Integrated Testing of a 4-Bed Molecular Sieve

and a Temperature-Swing Adsorption Compressor for

Closed-Loop Air Revitalization

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ABSTRACT

Accumulation and subsequent compression of carbon dioxide that is removed from space cabin are two important processes involved in a closed-loop air revitalization scheme of the International Space Station (ISS). The 4-Bed Molecular Sieve (4BMS) of ISS currently operates in an open loop mode without a compressor. This paper reports the integrated 4BMS and liquid-cooled TSAC testing conducted during the period of March 3 to April 18, 2003. The TSAC prototype was developed at NASA Ames Research Center (ARC)[1]. The 4BMS was modified to a functionally flight-like condition at NASA Marshall Space Flight Center (MSFC)[2]. Testing was conducted at MSFC. The paper provides details of the TSAC operation at various CO_2 loadings and corresponding performance of CDRA.

INTRODUCTION

The TSAC is a candidate technology to provide buffering of the carbon dioxide (CO_2) stream between the 4BMS and the Sabatier components, part of a closed loop atmosphere revitalization system (ARS). In this paper, the ARS will be briefly described first. The TSAC and 4BMS hardware will be discussed next. Then the combined operation of the TSAC and 4BMS will be described together as a tightly coupled system. Test objectives and operational steps will be outlined. Finally, test data from the integrated testing will be presented and conclusions drawn.

ATMOSPHERE REVITALIZATION SUBSYSTEM

As part of the International Space Station (ISS) growth to support six to seven crewmembers, development is underway of a Sabatier CO_2 Reduction assembly. A 4BMS is currently on the ISS Destiny module for removal of metabolic CO_2. An identical 4BMS is being prepared for Node 3. These and other elements of the Node 3 environmental control and life support system (ECLSS) are shown in Figure 1. Those elements pertaining to this paper are described in the following paragraphs.
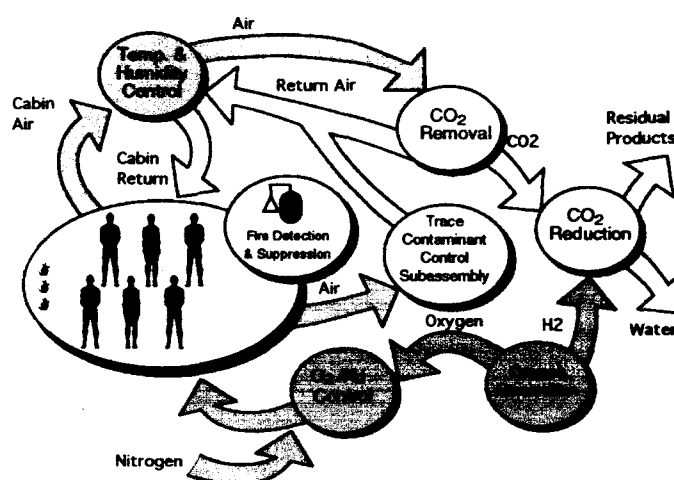

Figure 1. Atmosphere Revitalization Subsystem

TEMPERATURE AND HUMIDITY CONTROL (THC) – In addition to the ARS, the common cabin air assembly, or CCAA function of the THC subsystem is shown in Figure 1. By providing air conditioned in a condensing heat exchanger to the carbon dioxide removal assembly

(CDRA), the THC aids the CDRA in supplying low water content CO_2 to the CRA. The CCAA for Node 3 is identical to that in the Destiny module, and provides the same function for the CDRA in both modules.

OXYGEN GENERATION ASSEMBLY – The OGA shown in Figure 1 is unique to Node 3. It will electrolyze water to provide oxygen for the crew and hydrogen for the Sabatier reaction.

CARBON DIOXIDE REDUCTION – The CRA shown in Figure 1 is also unique to Node 3. It will react hydrogen from the OGA and CO_2 from the CDRA to produce methane and water. By converting the CO_2 that is currently vented overboard to water, the water resupply requirements and dependence of the ISS on shuttle fuel cell water will be reduced. For a full crew complement, it is estimated that resupply can be reduced by 900 kg per year[3]. The CRA is currently being developed under Advanced Life Support (ALS) NASA funding. Space for the CRA is provided in the Node 3 OGS rack.

CDRA TO CRA INTERFACE REQUIREMENTS

Figure 1 showed the CO_2 flow between the CDRA and CRA. This depiction is highly simplified, however, since the effluent of the 4BMS is cyclic and extremely transient, whereas the Sabatier requires a relatively constant stream during operation. For example, typical TSAC flows from the 4BMS and to the CRA are shown in Figure 2.
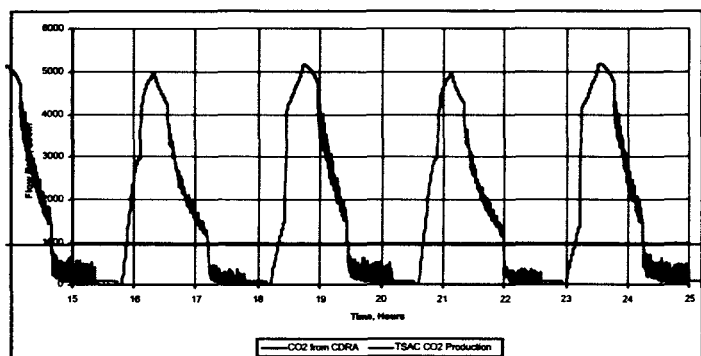

Figure 2. 4BMS CO_2 Effluent and Sabatier Influent

It is clear from Figure 2 that storage and regulation of CO_2 is required in order to provide a constant flow to the Sabatier. The baseline approach is the conventional one, that is, to use a mechanical compressor and accumulator as shown in Figure 3.
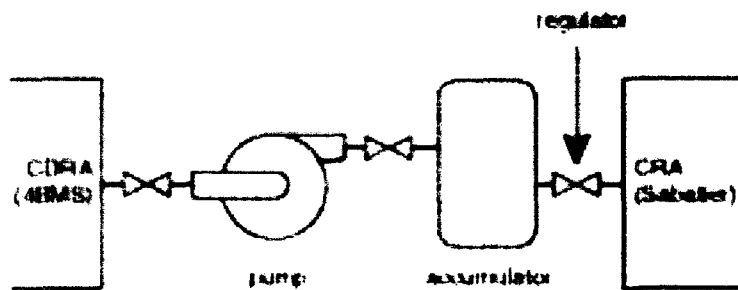

Figure 3. Mechanical Compressor Interface

The limitations of the mechanical compressor are due to rapidly moving parts, and include wear, noise, vibration, reliability, and electromagnetic interference. In contrast, the TSAC is virtually solid-state, thus avoiding these drawbacks. Perhaps most critical for missions beyond the ISS is the limited lifetime of the compressor, especially since wear is aggravated by the presence of zeolite dust.

TEMPERATURE SWING ADSORPTION COMPRESSOR

The TSAC compressor has been in development at NASA Ames Research Center for a number of years and has been described in detail elsewhere (1,4,5) and we will only briefly describe it here.

The TSAC takes advantage of the properties of molecular sieves to provide the same function as a mechanical compressor. First, sorbent loading increases dramatically with decreasing temperature. Secondly, the sorbent loading increases with increasing partial pressure of the sorbate gas. An adsorption-based compression cycle is illustrated in Figure 4.

In step 1, the TSAC captures CO_2 from the 4BMS at low temperature and pressure. Bed heating increases the temperature in steps 2 and 3, first pressurizing and then delivering CO_2 to the Sabatier above ambient pressures. Finally, the sorbent is cooled in step 4 to prepare for the next cycle. The TSAC used for this testing was cooled with liquid water; there is also in development an air-cooled system[6].
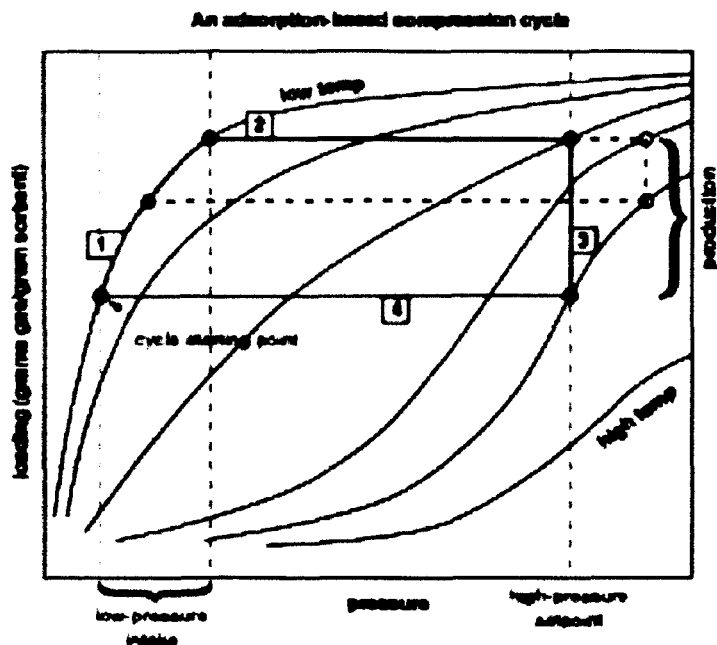
Figure 4. A Four-Step Adsorption Compression Cycle

Figure 5 provides a schematic of the liquid-cooled TSAC. The 2-bed prototype of TSAC has two identical sorbent beds that operate cyclically to acquire and compress CO_2 continuously. For testing with the MSFC 4BMS, the interface labeled "CDRA Simulator" is the 4BMS interface. CO_2 product from the TSAC was vented through the "Sabatier Simulator" interface. The vacuum interface is coupled to the facility supplied space vacuum simulator.
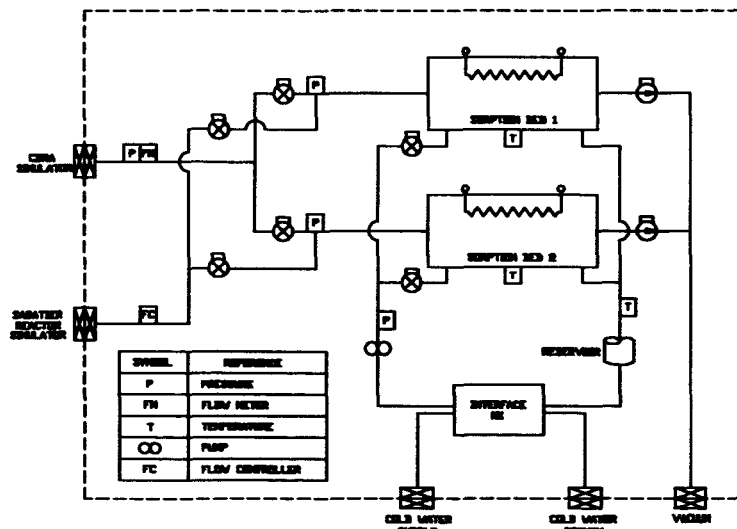

Figure 5. Schematic of a Liquid-Cooled TSAC

4-BED MOLECULAR SIEVE

The carbon dioxide removal assembly used on the International Space Station is the 4-bed molecular sieve, which is shown schematically in Figure 6 below.
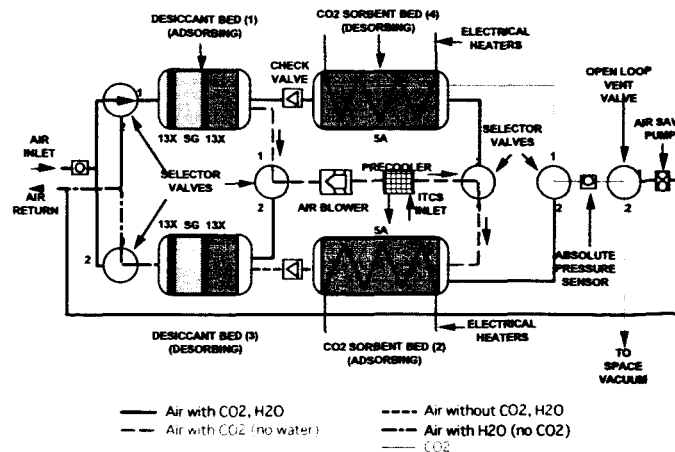

Figure 6. 4-Bed Molecular Sieve Schematic

Since the 4BMS has been described in detail elsewhere (2,7) it will be briefly discussed here. The 4BMS continuously removes CO_2 from the ISS atmosphere. The four beds consist of two desiccant beds and two CO_2 sorbent beds. The system operates such that one desiccant bed and one CO_2 sorbent bed are adsorbing while the other two beds are desorbing.

Starting at the "Air Inlet" in Figure 6, the air stream passes first through a desiccant bed to remove essentially all of the moisture from the process air. The process air is then drawn through the system blower and then through an air-liquid heat exchanger or precooler before entering the CO_2 sorbent bed. Here the main function is accomplished, that is, removal of CO_2 from the air stream.

Prior to returning to the cabin, the air stream passes through the desiccant bed that adsorbed moisture from the previous half cycle. The wet desiccant bed desorbs this moisture to the air stream and returns it to the cabin atmosphere. Following a 10-minute ullage pumping of free nitrogen and oxygen from the alternate CO_2 sorbent bed to the cabin, it is desorbed by heating with integral electrical heaters and application of vacuum. Vacuum may be established by opening the line to space vacuum or, for closed loop ARS operations, the low pressure inlet to a compressor.

Time (min)	Segment	Air-Save Pump	Heaters		Blower
			Primary	Secondary	
0-10	1	On	On	Off	On
10-134	2	Off	On	On	On
134-144	3	Off	On	On	On

Table 1. Four-Bed Molecular Sieve Segments

For open loop ARS operations, CO_2 is vented overboard. For closed loop ARS operation with a TSAC, the 4BMS

provides CO_2 to the TSAC via the interface labeled "To Space Vacuum".

INTEGRATED OPERATION OF THE 4BMS AND TSAC

TSAC-4BMS HARDWARE INTEGRATION: Integration of the 4BMS and TSAC requires the addition of two shut-off valves, labeled V1 and V2 in Figure 7 below.
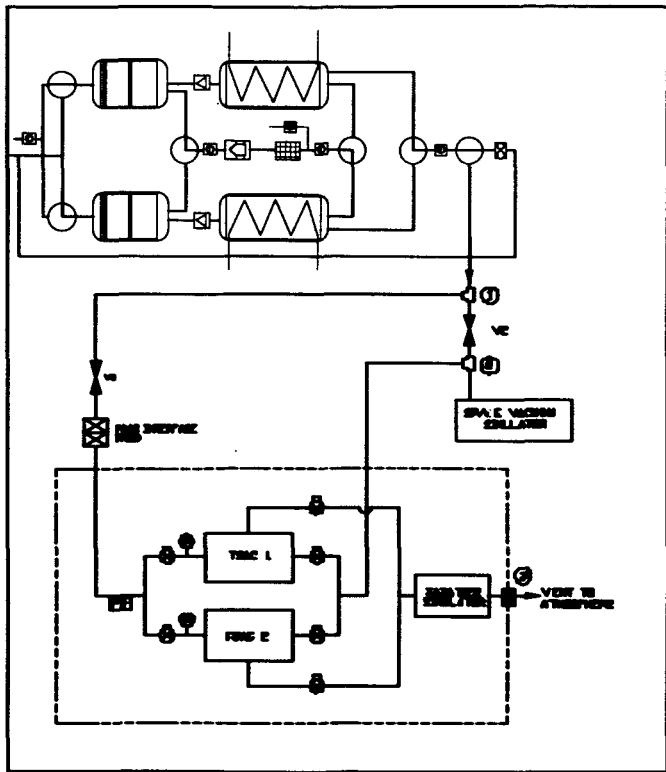

Figure 7. TSAC-CDRA Interface Schematic

Placing V2 in the space vacuum line allows the TSAC to intercept CO_2 at appropriate times in the 4BMS half-cycle. Note that space vacuum is simulated during ground testing by a large accumulator evacuated by vacuum pumps. CO_2 flows to the TSAC during the mode shown in the 134 to 144 minute time slot in Table 2. Valve V1 allows isolation of the TSAC during the final 10 minutes of each half cycle, when the sorbent bed is fully desorbed via space vacuum.

TSAC-4BMS SYNCHRONIZED OPERATION: The 4BMS, TSAC, and V1 and V2 modes are shown in Table 2 below.

TIME (Minutes)	4BMS	TSAC	V1	V2
0-10	Air-save	Cooling	Closed	Closed
10-20	Standby	Cooling	Open	Closed
20-134	Desorbing	Adsorbing and cooling	Open	Closed
134-144	Evacuating directly to	Warming up	Closed	Open
	vacuum			

Table 2. Synchronized Schedule of CDRA and TSAC

These modes may be illustrated further by looking at temperature and pressure conditions in the 4BMS CO_2 sorbent bed and the TSAC beds over a full cycle, as shown in Figure 8 below.
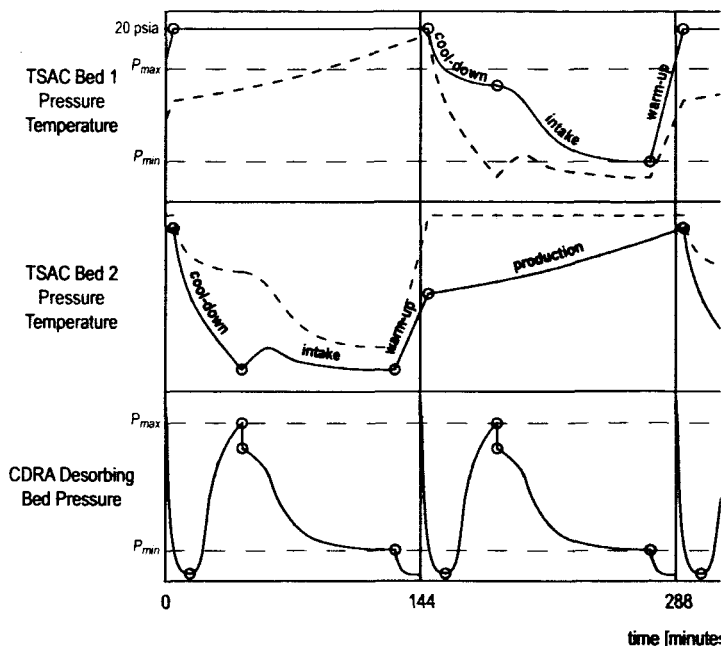

Figure 8. TSAC and 4BMS beds pressure and temperature

The correspondence for TSAC Bed 1 between Figure 8 and Figure 4 is as follows: From 0 to 20 minutes is step 4, cooling in preparation for the intake step. From 20 to 134 minutes is step 1, where the TSAC intakes CO_2 from the 4BMS. From 134 minutes to 144 minutes is step 2, or warm-up in preparation for the production step. Finally, from 144 minutes to 288 minutes is step 3, the production step.

Referring to the 4BMS desorbing bed in Figure 8, the segments are as follows: From 0 to 10 minutes is segment 1, when the desorbing bed is being evacuated to cabin via the air save pump and the primary heater is energized. Segment 2 is from 10 to 134 minutes; here primary and secondary heaters energized. The bed is isolated for the first ten minutes of segment 2 to allow cooling of the TSAC bed. For the remainder of the segment, it is desorbing to the TSAC. Finally, during segment 3, the bed communicates with space vacuum for more complete desorption at low pressure.

TSAC AND 4BMS BED VENT VALVES: Two methods were used for control of bed pressures during integrated TSAC-4BMS operations. On Figure 6, the check valves shown allow flow in one direction only from the CO2 sorbent bed to the desiccant bed. During sorbent bed desorption, this flapper valve is closed to isolate the bed from the remainder of the system. While the bed is connected to vacuum, the flappers are held shut by the

negative pressure differential. However, for open loop ARS operation, it is possible for a positive pressure to overcome the light springs and release the CO2 intended for the TSAC. For the MSFC testing, the software was configured to vent the 4BMS sorbent bed to space via valve V2 for a bed pressure of 517 torr (10 psia). While reviewing test data, we will see that this control can interfere with the next one discussed, the TSAC purge valves.

In order to prevent buildup of inert gases (N2 and O2) in the TSAC beds, the TSAC purge valves are programmed to vent when the adsorbing TSAC bed goes 10 torr above the intake step pressure setpoint, and continues venting until the pressure decreases below the setpoint pressure. As a result, non-adsorbing gases are purged to space vacuum and high TSAC CO2 product purity is maintained. TSAC effluent sampling verified the importance of purging the beds.

TEST CASES

Testing was performed from 3-3-03 to 4-19-03 at Marshall Space Flight Center. The TSAC is shown during test in Figure 9 below.
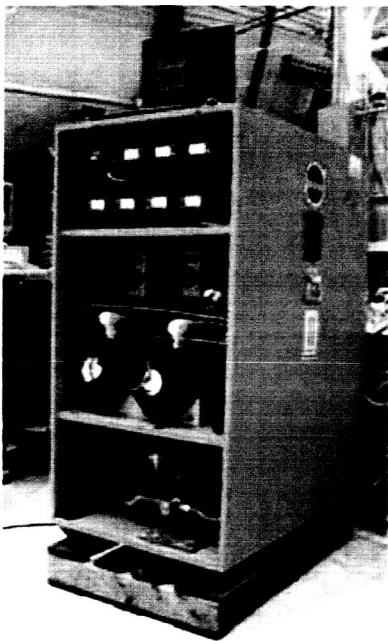

Figure 9. TSAC in Operation at MSFC

Numerous test cases were run during this period; they are summarized in Table 3 below.

Start Date	Test No.	Intake Pressure (torr)	TSAC Production Flow (kg/day)	4BMS Inlet Percent CO2
3-3-03	B-1	N/A	N/A	0.71
3-4-03	I-1	400	2.7	0.71
3-5-03	I-2	500	3.6	0.71
3-6-03	I-3	200	2.7	0.43

4-8-03	B-2	N/A	N/A	0.28
4-9-03	I4	200	2.0	0.28
4-16-03	I5	500		0.71
4-18-03	I6	200		0.43

Table 3. Integrated TSAC-4BMS Test Runs

RESULTS AND DISCUSSION

TSAC OPERATION AT NORMAL CONDITIONS: The TSAC prototype was conservatively designed to produce 2 kg of CO_2 per day. However, we had proven in earlier laboratory tests that it can produce as much as 2.7 kg of CO_2 per day at the design loading pressure which is equal to 200 torr. This was based on the assumption that we need to maintain a pressure of 200 torr or lower in the vacuum line of CDRA in order for it to regenerate completely within the scheduled cycle time, when TSAC is connected. In other words the TSAC was sized under the assumption that during adsorption, CO_2 flow from the CDRA to the TSAC stops when the pressure inside the TSAC canister equilibrates at 200 torr at the lower temperature limit (about 30°C). The remaining CO_2 in the CDRA will be vented to vacuum. Our main objective was to repeat the TSAC performance that we obtained under these normal conditions when during the integrated operation. The following figures represent the results of TSAC operation under this normal test conditions at MSFC. Figure 10 represents the steady CO_2 production and internal pressure of the TSAC canisters. Figure 11 and Figure 12 represents the internal temperature profiles of the TSAC canisters. The temperature data, especially the touch temperature, indicates that the insulation package needs to be improved to minimize the heat loss. The specification for touch temperature was 45°C.
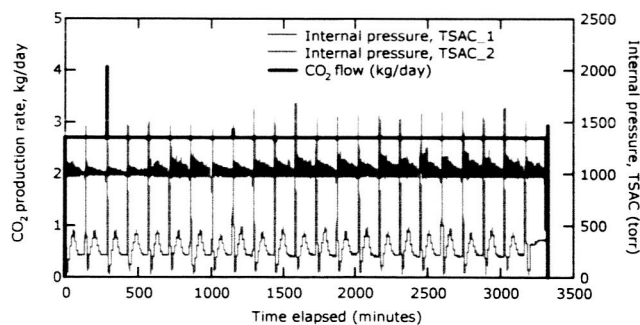

Figure 10. CO_2 production profile of TSAC at 200 torr loading
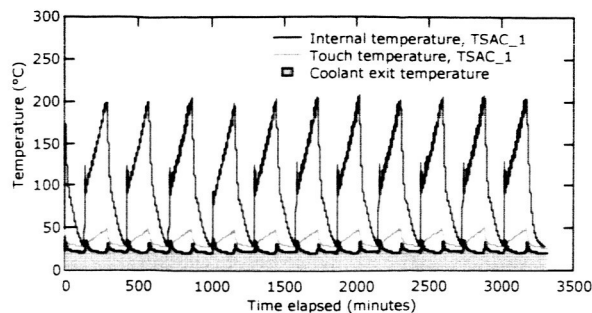
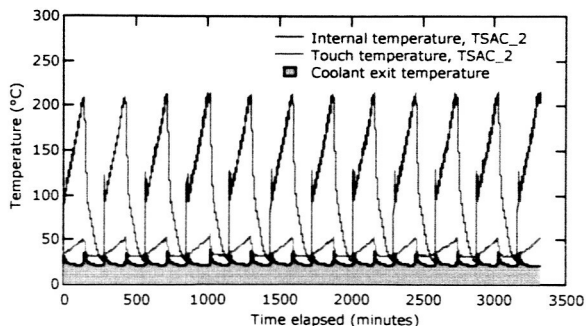**Figure 11.** Pressure profiles of TSAC at 200 torr loading

Figure 12. Temperature profiles of TSAC at 200 torr loading

TSAC OPERATION AT NORMAL CONDITIONS: The efficiency of TSAC for CO2 production mainly depends on the amount of CO2 that it receives from the CDRA. Increasing the loading pressure of the TSAC will increase the CO2 production capacity of the TSAC. There are two risks associated with increasing the loading pressure of TSAC for the current CDRA design. First, increasing the loading pressure of TSAC can cause a backpressure in CDRA and subsequent actuation of the check valve, usually set at 10 psia. Second, the CDRA performance may be affected due to insufficient regeneration, within the scheduled time, if the downstream pressure sets too high. We performed a number of experiments on the TSAC to determine its performance when the TSAC CO2 loading was 500 torr. The results of these experiments are shown in Figure 13 and Figure 14.
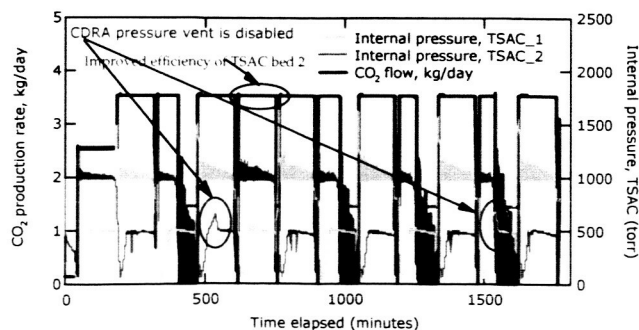

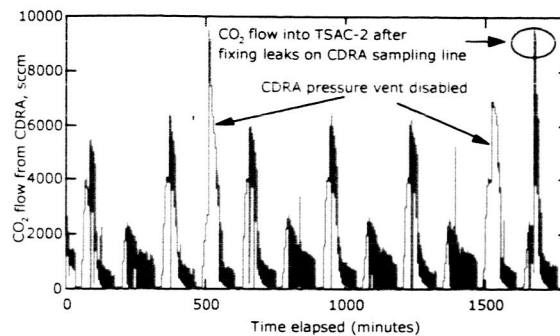**Figure 13.** TSAC performance with CO2 loading of 500 torr

Figure 14. CO2 flow profile from the 4BMS to TSAC at 500 torr loading condition

The setpoint for the compressed CO2 flow rate from the TSAC was about 3.6 kg/day. This flow rate was estimated from the adsorption isotherm of the sorbent at 500 torr. In these experiments, we noticed that, unlike the runs at 200 torr loading, the performance of the two TSAC beds vary significantly. Bed 1 consistently produced a steady flow of CO2 at a rate of 3.6 kg/day for about 137 minutes within the 144-minute half cycle (corresponds to about 3.3 kg/day average flow). However, as shown in Figure 13, the CO2 in TSAC bed 2 could produce compressed CO2 for only about 75 minutes at this rate. We determined that the inferior performance of the TSAC bed 2 during this experiment was caused by leaks in the CDRA bed and in the purge line of TSAC bed 2 in combination with frequent activation of 4BMS's vacuum vent valve.

Bed 2 of the TSAC was synchronized to the CDRA bed that has a higher leak rate than the other during this test. We observed that there was an open sampling line of CDRA (bed A) and a loose fitting in the purge line of TSAC bed 2 (between purge valve and vacuum) contributed to significant part of this leak. Nonadsorbing gases such as N2 and O2 (air) enter the TSAC beds when there is a leak either in the CDRA or anywhere in the plumbing between CDRA and TSAC. The TSAC has a purge valve to purge out these non-adsorbing gases. This purge valve activates when the pressure inside the TSAC bed reaches the loading pressure set point (500 torr in this case) during CO2 adsorption. This purge valve also can act as a vent for CDRA pressure to avoid the check valve activation. Purging of nonadsorbing gases would not be effective unless the TSAC internal pressure rises above the loading pressure setpoint. At same time, if nonadsorbing gases are not purged out, the adsorbing TSAC bed will reach a state of pseudo equilibrium and the pressure will quickly build up to the setpoint pressure, preventing further flow of CO2 into the TSAC from CDRA. This situation can occur when the CDRA vacuum vent valve turns on frequently, venting CO-2 to vacuum, due to a low setpoint pressure for valve control.

During our tests at 500 torr loading, we noticed that the TSAC purge valve action was not sufficient to keep the CDRA pressure down to a safe level. The vacuum vent valve of the CDRA was set at 18 psia (which corresponds to about 9 psia inside the CDRA bed). At

this setting, the CDRA vacuum vent valve was being activated causing frequent evacuation of CO2 to vacuum instead to the adsorbing TSAC bed. It was difficult for us to determine the optimum setpoint for the vacuum vent valve during these experiments since the TSAC and CDRA pressure sensors were at different locations, separated by long sections of tubing, valves, and fittings. In addition, we were operating at 500 torr (about 9.7 psia) which is very close to the threshold pressure of CDRA check valve. As shown in Figure 15, at lower loading pressures, such as 200 torr, this problem did not occur since we were able to set the pressure control limit of the vent valve higher than the purge control setpoint of TSAC and considerably lower than the check valve activation pressure of CDRA.
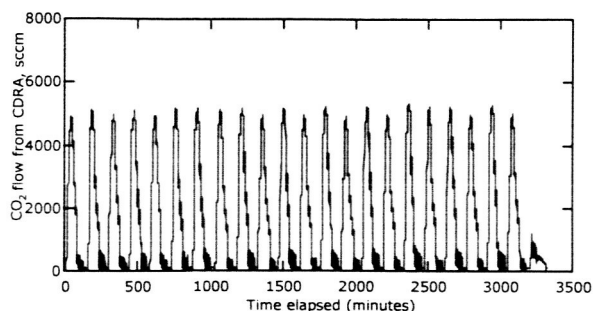

Figure 16. Temperature profile of TSAC bed 2 at 500 torr CO2 loading

Our observations were confirmed by repeated experiments under same conditions after CDRA leak tests and also by the gas chromatograph (GC) analysis of the product CO2 from TSAC, discussed in subsequent sections of this report.

TSAC PERFORMANCE AFTER CDRA STARTUP: We repeated the 500 torr loading test after performing a leak test on CDRA, a few weeks later. The performance of the TSAC after CDRA leak tests and subsequent exposure to moisture is shown in the following figures. The CDRA vacuum vent valve was disabled during these experiments. The performance of TSAC, however, was inferior to previous results. The declining performance was due to exposure of the TSAC bed to moisture from CDRA during a failed startup process. However, these experiments confirmed our earlier assumptions that the leaks in CDRA and vacuum vent activation caused dissimilar performance profiles for TSAC beds 1 and 2 (as shown in Figure 11). Figure 17 shows identical behavior of the TSAC beds 1 and 2, indicates insignificant CDRA leaks. This is also evident in the CO2 flow profiles from CDRA to TSAC, in Figure 18. We completed all the experiments under different conditions to satisfy our second set of goals, to test TSAC under non-standard conditions. However, the results were inconclusive since the TSAC sorbent beds were exposed to moisture. The TSAC beds were regenerated to recover from moisture, while connected to CDRA for further experiments.

Figure 15. CO2 Flow profile from 4BMS to TSAC at 200 torr loading condition

Difference in the CO_2 flow from CDRA into the two TSAC beds is apparent in Figure 14 during the 500 torr loading tests, before and after fixing the leaks on the sample line and purge line of CDRA and TSAC respectively. Figure 14 indicates that the CO_2 flow into TSAC bed 2 is lower than to bed 1 during all half cycles except 4 and 11 (at elapsed times about 500 and 1700 minutes). The CO_2 production rates of the TSAC beds 1 and 2 that are shown in Figure 13 are consistent with the CO_2 flow pattern that is displayed in Figure 13. During the 4th half cycle when the TSAC bed 2 was adsorbing, we set the vacuum vent setpoint to 19.5 psia so that the vacuum vent valve remained closed and the TSAC purge control was properly activated. It is obvious from Figure 13 that subsequent production cycle of TSAC 2 was identical to that of bed 1. This also indicated by the sharper temperature profile of the TSAC bed 2 as shown in Figure 16. The same experiment was done on TSAC bed 1 during the 11th half cycle and the effect is displayed in Figure 14 (about 1750 minutes of elapsed time).
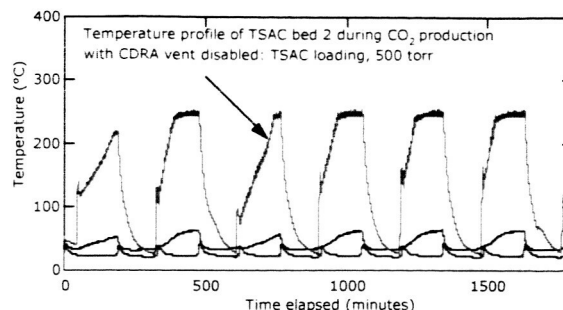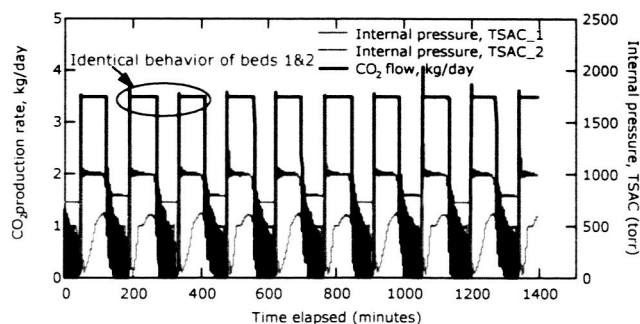

Figure 17. TSAC performance at 500 torr loading after 4BMS leak test and subsequent exposure to moisture
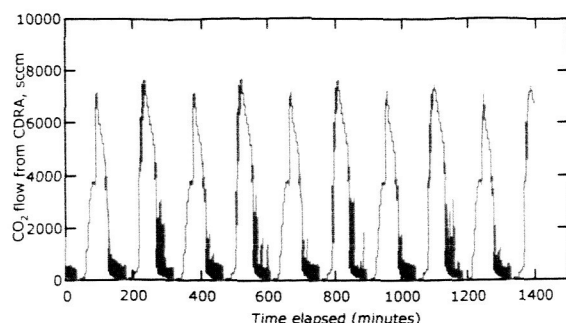
Figure 18. CO2 flow profile from CDRA to TSAC at 500 torr loading after CDRA leak test and subsequent exposure to moisture
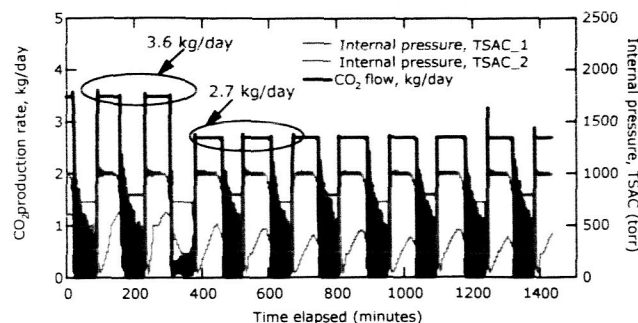

Figure 19. TSAC performance at 200 torr loading after CDRA leak test (TSAC sorbent beds were exposed to moisture from CDRA during this experiment)

CO2 ANALYSIS: The CO2 produced from TSAC beds 1 and 2 were analyzed for N2 and O2 at various stages of the production cycle for various experiments during the first week. The average values of the analysis results are summarized in Table 2.

time (minutes)	CDRA vacuum vent activated								CDRA vacuum vent disabled							
	TSAC bed 1				TSAC bed 2				TSAC bed 1				TSAC bed 2			
	500 torr		200 torr		500 torr		200 torr		500 torr		200 torr		500 torr		200 torr	
	N_2	O_2	N_2	O_2	N_2	O_2	N_2	O_2	N_2	O_2	N_2	O_2	N_2	O_2	N_2	O_2
10	2.7	.28	.41	.12	9.7	3.5	2.5	.36	.17	.05			1.2	.36		
20	-	-	NA	.02	-	-	.55	.05	NA	NA			.05	.02		
30	-	-	-	-	5.3	1.2	-	-					NA	NA		
60	NA	NA	-	-	.09	.03	-	-								
120	-		-	NA	-	-	NA	NA								

Table 4. Summary of the GC analysis of CO2 produced by TSAC (concentrations are in % by volume, NA represents concentrations below detectable limit)

The following observations were made based on the GC analysis.

- Overall, N2 and O2 contents in the CO2 samples collected within the first ten minutes of production cycle are higher than that in the samples collected later.
- All samples collected from the TSAC bed 2 shows much higher N2 and O2 contents than bed 2. This is because the TSAC bed 2 was synchronized with the CDRA bed with a higher leak rate. In addition, there was a small leak on the purge line of TSAC bed 2 that affected the purge operation. (We verified the CDRA leaks with a GC analysis that showed CDRA bed A has 10 times higher leak rate than bed B).
- The CO2 samples taken during the production cycle of TSAC 2, at 500 torr loading with the CDRA vent valve activated had the highest concentrations of N2 and O2. During experiments where the CDRA vent valve was disabled, the TSAC purge control was very effective and showed significantly lower concentrations of N2 and O2. This also confirms our explanation for inferior performance of TSAC bed 2

compared to bed 1 at 500 torr loading tests, as shown in Figure 11.

- For both TSAC beds, and for bed 1 in particular, the N2, and O2 contents were low in the CO2 produced in experiments with a CO2 loading pressure of 200 torr. This is because under this condition, regardless of the CDRA vacuum vent activation, there was ample CO2 flow into the TSAC bed to build up the pressure above the purge setpoint during adsorption. This will enable the TSAC purge valve to activate and purge out N2 and O2.

TSAC VALIDATION TEST AFTER MOISTURE EXPOSURE: The experiments at MSFC were suspended due to computer hardware problems right after the regeneration process. After receiving the TSAC back into our laboratory at ARC, we did a validation test to verify normal performance of the TSAC after regeneration. The results are shown in Figure 20. We ran a weeklong continuous test and the results indicated that the TSAC retains its efficiency after regeneration, produced CO2 at a rate of 2.7 kg/day at 200 torr loading.
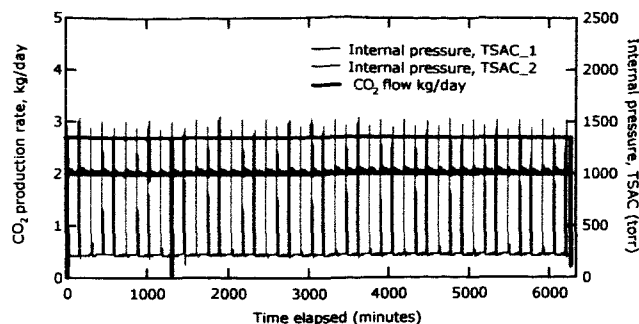
Figure 20. TSAC performance in the laboratory at 200 torr CO2 loading after regeneration to relieve moisture exposure

POWER CONSUMPTION: The average power consumption rates of TSAC at 200 torr and 500 torr are shown in Figure 21 and Figure 22 respectively. The determination of the peak power, however, was not meaningful in these experiments since the watt density of the heaters that we used are many times larger than the actual power requirement of the system. Maximum power consumption occurs when both heaters come ON simultaneously at the end of the production and beginning of the warmup cycle (at 134 minutes of each half cycle) for a brief period. The power consumption can be minimized significantly by improving the insulation package and optimizing the watt density of heaters.
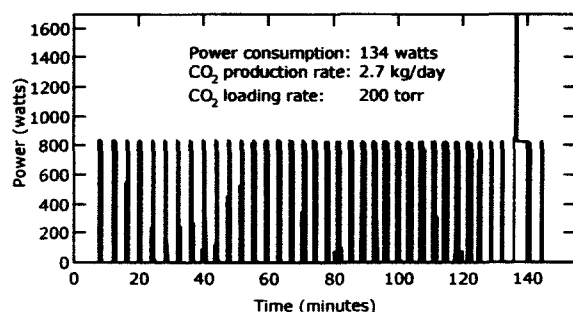

Figure 21. Power consumption by TSAC at 200 torr loading and at a CO2 production rate of 2.7 kg/day
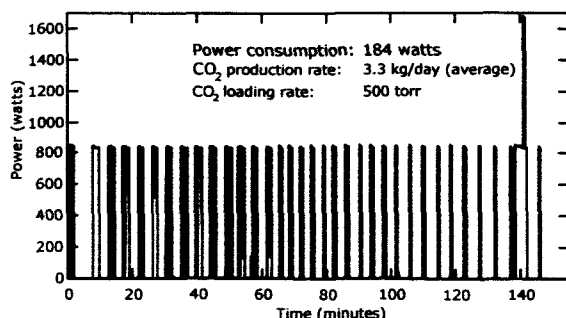

Figure 22. Power consumption by TSAC at 500 torr loading and at a CO2 production rate of 3.3 kg/day

CHALLENGES

We faced some issues with the computer hardware used for data acquisition during the tests. The operating software timer of the TSAC was set up such that it was synchronized to the computer clock. In our early experiments, we observed that the data acquisition becomes sluggish over a period of time and eventually goes out of sync with the computer clock, especially after synchronizing the computer clock with the CDRA timer. This caused the TSAC to be stuck on the production mode after a few random cycles. We did some troubleshooting and the performance was improved in later experiments. We decided to suspend the experiments at MSFC, after three months of operation, when we came across another problem where the computer hardware failed to restart normally.

CONCLUSIONS

The TSAC-CDRA integrated testing at MSFC was completed successfully by accomplishing all the original targets as scheduled. Furthermore, the tests were extended to obtain additional data to demonstrate features of the TSAC that were not a part of the original test plan. The TSAC operated continuously, except for the time when CDRA was being leak checked, performing compression tests at various test conditions. Three major features of the TSAC was demonstrated in the TSAC-CDRA integrated tests conducted at NASA MSFC during the period of March 3-May 30, 2003.

1. The TSAC demonstrated continuous removal of CO2 from CDRA and subsequent compression, as per the design specifications, for more than 48 hours (10 cycles)
2. The TSAC demonstrated its ability to purge N2 and O2 from the CDRA CO2 stream, a feature that is unique to TSAC compared to a mechanical compressor
3. The TSAC demonstrated its ability to recover from moisture exposure from CDRA, another advantage that the TSAC has over its mechanical counterpart.

The test results also provided the following information:

- From various experiments it was determined that the efficiency of the TSAC can be increased by as much as 25% if the CO2 loading pressure is increased to 500 torr.
- Preliminary analysis of the CDRA indicated less than 5% reduction in efficiency when CO2 loading on the TSAC was 500 torr.
- The average power consumption (for heater) of the TSAC was 134 watts and 184 watts at CO2 production rates of 2.7 kg/day and 3.3 kg/day respectively. The estimated average power consumption of the TSAC for the production of CO2 at a flow rate of 2 kg/day was 150 watts.

FUTURE WORK

We will continue to do experiments on the liquid-cooled TSAC in our laboratory to collect the long-term performance data of the TSAC. Meanwhile, we are also

developing and air-cooled TSAC toward the same purpose. The objective of this project is to optimize the design features of the TSAC based on the test data obtained from the liquid-cooled version and eventually build an engineering development unit (EDU) that could qualify a technology readiness level (TRL) of 6. We will be focusing on the following aspects of the design during this project.

- Insulation packaging
- Thermodynamic analysis
- Sorbent selection

- Improved purge controls for non-adsorbing gases

We are also planning an integrated test of the TSAC (either air or liquid-cooled) with the flight-like CDRA and the Sabatier EDU unit. This test, however, has not been scheduled.

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