

RAPID CYCLING CO₂ and H₂O REMOVAL SYSTEM for EMU

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ABSTRACT

The National Aeronautics and Space Administration (NASA) 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 Extravehicular Mobility Unit (EMU) is of critical importance to NASA, both for low orbit operations and for long duration manned missions.

TDA Research, Inc. is developing a high capacity, rapid cycling, sorbent to control CO₂ 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.

INTRODUCTION

NASA's future missions require dramatic reductions in the weight and volume of the Portable Life Support System (PLSS) (Fullerton, 2001). To minimize the logistics costs associated with an expendable CO₂ removal system, NASA funded the development of a regenerable CO₂ 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 CO₂ generated during the EVA. Existing suit designs include separate CO₂ and humidity control units that are designed to operate for 8 hours or more. After each EVA, the MetOx canister is thermally regenerated inside the spacecraft driving off the CO₂ in an oven (Butler,

1998). This system has been successfully used for several years.

The capacity of the CO₂ control unit limits the duration of the EVA. 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). If the sorbent regeneration can be carried out *during* the extravehicular activity (EVA) with a relatively high regeneration frequency, the EVA duration could be increased and the size of the sorbent canister and weight can be significantly reduced.

A next-generation space suit design that uses a regenerable CO₂/H₂O removal system is under consideration; it is referred to as the Rapid Cycling Amine (RCA) system (Dean, 1998). The RCA system relies on two alternating beds of solid amine sorbent to remove CO₂ and H₂O from the vent loop and is regenerated cyclically during the EVA. Although the solid amine system is simple, durable and dependable, the performance of a rapid-cycling CO₂ and H₂O control unit could be further improved with the use of a higher capacity and faster cycling sorbent.

TDA Research, Inc. (TDA) is developing a regenerable, long-life sorbent to control CO₂ and humidity levels in the gas breather loop of 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 CO₂ and H₂O from the ventilation loop while the other regenerates under space vacuum (without additional heating).

Sorbent Development

The effective sorbent should have a strong affinity for CO₂ for its effective removal, however it should not bind it too strongly so that the regeneration can be performed without increasing the bed temperature and using space vacuum only. TDA uses a proprietary material to remove CO₂ from the gas mixture. The active phase is prepared on commercially available high surface area (550 m²/g) silica, which provides favorable support for the active phase and also serves as an excellent sorbent for water vapor removal. The powder is then pelletized using TDA's proprietary geode technology to form 1/16" or 1/8" cylindrical pellets. This geode structure allows combining 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, and 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, a single-best formulation was identified and then further tested to evaluate its performance during a multiple-cycle test.

Sorbent Testing

Preliminary Thermogravimetric Analyzer Tests:

The initial capacity screening of the sorbent formulations was carried out using a Shimadzu TGA-50 Thermogravimetric Analyzer. Gas streams composed of CO₂ only or moisture-laden CO₂ to identify the combined and individual H₂O and CO₂ sorption capacity of the sorbents were used. The operating parameters (i.e., adsorption and regeneration time and temperature) were varied to identify sorbent performance under the conditions of interest. Temperatures in the 25-35°C and 25-60°C range were used for adsorption and regeneration, respectively. Although an ideal system should not require any heat input for the regeneration step, potential capacity improvement resulting from bringing heat to the adsorption side was explored. The adsorption duration was also optimized during the initial TGA tests. For example, the adsorption

duration was limited to the point where the steepest change in the slope (the slope indicates the rate of CO₂ removal, dW/dt) was observed; the fastest increase was usually observed when CO₂ was first introduced into the system. The rate of removal slowed down after the first several minutes of adsorption, and longer CO₂ exposures were determined to be less beneficial. Tests showed that lower temperatures promote higher CO₂ capacities. Also, higher weight gains were observed in those cycles where humidity was introduced, which indicated that the sorbent was simultaneously removing CO₂ and water vapor. Once the best sorbent was identified via TGA screening tests, more extensive testing was carried out for this best performing sample. For this sample CO₂ capacity above 2% wt. on saturation basis and 2.8% wt. water vapor capacity were observed. Next, an extended duration test designed to measure the long-term capacity of the selected formulation was performed using the TGA. A total of 509 cycles (Figure 1 shows the representative cycling details) were performed on the pelletized sorbent. Testing of the best sorbent in the pellet form provided 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% CO₂/N₂ and regeneration done under 100% N₂. During the first 130 cycles the sorbent achieved an average of 0.64% wt. CO₂ capacity without showing any signs of degradation. As the sorbent was sufficiently 'aged', optimization of the cycling conditions (by varying the time of adsorption and/or regeneration) was performed. It was noticed that longer adsorption times resulted in an increase

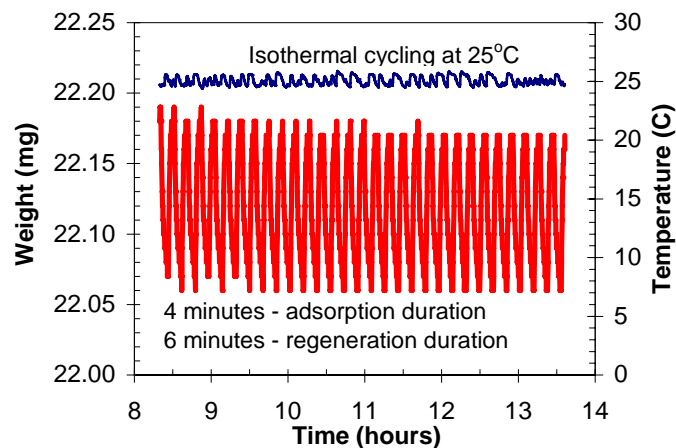


Figure 1. TGA multi-cycle test details.

in capacity; however, capacity was not significantly affected by a regeneration time increase. Due to its stable performance and high capacity during the conducted 509 cycles, this sample was selected for larger scale testing in the flow reactor.

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 its pre-breakthrough sorption capacity. Figure 2 presents a picture of the apparatus. In this design, two vacuum pump assemblies were integrated to simulate a 3.65 psia canister pressure during adsorption and a high vacuum (less than 0.5 torr) during regeneration (the vacuum was provided by a mechanical roughing pump). In order to conduct the tests in the presence of water, the CO₂ balanced N₂ 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 – 20 cc) of pellets. A valve system allowed the gas stream to bypass the reactor and flow directly to the analytical system for accurate measurement of the feed gas composition. The CO₂ concentration and relative humidity were measured using an on-line CO₂ analyzer (California Analytical), and a moisture analyzer (Vaisala), respectively. The apparatus was fully automated and could run without an operator for long periods of time, including overnight. Control EG software was used to control test conditions, log analytical data, and safely shut down the apparatus in case of a malfunction.

Bench-Scale Test Results: Some of the initial flow reactor experiments were conducted at ambient pressure. The CO₂ and H₂O concentrations in the tests were adjusted so that they matched the same CO₂ and H₂O partial pressures at the canister inlet. In most of the tests, an inlet partial pressure for CO₂ and H₂O was maintained at the 6.2-7.6 torr and 15.0-21.0 torr level, respectively, and nitrogen was used as a balance gas. During the regeneration step either vacuum or nitrogen was used to desorb CO₂ and H₂O off the sorbent.



Figure 2. Picture of the bench-scale test unit.

Simulations of a full adsorption/regeneration cycle were conducted during which the breakthrough times, pre-breakthrough and ultimate sorbent capacity for CO₂ and H₂O were measured. Usually the breakthrough for CO₂ was observed first followed by the breakthrough for water vapor. In some tests, the ultimate adsorption capacity of the sorbent was measured by fully saturating the sorbent with CO₂ and H₂O. Following the completion of the adsorption step, the system was purged with nitrogen to flush out the CO₂ and H₂O remaining in the lines and reactor dead volume. Once a zero baseline in the analyzers was maintained, either vacuum or nitrogen was used to drive off the CO₂ and H₂O from the bed. Both CO₂ and H₂O were monitored with on-line analyzers. The analyzers' readings were converted into mass units to obtain an overall CO₂ and H₂O uptake capacity of the sorbent (the current humidity and CO₂ analyzers were not sensitive enough to

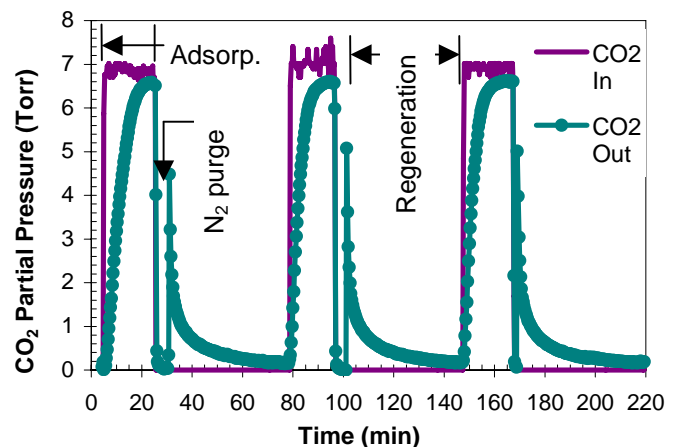


Figure 3. Typical saturation test-profile for multiple-cycle test.

measure the CO₂ and H₂O given off during regeneration under vacuum). After the regeneration step was complete, the reactor was ready for the next adsorption/regeneration cycle.

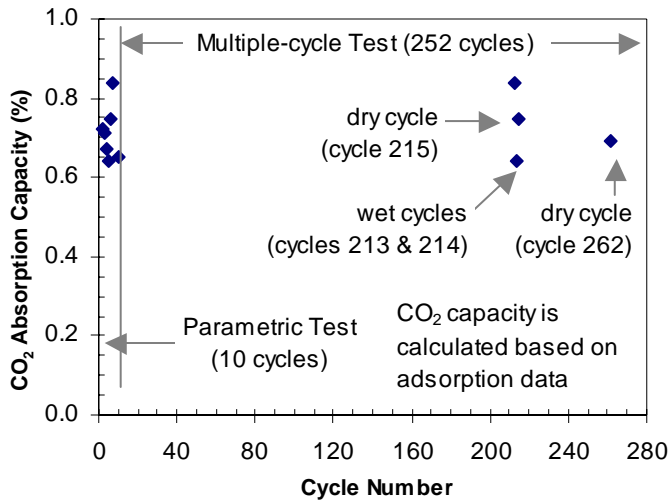


Figure 4. Multiple-cycle tests.

To demonstrate the long-term cyclic capacity of the sorbent 262 consecutive cycles at conditions simulating the actual operation of the system (temperature of 22°C and Gas Hourly Space Velocity (GHSV) of 2,700 h⁻¹ during adsorption) were performed. The inlet CO₂ and water vapor concentrations were set at 7.6 torr and 18.0 torr, respectively, to simulate the CO₂ and water vapor levels in the breather loop based on average metabolic load. While several saturation cycles were conducted at the beginning of the test (Figure 3), for all the following cycles 6 minute half cycles were maintained. Regeneration was carried out under nitrogen at GHSV of 2,700 h⁻¹. For some of the tests vacuum was used to regenerate the sorbent (no nitrogen flow was present in the loop). The sorbent exhibited an average 0.71% wt. CO₂ adsorption capacity throughout these tests (Figure 4). The constant CO₂ 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. The bench-scale reactor test results clearly demonstrate that: (1) the sorbent can be used effectively for the combined CO₂ and H₂O removal; (2) the sorbent can remove and release CO₂ and H₂O at low temperatures (20°C–25°C); (3)

the sorbent is regenerable and maintains its activity for at least 262 cycles.

Preliminary System Analysis

The operation of TDA's system (Figure 5) is similar to any two-bed, regenerable system. This requires the use of two alternating sorbent beds operating in a cyclic manner to simultaneously adsorb CO₂ and H₂O from the space suit ventilation loop. The sorbent beds are continuously cycled, alternately adsorbing CO₂ and humidity from the vent loop while the regenerating bed is 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 metabolism. The removal of the impurities is not required for operating the sorbent since the sorbent will not be poisoned, but for the comfort of the crew person and to avoid any potential safety issues with the buildup of these trace contaminants. The sorbent canister design also includes fine particle filters to prevent any migration of particulate matter away from the bed, as well as a trapping point for any particulate that may be generated in the space suit.

The successful operation of the sorbent requires effective heat management. The adsorption of CO₂

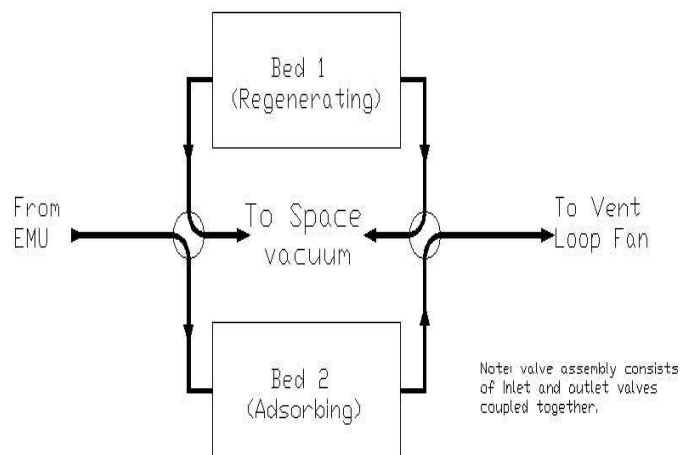


Figure 5. Schematic of TDA's system.

and H₂O 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 CO₂ from the bed. The issue of heat management is addressed by relying on the sensible heat capacity of the sorbent bed and the reactor components; also, the heat released during the adsorption only slightly increases the bed temperature. During the regeneration step, the endothermic desorption of CO₂ and H₂O lowers the bed temperature. At approximately 1% capacity for both CO₂ and H₂O, such heat effect is relatively low. An intelligent reactor design such as the one suggested for the RCA allows transferring the heat from where it is given off (the adsorption bed) to where it is needed (the regeneration bed).

In one potential design shown in Figure 6, 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. 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. The sorbent is held in place with 150 micron screens at the inlet and outlet of each bed. 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. The diverter valve assembly would be mounted on the topside of the beds.

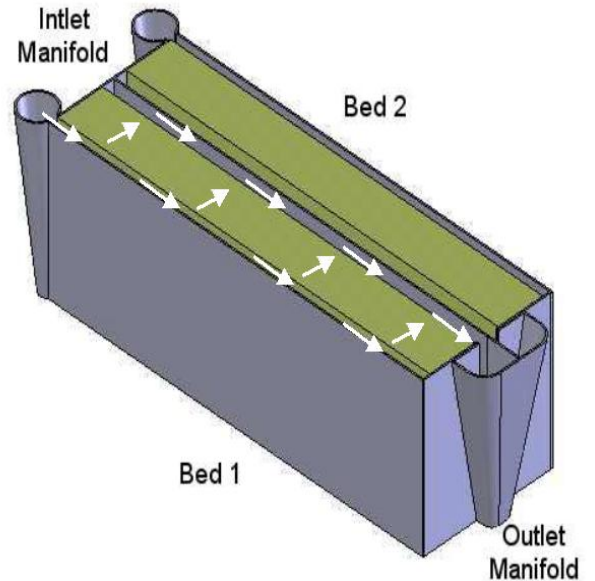


Figure 6. Bed design #1.

The re-circulation of the gases, as in the case of every closed-loop or low-venting life support system, 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 International Space Station (ISS) uses similar valves that allow vacuum regeneration of the CO₂ absorbent while providing sufficient sealing and safe operation. The linear motion spool valve design developed by Hamilton Sundstrand for the Rapid Cycling Amine (RCA) system is also easily adaptable. The spool valve design not only changes the adsorb/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 CO₂ and H₂O during regeneration. The loss of oxygen can be minimized by increasing the adsorption capacity of the sorbent (i.e., achieving a high sorbent CO₂ uptake in

comparison to the amount of oxygen trapped in the bed) and by tightly packing the sorbent in the bed. 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.

A detailed system analysis (and also system integration) will be carried out in the future to further quantify the benefits of the new sorbent.

CONCLUSION

TDA developed a new, high capacity, regenerable adsorbent for CO₂ and H₂O removal that can be regenerated by pressure swing only without increasing the bed temperature. TDA 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.

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