Rapid Cycle Amine (RCA) system is also easily adaptable to our system. The spool valve design not only changes the absorb/desorb flows but also partially equalizes the pressure between the two beds while switching positions. An important consideration in any rapid cycling system is the loss of oxygen trapped in the sorbent along with the CO<sub>2</sub> and H<sub>2</sub>O during regeneration. The loss of oxygen can be minimized by increasing the adsorption capacity of the sorbent (i.e., achieving a high sorbent CO<sub>2</sub> uptake in comparison to the amount of oxygen trapped in the bed) and by tightly packing the sorbent in the bed. Our initial estimates indicate that the oxygen consumption will only increase to 2-3% above that required for metabolic use if a reasonably high CO<sub>2</sub> adsorption capacity (0.5-1% on weight basis) can be maintained. The recent spool valve designs that allow pressure equalization between the adsorption and regeneration beds may further reduce losses, by saving the oxygen that would normally be required to re-pressurize the bed exposed to vacuum.

**Sorbent Bed Design:** We carried out the calculations based on the performance data of the sorbent that has a capacity of 0.71 %wt at a GHSV of 2400 hr<sup>-1</sup> at an inlet of 7.6 torr CO<sub>2</sub> and 18.0 torr of H<sub>2</sub>O. In a scaled up system, each sorbent bed should contain approximately 1125 cc to have a similar retention time.

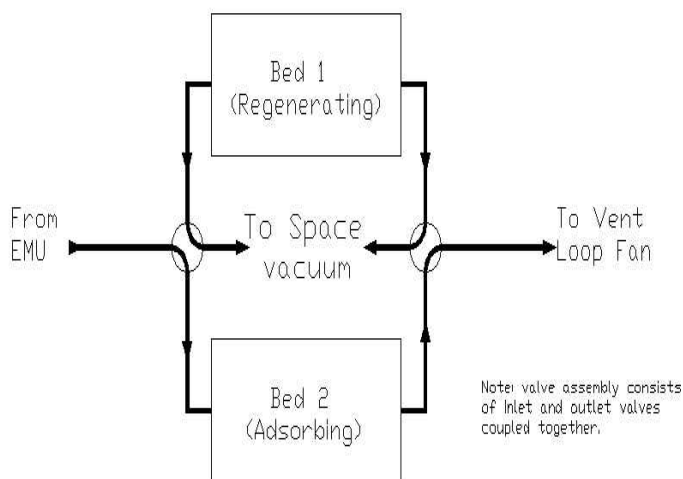


Figure 5. Schematic of TDA's system.

Table 1 presents a partial listing of the pertinent requirements for the system. The design of the components aims at reducing both mass and volume. Ideally, the volume of the proposed system should be less than that of the MetOx canister to enable its easy integration with the current EMU design as well as with advanced space suits. The new system should weigh less than 4.6 kg (this is the weight of the RCA system being developed by Hamilton Sundstrand). Since their system volume is fixed, the overall package including spool valve, solenoid valves and solid amine beds occupies an envelope of 23.22x13.33x14.24 cm. The system is designed to treat a 7.0 acfm oxygen flow at minimal pressure drop (less than 1.0 inH<sub>2</sub>O), without increasing the power draw of the fan used for gas circulation in the breather loop. The sorbent bed will be designed to remove 0.32 lb/hr CO<sub>2</sub> (which corresponds to 1,600 Btu/hr metabolic load) and 0.2 lb/hr H<sub>2</sub>O. The system pressure will operate at a pressure range of 3.3 to 15.1 psia on the adsorption side and regenerate with space vacuum. The nominal temperature range for its operation is between 50 to 90°F.

Table 1. Partial listing of pertinent requirements.

Parameters	Goal
Volume	Less than MetOx Canister
Weight	Less than 4.6 kg
Flow Rate	7.0 CFM O <sub>2</sub>
Pressure Drop	Less than 1.0 inH <sub>2</sub> O
CO <sub>2</sub> Adsorption Rate	0.32 lb continuous
Humidity Removal	0.2 lb/hr
Nominal Adsorption Pressure	3.3-15.1 psia
Nominal Temperature Range	50-90 °F

TDA has also identified two alternative designs. The process diagram is independent of which bed design is chosen, since all *in-situ* regenerable designs will need to incorporate two beds, the housing and plumbing for these beds, and a diverter valve to direct the flow of ventilation loop gas through the system. Bed designs were based on the sorbent that has a sorption capacity of 0.8% wt. at a GHSV of 2700 hr<sup>-1</sup> and under ambient pressure/temperature using a dry gas. In a scaled up system, each sorbent bed should contain approximately 1125 cc (488 g) of sorbent to have a similar retention time.

Bed design #1 (Figure 6) incorporates two parallel beds capable of continuous cyclic operation. The

overall dimensions of the housing are 16.2 cm height, 31.5 cm wide, and 8.5 cm deep. The total weight for this bed design is approximately 2 kg, including all supporting equipment such as the connectors, screens etc. The sorbent is held in place with 150 micron screens at the inlet and outlet of each bed. The main benefit of this design is being able to fit a cycling system into the volume of the MetOx system, while still meeting the other design requirements of capacity, weight, mass, and pressure drop. The diverter valve assembly would be mounted on the topside of the beds.

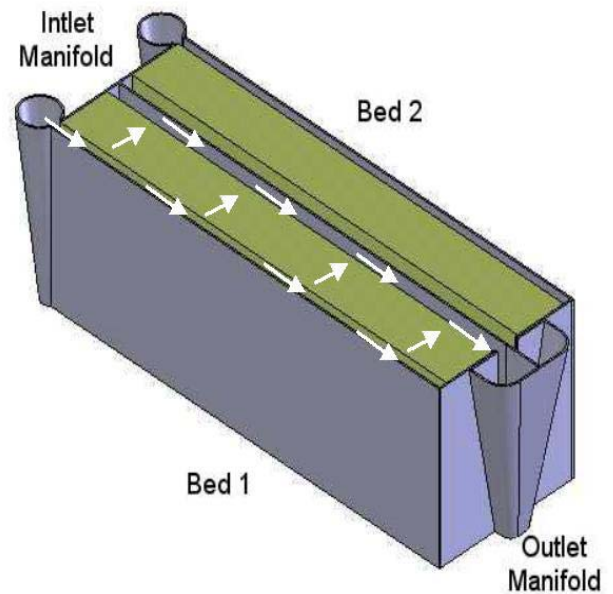


Figure 6. Bed design #1.

In this design the gas is introduced at the bottom of the Bed 1, collected at the top of the bed, and then diverted into an outlet manifold. A separator plate will be shared by the two beds, which will also transfer heat from one bed to the other. The heat transfer from the adsorption bed to the regeneration bed is improved with the addition of reticulated aluminum foam, which fills both the manifold areas and the sorbent areas. The foam performs several functions including: (1) providing a support to the bead retention screens, (2) providing a heat transfer media between the adsorbing and desorbing sorbent beds, and (3) accommodating any growth or shrinkage. We will adapt a very similar design to Hamilton Sundstrand's thermally conductive metal foam used in the RCA system to improve the heat transfer between the beds. This design minimizes the heat conduction distances and maximizes the

heat transfer area by arranging beds so that they share the common wall. Alternatively, this design can be constructed with the use of K1100 carbon fiber material internal to the beds to maximize the heat transfer between adsorbing and desorbing beds. K1100 carbon fiber has a thermal conductivity of about 4 times that of aluminum.

Bed design #2 (Figure 7) utilizes alternating plates of adsorbing and desorbing chambers to maximize the heat transfer between the exothermic adsorbing bed, and the endothermic desorbing bed. This design is similar to the compact flat plate type heat exchangers in common use. Each bed is comprised of 10 chambers, and each chamber holds 123 cm<sup>3</sup> of sorbent. In this configuration, the total volume of sorbent in each bed would be 1230 cm<sup>3</sup>, however, the setup could allow the number of chambers to be changed in the event that a better sorbent material is developed. Figure 7 shows how the separate chambers are stacked on top of one another (the front manifold has been removed from the figure for clarification). The total weight for this bed design is approximately 3 kg. The heat released due to the adsorption of CO<sub>2</sub> and water vapor to the sorbent may lead to an increase in the bed temperature that may lower the sorbent's capacity. There will be a benefit from the close proximity of the chambers, and the chambers ability to thermally conduct that heat generated to the adjacent desorbing beds. In return,

the desorbing bed will benefit from the added energy. The beds can also be cooled by an active cooling loop, circulating fluid through the chambers, but it would add to the complexity of any system; thus, passive components are more desirable.

Each chamber is 0.9 cm thick and separated from the next chamber by a bed 2 chamber. The flow of gas enters the inlet manifold, distributes through the inlet retention screens (not shown), and flows across the individual chambers through the outlet retention screens, to be collected in the outlet manifold. For the desorbing bed, the alternating chambers will be opened up to space vacuum on both the inlet and outlet, and due to the close proximity of the higher temperature adsorbing bed, will desorb better to space.

Table 2 presents the comparison of the weight equivalency between TDA's CO<sub>2</sub> and H<sub>2</sub>O removal system and the MetOx canister used in the existing EMU design. Due to the increased regeneration frequency of the CO<sub>2</sub> adsorption capacity of the sorbent, the weight and volume associated with TDA's system hardware is 10.9 kg and 2 L volume lower than that of the MetOx canister using bed design #1, indicating weight and volume savings of 75% and 27%, respectively. Using bed design #2 these savings are 69% for weight and 41% for volume. Because our sorbent provides both CO<sub>2</sub> and humidity control in the same system, additional weight and volume gains are expected with the elimination of the condensing heat exchanger and rotary water separator. Although the weight equivalency associated with power draw is slightly higher with TDA's system due to the energy requirement to drive flow selection valve, it is expected to be very small.

Table 2. Weight and volume comparison of TDA's advanced CO<sub>2</sub> and H<sub>2</sub>O removal system with the MetOx system.

	Volume (L)	Weight (kg)
Bed design #1	5.4	3.6
Bed design #2	4.4	4.5
MetOx	7.4	14.5

**Flow Selection Valve Design:** Pressure drop calculations were performed for the different

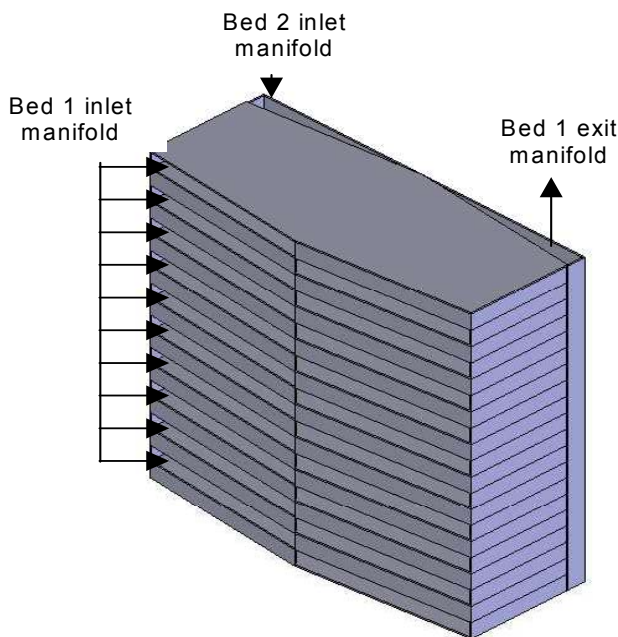


Figure 7: Bed design #2.

arrangements using the Ergun equation. The goal of each design was to minimize the pressure drop while maintaining the maximum bed loading possible. The calculations were based on the beds only, since there was no data available on the spool valve from Hamilton Sundstrand, however the valve pressure drop is assumed to be much less than that of the bed anyway. The pressure drop for bed design #1 shows the lowest of all designs since it is only 0.06 inH<sub>2</sub>O. This is due to the short bed length of 3cm, and the large flow area of 375 cm<sup>2</sup>. The bed design #2 pressure drop was the largest at 0.89 inH<sub>2</sub>O, due mainly to the flow path through the beds. By placing TDA sorbent into the Hamilton Sundstrand RCA system, it was calculated to be approximately 0.16 inH<sub>2</sub>O. As can be seen, all designs meet the goal of less than 1 inH<sub>2</sub>O pressure drop, however, more detailed analysis will be done in the future depending on what the specific beds, manifolds and valves become.

## CONCLUSION

TDA developed a new, high capacity, regenerable adsorbent for CO<sub>2</sub> and H<sub>2</sub>O removal that can be regenerated by pressure swing only without increasing the bed temperature. We showed that the sorbent maintains its activity over extended cycling by carrying out a total of 262 consecutive cycles during which the sorbent demonstrated its durability and cyclic activity.

We showed that the proposed CO<sub>2</sub> and H<sub>2</sub>O removal system generates significant weight reductions in the system hardware. A preliminary system analysis that included all the major components used in the system (sorbent reactors, valves, manifolds etc.) suggests that TDA's advanced CO<sub>2</sub> and H<sub>2</sub>O removal system could weigh less than 4.6 kg, and fit into the existing framework for the MetOx canister in the current EMU designs. The preliminary analysis results indicate that due to the increased regeneration frequency of the sorbent, the weight and volume associated with TDA's system hardware is 10.9 kg and 2 L lower than that of the MetOx canister, indicating weight and volume savings of 75% and 27%, respectively.

The current EMU uses a condensing heat exchanger and rotary water separator for humidity control. This system is complex and creates interdependency

between the EMU vent and water-cooling loops. By simultaneously removing the H<sub>2</sub>O and CO<sub>2</sub>, TDA's system eliminates the need for a separate humidity control system. Elimination of the condensing heat exchangers and gas/liquid separators saves weight, but more importantly, reduces complexities associated with liquid separation in microgravity. Thus, the overall PLSS will become much simpler, easier to operate and more reliable.

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