# 4BMS-X Design and Test Activation

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**In support of the NASA goals to reduce power, volume and mass requirements on future CO2 (Carbon Dioxide) removal systems for exploration missions, a 4BMS (Four Bed Molecular Sieve) test bed was fabricated and activated at the NASA Marshall Space Flight Center. The 4BMS-X (Four Bed Molecular Sieve-Exploration) test bed used components similar in size, spacing, and function to those on the flight ISS flight CDRA system, but were assembled in an open framework. This open framework allows for quick integration of changes to components, beds and material systems. The test stand is highly instrumented to provide data necessary to anchor predictive modeling efforts occurring in parallel to testing. System architecture and test data collected on the initial configurations will be presented.**

## Nomenclature

| | | |
|---|---|---|
| *AES* | = | Advanced Exploration Systems |
| *ARREM* | = | Atmosphere Resource Recovery and Environmental Monitoring |
| *4BMS* | = | Four Bed Molecular Sieve |
| *4BMS-X* | = | Four Bed Molecular Sieve for Exploration |
| *CO2* | = | Carbon Dioxide |
| *CDRA* | = | Carbon Dioxide Removal Assembly |
| *DWP* | = | Dewpoint |
| *ECLSS* | = | Environmental Control and Life Support Systems |
| *HEO* | = | Human Exploration and Operations Directorate |
| *HX* | = | Heat Exchanger, Precooler |
| *HC* | = | Half Cycle |
| *ISS* | = | International Space Station |
| *LSSP* | = | Life Support Systems Project |
| *MSFC* | = | Marshall Space Flight Center |
| $ppCO_2$ | = | Partial Pressure of Carbon Dioxide (torr) |
| *POIST* | = | Performance and Operational Issues System Testbed |
| *SLPM* | = | Standard Liters per minute |
| *SMT* | = | System Maturation Team |

## I. Introduction

FROM FY12 to FY14, the Atmosphere Revitalization Recovery and Environmental Monitoring (ARREM) project under the AES program included efforts to improve the CO2 (Carbon Dioxide) Removal state-of-the-art by seeking more robust sorbents and evaluating alternate sorbent formats and fixed-bed configurations. This scope was broadened when, in early 2014, the ISS (International Space Station) Program Manager requested that the NASA ECLSS (Environmental Control and Life Support Systems) Systems Maturation Team (SMT) review all possible alternate technologies and provide a recommendation to the ISS Program to guide decisions relative to the next steps for CO2 removal. This recommendation was to include goals for both ISS and future Exploration missions[1].

To meet these goals, one of the two decision paths focused on the current ISS CDRA (Carbon Dioxide Removal Assembly), with improvements in reliability and performance. Using the ISS CDRA configuration as a basis, the team began a design for the next generation CO2 removal system with appropriate attributes for a 2-year mission with

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no resupply. The effort was to conclude with the fabrication of a technology demonstrator to be flown to ISS by 2019. The brass-board test bed was named 4BMS-X for four Bed Molecular Sieve for Exploration. The design of the new 4BMS system addressed reliability and performance improvements.

Dust production from pelletized zeolite reduces performance through an increase in pressure drop as the dust accumulates at the sorbent bed outlet. A redesigned sorbent bed using a cylindrical design strategy and new heater technology could reduce channeling and fluidization of the sorbent. Detailed characterization tests were performed on multiple pelletized sorbents to provide a more durable zeolite.[3] A system design with a reduction in heater temperature would reduce cyclic thermally induced stress on the sorbent, improving longevity.

While a reduction in dust production is expected in the new design, the team also focused on creating a system that had increased tolerance to dust. A valve design with specific dust tolerant features reduces the likelihood of valve failures. A maintainable filter design would allow the removal of dust before an increase in system pressure drop reduced CO2 removal rate.

Performance requirements for the new design necessitate a higher performing system with 4.16 kg/day of CO2 removal at an inlet CO2 partial pressure of 2 torr. An increase in CO2 removal can be accomplished through changes in desiccant bed material, sorbent bed material, and system flow rate. CDRA desiccant beds have more 13X zeolite than is required to supply dry air to the sorbent beds. The unused 13X holds up some CO2, which is exhausted to the cabin during mode changes without traveling to the sorbent bed. A reduction in desiccant bed 13X would improve CO2 removal rates. Detailed sorbent characterization trials were performed to identify a sorbent with increased capacity and kinetics[3]. An increase in system flow can be achieved by operating the blower at higher power, which increases CO2 removal at the cost of system power and efficiency. System modeling[2] has been and will be continue to be used to determine system optimized performance, volume, mass and power.

The team is currently testing a system that uses heritage hardware to guide the design of the future configuration. This paper will describe performance changes as a function of desiccant and sorbent material and mass changes, as well as variations in inlet test conditions. A future paper will describe the performance of the final hardware configuration

## II. Test Objectives

The initial test program used heritage rectangular sorbent beds packed with RK-38 zeolite and heated with Kapton flexible heater sheets. While new beds were under construction, the team created a performance baseline while tuning the PID controlled facility, shown in Figure 1, to deliver precisely controlled inlet conditions. In the second test phase, 50% of the 13X in the desiccant beds was replaced with inert glass beads. In the third phase, 70% of the sorbent bed volume was replaced with 13X zeolite, and the remainder filled with inert glass beads. Overall test objectives were:

1. Baseline operation with heritage configuration
   A. Comparison to heritage systems
   B. Oscillating vs steady state inlet conditions
2. Performance benefits with reduced 13X in desiccant bed
   A. CO2 removal
   B. Various flow rates, same total air flow per half cycle
   C. Sensitivity to inlet dewpoint and temperature
   D. Desiccant Bed Margin
3. Replacement of Sorbent With a Reduced Amount of 13X zeolite
   A. CO2 Removal Rate after Sorbent Replacement
   B. Various flow rates, same total air flow per half cycle
   C. Addition of Intermediate CO2% Measurement

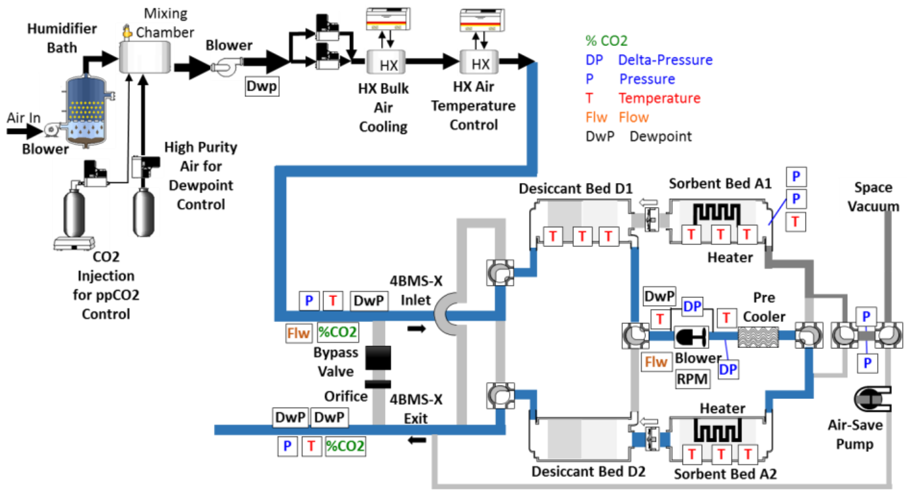



**Figure 1. 4BMS-X Integrated with Conditioned Air Facility**

## III. Hardware and Test Facility

4BMS-X is a brass board 4BMS system identical in concept to CDRA, shown in Figure 2. The initial configuration used rectangular sorbent beds, desiccant beds and check valves from the heritage POIST (Performance and Operational Issues System Testbed) 4BMS test program which are nearly identical in all aspects to CDRA shown in Figure 3. The 4BMS-X precooler features the same technology and size as the CDRA precooler, but with a 90-degree flow path for packaging also shown in figure 3. 4BMS-X uses commercial valves, chillers, an off-mounted blower and an airsave pump to reduce cost and procurement timelines. 4BMS-X is mounted on an 80/20® framework that allows efficient modification for new materials, bed geometry, active components or instrumentation as shown in Figure 1.

In order to isolate and compare operational characteristics, as well as aid in validation of computer modeling, the process air inlet conditions are precisely controlled. The facility software features multiple PID loops for temperature, flow, CO2 partial pressure and dewpoint. The facility Lab VIEW control software is customized to allow on-the-fly changes as components are upgraded. Over 135 pieces of instrumentation provide data for feedback control, operational comparisons, and model verification. The first generation 4BMS-X system does not include a CO2 reduction system, and CO2 is desorbed through a vacuum system tuned to match heritage vacuum levels.

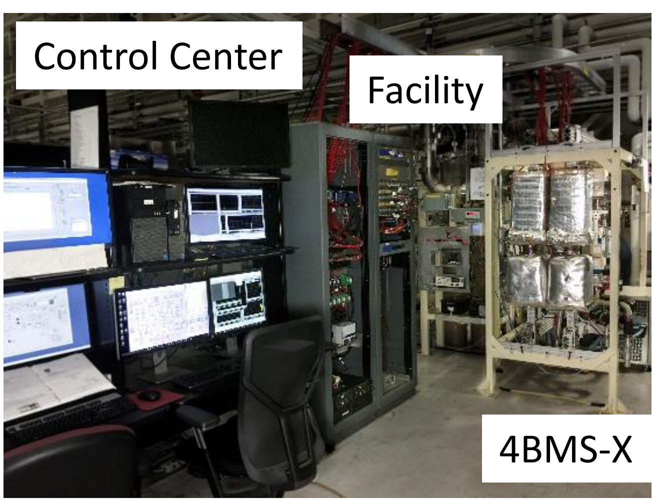



**Figure 2. 4BMS-X with Integrated Facility**

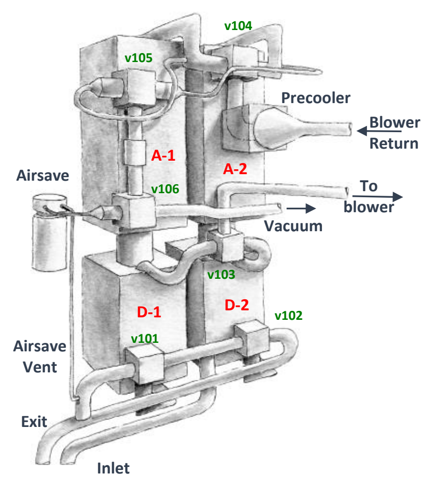



**Figure 3. 4BMS-X Isometric**

## IV. Objective 1A: Comparison to Heritage Performance

The first 4BMS-X test series simulated historical test program conditions to insure 4BMS-X performed similarly using the same inlet conditions and half cycle. Once the baseline performance was established, differences resulting from hardware and operational changes could be traced for comparison to the flight system. Inlet conditions used in the proto-flight CDRA test series were used on the first 4BMS-X test series.

Hardware Configuration: r1
- Rectangular bed shape
- Desiccant Bed: fully packed with 13X, silica gel and Sorbead
- Sorbent bed: fully packed RK-38

Inlet conditions:

| | |
|---|---|
| 15-130-10 | Half cycle: A (airsave mode) = 15 minutes, B = 130 minutes, C = 10 minutes |
| 10.4C (50.7F) | Inlet process air temperature |
| 5.7C (42.3F) | Inlet process air dewpoint |
| 575 SLPM (20.3scfm) | Inlet airflow calculated with 0C and ambient pressure |

| Half Cycle [min] | ppCO2 [torr] | Air Flow [SLPM] | Inlet Temp [C] | Inlet DP [C] | HX Exit Air Temp [C] | CO2 Removal [kg/day] |
|---|---|---|---|---|---|---|
| 15-130-10 | 2.00 | 573 | 10.4 | 5.7 | 11.1 | 3.50 |
| 15-130-10 | 2.99 | 573 | 10.4 | 5.7 | 11.4 | 5.31 |
| 15-130-10 | 3.89 | 574 | 10.4 | 5.7 | 10.4 | 6.61 |

**Table 1. Comparison to Heritage Configuration.** *Tabulated values represent averages over entire test.*

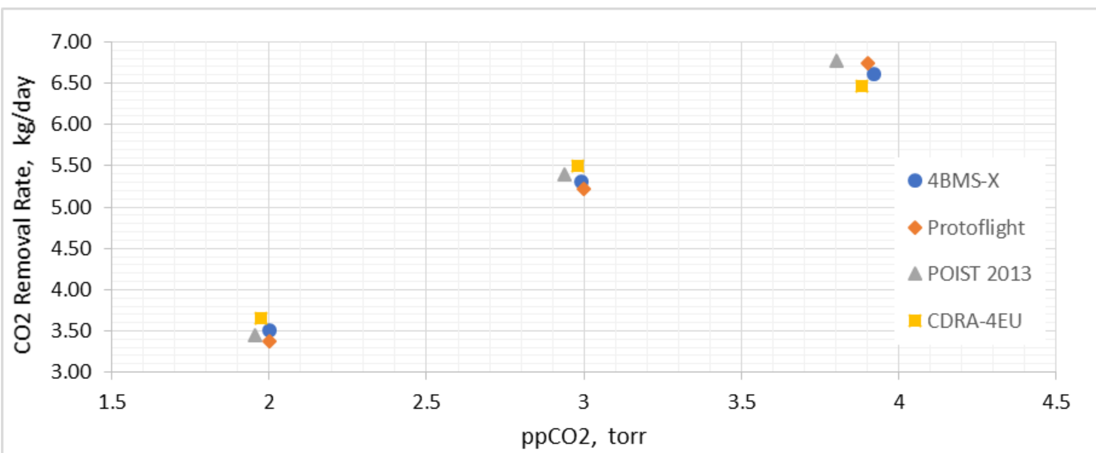



**Figure 4. Heritage Performance Comparison of Removal Rate vs Inlet ppCO2**

Conclusion

CO2 removal measured on 4BMS-X, shown in Table 1 and graphically in Figure 4, was consistent with 3 historical references using the same inlet conditions and half cycle duration. From this dataset we assume that future results can be compared to the current flight system.

## V. Objective 1B: Cyclic vs Steady Inlet Conditions

The 4BMS-X conditioned air facility uses control systems to provide constant inlet values for the purposes of test-to-test comparisons and to ease validation of computer models. The condition of the air in the 4BMS-X air outlet has no effect on the inlet conditions. However, the cyclic ISS CDRA exit air temperature and humidity affects the inlet conditions because CDRA exhausts to an enclosed environment that feeds back to the inlet. The team conducted a 4BMS-X test using 4BMS-X inlet conditions matching the average of a cyclic test performed in the enclosed E-Chamber using the CDRA-4EU hardware. Results are shown in Table 2 and Figure 5.

<u>Hardware Configuration</u>: r1

Rectangular bed shape
Desiccant Bed: fully packed with 13X, silica gel and sorbead
Sorbent bed: fully packed RK-38

<u>Inlet conditions:</u>

| | |
|---|---|
| 10-124-10 | Half cycle: A (airsave mode) = 15 minutes, B = 130 minutes, C = 10 minutes |
| 12.2C (53.9F) | Inlet process air temperature |
| 6.9C (44.5F) | Inlet process air dewpoint |
| 498 SLPM (17.6scfm) | Inlet airflow calculated with 0C and ambient pressure |

| | Half Cycle [min] | ppCO2 [torr] | Air Flow [SLPM] | Inlet Temp [C] | Inlet Dwpt [C] | HX Exit Air Temp [C] | CO2 Removal [kg/day] |
|---|---|---|---|---|---|---|---|
| Steady | 10-124-10 | 3.0 | 499 | 12.2 | 6.9 | 4.8 | 4.690 |
| Cyclic | 10-124-10 | 3.0 | 498 | 12.2 | 6.9 | 4.4 | 4.790 |

**Table 2. Comparison of Steady vs Cyclic Inlet Conditions**

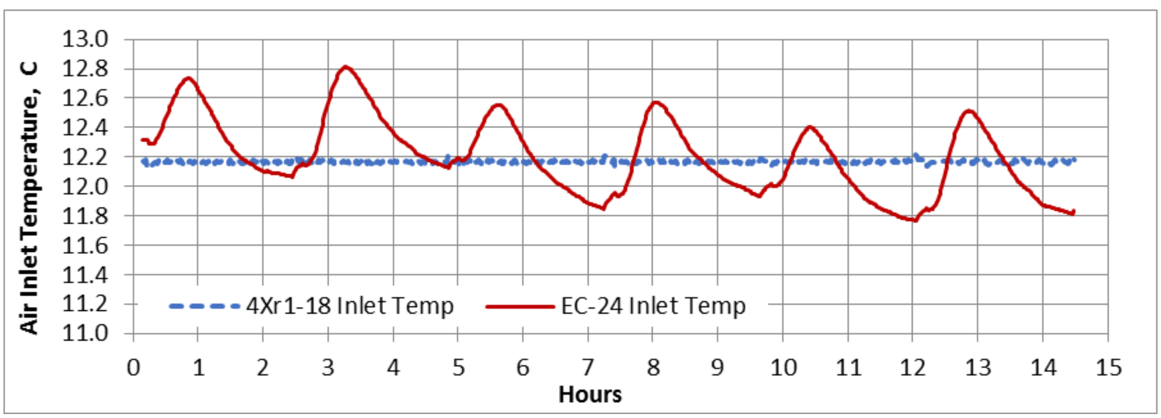



**Figure 5. Inlet Process Air Temperature for Oscillating CDRA-4EU System and 4BMS-X System**

<u>Conclusion</u>

The difference of 2% between oscillating conditions in an enclosed system test and a constant 4BMS-X inlet conditions will be treated as insignificant.

### Hardware Configuration Change – 50% Reduction of 13X in Desiccant Beds

13X in the desiccant bed will adsorb CO2 if the process air is dry when it reaches the 13X layer in the desiccant bed. CO2 stored in the desiccant bed, or held up in the desiccant bed, does not reach the sorbent bed and is returned to the cabin during desiccant bed desorption. Models predicted that the CO2 holdup in the desiccant bed constituted a significant CO2 performance loss at normal operational conditions where sorbent bed CO2 breakthrough is minimal during a half cycle.

For schedule convenience, the heritage rectangular beds were used with a reduced amount of 13X. This initial performance data would be used to compare to modeling data and guide future mechanical design options. Future designs will use cylindrical beds that will be sized based on the results measured on this test series. The team decided to use glass beads as an inert spacer. The total heat capacity of the glass beads was estimated to be equivalent to the 13X removed from the desiccant beds. The glass beads were placed furthest from the check valve so heated air flowing from the sorbent bed during desiccant bed desorption would heat the 13X and silica gel rather than the inert glass beads. See Figure 6.

The desiccant beds were removed from 4BMS-X and all material removed, dried, and weighed to provide inputs for computer models. The desiccant beds were repacked with the same 13X material that was removed from the bed, but only 50% of the 13X mass was replaced in the bottom of the desiccant bed. Glass beads and Silica Gel layers were replaced in the same order as originally packaged. The void farthest from the check valve was filled with additional 3mm glass beads, as shown in Figure 6. The desiccant beds were dried in an environmental chamber at 190°C with 120 SLPM GN2 flow through the beds.

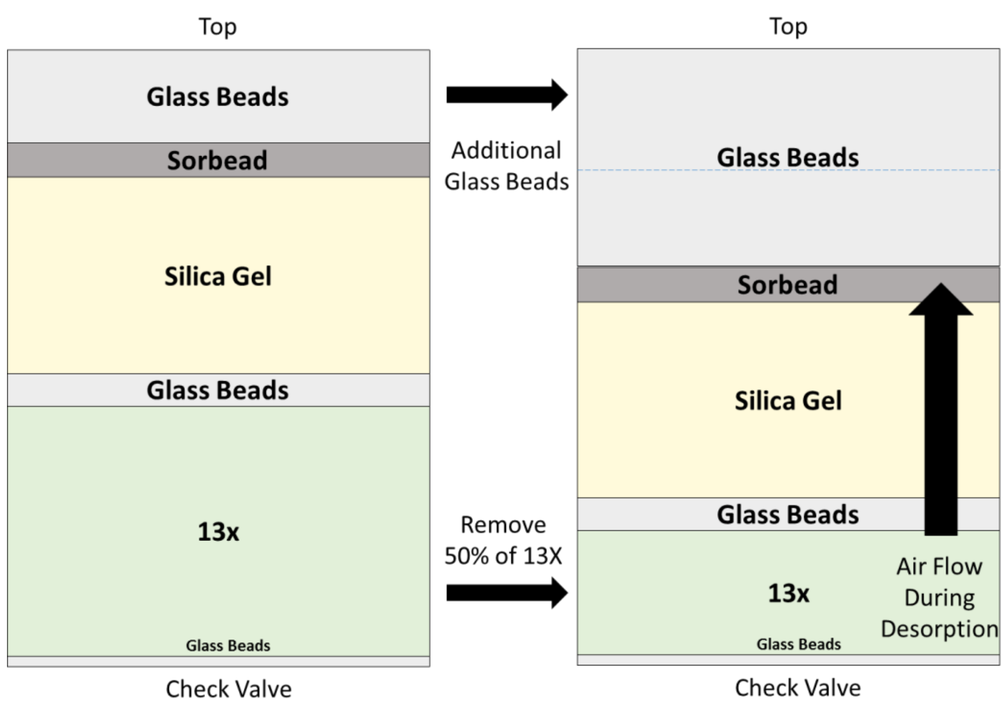



**Figure 6. Changes in Desiccant Bed Material Configuration.**

## VI. Test Objective 2A: CO2 Removal

Determine the change in CO2 removal and investigate changes in cyclic parameters for model comparison. A total of three tests were performed using an 80 minute half cycle and process air flow of 780 SLPM (28 SCFM). The computer simulation predicted maximum performance at these conditions. Each test configuration will use these conditions as a comparable reference case even if the eventual configuration is optimized differently.

Hardware Configuration: r2

Rectangular bed shape

Desiccant Bed: 50% of 13X replaced with inert 3mm glass beads.

Sorbent bed: fully packed RK-38

Inlet conditions:

| | |
|---|---|
| 10-60-10 | Half cycle: A (airsave mode) = 15 minutes, B = 130 minutes, C = 10 minutes |
| 11.7C (53F) | Inlet process air temperature |
| 10C (50F) | Inlet process air dewpoint |
| 778 SLPM (27.5scfm) | Inlet airflow calculated with 0C and ambient pressure |

CO2 removal was consistent across tests on different days with minor changes in inlet conditions, as shown in Table 3. For clarity, only test 4Xr1-19 (before 50% 13X removal) and 4Xr2-24 (after 50% 13X removal) will be presented.

| Test | Half Cycle [min] | ppCO2 [torr] | Air Flow [SLPM] | Inlet Temp [C] | Inlet DP [C] | HX Exit Air Temp [C] | CO2 Removal [kg/day] |
|---|---|---|---|---|---|---|---|
| Reference | 10-60-10 | 2.02 | 784 | 11.7 | 10.0 | 17.2 | 4.48 |
| Reference | 10-60-10 | 2.00 | 777 | 11.7 | 10.0 | 16.7 | 4.46 |
| -50% 13X | 10-60-10 | 1.99 | 782 | 11.7 | 10.0 | 13.8 | 4.97 |
| -50% 13X | 10-60-10 | 1.99 | 787 | 11.7 | 9.8 | 13.7 | 4.98 |
| -50% 13X | 10-60-10 | 2.01 | 783 | 11.7 | 12.1 | 14.4 | 5.04 |

**Table 3. Increase in CO2 Removal After 50% Reduction of 13X from Desiccant Bed.**

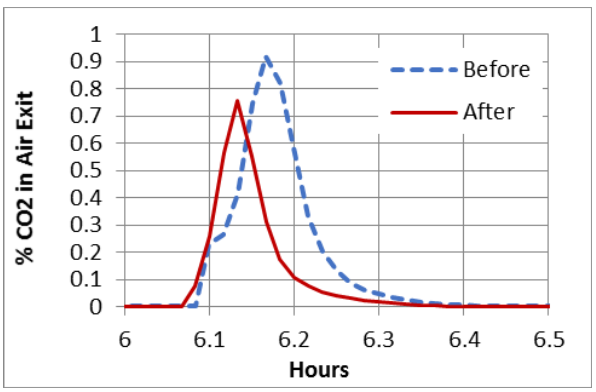



**Figure 7. CO2 % During HC Change.**
*Measured in the air exit during HC change.*

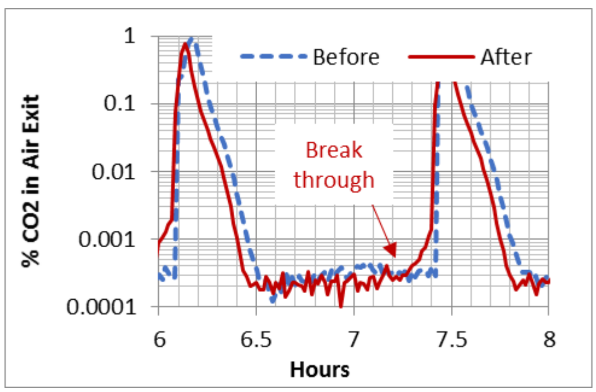
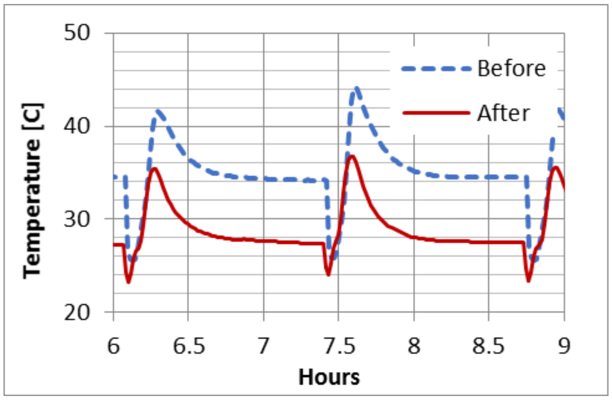



**Figure 8. CO2 % During Adsorption Cycle.**
*Measured in the air exit during HC change.*

The CO2% peak, Figure 7, measured at the air outlet just after the cycle change is lower and narrower after the 13X was reduced in the desiccant bed. Because less CO2 was adsorbed into the desiccant bed, more CO2 reached the sorbent bed improving CO2 removal performance. In the original reference test, CO2 system breakthrough, measured at the air system exit, did not occur during the 80 minute half cycle. After the 13X was removed, CO2 system breakthrough, measured at the air system exit, occurred just prior to the end of the half cycle because more CO2 was reaching the sorbent bed. See Figure 8.



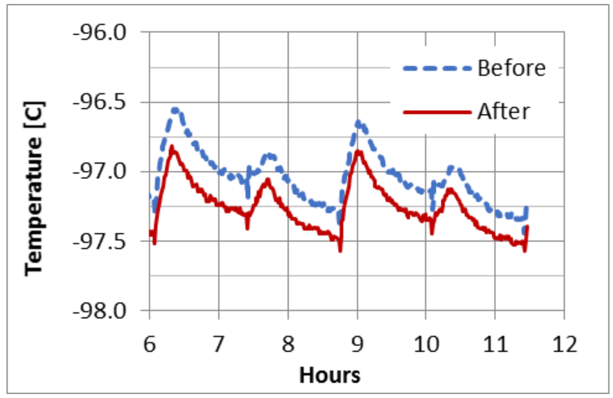
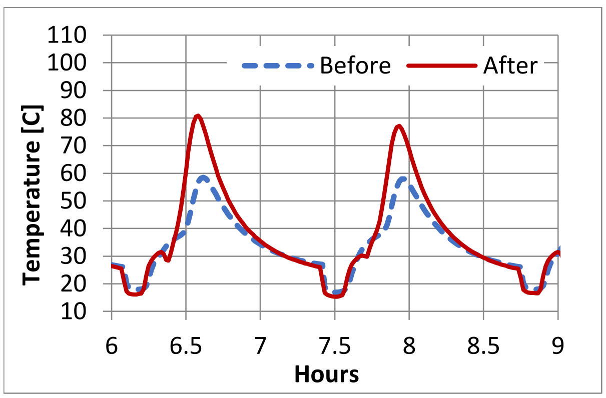




**Figure 9. Desiccant Bed Outlet Temperature.**
*Measured between desiccant bed and blower*

**Figure 10. Desiccant Bed Out Dewpoint Temperature.**
*Measured between desiccant bed and blower*

Desiccant bed outlet temperature, Figure 9, was lower after 13X removal because less zeolite was available to generate heat of adsorption. Despite less 13X in the bed, the desiccant bed outlet dewpoint was slightly lower after the 13X was removed (Figure 10). The dewpoint values are below the rated value of the sensor, but the trend shows that drying capacity of the desiccant beds did not substantially change.



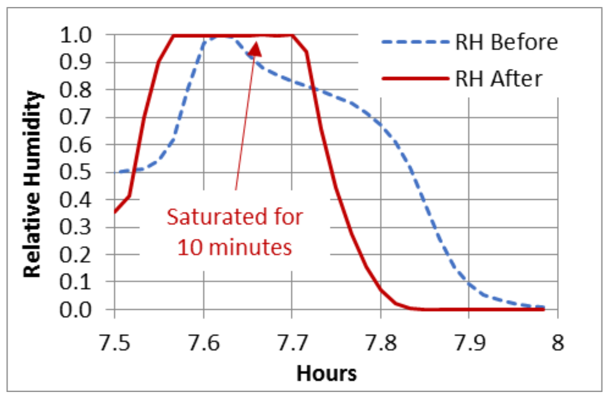




**Figure 11. System Outlet Air Temperature**

**Figure 12. System Outlet Relative Humidity**

The 4BMS exit air stream is 20C warmer after the desiccant 13X mass was reduced, as shown in Figure 11. Because the desiccant bed contained 50% less 13X, less sorbent was available to absorb the heat emanating from the sorbent bed after the cycle change, allowing more heat to escape the system. The 'before' system exit experienced saturated air conditions for less than 2 minutes, but the saturated duration extended to 10 minutes as shown in Figure 12 after the change. Ancedotally, more water condensation was located on the floor under the system air exit after the dessicant bed 13X was reduced.

<u>Conclusions</u> CO2 removal increased from an average rate of 4.46 kg/day to 4.97 kg/day after a 50% reduction of desiccant bed 13X zeolite. The reduction in magnitude and duration of the CO2 spike in the exit process air stream at the beginning of the half cycle change constitutes a majority of the CO2 removal increase, substantiating the desiccant bed 13X CO2 holdup theory. Desiccant bed outlet temperature dropped by 5.5C (10F) due to a reduction in the heat of adsorption. The desiccant bed outlet dewpoint dropped 0.2C (0.4F), within measurement tolerance of sensor.

## VII. Test Objective 2B: Sensitivity of Process Air Flow and Half Cycle

In order to meet the exploration goal of greater than 4 kg/day CO2 removal rate at two torr inlet ppCO2, we anticipate higher process air flow rates. Process airflow and half cycle durations cannot be selected independently because the desiccant beds are limited in capacity to an integrated volumetric flow (defined as volumetric flow rate times HC time) of humidified air. As process airflow is increased, the half cycle is decreased to maintain the total amount of water adsorbed into the desiccant beds. Three test points were chosen to keep the integrated volumetric flow constant, varying the half cycle duration inversely to the airflow rate.

(Half cycle minutes) x (flow/minute) = (80 min) x (792.4 SLPM) = constant = 63392 liters (2240 cubic feet).

<u>Hardware Configuration</u>: r2

Rectangular bed shape

Desiccant Bed: 50% of 13X replaced with inert 3mm glass beads.

Sorbent bed: fully packed RK-38

<u>Inlet conditions:</u>

| | |
|---|---|
| 11.7C (53F) | Inlet process air temperature |
| 10C (50F) | Inlet process air dewpoint |

| Half Cycle [min] | HC Duration [min] | ppCO2 [torr] | Air Flow [SLPM] | Inlet Temp [C] | Inlet DP [C] | HX Exit Air Temp [C] | CO2 Removal [kg/day] | CO2 in/out [Ratio] |
|---|---|---|---|---|---|---|---|---|
| 10-73-10 | 93 | 1.99 | 676.5 | 11.67 | 9.97 | 11.31 | 4.36 | 0.867 |
| 10-60-10 | 80 | 1.99 | 781.6 | 11.67 | 9.97 | 13.76 | 4.97 | 0.856 |
| 10-50-10 | 70 | 1.99 | 898.9 | 11.67 | 10.05 | 17.87 | 5.55 | 0.831 |

**Table 4. Change in Half Cycle Duration and Process Air Flow Holding Total Volume Constant.**

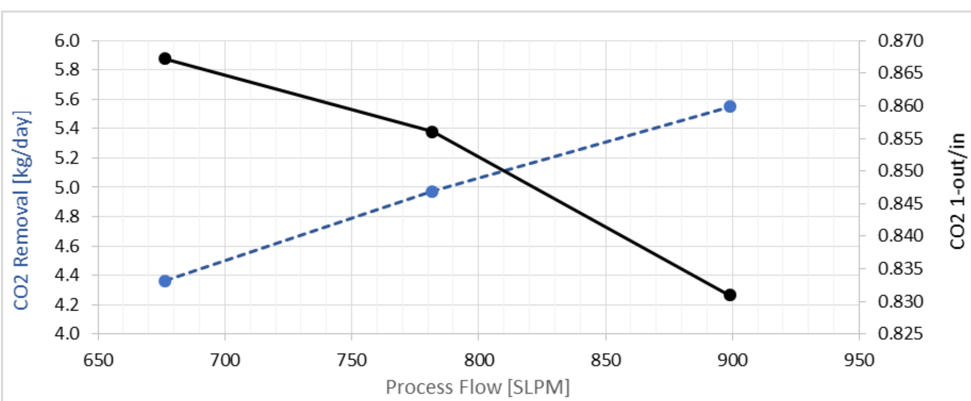



**Figure 13. CO2 Removal and Efficiency as a function of Process Air Flow and Half Cycle Duration**

<u>Conclusions</u>

As process airflow increased, heat added through additional mass and blower compression increased the air temperature downstream of the precooler as shown in Table 4. The precooler-chiller combination was unable to remove all of the additional heat and the air temperature entering the sorbent bed also increased. Because increased air temperature reduces CO2 adsorption, a more efficient heat exchanger could increase CO2 removal at higher flowrates. With this specific system (full RK-38 beds and reduced 13X in the desiccant beds) the 4kg/day CO2 removal requirement could be met at ~623 SLPM (22scfm) flow, well below the current blower maximum operating limit.

## VIII. Test Objective 2C: Sensitivity of Inlet Temperature and Dewpoint

Inlet air containing less water vapor, a lower dewpoint, would leave more 13X in the desiccant bed available for adsorption of CO2. Because the flight CDRA process air is delivered from a condensing heat exchanger, the air temperature is slightly warmer than the dewpoint due to heat absorbed into the process air inlet line. A reduced level of dewpoint and air temperature was selected for a single test.

Hardware Configuration: r2
Rectangular bed shape
Desiccant Bed: 50% of 13X replaced with inert 3mm glass beads.
Sorbent bed: fully packed RK-38

Inlet conditions:

| | |
|---|---|
| 10-60-10 | Half cycle: A (airsave mode) = 15 minutes, B = 130 minutes, C = 10 minutes |
| 11.7C (53F) | Inlet process air temperature |
| 10C (50F) | Inlet process air dewpoint |
| 778 SLPM (27.5scfm) | Inlet airflow calculated with 0C and ambient pressure |

| | Half Cycle [min] | ppCO2 [torr] | Air Flow [SLPM] | Inlet Temp [C] | Inlet Dwpt [C] | HX Exit Air Temp [C] | CO2 Removal [kg/day] |
|---|---|---|---|---|---|---|---|
| Nominal | 10-60-10 | 1.99 | 786.6 | 11.67 | 9.83 | 13.66 | 4.98 |
| Cold & Dry | 10-60-10 | 2.01 | 786.7 | 7.88 | 2.55 | 13.08 | 4.87 |

**Table 5. Effect of Lowered Inlet Air and Dewpoint on CO2 removal rate.**

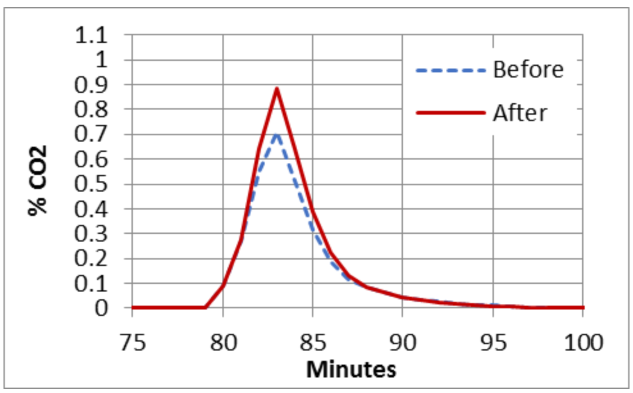



**Figure 14. CO2 % During HC Change.**

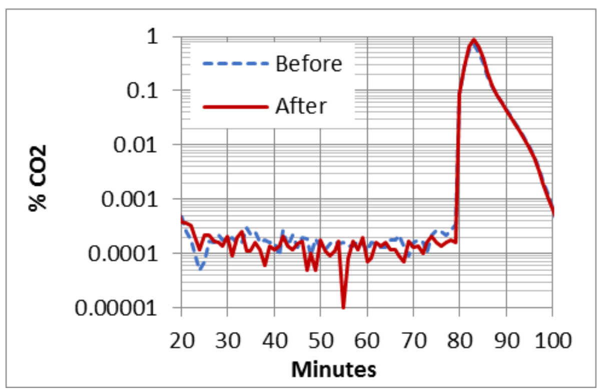



**Figure 15. CO2 % During Adsorption Cycle.**

Conclusions

Reducing inlet temperature and dewpoint of this specific hardware configuration decreased CO2 removal by 2%, a minimal change, seen in table 5. However, the change in performance was in the expected direction. If incoming air is carrying less water vapor, less water adsorbed into the desiccant beds would allow more CO2 to adsorb into the desiccant 13X material. The additional CO2 holdup in the desiccant bed caused a larger exhaust spike in the exit when the half cycle changed, as seen in Figure 14. Because the cold/dry test did not break through on either case (Figure 15) the improvement in CO2 removal was due to the reduction in the spike at the half cycle change.

## IX. Test Objective 2D: Cyclic H2O Breakthrough of the Desiccant Bed

A 50% reduction of the desiccant bed 13X reduces the H2O adsorption capacity of the desiccant bed, but the amount of desiccant margin had not been measured. An unrealistically high system flow and long half cycle were chosen to accelerate water breakthrough of the desiccant bed. The test data was to be compared with COMSOL modeling results to determine desiccant bed H2O breakthrough margin. An increase in desiccant bed outlet dewpoint and corresponding increase in CO2 removal rate would indicate breakthrough had begun.

Hardware Configuration: r2
Rectangular bed shape
Desiccant Bed: 50% of 13X replaced with inert 3mm glass beads.
Sorbent bed: fully packed RK-38

Inlet conditions:

| | |
|---|---|
| 11.7C (53F) | Inlet process air temperature |
| 10C (50F) | Inlet process air dewpoint |
| 778 SLPM (27.5scfm) | Inlet air flow calculated with 0C and ambient pressure |
| 10-124-10 | Half cycle: A (airsave mode) = 10 minutes, B = 124 minutes, C = 10 minutes |

Results

After 290 accumulated hours of cyclic operation, the system displayed no evidence of water breakthrough in either desiccant bed. Large sinusoidal oscillations in CO2 removal rate were observed during the test. Analysis determined that external temperature swings caused by facility maintenance during cold weather correlated to CO2 removal rates. In the current configuration, both the precooler and chiller are operating at their maximum capacity. When external temperature dropped, the chiller could remove more heat from the process air supply, reducing the process air temperature. This in turn increased CO2 adsorption into the sorbent beds, increasing the CO2 removal calculation. We correlated CO2 removal to chiller water temperature and applied the correlation to CO2 removal to help identify global changes in CO2 removal rate. Both traces are shown in figure 16.

Data did not indicate CO2 breakthrough in the sorbent bed. Nor was desiccant bed H2O breakthrough apparent. Because the test window was about to close, the half-cycle duration was increased from 144 minutes to 180 minutes. After an additional 195 hours of cycle testing (total of 480 hours) using 180 minute half cycles, water had still not broken through the desiccant bed. Because we only had one day left it the test window, we operated at a short half-cycle duration and cool, dry inlet conditions to dry out the desiccant beds and regenerate the sorbent beds for another test

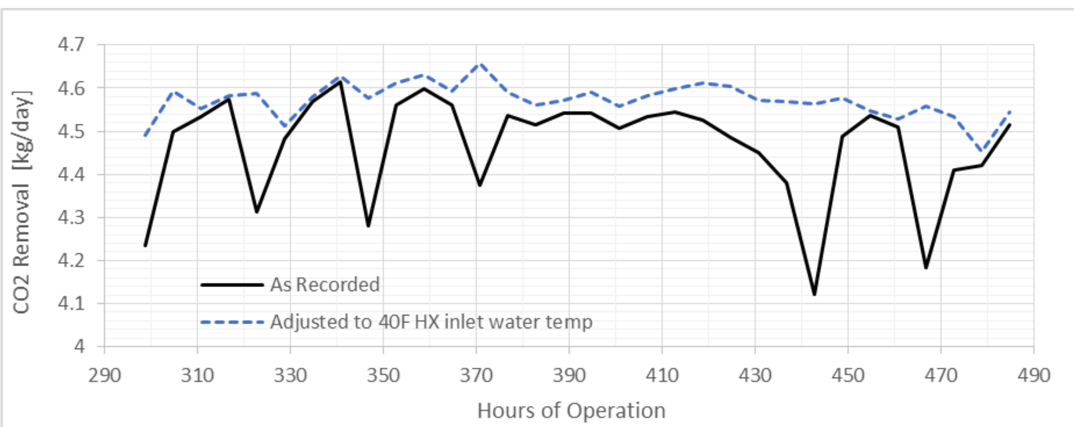



**Figure 16. Effect of External temperature and Heat Exchanger on CO2 Removal.**
*Raw CO2 removal rate, and temperature corrected using a correlation from the heat exchanger chiller water temperature. Because the chiller was operating near its maximum capacity, the heat rejected was related to ambient temperature.*

## X. Test Objective 2E: Continuous Operation H2O Breakthrough of the Desiccant Bed

Identical inlet conditions were repeated from the previous test. The half-cycle was set to 400 minutes and the test manually terminated when desiccant bed breakthrough was evident in the desiccant bed outlet dewpoint and CO2 breakthrough in the air exit.

Hardware Configuration: r2

Rectangular bed shape
Desiccant Bed: 50% of 13X replaced with inert 3mm glass beads.
Sorbent bed: fully packed RK-38

Inlet conditions:

| | |
|---|---|
| 2 torr | ppCO2, partial pressure CO2 |
| 11.7C (53F) | Inlet process air temperature |
| 9.3C (48.7F) | Inlet process air dewpoint |
| 778 SLPM (27.5scfm) | Inlet air flow calculated with 0C and ambient pressure |
| 10-380-10 | Half cycle |

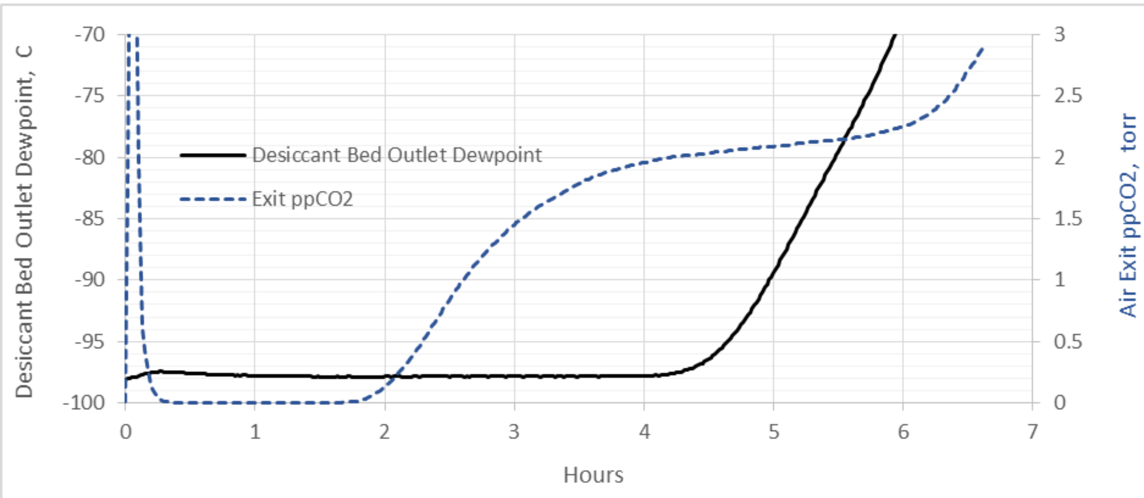



**Figure 17. Indicators of H2O Breakthrough in the Desiccant Bed.**

Conclusion

When flowing 778 SLPM process air at standard conditions, sorbent bed CO2 breakthrough began 100 minutes into the test as shown in Figure 17. The ppCO2 measured at the system air exit slowly approached the measured inlet ppCO2 value of 2 torr. Approximately 4 hours into the test the desiccant bed outlet dewpoint began to rise, indicating water breakthrough of the desiccant bed. At the same time, roll-up behavior was observed, that is, the ppCO2 exiting the system rose to a value higher than the input because water originating from the desiccant bed traveled to the sorbent bed and displaced the CO2 at that location. H2O breakthrough of the desiccant did not begin until 4 hours into the test, significantly longer than anticipated.

**Hardware Configuration Change – Replacement of Sorbent With a Reduced Amount of 13X**

Because of the increased capacity and resistance to dusting, the team replaced the heritage RK-38 material with 13X. System modeling predicted greater than 4 kg/day CO2 removal even if the bed volume was reduced by 30% due to the increased adsorption capacity of 13X. For schedule convenience, the heritage rectangular beds were packed in the same manner as the desiccant bed modification described previously in this report.

The sorbent beds were removed from 4BMS-X and all material removed, dried, and weighed to provide inputs for computer models. The sorbent beds were repacked with 13X using the flight packing procedure until 70% of the volume was occupied. The 30% void at the top of the bed was packed with inert 3mm glass beads as shown in Figure 18. The mass of 13X was measured in its dry state to provide accuracy for the system model. The desiccant beds were dried in an environmental chamber at 175°C with 120 SLPM GN2 flow through the beds. The team desired a 200°C drying temperature to remove all moisture from the 13X, but limitations of the environmental chamber only allowed 175°C. The incomplete drying would have an effect described in the next section.

During this test period, the team learned the likely location on ISS for a proposed, but not funded, 4BMS flight demonstration would provide 10°C water coolant to the system precooler. All tests in the following test series used 10°C inlet water coolant temperature rather than 4.4°C coolant used in previous tests. Increasing the precooler water temperature increases the precooler exit air temperature before entering the sorbent bed. The increase in air temperature reduces system CO2 adsorption capacity.

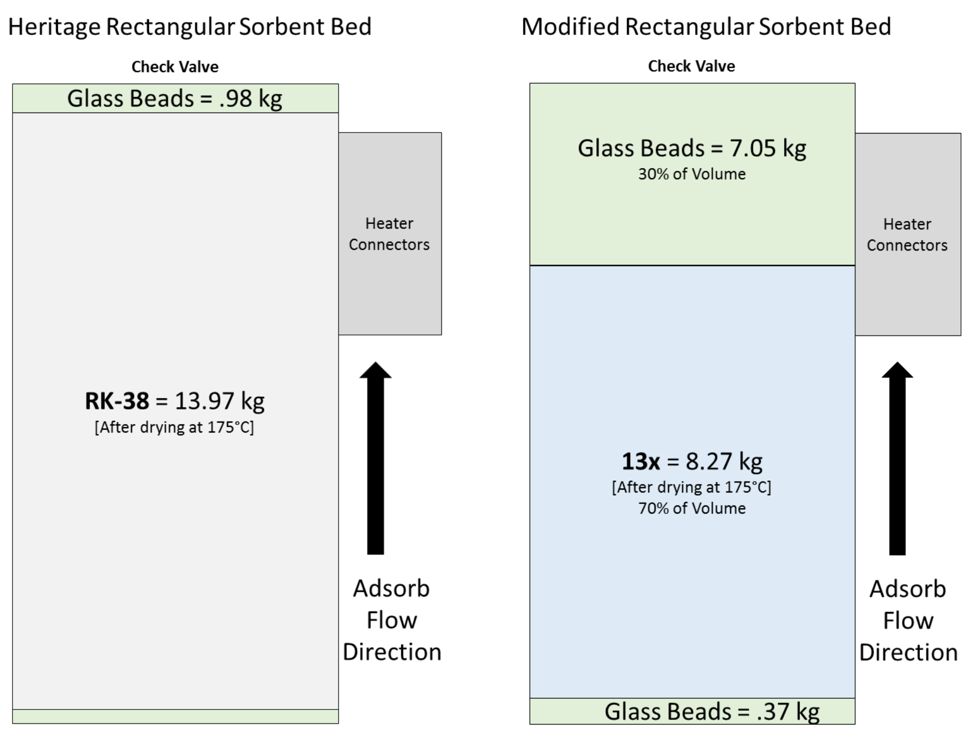



**Figure 18. Changes in Sorbent Bed Material Configuration.**

# XI. Test Objective 3A: CO2 Removal Rate after Sorbent Replacement

At standard conditions, the 4BMS-X system initially removed 3.95 kg/day of CO2, but slowly increased during the first 2 days of operation. Believing the CO2 removal rate had reached a plateau, the team tested other test objectives during the next 3 days. The data collected during the subsequent tests indicated high uncertainty, so the original test condition was reestablished and allowed to run for an additional week. The CO2 removal rate, shown in Figure 19, climbed slowly and reached a plateau of 4.75 kg/day at the end of 9 days accumulated testing. Inlet conditions and performance calculations at the end of the 9 day run are shown in Table 6. The air system exit CO2 measurement and breakthrough behavior, shown in Figure 20, was plotted to investigate the source of the increasing CO2 removal rate.

Hardware Configuration: r3

Rectangular bed shape

Desiccant Bed: 50% of 13X replaced with inert 3mm glass beads.

Sorbent bed: 70% 13X by volume, 30% 3mm glass beads by volume

Inlet conditions:

| | |
|---|---|
| 2 torr | ppCO2, partial pressure CO2 |
| 11.7C (53F) | Inlet process air temperature |
| 10C (50F) | Inlet process air dewpoint |
| 778 SLPM (27.5 SCFM) | Inlet air flow, 0C and ambient pressure |
| 10-60-10 | Half cycle |

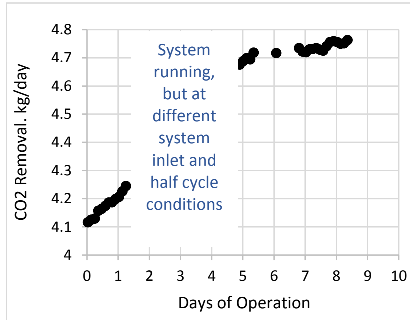



**Figure 19. Change in CO2 Removal Rate**

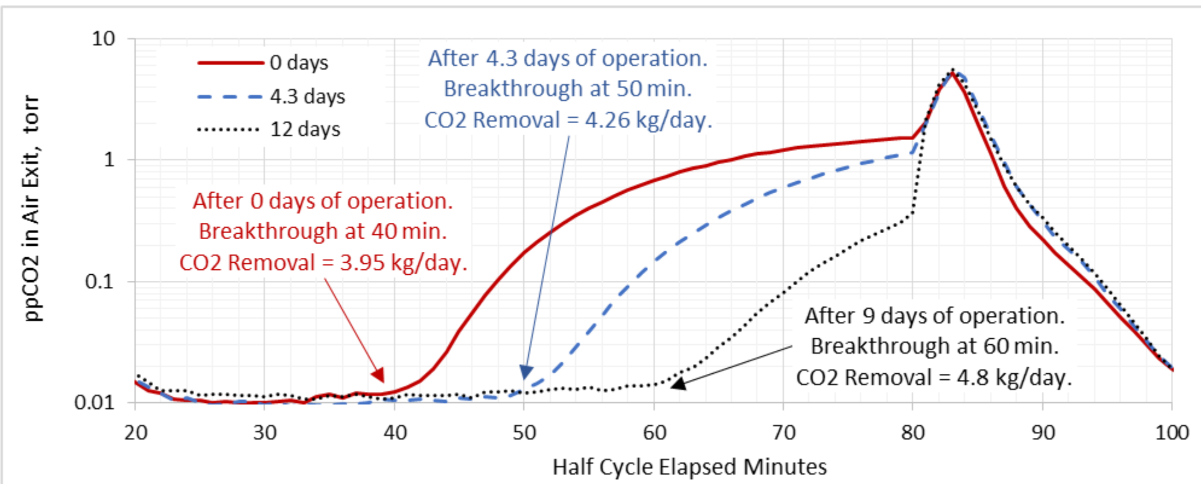



**Figure 20. Change in System CO2 Breakthrough over Time.**

| Test | Half Cycle [min] | ppCO2 [torr] | Air Flow [SLPM] | Inlet Temp [C] | Inlet DP [C] | HX Exit Air Temp [C] | CO2 Removal [kg/day] |
|---|---|---|---|---|---|---|---|
| Reference | 10-60-10 | 2.02 | 787 | 11.7 | 10.0 | 14.2 | 4.75 |

**Table 6. CO2 Removal Rate after 9 days accumulated testing.**

Conclusion

The system CO2 removal rate steadily increased over the first two weeks of operation. We believe the primary factor for the increasing CO2 removal rate is the reduction of residual moisture from the sorbent beds caused by suboptimal sorbent drying during system assembly. While the additional moisture content was undesirable, the system demonstrated resiliency in returning the bed to a regenerated state during nominal operation. CO2 removal rate exceeded and maintained 4.75 kg/day after system equilibrium was established.

## XII. Test Objective 3B: Sensitivity of Process Air Flow and Half Cycle

Inlet flow rate varied inversely with half cycle duration such that the integrated volumetric flow per half cycle was constant.

(Half cycle minutes) x (flow/minute) = (80 min) x (787 SLPM) = constant = 62960 liters (2225 cubic feet).

Hardware Configuration: r3

Rectangular bed shape

Desiccant Bed: 50% of 13X replaced with inert 3mm glass beads.

Sorbent bed: 70% 13X by volume, 30% 3mm glass beads by volume

Inlet conditions:

| | |
|---|---|
| 11.7C (53F) | Inlet process air temperature |
| 10C (50F) | Inlet process air dewpoint |

| Half Cycle [min] | HC Duration [min] | ppCO2 [torr] | Air Flow [SLPM] | Inlet Temp [C] | Inlet DP [C] | HX Exit Air Temp [C] | CO2 Removal [kg/day] | CO2 in/out [Ratio] |
|---|---|---|---|---|---|---|---|---|
| 10-55-10 | 75 | 1.99 | 849 | 11.6 | 10 | 59.5 | 5.05 | 0.805 |
| 10-60-10 | 80 | 2 | 787 | 11.6 | 10 | 57.5 | 4.75 | 0.82 |
| 10-66-10 | 86 | 1.99 | 736 | 11.6 | 10 | 57.8 | 4.51 | 0.828 |
| 10-73-10 | 93 | 2 | 676 | 11.6 | 10 | 56.8 | 4.19 | 0.84 |

**Table 7. Change in Half Cycle Duration and Process Air Flow Holding Total Volume Constant.**

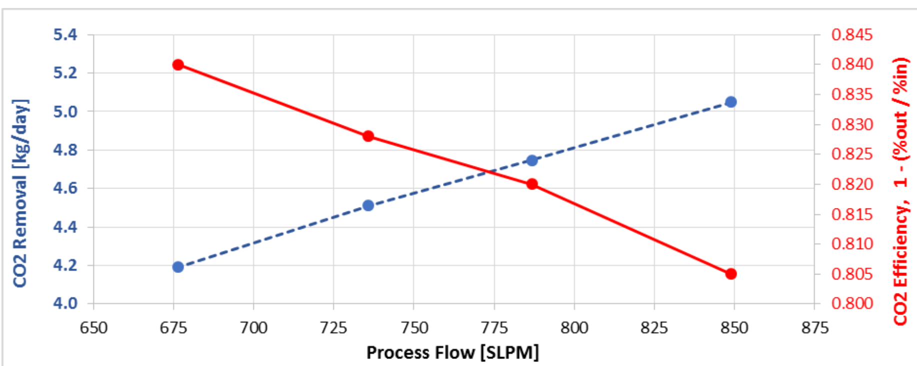



**Figure 21. CO2 Removal and Efficiency as a function of Process Air Flow and Half Cycle Duration**

Conclusions

This data will be used to optimize the next system configuration for CO2 removal, power usage and blower requirements.

## XIII. Test Objective 3C: Addition of Intermediate CO2% Measurement

For the final test of this 4BMS-X hardware configuration, shown in Table 7, an intermediate sample port was added through the adsorbing effluent of the D2 desiccant bed, drawn in Figure 22. Detailed analysis of the transient traces plotted in Figure 23 is not yet available because data was recorded the day before the report deadline. This data will be used to refined the system computer model and optimize the reduced-volume, cylindrical hardware configuration currently in fabrication.

| Test | Half Cycle [min] | ppCO2 [torr] | Air Flow [SLPM] | Inlet Temp [C] | Inlet DP [C] | HX Exit Air Temp [C] | CO2 Removal [kg/day] |
|---|---|---|---|---|---|---|---|
| Reference | 10-60-10 | 2.01 | 784 | 11.6 | 10 | 15.3 | 4.81 |

**Table 7. Test Conditions for Intermediate CO2% measurement**

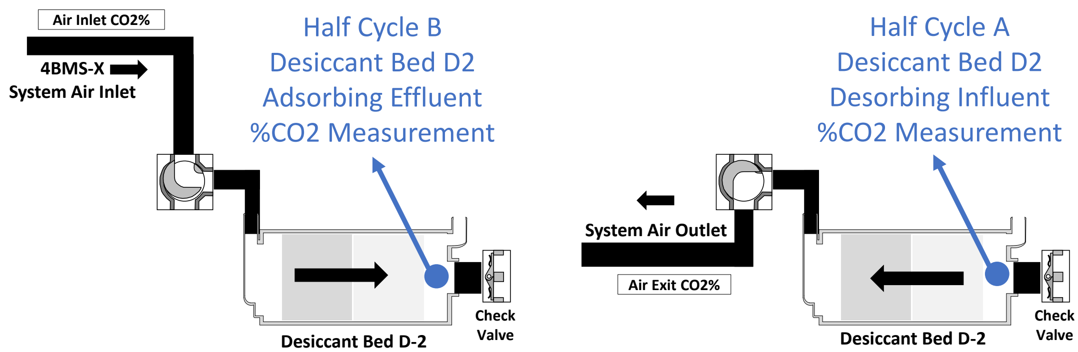



**Figure 22. Changes in Sorbent Bed Material Configuration.**

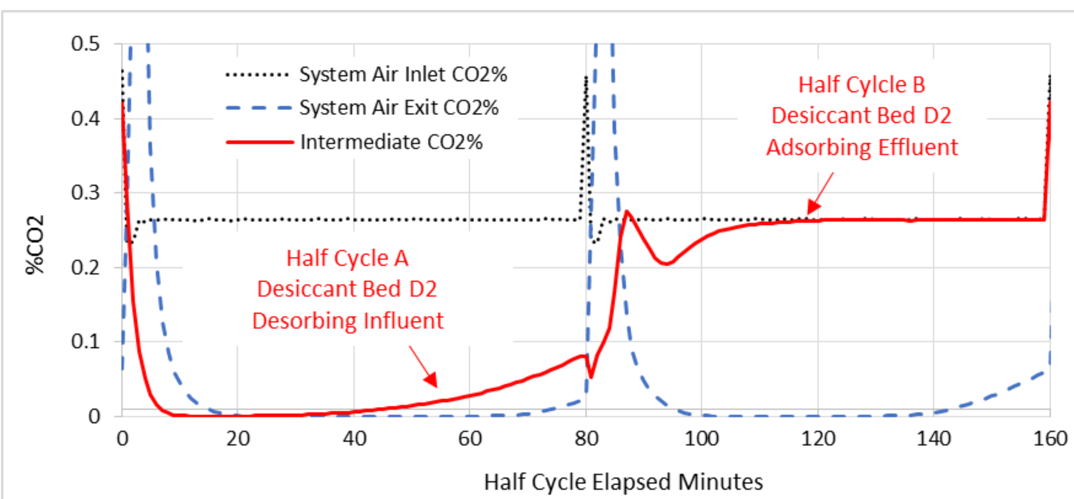



**Figure 23. Intermediate %CO2 Measurement**

## XIV. Conclusion

Removal of 50% of the 13X material from the desiccant bed increased the CO2 removal rate by 0.5 kg/day, verifying the holdup theory and improving performance. We expect the pressure drops to decrease in the next generation hardware when glass beads used as temporary spacers are no longer needed. Removing the temporary glass beads will also reduce the thermal mass and the heat necessary to maintain the desorption temperature of the system. Despite the removal of 50% of the 13X from the desiccant bed and the resulting reduction in total water adsorption capacity, desiccant bed water breakthrough only occurred after 4 hours using high process airflow and high humidity inlet conditions, demonstrating system margin. The last temporary 4BMS-X hardware configuration, using 13X zeolite in the reduced volume rectangular sorbent bed, produced system CO2 removal rates in excess of 4.2 kg/day. The next phase of the 4BMS-X program will optimize the system for optimum volume, mass and power at the desired 2 torr ppCO2 inlet conditions and > 4.16 kg/day CO2 removal.

## References


[1]James C. Knox[1], Robert Coker[2], David Howard[3], Warren Peters[4], and David Watson[5]., "Development of Carbon Dioxide Removal Systems for Advanced Exploration Systems 2015-2016," *International Conference on Environmental Systems,* Vienna Austria, 2016

[2]Robert F. Coker[1] and James C. Knox[2]., "Predictive Modeling of the CDRA 4BMS," *International Conference on Environmental Systems,* Vienna Austria, 2016

[3] James C. Knox[1] , David W. Watson[2] , Timothy J. Giesy[3], Gregory E. Cmarik[4] , and Lee A. Miller,[5] "Investigation of Desiccants and CO2 Sorbents for Exploration Systems 2016-2017," *International Conference on Environmental Systems,* Charleston South Carolina, USA, 2017