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A Lightweight EVA Emergency System

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ABSTRACT

The selection of technologies for an evolutionary Space Station Freedom or a planetary (lunar or Martian) extravehicular mobility unit (EMU) are strongly driven by the system volume and weight as well as life cycle costs, reliability and safety.

TDA Research, Inc. (TDA) is developing a compact, lightweight emergency system that provides 30-minute life-support in the case of system or component failures in the Portable Life Support System (PLSS). The system uses a low ventilation rate to reduce the amount of stored oxygen, reducing the associated weight and volume penalty. Operation of the system requires an effective sorbent that would remove carbon dioxide and moisture from the suit. We developed a regenerable sorbent that is suitable for the conceptual system. We also carried out a preliminary system analysis to show that the design saves significant weight.

INTRODUCTION

In the future, mankind will be extending the exploration of space; first in the space station, then in lunar exploration and potentially with exploration of Mars. As we reach out into space, more extensive use of EVAs will be required both for maintenance of the spacecraft and for surface exploration. Whether designed for orbital operations or planetary surface exploration, the extravehicular mobility unit (EMU) must provide a high degree of performance capabilities while maintaining safe and reliable operation. However, with an increased rate and length of EVA, a low, but statistically significant possibility exists for system and component failures. In that potential event, it is critical to provide: (1) oxygen support, (2) carbon dioxide and moisture removal and (3) thermal control to EVA crew person.

The current EMU uses a secondary oxygen package (SOP) to satisfy all these requirements. In this open loop system, oxygen is stored at 5,800 psia in a secondary high-pressure canister and flowed into the suit in a controlled manner. Suit CO_2 and H_2O concentrations are controlled by constant venting of these gases into the space along with oxygen. If maintained at 4.0 cfm, this stream also provides enough cooling for the crewman during the 30-minute emergency duration (in fact, the oxygen flow rate is dictated by the cooling requirement). Although the existing emergency system is very simple and easy to operate, open loop operation consumes large quantities of oxygen. The weight of the stored oxygen and more importantly, the weight of the thick walled storage canister impose a large penalty (the stored oxygen and the canister weight is 8.6 lbs, representing 36% wt. of the overall emergency system).

TDA Research, Inc. is developing a compact, lightweight emergency system that provides 30 minutes life-support in the case of system or component failures in the PLSS. The system aims maximum weight reduction, which is accomplished by minimizing the vent rate (by using a sorbent for CO_2 and humidity control) and in turn minimizing the amount of oxygen. The system provides the required gas flow rate through the suit by circulation. As a result, the oxygen stored in the proposed system is a factor of eight less than that of the current emergency system. The motive force to drive the circulation is provided by using a simple ejector and expanding the high-pressure oxygen. In fact, the amount of oxygen that needs to be carried is set by the motive force requirement. The CO_2 and H_2O concentrations in the low-venting system are controlled by a regenerable sorbent. The sorbent can be activated in a simple oven for reuse. In the emergency system, the heat generated by the absorption of CO_2 and moisture is removed by a space radiator located downstream of the sorbent bed in the circulation loop, reducing the temperature of the circulating gas stream to comfortable levels.

MAIN SECTION

NASA's planned future missions set stringent requirements on the design of the life support systems. Missions under study entail ambitious tasks, demanding environments and long durations. These factors will require dramatic reductions in weight, decreased reliance on supplies and greater flexibility on the types of missions that can be accommodated. The assembly of the International Space Station has begun, requiring more frequent and demanding Extravehicular Activity (EVA) work in space than any period in history. EVA will

also be used extensively in future extended duration space missions such as planetary explorations. At space transportation costs in excess of $10,000/kg (much higher for lunar and Martian explorations), the increased EVA hours translates into tremendous launching costs (Frankie, 1999; Ericksson, 1997). Thus, the use of lightweight hardware technologies based on regenerable components is imperative, mandating changes in some of the existing systems to reduce the logistics burden for the EVA. The biggest advantage of the lighter PLSS components will be perhaps the potential of increasing a crew person's efficiency due to the reduced momentum associated with the carried mass. Particularly, for the EVA missions envisioned in the coming decades, weight reduction will appraise more even more significance. PLSS technologies to be used at 0.38g Martian gravity and 0.16g lunar will require substantial weight reductions.

Extravehicular mobility unit (EMU) is a self-sustained spaceship, equipped with a compact life support system providing oxygen, pressure control, and the removal of waste heat, carbon dioxide and moisture. PLSS has been combined with insulated pressure suits with advanced mobility features to allow effective work in space for long durations. PLSS components are reliable and provide safe operation for the Extravehicular Activity (EVA) in the space environment. However, as the number and the length of EVAs increases, the possibility of system and component failures also increases. During an EVA, a number of events can trigger a life-threatening occasion, some of which are listed in Table 1. Most of these events require activation of an emergency system with the primary requirements: (1) to maintain a continuous flow of life supporting oxygen, (2) to remove CO_2 and H_2O from the suit, and (3) to prevent the crew person from overheating.

Table 1. Typical life threatening EVA events.

Suit puncture/tear	Spatial disorientation
Suit Life Support System damage	Explosion
Mechanical failure of LSS components	Extremity crushing
Suit Environmental Control failure	Heart attack
Power loss	Airlock malfunction
Helmet fogging	Communication loss
Exceeding maximum O_2 supply	Electrical shock
Gas Embolism	Unconsciousness
Detachment form worksite	Entanglement

In the event of emergency, a secondary oxygen package (SOP) attached to the bottom of the LSS is activated to give life support long enough for the crewman safely return to the Space Station/Space Shuttle interior. The SOP stores 2.631 lb of oxygen for a 30 minute emergency providing oxygen for the metabolism, compensating for minor leakage and purging CO_2 and H_2O from the helmet. Oxygen flow emanates from the secondary oxygen canisters in the SOP and enters the suit at a flow rate of 4.0 cfm (actual). Suit pressure is maintained at 3.65 psia, where the flow is controlled by a series of regulators and valves. The oxygen flows over the face and sweeps the interior of the helmet, flushing the CO_2 and H_2O from crewman's breath out of the suit into the space through a vent valve. The current system stores oxygen in the secondary canister at 5,800 psia, which represent a favorable volume (for the current system to be contained in a reasonable size high pressure storage is mandatory).

The minimum oxygen requirement during the 30-minute EVA emergency is estimated to be 0.092 lb/crewman, including the metabolic consumption and an allowance for the system and spacesuit leakage rate of 100 sccm. This is only 3.5% of the oxygen flow provided by the SOP. This illustrates that the oxygen requirement in the existing design is set by the need to provide cooling and to maintain low levels of CO_2 and H_2O. In the current open loop configuration, CO_2 and H_2O is primarily controlled by venting, requiring large quantities of oxygen to be vented as well, due to the fact that CO_2 and H_2O only constitute less than 4% of the gas stream on volume basis. As a result, large oxygen consumption requires that large quantities must be stored. The need to minimize the storage volume drives the storage pressure to extreme levels, requiring use of a thick-walled Inconel (Ni alloy) canisters, adding up to the weight penalty. The system weight can be reduced dramatically if the venting of the oxygen is reduced. However, a low-venting system must still satisfy all emergency life support requirements (i.e, CO_2 and H_2O removal and cooling).

TDA'S LOW-VENTING EMERGENCY SYSTEM

TDA's system minimizes the overall mass by reducing the vent rate and in turn the quantity of oxygen stored in the secondary oxygen canister. It stores high-pressure oxygen as well, which provides life-sustaining oxygen for the crew person for 30-minute emergency duration and compensate for the leakage from the suit. High-pressure oxygen is also used as the motive gas in a downstream ejector to provide circulation of gases in the emergency loop. However, the quantity of the oxygen stored in the low-venting system is 8 times lower than that of the existing system.

Figure 1 presents a schematic of TDA's EVA emergency system. High-pressure oxygen in the canister is introduced into the circulation loop through a two-stage pressure regulator to provide a continuous oxygen flow at 300 psia. This oxygen stream is then expanded in a single-stage ejector, generating suction to maintain circulation in the loop. The single-stage ejector consists of an inner converging-diverging nozzle through which the driving fluid is fed (high pressure oxygen from the canister) and generates suction in the outer nozzle. The larger nozzle acts as a converging-diverging diffuser in which the pressure rises and velocity decreases. Use of

the ejector enables circulation without using a fan (i.e., power), increasing the reliability of the system. At the ejector section, the fresh oxygen from the canister mixes with the rest of the gases in the circulation loop (mostly oxygen with very low levels of CO_2 and H_2O). The system is designed to maintain CO_2 and H_2O partial pressures at the exit of the ejector below 12.0 torr and 5.5 torr, respectively. A constant flow of gases at 4.0 acfm and a suit pressure of 3.65 psia are maintained at all times during the entire emergency duration.

source to achieve the desired circulation. Having sufficient oxygen is in fact a necessary requirement in every emergency application to sustain life, and due to volume restrictions, oxygen is always stored at pressure.

The system includes three additional passive components that in sum weigh far less than the 5,800 psia oxygen bottles; an ejector, radiator and sorbent canister. The use of ejector and radiator technologies in space applications are well established. Ejectors with

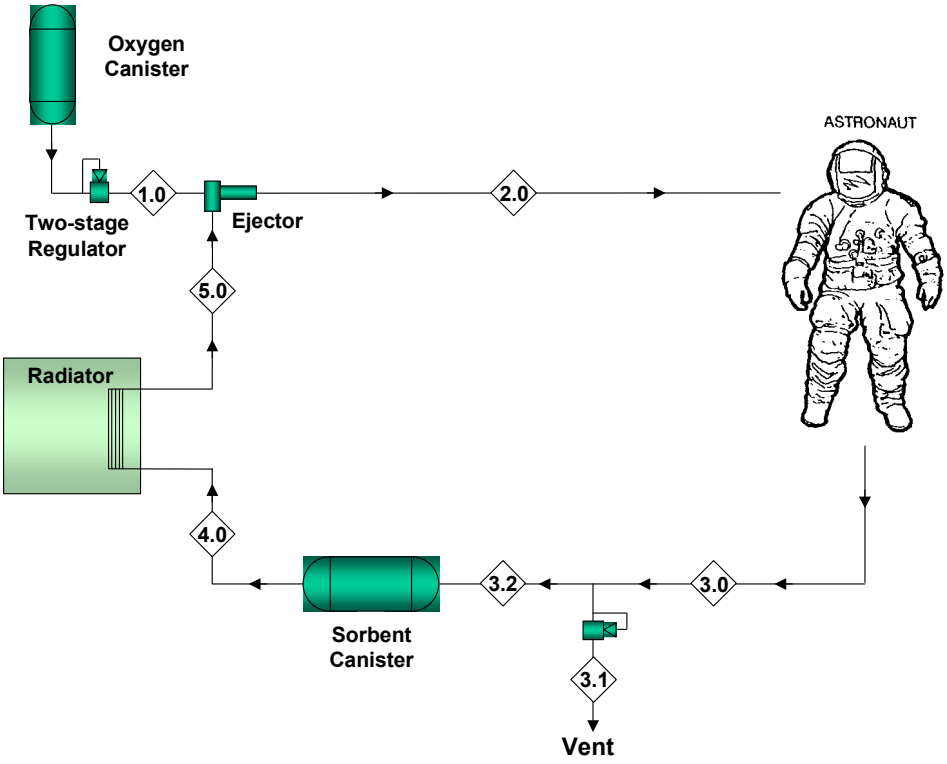

Figure 1. Schematic of TDA's EVA emergency system.

After flowing through the suit, a small fraction of the gases, which are now laden with moisture and CO_2, are vented to space, in order to maintain the desired suit operation pressure. The main gas flow is fed to the sorbent canister where the sorbent reacts with CO_2 and H_2O, removing them from the circulation loop. The absorption of CO_2 and H_2O is exothermic, and the reaction exotherm can increase the gas temperature by up to 115°C. The heat provided by these reactions is removed with a space radiator, located downstream of the sorbent canister. The heat ejection reduces the temperature of the gases in the circulation loop to 25°C again, ready for the circulation (the radiator area is adjusted to provide the desired degree of cooling for the crewman under different metabolic loads).

TDA's low-venting emergency system provides life-support for 30 minutes under all emergency circumstances. It is designed as a self-sufficient system, independently working from the primary life-support system. The unit requires only a high-pressure oxygen

properly sized orifice operating as a simple sonic primary nozzle have been successfully used previously in the Apollo program as a part of a personal life support equipment. Under typical operating conditions, devices of this type can produce circulating secondary flow rates approximately eight times as large (in mass flow rate) as the higher pressure primary flow which drives them (Rouen, 2001). These characteristics were also confirmed in tests of Apollo era ejectors. The use of the ejector eliminates the need for an electrically powered fan, and the elimination of the components with moving parts increases the reliability of the emergency system. Similarly, radiators have also found extensive use in space applications. The only under developed part of TDA's EVA emergency system is an effective sorbent that can remove CO_2 and H_2O. In our research, we develop a low-weight, long-life, high-capacity, regenerable sorbent that can maintain its activity under the harsh space environment. This paper summarizes the results of our sorbent development effort.

SORBENT DEVELOPMENT

In our research, we prepared and tested a variety of sorbent formulations that can remove CO_2 and H_2O from air (oxygen) under representative conditions.

Thermogravimetric Analysis (TGA) Tests

The initial screening of the sorbent formulations based upon their ultimate CO_2 and H_2O absorption capacities was carried out by a Shimadzu TGA-50 Thermogravimetric Analyzer. In these tests, a small quantity of sorbent is placed into the sample holder in connection with a very sensitive microbalance with the capability of recording weight over time. The setup also provided control of the temperature, flow rate and composition of the gases. We used gas streams composed of CO_2 only, water vapor only or moisture-laden CO_2 to identify the combined and individual H_2O and CO_2 absorption capacity of the sorbent. The weight change due the gas-solid interaction (e.g., CO_2 absorption) was measured, and a loading value calculated by dividing the weight change with the weight of the sorbent. This value is used as a comparison criterion for the performance of sorbent formulations. We screened these formulations in the form of pellets with TGA. The sample holder is large enough to tests an individual pellet. Carrying out tests with the pellets is important, since the results reflect the pore and external film diffusion limitations related with pellet characteristics.

In these tests, we used a test sequence that would provide gas streams composed of:

1) CO_2 only,
2) water vapor only,
3) CO_2 only again, with in between regenerations.

This sequence allowed us to determine the loading level that can be achieved for the individual compounds. Testing CO_2 loading level in the third cycle also provided information on the durability and regenerability of the sorbents.

Figure 2 presents the TGA test profile that measures the CO_2 and H_2O absorption capacity for TDA 413-47 sample. For this particular sample tested over here, the loading level for the first and third cycle with CO_2 was 9.9% and 9.5% wt, with a 9.2% wt. water vapor loading observed in the 2nd cycle. In these tests, we used simulated gas streams with CO_2 and H_2O concentrations of 2.0 and 2.5% vol., respectively. We also limited the absorption duration with 30 minute to simulate an EVA emergency.

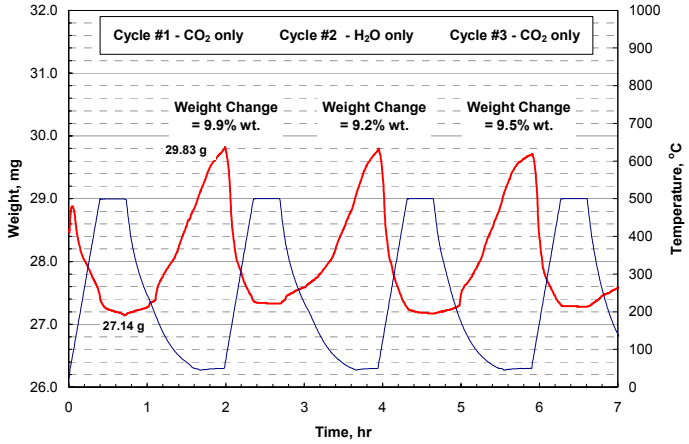

Figure 2. TGA test profile for the TDA 417-43 sample.

Through the TGA tests, we measured the absorption capacities of different samples. Based upon the TGA results, we selected a single-best material to be tested in the bench-scale continuous flow reactor for breakthrough tests.

Bench-scale Reactor Tests

The best sorbent formulation (the one with the desired physical properties and the highest CO_2 and H_2O absorption capacity) was then tested for activity and durability in a bench-scale reactor under simulated reaction conditions to identify pre-breakthrough absorption capacity. In this setup, 8.0 to 16.0 g (8-20 cc) of catalyst pellets are placed in a reactor cell, inserted in a tube furnace with an isothermal zone of 8.0" (Figure 3).

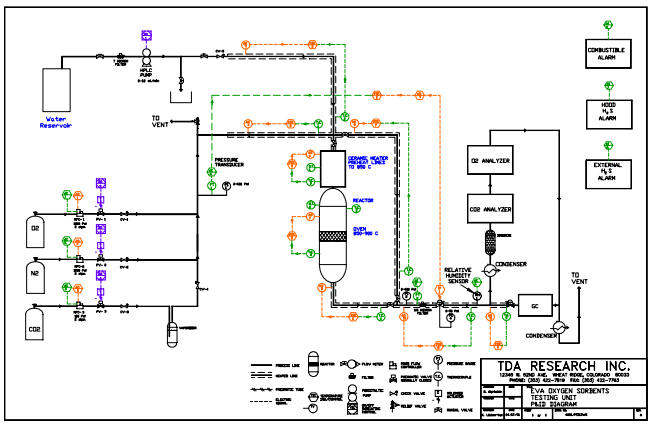

Figure 3. P&ID of the bench-scale reactor.

The reactor section consists of stainless steel tubing with 1.0 in OD with 0.049 in wall thickness. Without channeling in the bed, we can test pellets up to 0.125" (3.175 mm) in diameter with our current system. The pressure of the system is controlled by a Badger pressure control valve located at the downstream of the test section. The gas streams of N_2, O_2 and CO_2 (certified mixture of 4.0% vol. CO_2/O_2) are introduced into the system by Porter mass flow controllers. The moisture is introduced by sparging the gases through a

humidifier. Water vapor partial pressure at the inlet of the reactor is adjusted to the desired level by controlling the temperature of the humidifier. Gas concentrations in the reactor outlet are continuously monitored by on-line CO_2 and O_2 analyzers (California Analytical) and a humidity sensor (Visala). A reactor bypass line also allows analysis of the reactor inlet. The system uses Control E/G software to control the apparatus in order to provide unattended operation.

We carried out these tests at ambient pressure, this total pressure is about 4 times higher than what is in the space suit, but we adjusted CO_2 and H_2O concentrations in our tests so that they matched the same CO_2 and H_2O partial pressures at the inlet of the sorbent canister in the emergency system. In most of the tests, we maintained an inlet partial pressure of 15.0 torr and 18.3 torr for CO_2 and H_2O, respectively, balance with oxygen. We ran simulations of a full absorption and regeneration cycle. We measured the breakthrough times, pre-breakthrough and ultimate absorption capacities for CO_2 and H_2O. Figure 4 presents a typical test profile. We monitored the CO_2 and H_2O concentrations in the reactor exit. As the sorbent saturates with these compounds their concentration in the exit increases, eventually reaching to the levels at which they are fed to the system. In these tests, usually we first observe the breakthrough in water vapor, then CO_2, as the sorbent gets saturated. After observing the breakthrough we continue to flow CO_2/H_2O to measure the ultimate absorption capacity of the sorbent.

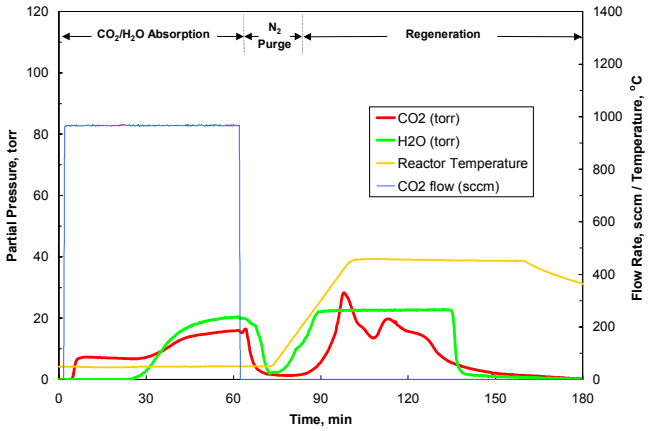

Figure 4. Test profile.

Following sorbent saturation with CO_2 and H_2O, the flow of these gases into the reactor is stopped, and the reactor is purged with nitrogen (i.e., 500 sccm N_2 flow) to flush out the CO_2 and H_2O remaining in the lines and reactor dead volume. Once a zero baseline in the analyzers is maintained, the sorbent bed is heated up under nitrogen flow to carry out the regeneration. The CO_2 and H_2O coming off of the bed are monitored with an on-line CO_2 analyzer and a humidity sensor, and converted into mass units to obtain an overall CO_2 and H_2O uptake capacity of the sorbent. We calculated the area underneath the CO_2 and H_2O concentration curves during regeneration step and correlated to the mass of each of these species. The reactor is again purged with N_2 until all the CO_2 and H_2O is removed from the system. After the regeneration is complete, the reactor is ready for the following cycle.

Effect of Gas Hourly Space Velocity

In the reactor tests, we varied gas hourly space velocities (GHSV) over the range of 1,000 h^{-1} and 8,000 h^{-1}. GHSV is a measure of the contact time of the gases with the sorbent bed. In the proposed system the flow rate of the gases is fixed (i.e., 4.0 acfm), as a result the residence time can only be increased with increasing the bed size, which would increase the weight of the system. From the breakthrough analysis, we identified the maximum space velocities (minimum allowable contact time and minimum bed size). Figure 6 and Figure 5 illustrate the breakthrough profiles for CO_2 and H_2O as a function of GHSV, respectively.

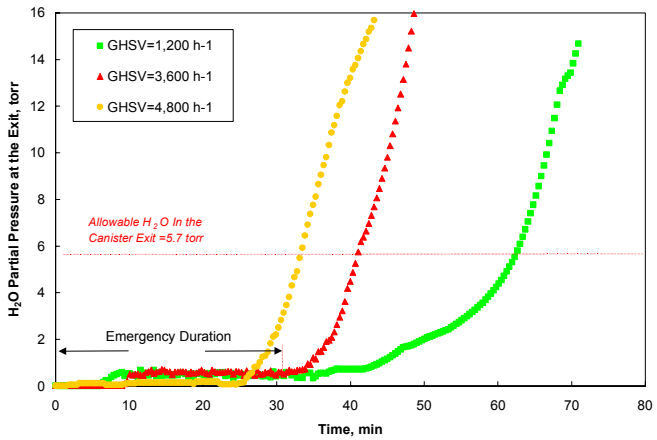

Figure 5. Effect of GHSV on H_2O breakthrough.

In these particular tests, the CO_2 and H_2O concentrations at the inlet of the bed were 15.0 and 18.3 torr, respectively. Depending on the space velocity, CO_2 and H_2O concentrations are maintained below 13.1 and 5.7 torr, respectively for more than 30 minutes, followed by a gradual increase as sorbent gets saturated, finally passing above the allowable canister exit level (13.1 torr for CO_2 and 5.7 torr for H_2O). The breakthrough tests clearly indicate that CO_2 and H_2O partial pressures can be maintained at the desired level during the entire EVA emergency. Based upon these curves we calculated the pre-breakthrough CO_2 and H_2O absorption capacities to be used in our final design.

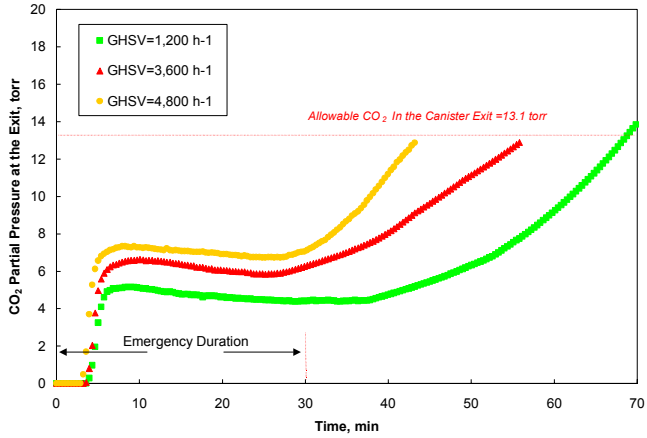

Figure 6. Effect of GHSV on CO_2 breakthrough.

Effect of Temperature

We also investigated the effect of temperature on the absorption capacity of the sorbent. Since the absorption of both the CO_2 and H_2O are highly exothermic, the sorbent must maintain its activity over a range of temperatures. Prior to the tests where we examined the effect of temperature on the absorption capacity, we developed a 5-mode transient model to estimate the temperature rise as a function of time at the reactor exit. In the simplified model, we estimated the temperature of the exiting gases under two different assumptions: (1) no heat loss well insulated reactor, (2) maximum heat loss, allowing radiation into the other components in the backpack. The model allowed us to identify the temperature range of interest for our tests (Figure 7).

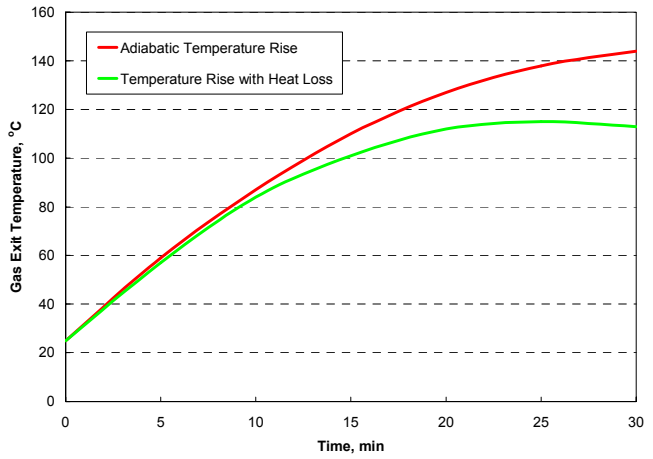

Figure 7. Estimated temperature rise with respect to CO_2 and H_2O absorption.

Once we identified the proper temperature range, we carried out tests to measure the CO_2 and H_2O absorption capacities. In these tests, we maintained a GHSV of 3,600 h^{-1} and varied the temperature in 30-120°C range. The result of these tests, given in Figure 8, indicates that at 3,600 h^{-1} GHSV (1 sec contact time), the sorbent is capable of absorbing CO_2 even at the highest operating temperature.

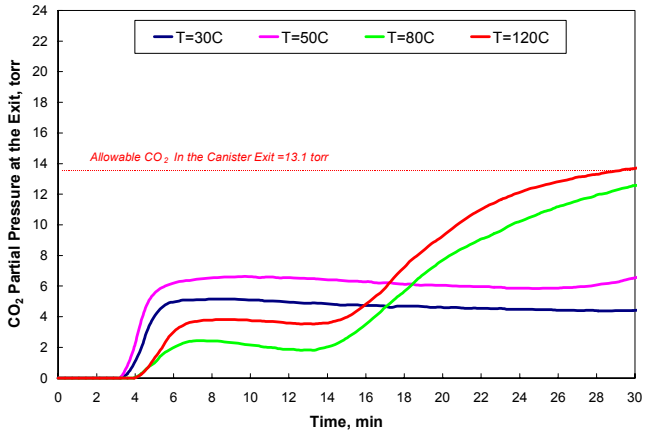

Figure 8. Effect of temperature on CO_2 breakthrough.

We observed that the CO_2 and H_2O absorption capacity of the sorbent is a very strong function of the temperature (Figure 9). CO_2 absorption capacity droped from 11.8% wt. at 30°C to 4.4% wt. at 120°C. The decrease in the capacity in the case of H_2O is more pronounced (15.6% at 30°C to 4.1% wt. at 120°C). Since temperature of the sorbent will increase as CO_2 and H_2O are absorbed, we calculated an average uptake capacity of 7.99% wt. and 8.62% wt. for CO_2 and H_2O, respectively, to be used in the canister design.

We repeated the absorption and regeneration cycles to measure the cyclic capacity of the sorbent. Altogether, we ran 20 cycles (at changing conditions) to measure the durability and extended cyclic activity of the sorbent. We carried out the first cycle at a GHSV of 3,600 h^{-1} and a temperature of 50°C. We revisited this condition throughout the parametric tests, in which we measured the effect of temperature and space velocity on absorption capacity.

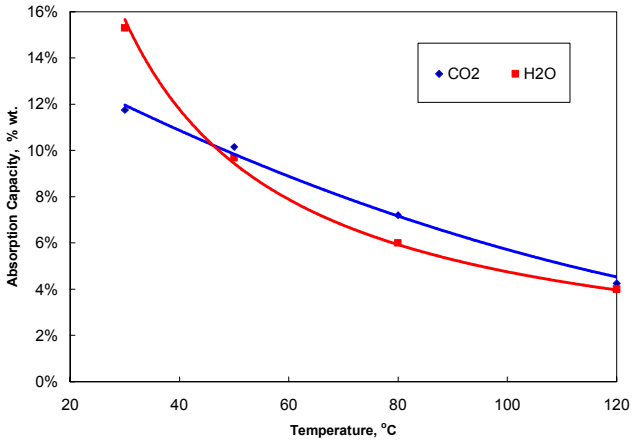

Figure 9. CO_2 and H_2O absorption capacity of the sorbent as a function of temperature.

We also carried out three cycles at the end of the experiments to observe changes in the activity. Figure 10 presents the CO_2 uptake of the sorbent for each cycle, where the pre-breakthrough and the ultimate CO_2 absorption capacities are illustrated. The sorbent can achieve an average of 9.85% wt. CO_2 uptake through the

20 cycles at 50°C, with no apparent loss in the absorption capacity. Similarly, an average ultimate CO_2 absorption capacity of 12% wt. can be achieved through 20 cycles. The constant uptake of CO_2 throughout the 20 cycles indicates that sorbent is durable and maintains its absorption capacity through cycling.

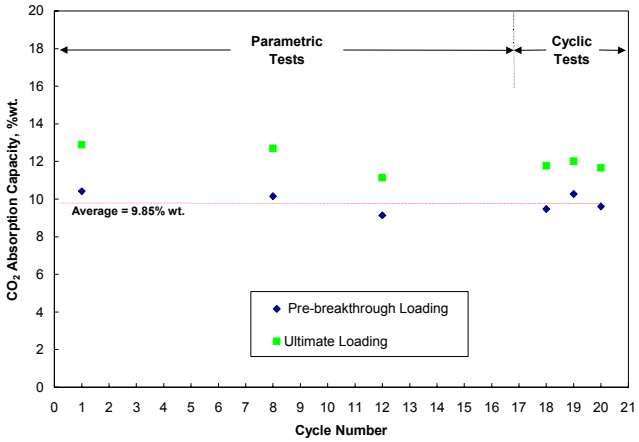

Figure 10. Cyclic CO_2 absorption capacity of the sorbent.

We observed similar results for moisture as well (i.e., the moisture loading at the 20th cycle was 10.77% wt. compared to 11.02% wt. at the 1st cycle, with an average loading level of 10.82% wt. through 20 cycles).

We characterized the sorbent samples before and after the multiple-cycle testing. We did not observe any significant change in the physical properties of the pellets. We were able to recover all the pellets at the end of 20-cycle test, without any spalling and deformation in their structures. Table 1 presents the physical characteristics of the fresh and tested sorbent pellets. Crush strength (the best measure of mechanical integrity of the pellets) for fresh and tested sorbent pellets remained unchanged (the small increase after testing is within the experimental measurement error). We also measured the surface area and porosity of the sorbent with BET technique. Although the surface area of the sorbent dropped from 71 to 61 m^2/g, the pore volume increased from 0.18 to 0.23 cc/g, compensating the negative effect of the surface area loss).

Table 2. Comparison of physical characteristics of the sorbent before and after testing

	Surface Area m^2/g	Pore Volume cc/g	Crush Strength lb/mm
Fresh Sorbent	71.9	0.18	3.28
Aged Sorbent	61.8	0.23	3.39

We also characterized the bulk structure of the sorbent before and after the tests by an x-ray diffractometer. X-ray diffraction patterns indicate no change in the chemical structure of the sorbent. The characterization results indicate no major changes in the chemical and physical properties of the sorbent.

CONCLUSION

TDA developed a high capacity CO_2 and H_2O absorbent, and showed that these sorbents are regenerable and they maintain their activity over extended cycling.

The bench-scale reactor test results clearly demonstrate that:

1. The sorbent can effectively remove CO_2 and H_2O from the suit
2. Sorbent loading is much higher at lower temperatures
3. Sorbent can remove CO_2 and H_2O at temperatures approaching 150°C, while achieving the desired pre-breakthrough suit CO_2 and H_2O concentrations below 3,600 hr^{-1} at all temperatures
4. The sorbent is regenerable and reusable
5. The sorbent maintains its activity for at least 20 cycles

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