Progress on the CO_2 Removal and Compression System

Tra-My Justine Richardson[1]
Wyle/Logyx LLC, NASA Ames Research Center, Moffett Field, CA 94035-1000

Darrell Jan, [2]John Hogan,[3] Gary Palmer,[4] Brian Koss, [5] Jason Samson[5]
NASA Ames Research Center, Moffett Field, CA 94035-1000

Roger Huang[6]
Wyle, NASA Ames Research Center, Moffett Field, CA 94035-1000

And

James Knox[7]
NASA Space Flight Center, Huntsville, Alabama, 35812

The Carbon Dioxide Removal and Compression System (CRCS) is designed to perform both the Carbon Dioxide (CO_2) removal and compress CO_2 for further processing. The CRCS was designed as a lower power requirement option to the one currently being used on the International Space Station (ISS). This paper describes the final design, fabrication, assembly, and testing of the integrated CRCS. Initial results indicated that the spiral heaters used did not yield uniform heating within both the adsorption and compression beds. In addition, the heaters for the compression bed were insufficient and an additional HVAC jacket was employed to provide heat to the bed.

Nomenclature

4BMS	=	*4 Bed Molecular Sieve*
ARC	=	*Ames Research Center*
BAD	=	*Bulk Air Dryer*
CO_2	=	*Carbon Dioxide*
CRCS	=	*Carbon Dioxide Removal and Compression System*
ESM	=	*Equivalent System Mass*
HVAC	=	*Heating Ventilation And Cooling*
ISRU	=	*In-Situ Resource Utilization*
ISS	=	*International Space Station*
MSFC	=	*Marshall Space Flight Center*
NASA	=	*National Aeronautics and Space Administration*
OGA	=	*Oxygen Generation Assembly*
PSA	=	*Pressure Swing Adsorption*
RAD	=	*Residual Air Dryer*
RTD	=	*Resistance Temperature Detector*
SCFM	=	*Standard Cubic Feet per Minute*
SS	=	*Stainless Steel*
SwRI	=	*Southwest Research Institute*
TSAC	=	*Temperature Swing Adsorption Compressor*
UOP	=	*Universal Oil Products, a Honeywell Company*

[1] Scientist/Engineer, Bioengineering Branch, and NASA Ames Research Center, Mail-Stop 239-15, Moffett Field, CA 94035.
[2] Air Revitalization Lead, Bioengineering Branch, and NASA Ames Research Center, Mail-Stop 239-15, Moffett Field, CA 94035.
[3] Physical Scientist, Bioengineering Branch, and NASA Ames Research Center, Mail-Stop 239-15, Moffett Field, CA 94035.
[4] Engineering Technician, Bioengineering Branch, and NASA Ames Research Center, Mail-Stop 239-15, Moffett Field, CA 94035.
[5] Mechanical Design Engineer, Bioengineering Branch, and NASA Ames Research Center, Mail-Stop 239-15, Moffett Field, CA 94035.
[6] Engineer, Bioengineering Branch, and NASA Ames Research Center, Mail-Stop 239-15, Moffett Field, CA 94035.
[7] Aerospace Engineer, Space Systems Dept./ES62.NASA MSFC, Huntsville, Alabama 35812.

I) Introduction

The Carbon Dioxide Removal and Compression System(CRCS) concept was initiated as part of the Low Power Carbon Dioxide Removal System (LPCOR) in 2003[1] as an advanced low-power and low-mass carbon dioxide (CO_2) removal system for spacecraft. The CRCS design is well documented in previous ICES conference papers[2, 3, 4, 5, 6, 7, 8]. This paper will report the updated design, fabrication, assembly, and testing of the CRCS integrated system.

A) Background

The CRCS consists of two units, CRCSa and CRCSb. Each unit alternates in its function of CO_2 adsorption and desorption to maintain the cabin air at 2600ppm CO_2. Each CRCS unit consists of two concentric cylinders correlating to two stages, stage 1 and stage 2. Stage 1 of one bed (i.e. CRCSa) adsorbs the dry CO_2 from the dryer (i.e. silica gel) and then feeds the concentrated CO_2 to stage 2 (i.e. CRCSb) of the next bed. Stage 2 acts as a CO_2 compression, storage, and delivery device. Figure 1 shows the represented CRCS duty cycle. In a full cycle of approximately 120 minutes, stage 1 first adsorbs CO_2 from dry cabin air then airsave occurs where a vacuum pump removes the residual air. In the next half cycle, stage1 then is heated to desorb the CO_2.

The advantages of the CRCS are that stage 1 and stage 2 are both heated at the same time, thereby, lowering the power requirement. The other advantage is that the CRCS has the dual functions of adsorbing CO_2 and compressing it at the same time (comparible the 5A bed of the 4BMS and the mechanical compressor currently onboard ISS).

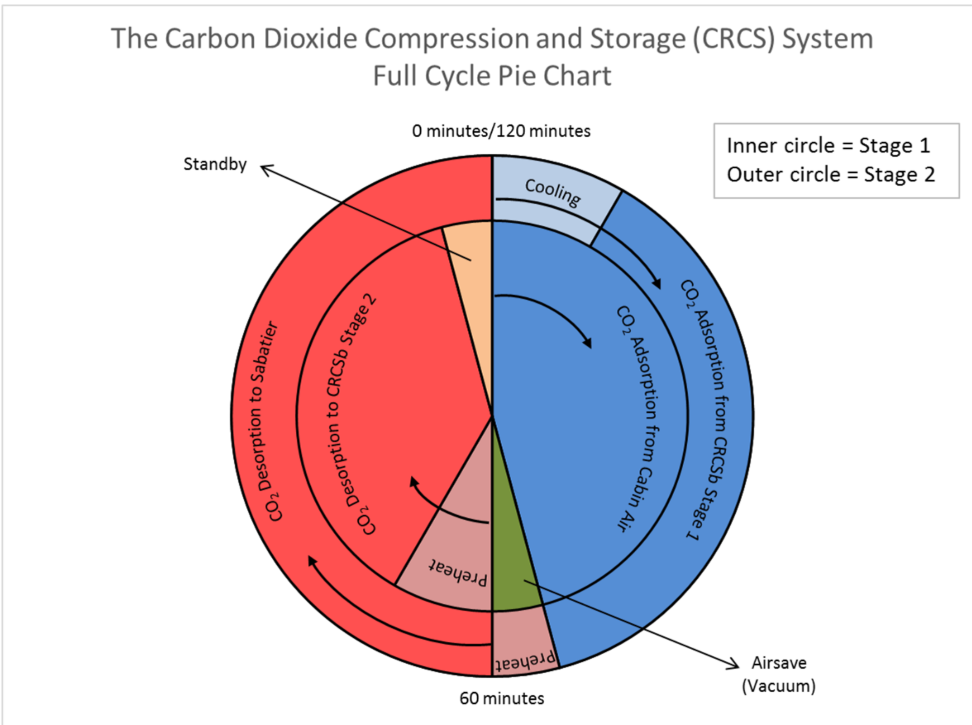

Figure 1: A representative designed duty cycles of one of the CRCS unit, a two-stage system.[4]

B) Current CRCS design specification

Initial design parameters were described in previous LPCOR and CRCS papers. Table 3 list the final modified design parameters. The major modification here was the installation of a HVAC jacket heater. The HVAC heater will be used to heat stage 2 sorbent to a 275˚C within the first 30 minutes of the 60 minute half-cycle. The 13X Grace Davidson 544 sorbent was used for stage 1 instead of the 5A material because of sorbent availability. The 35 micron Dutch weave mesh was used as sorbent containment for both the top and the bottom of the canister. The 180 microns Dutch weave mesh was used only at the bottom as structural support for the spiral heaters.

Only 1¾" Solemide insulation was used on the top and bottom lids because of space constrains in the rack. The two inches insulation on the sidewalls were designed to result in a 65˚C touch temperature on the outside layer.

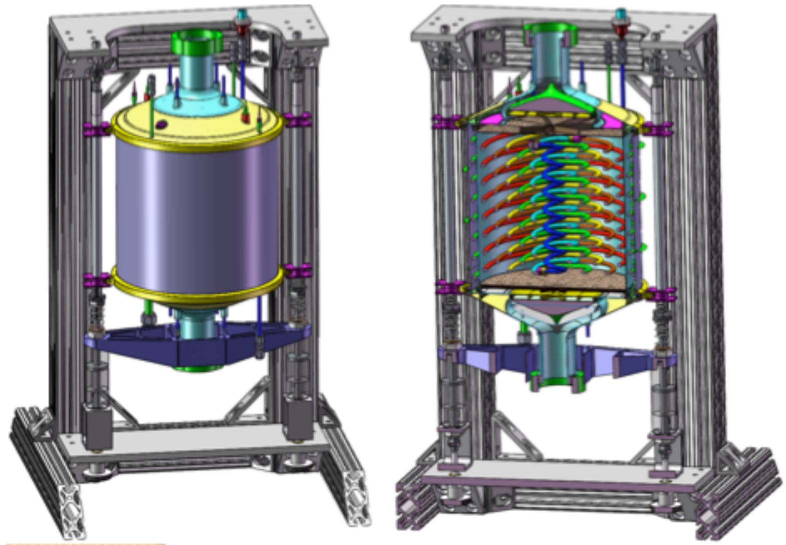

Figure 2: Design illustrations of the CRCS showing the lids, heaters, and retaining screens.

Table 1: CRCS Adsorbent Compression Canister Design specifications. All data are for ONE canister only.

	Stage 1	Stage 2
Number of Crew members	4	
CO_2 inlet concentration, ppm	2600	
CO_2 removal efficiency, %	85	
Material of construction	SS 316	
Canister shape	Concentric Cylinders	
CO_2 input concentration, ppm	2600	TBD
Canister total empty volume, L	12	2.77
CO_2 delivery pressure, psia	3	20
Adsorbent size and shape		UOP 5A-MG-16X40
Adsorbent mass, kg	9.480	2.370
Adsorbent density, g/cc	.79	
Void space, L	0.67	.27
Heaters capacity, W	1249	422.94
Regeneration temperature, ˚C	250	250
Bake out temperatures, ˚C	280	280
Number of heater coils	6	1
# of 2-wire RTDs on heater coils	6	2
# of 2-wire RTDs in adsorbent material	12	3
Cooling jacket	SS316 sheet : ¼" gap	
Blower, SCFM	20	
Insulation	High Performance SOLIMIDE Polyimide Foam Insulation (2" on the side walls and 1 ¾" on the top and bottom lids)	
Screens on the top	Super-Small Particle-Filtering Stainless Steel Wire Cloth, Woven, 316 Stainless Steel, 50x250 (35 microns) Mesh.	
Screens on the bottom	Super-Small Particle-Filtering Stainless Steel Wire Cloth, Woven, 316 Stainless Steel, 50x250 (35 microns) and 80 x 700 (180 microns)Mesh	
Fabric Screen used for sorbent containment	¼" Low Density Techmat	

II) Methodology

A) Hardware fabrication and assembly

For integrated testing, CRCSb was assembled similarly to the previously assembled CRCSa. Additional plumbing was connected in between the canisters for CO_2 exchange as shown in the Piping and Instrumentation Diagram (P&ID). Instrumentation was added for automatic control via LabView. The HVAC jacket was designed, fabricated, and assembled as shown in Figure 4. Also shown, is the assembly stand fabricated to accommodate easy assembly of the internal heating components as well as the outside walls and insulation.

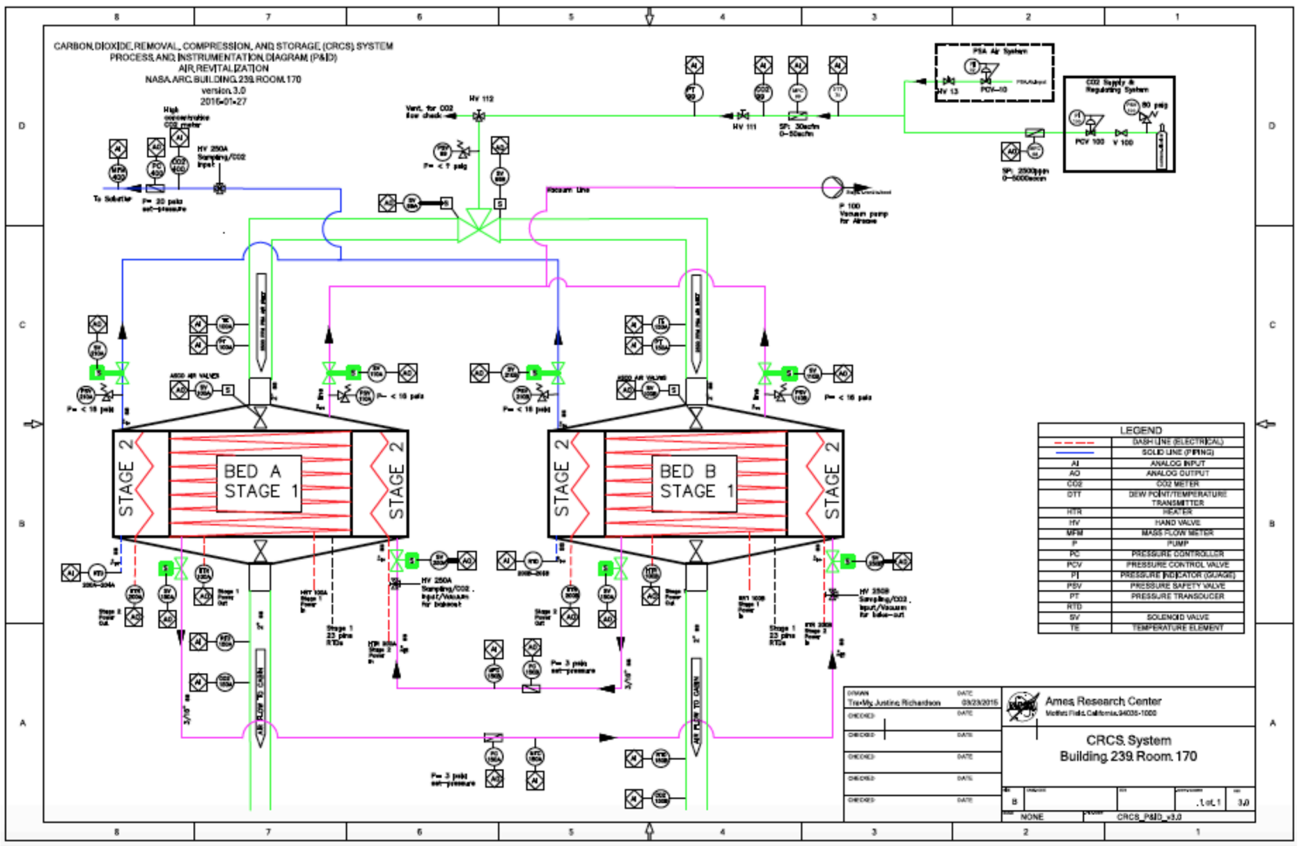

Figure 3: The CRCS final P&ID.

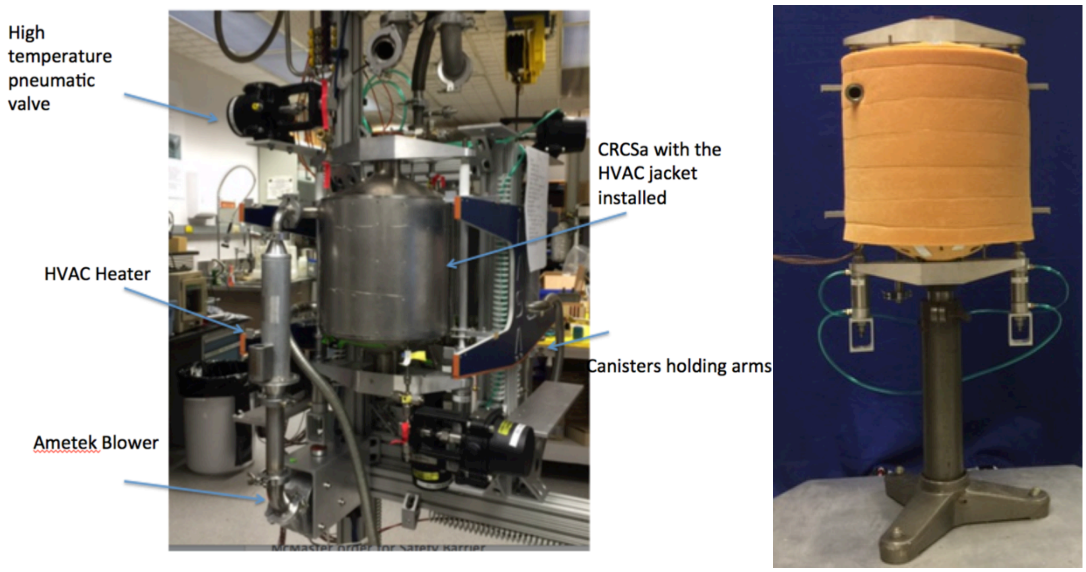

Figure 4: (left) The CRCSa unit installed without the insulation and (right) the assembly stand holding the CRCSb canister with the insulation installed.

B) Controls

For automatic control, National Instrument cRIO 9022 controllers were used along with two NI 9144 slaves. The objective of the automatic control is to be able to cycle in between the two CRCS units as well as between stage 1 and stage 2. Other control objectives are to heat and cool the sorbent beds, to open and close the necessary valves, to control the CO_2 delivery pressures, and to measure various operating parameters (i.e. temperatures and CO_2 concentration). PID loops were used for controlling the CO_2 input concentration and the six heaters. A screen shot of the LabView front panel is in Figure 5.

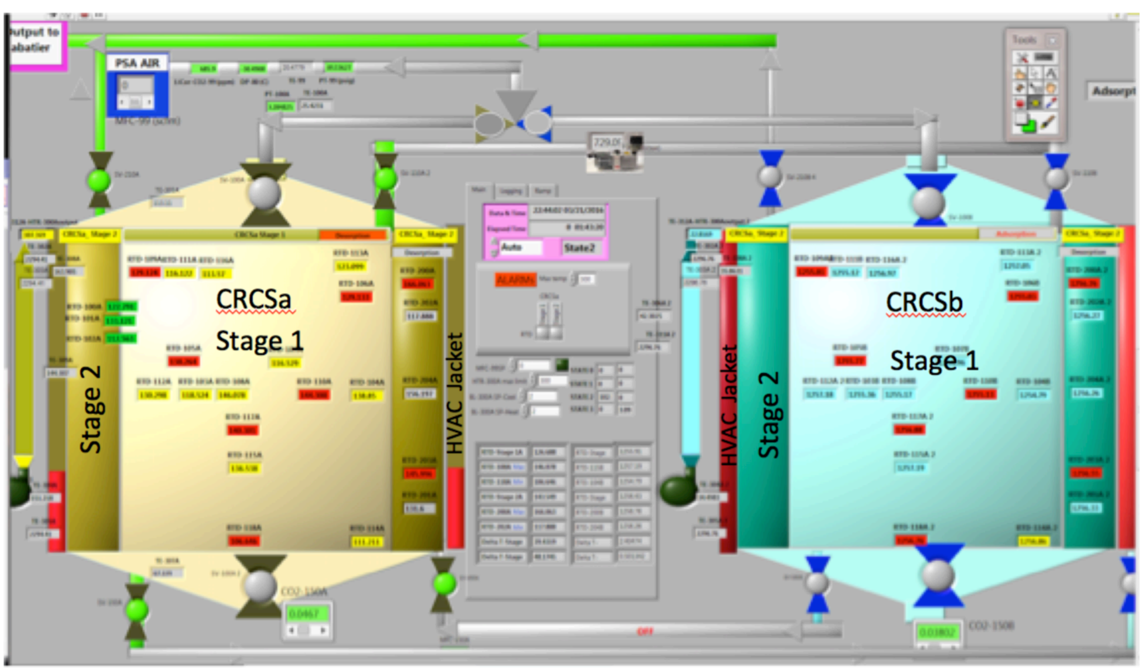

Figure 5: The CRCS LabView showing the process flow and a front view of the canisters.

C) 2600ppm CO_2 input air

In order to provide the 2600ppm CO_2 input air to stage 1, a Pressure Swing System (PSA) was used as a dry air source alongside a mass flow controller that feed concentrated CO_2 from a gas cylinder. PSA air contain less than 400ppm CO_2 at 30SCFM.This is because the PSA air input is from compressor that uses room air. A PID controller is used to adjust the mass flow controller such that 2600ppm CO_2 is input into stage 1.

D) Test Matrix

The tested matrix for the subsystem and the integrated tests are listed in Table 2. The subsystem tests were conducted on each unit (either CRCSa or CRCSb) to develop baseline parameters such as thermal and mass transfer and/or overall performance. These tests included CO_2 breakthrough (run 9-11), HVAC jacket operating parameters (run 1-6), and integrated tests (run 12-14). Before each subsystem test, a full ramp bakeout was conducted.

For the ramped bake-out, the sorbent was heated to 280˚C in three separate steps: ramp at 4˚C/min to 50˚C and allow to soak for 30 minutes; ramp at 4˚C/min to 100˚C and allow to soak for one hour; and then ramp at 15˚C/min to 280˚C and allow to soak for 6 hours.

In integrated tests, bake out will only be conducted at the onset. During the run, the desorption cycle will be used as the CO2 removal step. In the desorption cycle, a maximum desorption temperature of 280˚C was set as the temperature set point. The heater then is controlled by an on and off action of a solid-state relay. It is also noted here that there are RTDs on both the heater coils (Figure 6), as well as imbedded in the material. The RTD reading on the coil is usually higher than those on the material. However, these coil RTD higher readings must be taken as the temperature set point instead of the material RTD readings otherwise the material around the coil will be scorched. These precautions were taken as we approached the first cycle of testing. As preliminary tests are completed, these parameters can be adjusted as stressors to the system to evaluative maximum performance.

Table 2: The CRCS test matrix

	INTEGRATED TEST											
					Stage 1				Stage 2			
Test squence	CYCLIC TEST	time (days)	Objective	UOP-Bake-Out	Heat	Cool	CO2 input concentration	CO2 delivery to Sabatier	Heat	Cool	CO2 flow	CO2 to Stage 1
							ppm	psia			sccm	psia
A	run 13	3	1. demonstrate cyclic operation	UOP ramp rate	280˚C	PSA air at 30SCFM	2600ppm total	20psia to Sabatier	280˚C	blower at 20scfm		? L/min
			2. determine the delivery pressure form CRCS a stage 1 to CRCSb stage2		no ramping				no ramping			
			3. 60 minutes half cycle	UOP ramp rate	280˚C	PSA air at 30SCFM	2600ppm total	17psia to Sabatier				
			4. determine CO2 output concentration (in stage 1 exit air stream and to Sabatier)									
A-completed	run 16		30 minutes half cycle					17psia to Sabatier				
B	run 14	3	45 minutes half cycle	none	280˚C	PSA air at 30SCFM	2500ppm total					
B	run 15	3	90 minutes half cycle	none								

	HEAT TRANSFER TEST											
	For both CRCS a and b				Stage 1				Stage 2			
Run series	HEAT TRANSFER	time (days)	Objective	Bake-out	Heat	Cool	CO2 flow	CO2 delivery Psia	Heat	Cool	CO2 flow	CO2 delivery Psia
A	run 1	2	stage 1 heating effects	UOP ramp	280˚C	30SCFM PSA air				no blower		
B	run 2	2	stage 2 heating effects	UOP ramp					280˚C	no blower		
A	run 3	2	Stage 2 cool with flow	UOP ramp					280˚C	HVAC blower at 20scfm		
B	run 4	2	Stage 2 cool with decrease flow	UOP ramp					280˚C	HVAC blower at 10scfm		
B	run 5	2	cooling without the blower	UOP ramp	280˚C	30SCFM PSA air			280˚C	no blower		
A	run 6	4	cooling with the blower	UOP ramp	280˚C	30SCFM PSA air			280˚C	HVAC blower at 20scfm		

	MASS TRANSFER TEST											
	For both CRCS a and b				Stage 1				Stage 2			
	MASS TRANFER		Objective	Bake-out	Heat	Cool	CO2 flow	CO2 delivery Psia	Heat	Cool	CO2 flow	CO2 delivery Psia
A	run 7	2	CO2 breakthrough at 2500ppm stage 1 only	UOP ramp	280˚C	PSA air at 30SCFM	2500ppm total			no blower		
A	run 8	2	CO2 breakthrough pure CO2 at ... stage 2 flow rate?	UOP ramp					280˚C	blower at 20scfm	? L/min	? L/min
B	run 9	2	CO2 breakthrough at 2500ppm stage 1 only	UOP ramp	280˚C	PSA air at 30SCFM	2500ppm total			no blower		
B	run 10	2	CO2 breakthrough pure CO2 at ... stage 2 flow rate?	UOP ramp					280˚C	blower at 20scfm	? L/min	? L/min

Figure 6: The CRCSb heating coils inside the stage 1 and stage 2 cylinders.

E) Bake-out procedure and related issues

Before installing the sorbent into the canister, the sorbent were baked out in a ramp profile to 350˚C for 10 hours. After cooling, the sorbent containers were then removed and covered with aluminum foil. After the heaters were installed, the sorbent were packed into the canister in a laboratory environment. It is during this process, the sorbent is then re-exposed to humid air. Therefore, after assembly, bake-out is repeated in placed using the spiral heaters, under vacuum (50 torr), and with occasional nitrogen airflow. Because there is considerable temperature differential in the beds during heating, complete bake out may not be achieved. However, vacuum and nitrogen flow may compensate for the lack in heating uniformity. Further testing will reveal if these bake-out procedures are sufficient. An additional heater have been fabricated to allow for heated nitrogen air to flow through the beds for bake-out, if need. Because the design of the canisters and the valves attached, it is difficult to place the entire CRCS unit into an oven for bake out. In addition, the Kalrez o-rings install will not tolerate temperature above 315˚C.

III) Experimental Data and Discussion

Some integrated testing of system was completed according to on the test matrix. The goals of the integrated tests were to determine if the system yield data in according with the design intentions. The primary objectives of the integrated tests are: (1) To determine the delivery pressure and flow rates of concentrated CO_2 from stage 1 of one bed to stage 2 of another; (2) To determine the delivery pressures and flow rates of concentrated CO_2 of stage 2 to the Sabatier system. In addition to the primary objectives, dependent variables will also be examined to evaluate the performance and effectiveness subsystem components that contribute to the overall system operation. Some of these components under examination are the spiral heaters, the HVAC heaters, the blowers, and the insulations.

A) Temperature Distribution

Previous testing on individual CRCSa canister indicated that there are temperature distribution problems in both stages[9] 1 and 2. Uniform heating may lead to inadequate bake-out and regeneration. As results, for the integrated system, the cooling jacket was converted into a HVAC jacket. The HVAC jacket allows cooling during adsorption and assist in heating, if needed, during regeneration.

Figure 7 shows the temperature distribution comparison from the RTDs placed at the top, middle, and bottom of the bed. These graphs show that the middle of the bed is hotter than the top and the bottom. Multiple rational have been considered for this lack in uniformity. One, the spiral heater was not fabricated with variable resistance throughout the heated length. The constant resistance throughout the heater length contributed to the “oven effect” where the middle of the bed his hotter than the top, bottom or the sides. As a result, the bed behaves as a “sphere.” Two, there are considerable heat lost to both the top and the bottom lids. The comparison of the maximum, minimum, mean, and lid temperatures are shown in Figure 8.

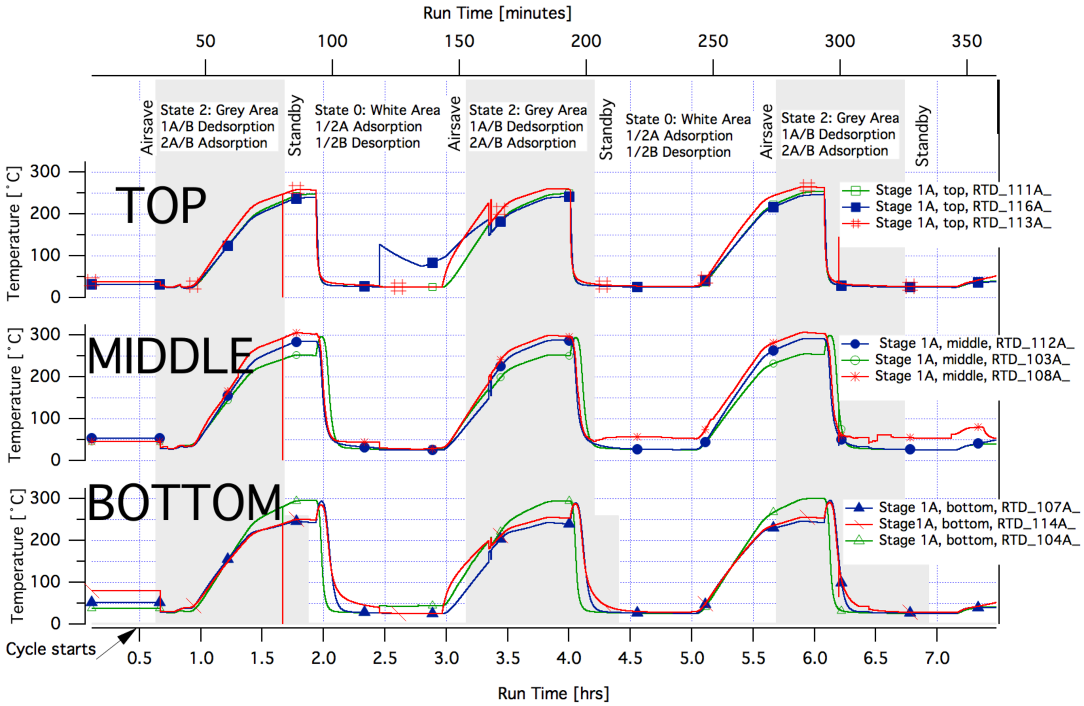

Figure 7: Graphs showing the temperature distribution in CRCSa stage 1 during 120 minutes cyclic testing. The white area is when CRCSa is adsorbing CO2 from cabin air. The grey area is when CRCSa is desorbing from stage 1 to stage 2 of CRCSb. These graphs show RTD readings imbedded in the material toward the top, the middle, and the bottom of the bed.

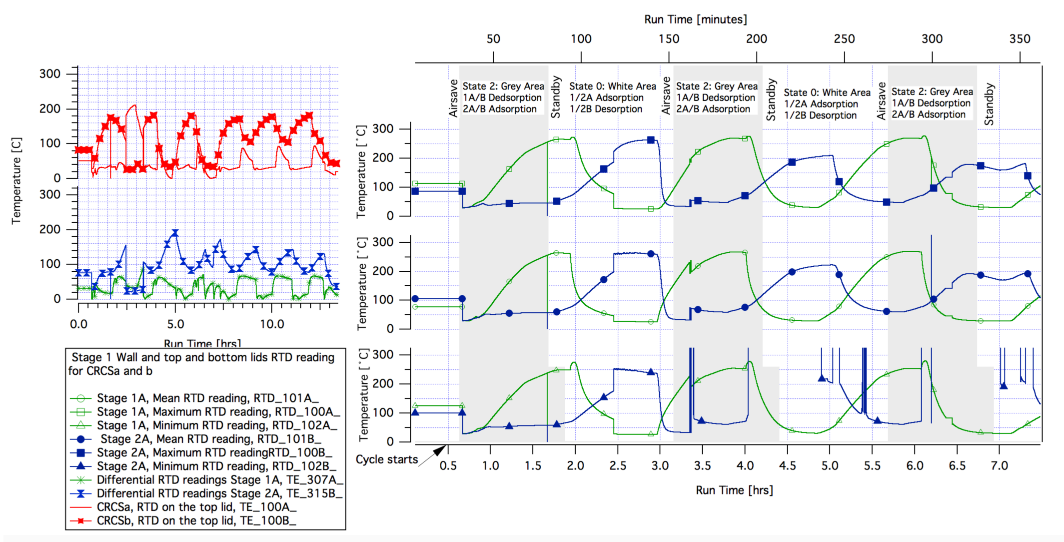

Figure 8: Graphs summarizing temperatures throughout CRCSa stage 1 and stage2. (Left-top) The thermocouple readings of RTDs placed on the top lid surface. (Left-bottom) Thermocouple readings of RTDs placed on the bottom lid surface. (Right) These graphs showed the maximum (right-top), mean (right-middle), and minimum (right-bottom) temperatures of both stage 1 and stage 2. The white area is when CRCSa is adsorbing CO_2 from cabin air. The grey area is when CRCSa stage 1 is desorbing CO2 to stage 2 of CRCSb.

B) CO_2 delivery

In order to understand the dynamics of carbon dioxide adsorption and desorption in the CRCS system, a simplified diagram of the CO_2 flow path during CRCSa desorption is shown in Figure 9. For clarity, the CRCSa side is shown larger than CRCSb; in reality they are the same size.

In Figure 9, starting at #1, when stage 1A is in the desorption mode and the heater is turned on. As a result, temperatures of the sorbent in stage 1A (indicated by the RTD readings in stage 1A) increase. When the material temperature increases, CO_2 is desorbed. As CO_2 is being desorbed, stage 1A pressure will increase. This increase in pressure is measured by the pressure controller/transducer, #2. As the pressure increases above the set point, CO_2 flow through the mass flow controller, #3, and enter stage 2 of CRCSb. This only occurs when the pressure in stage 2b is in equilibrium with stage 1a.

At the same time, stage 2A (which also has a shared wall with stage 1A) is also in desorption mode and the heater is on. When stage 2A is heated, the temperature of the sorbent, #4, increase. The temperature increases, causing the CO_2 in stage 2A to desorb. This increases the pressure in stage 2A, #5. When the pressure is above the pressure controller set point, CO_2 flow through the mass flow controller/meter, #6, and is delivered to the Sabatier system. Again, this only occurs if there if a pressure differential between stage 2A and the Sabatier system.

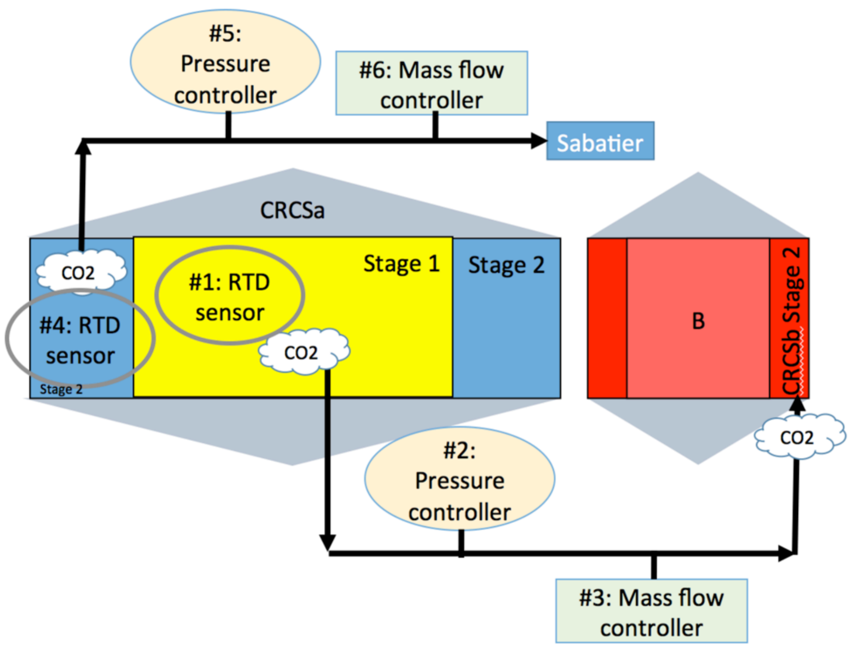

Figure 9: A simplified flow diagram of the flow of CO_2 during desorption in CRCSa stage 1 and stage 2.

C) Cyclic Testing

We have completed multiple integrated 30 minutes and 60 minutes half-cycle cyclic testing. Data have been collected various locations of the systems. Initial data show that as the beds are heated, pressure will increase, and flow detected. However, these data indicate that we may have incomplete bake-out due to heating uniformity, sensors issues and possible leaks. Although these issues are present, we have implemented solution that will resolve these issues before further testing.

IV) Conclusion

To date, preliminary integrated testing of CRCS (a and b) has demonstrated that basic functionality has been achieved. Multiple tests of both 30 and 60 minute half-cycles have yielded predictable temperature cycling in both Stage 1 and 2, which is the critical underlying functioning of both Stage 1 desorption and Stage 2 CO2 compression.

Additionally, Stage 2 TSAC functionality has been observed. The data also indicate that the overall control system that regulates the entire system is fundamentally sound.

Regardless, multiple areas require further definition and testing. Although several 30 and 60 minute integrated half-cycle tests were conducted, issues with heaters and sensors need to be resolved to complete all tests listed in the test matrix. While initial results indicate that the HVAC jacket and added insulation did increase the rate of Stage 2 heating, it did not substantially improve heating uniformity within the bed. Another ongoing process improvement is developing methods that very thoroughly regenerate Stage 1 and 2 beds after sorbent filling to ensure the absence of water, as water can substantially degrade overall system performance. Additional heating units and methods are being developed to address this issue.

I) Future Testing and Lesson Learned

As of this writing, initial functional and baseline tests have been conducted. Additional integrated performance testing is planned for the immediate future. Some addition lessons learned in addition to the one previously noted in are combined here for completeness, Table 3

Table 3: Lessons learned from the design, fabrication, and testing of the integrated system.

	Component	Issues encountered	Modification to CRCSb design, fabrication, assembly
1	23 pin macor connectors	Connectors cracks upon applied pressure during assembly	Re-design the feedthrough.
2	Top and bottom cap	Temperature differential from the top and bottom to the center of the canister can be as high as 100˚C	Design a “Hershey” kiss shape into the caps to improve temperature distribution and improve heat lost.
3	Heaters in stage 2	It takes 30 minutes for stage 2 temperatures to heat up to 250˚C.	Install the HVAC jacket.
4	Adsorbent used and temperature specification	300˚C temperature requirement for stage one delayed tasks and increase cost	None at this time.
5	Heaters Stage 1	Large temperatures variation between the top, middle, and bottom layer	No change at this time. The heating elements were not designed at varying resistance to account for the length of the heater. A new heater design is needed.
6	Heater Stage 2	Stage 2 material temperature does not reached 285˚C within the 60 minutes cycle	Longer cycle time considered. Recycle hot air from the other unit to the cooling jacket. The short term solution. The use of the HVAC jacket.
7	Macor feedthrough	Not enough feedthrough capacity to use a three 3 wires RTDs or install more RTDs for flow characterization.	None at this time.

Acknowledgement

The authors would like to thank all the previous designers and authors who were referenced in this paper in the development of the CRCS.

References

[1] Mulloth, L., et al. *Development of a low-power CO2 removal and compression system for closed-loop air revitalization in future spacecraft, SAE International*. Paper 2005-01-2944, 2005.
[2] Mulloth, L., Rosen, M., Varghese, M., Luna, B. et al., "*Performance Characterization of a Temperature-Swing Adsorption Compressor for Closed-Loop Air Revitalization Based on Integrated Tests with Carbon Dioxide Removal and Reduction Assemblies*," SAE Technical Paper 2006-01-2126, 2006, doi:10.4271/2006-01-2126.
[3] Varghese, M.M., Mulloth, L.M., Luna, B., and Hogan, J.A. "Development Status of a Low-Power CO_2 Removal and Compression System for Closed-Loop Air Revitalization." 40th *International Conference on Environmental Systems, San Francisco, CA*. 2010.
[4] Mulloth, L., Varghese, M., Luna, B., Hogan, J., LeVan, D. and Moate. J.R. Development Status of a Low-Power CO_2 Removal and Compression System for Closed-Loop Air Revitalization. No. 2008-01-2095. SAE Technical Paper, 2008.
[5] Mulloth, L.M., Varghese, M. and Luna, B.. "Power Optimization Options for a Temperature-Swing Adsorption Compressor Design." (2010).
[6] Hogan, J.A., Luna, B. Koss. B., Palmer, G.H., Linggi, P., Lu, Z., Varghese, M.M., and Mulloth, L.M. "The Low-Power CO_2 Removal and Compression System: Design Advances and Development Status." *AIAA Paper* 2012-3587 (2012).
[7] Hogan, J., Jan, D. Palmer, G.H., Richardson, T-M.J., Linggi, P., Lu, Z. and Kamiya, T. "Development and Testing of a Two-Stage Air Drying System for Spacecraft Cabin CO_2 Removal Systems." 44th International Conference on Environmental Systems, 2014.
[8] Hogan, J.A., Jan, D., Koss, B., Linggi, P., Lu, Z., Palmer, G., Melton, J. “ARREM FY12 Year End Report: Low Power CO_2 Removal (LPCOR) System Development.” NASA Ames Research Center, Moffett Field, CA (2012)
[9] Richardson, T.J., Hogan, J., Huang,R., Palmer, G., Samson, J., “Progress on the CO2 Removal and Compression System.” 45th International Conference on Environmental System ICES-2015-06412-16 July 2015, Bellevue, WA ICES-2015-064