CO2 Removal Onboard the International Space Station – Material Selection and System Design

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The previous three years of efforts have focused on the study of the sorbent materials available for use in a 4-bed molecular sieve system. The accumulation of knowledge has been invaluable for further decisions and for reflecting on the conclusions of past decisions. The goal of the next system is perfect uptime for nearly 20,000 hours of operation, but no complex life support system has yet reached this lofty goal. In addition to reliability, CO2 removal performance improvements have been intensively studied. The achievements toward this end include highly detailed isotherm measurements which drive system simulations as well as testing physical design improvements. Looking back on the successes and failures of past systems, correlating tests with long-duration data, and carefully projecting the future are all needed for the success of the next system. This work intends to reveal the path we have taken and illuminate the steps to come for CO2 removal life support with the 4BCO2 flight demonstration.

Nomenclature

4BCO2	=	4-Bed Carbon Dioxide Scrubber Flight Demonstration
CO2	=	Carbon Dioxide
CDRA	=	Carbon Dioxide Removal Assembly
NASA	=	National Aeronautics and Space Administration
MSFC	=	Marshall Space Flight Center
ISS	=	International Space Station
SG	=	Silica Gel
MS	=	Molecular Sieve
mmHg	=	millimeter of Mercury pressure
COTS	=	Commercial off the Shelf
SLM	=	Selective Laser Melting
BER	=	Basic EXPRESS Rack

I. Introduction

BASED on Space Policy Directive-1, NASA's stated goal for the agency is to "advance the nation's space program by increasing science activities near and on the Moon and ultimately returning humans to the surface." This shift to surface missions has not altered the ongoing efforts to advance CO2 removal technologies.[1] At Marshall Space Flight Center (MSFC), these efforts are focused on producing an International Space Station (ISS) flight demonstration of the next-generation four-bed molecular sieve (4BMS) system known as the 4-bed CO2 Scrubber (4BCO2).

Among NASA's long term goals is to have a long-duration crewed missions including a three year mission to Mars. Improving life support technologies is critical to ensuring mission success.[2] Existing technologies are insufficient in several regards: reliability, performance vs resource usage, and closed loop operation. 4-bed technology is presently operating in a partial closed-loop configuration onboard the ISS[3]. 4BCO2 is intended to prove the remaining concerns of reliability and performance have been mitigated.

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The 4BCO2 flight demonstration was commissioned to prove that 4-bed technology could be a reliable CO2 removal system for space flight. The redesign is incorporating numerous changes from CDRA and several testbeds based on lessons learned and direct test data. The first aspect is the selection of a new sorbent to replace the custom CDRA sorbent which is obsolete. The second aspect is redesign of the components of CDRA to minimize or eliminate causes of sorbent dusting. The third aspect is to integrate state-of-the-art components into the functional system for lifetime evaluation. This work will provide a brief summary of the work that led to the decisions that are being implemented in the 4BCO2 flight demonstration which is slated to begin operating on the ISS in 2020.

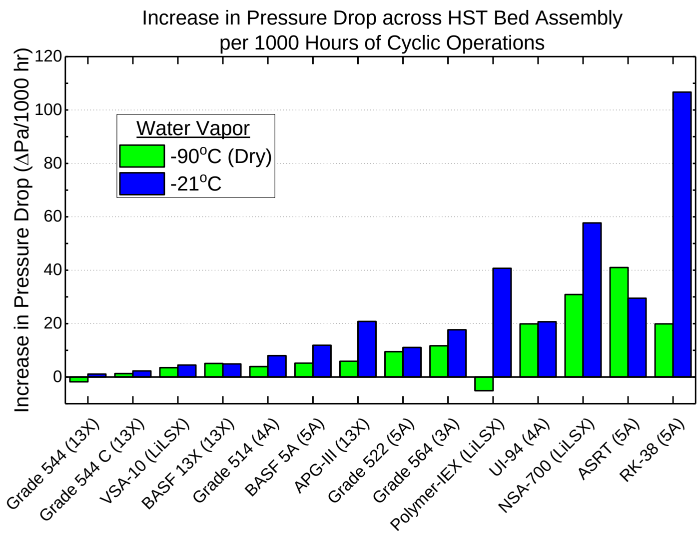

Figure 1. Rate of pressure drop increase which correlates to sorbent dust generation in sub-scale beds under dry and humid conditions subjected to thermal cycling

II. Redesign of 4-bed technology

A. Sorbent selection

Out of 14 candidate CO2 sorbents obtained from various manufacturers, 2 stand-out candidates emerged as exceptional for dust resistance: BASF 13X and Grace MS544 C 13X. These two candidates were robust in both dry and humid environments.[4-6] Between these two, MS544 has flight heritage and was selected on that basis. These two materials were projected to produce dust at one-tenth the rate of ASRT or lower.

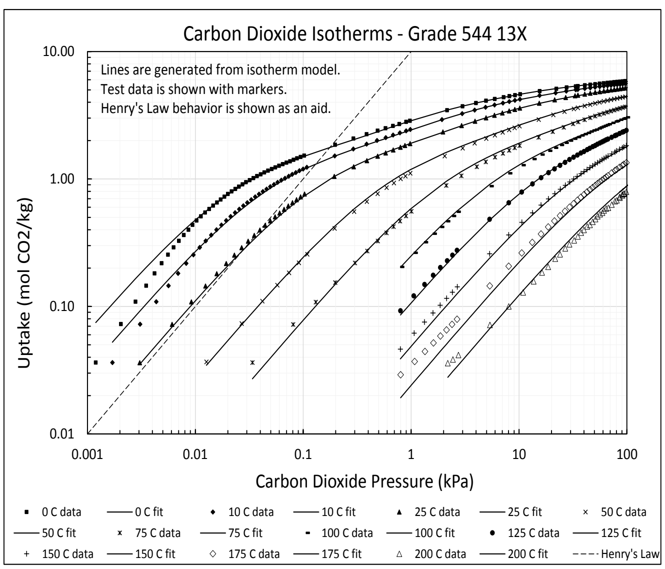

Figure 2. Pure component CO2 isotherms at temperatures from 0°C up to 200°C.

Pure component isotherms and breakthrough capacities were obtained to assess the potential performance of these materials.[7] High fidelity isotherms were obtained for the water vapor adsorption on SG B125 and MS544 13X from 25°C to 70°C as well as CO2 isotherms for MS544 13X from 0°C to 200°C.[8-10] Breakthrough testing at 25°C was used with thermal and equilibrium models to fit linear driving force coefficients.[11] The isotherms were used to derive heats of adsorption.[12]

One of the key lessons learned is that 13X zeolite requires drying at 350°C to fully regenerate the CO2 capacity. Since the adsorbent bed in CDRA and 4BCO2 is designed to heat only to 200°C, there is a natural concern about incomplete activation and reduced CO2 removal performance. If sufficient mass of water vapor enters the bed to impair CO2 capture performance, the thermogravimetric analysis (TGA) work predicted that nominal 4-bed operations would recover the removal performance quickly for 5A, slowly for 13X, and not at all for LiLSX.[4] Other trace contaminants were not detected in returned-from-flight zeolite samples, instead these compounds were captured in the layers of silica gel near the inlet of the desiccant beds.[13-15]

Simulations identified the need to quantify the impact of water loading on CO2 capacity in order to accurately model 4-bed operation. CO2 isotherm measurement with preloaded water on 13X was conducted with a custom instrument designed by Rubotherm, GmbH.[16] This data was used to fit a simplified co-adsorption model which could

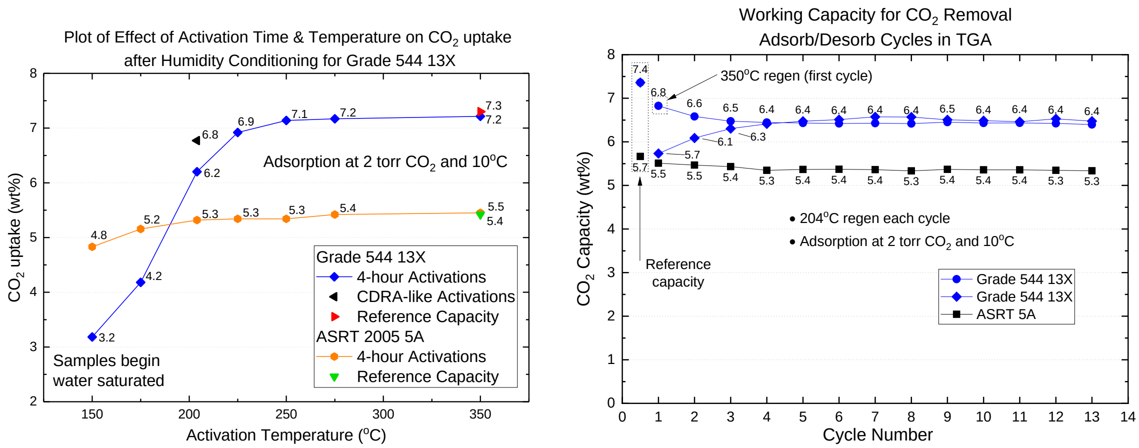

Figure 3. Effect of activation temperature on sorbent performance [left] and simulated 4-bed cyclic operation [right] for ASRT (5A) and Grade 544 (13X). Each point is the CO_2 capacity at end of each adsorption cycle. Reduced capacity is attributed to trace water vapor in bottled gas supply to TGA.

be used in a simulation. The 4-bed simulation resulted two main improvements: increased removal rate via reduction of 13X in the desiccant bed and optimization of flow rate, bed size, and cycle time for 2mmHg CO2 cabin air.[17-20] Thermal modelling of the heater cores for CDRA and 4BCO2 were used to optimize power consumption and heater control.[19, 21]

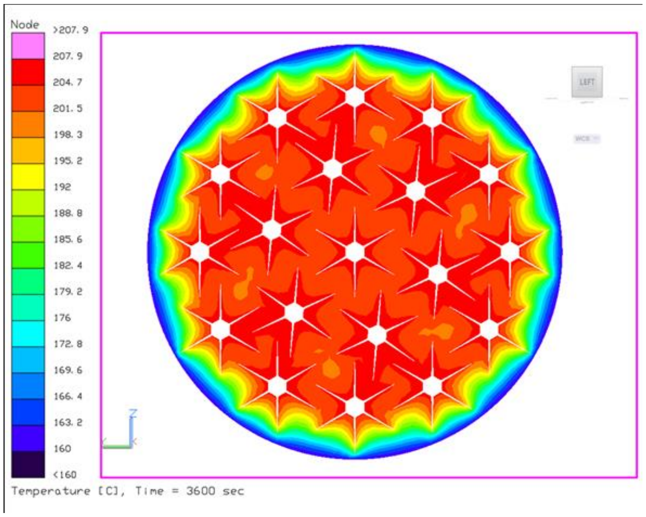

Figure 5. Simulated temperature cross-section of a heating 4BCO2 sorbent bed at the end of a half-cycle.

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The redesign of 4-bed technology to eliminate failures due to sorbent dusting included addressing every known and potential cause of dusting acquired over years of 4-bed operations and from industry. Besides addressing the dusting propensity of the sorbent itself, numerous changes were made to the design, assembly, and operation of 4BCO2. The first and most apparent change is the switch from rectangular sheet metal beds to cylindrical beds which eliminates the wall deflection that results from vacuum cycling and causes sorbent displacement. Cylinders also enable more reliable sorbent containment and compaction with internal spring-loaded

Figure 4. Pleated filter element and filter slide designed for use in 4BCO2. Pleating increases dust capacity. (cite Porvair?)

plates. A maintainable, pleated filter element was designed into the system to capture dust at the location which caused repeated dust-related failures in CDRA. The prototype filter elements re-iterated the importance of mechanical tolerances as a 0.1" out-of-round of the 7.5" element prevented re-insertion.

The second major change is to the heater core where in CDRA it was a monolithic element immersed in the sorbent beds which lead to many obstructed views and poorly packed sorbent volumes. The 4BCO2 heater core was designed with assembly in mind resulting in cartridge heaters with aluminum heater spreading fins cantilevered from a fixed support plate. The packing process utilizes a technique known as "snow storm" which effectively distributes sorbent beads and, due to heater core design, can be done in stages with direct observation of progress and efficacy.[22] This process nearly eliminates void spaces where dust is generated due to attrition of moving sorbent particles.

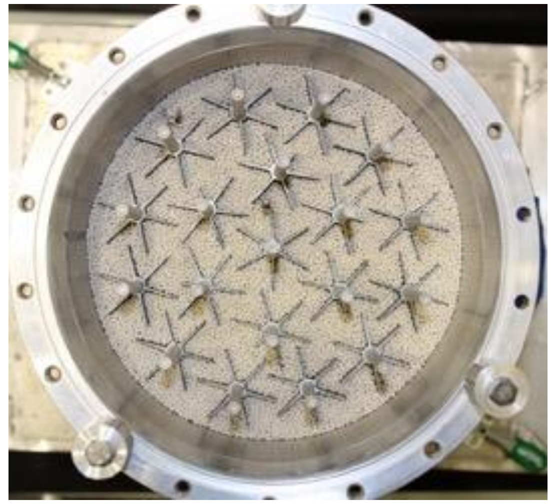

Figure 6. Partially filled sorbent bed for the prototype 4-bed 'Linus' system.

Specific components and operating behaviors were changed from CDRA to 4BCO2. New valves are being designed at MSFC and initial testing shows very high tolerance to dust and equivalent operating lifetimes in excess of 9 years. These new valves have a small port to allow modulated or choked repressurization of the sorbent bed during half-cycle transitions. Excessive air velocities generated during rapid repressurization with conventional valves was identified as a cause of dust generation. These new valves can also isolate the flow path ensuring leak tightness when desired.

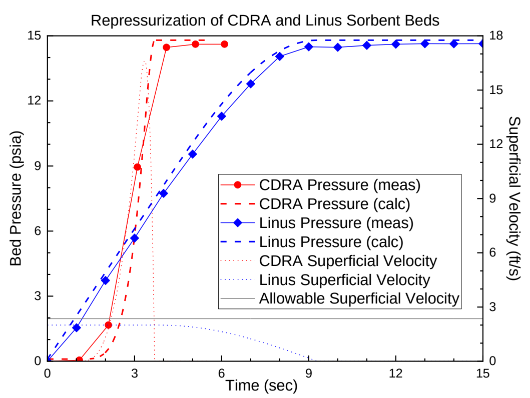

Figure 7. Measured repressurization profile with commercial ball valves and with the MSFC valve along with the maximum allowable superficial air velocity.

B. Operation of the new 4-bed:

The prototype 4-bed system currently operating at MSFC is colloquially known as 'Linus'. Linus is being used to map the performance envelope of the integrated hardware with regard to CO2 removal and power consumption. In addition, Linus is being used to conduct specific tests of new hardware as it is integrated, refine the computer model, and expose any unforeseen interactions of the many changes. The instrumentation for Linus includes additional pressure, temperature, CO2, and water vapor sampling.

Several positive changes have already been observed including the performance of the new precooler, the peak temperature of the outlet air, reduced dusting, reduced desiccant bed holdup, and reduced overall sorbent mass. A COTS dry scroll vacuum pump was integrated with a COTS brushless motor controller for successfu. One unexpected result has been a higher pressure drop through the sorbent beds versus the CDRA-like ground testbed. The improved packing procedures and reduced channeling lead to lower overall void space in the bed and higher pressure drop.

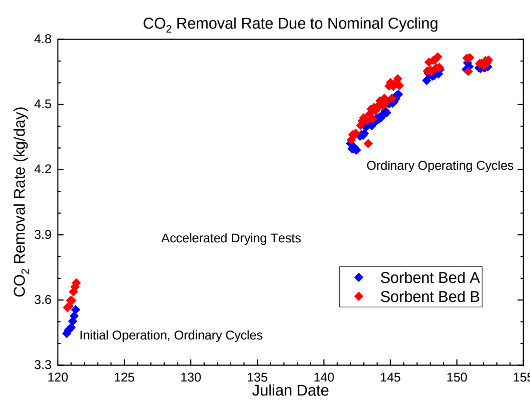

Figure 8. Recovery of CO2 removal performance after initial assembly which had exposed dry sorbent to ambient humidity. The CO2 removal was impaired but increased after numerous operating cycles to a steady-state.

Initial operation of Linus showed significant underperformance. The previously discussed TGA testing of the CO2 sorbent predicted this behavior and predicted that the performance would recover with nominal operating cycles. The

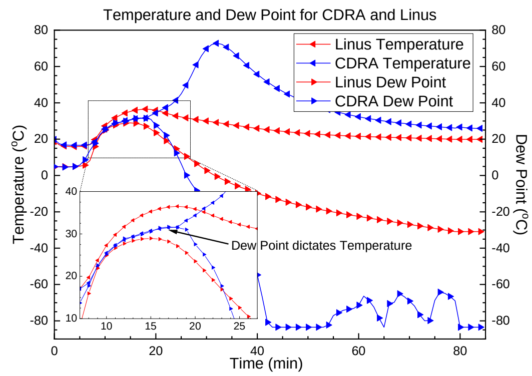

Figure 9. Temperature and dew point overlap indicating condensing conditions in the desorbing desiccant bed for the CDRA-like testbed whereas Linus does not exhibit this behavior.

CO2 removal performance did increase during the first few weeks of nominal operation.

Several other technologies are being implemented in the design of 4BCO2 based on 3D printing or Selective Laser Melting (SLM) technologies. The heater support plate would be a significant thermal leakage pathway if it was machined from aluminum stock. Instead, SLM techniques enable the heater plate to be manufactured from titanium while remaining structurally robust, retaining a high airflow cross-section, and having tortuous heat conduction paths. SLM is also being considered for air ducts with out-of-plane bends to reduce the pressure drop factors to one-third the value of mitered ducting.

One of the remaining unknown behaviors of CDRA was the cause of silica gel discoloration and performance degradation after many operating cycles. The possible causes of this silica gel degradation have been investigated extensively without a conclusive answer.[13, 15, 23] One possible cause was the desorption process of 4-bed technologies which leads to a condensing condition near the desiccant inlet which is correlated to silica gel degradation. Serendipitously, Linus does not exhibit the condensing conditions which were observed in CDRA and previous 4-bed testbeds. The smaller sorbent bed, lighter heater core, higher air flowrates, and shorter half-cycles all contribute to preventing the condensing conditions.

Linus has accumulated over 1800 hours of normal operating time. The system has been inspected for dusting at two points to-date. The first inspection was conducted after 800 hours and traces of dust were found on the new pleated filter element and on the surfaces of the sliding element. The Linus sorbent beds both settled 2-3mm, which was approximately 10% of the designed maximum plate travel. This amount of plate travel was attributed to residual compaction instead of sorbent attrition due to the displaced volume exceeding the observable dust by orders of magnitude. After the next 1000 hours, the filters were again removed and the beds inspected. The plates each travelled 1mm farther and 0.01(1) g of dust was captured from each filter element. Overall, the measurable mass of dust per operating time is roughly 1% of ASRT from CDRA-2 test, teardown, and evaluation measurements.

Figure 10. Dust recovered from Linus removable filters (also pictured).

C. Analysis and Data Reduction from Linus Testing

Not yet complete.

III. Conclusion

D. Outlook for Four Bed Technology and 4BCO2

The primary directive for the 4BCO2 flight demonstration was to prove 4-bed technology can operate reliably and that sorbent dusting would not lead to shutdowns or require anything but brief maintenance. The results obtained to date from Linus strongly suggest that dusting has been solved and that 4-bed technology will be reliable for long-duration missions.

Linus operation has found a performance envelope which surrounds the design point of 4 crew-equivalent CO2 removal rate at an inlet concentration of 2 mmHg CO2. Higher removal rates can be achieved at higher CO2 concentrations or by consuming more power to reduce half-cycle time and/or increase airflow. 4BCO2 is projected to be able to return air to cabin and a portion of the performance envelope enables the system to draw inlet air directly from the cabin. Additionally, the improved water heat exchanger may be able to operate at reduced water flowrates.

Software which will operate the 4BCO2 is being written with a deference towards the ETHOS operators. The experiences from over a decade of operating, troubleshooting, and maintaining the CDRA systems are being implemented in 4BCO2. The software is primarily designed to protect the individual hardware components and conduct the cycles as scheduled. To accelerate schedule, the software will include no critical hazard controls but instead rely on station systems to provide any absolute controls. The 4BCO2 will interface to ground operators via the Arcturus API using an Adlink miniPC instead of interfacing with station software as with CDRA.

While the performance outlook for 4BCO2 is depicted as rosy, the mass and volume packaging is not optimized due to time constraints. 4BCO2 is required to integrate into both a basic EXPRESS rack (BER) as well as the air revitalization (AR) rack, should it be selected to replace CDRA. The system is also slated to be a testbed for a next-generation air blower and controller which will require significant on-orbit installation work. Power optimization can be obtained after launch through further engineering unit work to determine reduced temperatures and/or half-cycle adjustments can be used.

Among the improvements already in planning are volume optimizations of the new valves, numerous mass reductions and structural optimizations, improved electronics cooling, noise mitigation features, … These improvements will not be successfully implemented in the 4BCO2 flight demonstration but would likely be part of designs for exploration or lunar missions. Software routines have been envisioned which would minimize the need for constant operator attention as well as be able to dynamically respond to changing cabin air conditions.

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References

[1]Sargusingh, M., Anderson, M., Perry, J., Gatens, R., Broyan, J., Macatangay, A., Schneider, W., and Toomarian, N. "NASA Environmental Control and Life Support Technology Development and Maturation for Exploration: 2017 to 2018 Overview." 48th International Conference on Environmental Systems, 2018.

[2]James, J., Matty, C., Meyers, V., Sipes, W., and Scully, R. "Crew health and performance improvements with reduced carbon dioxide levels and the resource impact to accomplish those reductions," *41st International Conference on Environmental Systems*. 2011, p. 5047.

[3]Jernigan, M., Gatens, R., Perry, J., and Joshi, J. "The Next Steps for Environmental Control and Life Support Systems Development for Deep Space Exploration." 48th International Conference on Environmental Systems, 2018.

[4]Knox, J. C., Cmarik, G. E., Watson, D. W., Giesy, T. J., and Miller, L. A. "Investigation of Desiccants and CO2 Sorbents for Exploration Systems 2016-2017," *47th International Conference on Environmental Systems*. Charleston, 2017.

[5]Watson, D., Knox, J. C., West, P., and Bush, R. "Sorbent Structural Testing of Carbon Dioxide Removal Sorbents for Advanced Exploration Systems," *46th International Conference on Environmental Systems*. Vienna, 2016.

[6]Watson, D., Knox, J. C., West, P., Stanley, C. M., and Bush, R. "Sorbent Structural Impacts due to Humidity on Carbon Dioxide Removal Sorbents for Advanced Exploration Systems." 45th International Conference on Environmental Systems, 2015.

[7]Knox, J. C., Cmarik, G., Watson, D., Wingard, C. D., West, P., and Miller, L. A. "Investigation of Desiccants and CO2 Sorbents for Advanced Exploration Systems 2015-2016," *46th International Conference on Environmental Systems*. Vienna, 2016.
[8]Cmarik, G. E. S., K. N.; Knox, J. C., *Standard isotherm fit information for dry CO2 on sorbents for 4BMS*; Technical Memo NASA/TM—2017-219847, **2017**.
[9]Huang, R., Belancik, G., Jan, D., Cmarik, G., Ebner, A. D., Ritter, J., and Knox, J. C. "CO2 Capacity Sorbent Analysis using Volumetric Measurement Approach," *47th International Conference on Environmental Systems*. Charleston, 2017.
[10]Cmarik, G. E., Richardson, Tra-My Justine, Knox, James C. "Water Vapor Isotherms on Silica Gel for use in the Model of the 4BCO2 Flight Demonstration," 2018.
[11]Knox, J. C., Ebner, A. D., LeVan, M. D., Coker, R. F., and Ritter, J. A. "Limitations of Breakthrough Curve Analysis in Fixed-Bed Adsorption," *Industrial & Engineering Chemistry Research*, 2016.
[12]Son, K. N., Cmarik, G. E., Knox, J. C., Weibel, J. A., and Garimella, S. V. "Measurement and Prediction of the Heat of Adsorption and Equilibrium Concentration of CO2 on Zeolite 13X," *Journal of Chemical & Engineering Data* Vol. 63, No. 5, 2018, pp. 1663-1674.
[13]Cmarik, G. E., Knox, J. C., and Huff, T. L. "Analysis of Performance Degradation of Silica Gels after Extended Use Onboard the ISS," *48th International Conference on Environmental Systems*. Albuquerque, 2018.
[14]Knox, J., Long, D., Miller, L., Thomas, J., Cmarik, G., and Howard, D. "Long Duration Sorbent Testbed," 2016.
[15]Huff, T., Knox, J. C., Boothe, R., and Bowman, E. "Evaluation of Sorbent Capacity Following Contamination in the ISS Atmosphere," *45th International Conference on Environmental Systems*. Bellevue, Washington, 2015.
[16]Cmarik, G. E., and Knox, J. C. "Co-Adsorption of Carbon Dioxide on Zeolite 13X in the Presence of Preloaded Water," *48th International Conference on Environmental Systems*. Albuquerque, 2018.
[17]Giesy, T. J., Coker, R. F., O'Conner, B., and Knox, J. C. "Virtual Design of a 4-Bed Molecular Sieve for Exploration," *47th International Conference on Environmental Systems*. Charleston, 2017.
[18]Coker, R. F., and Knox, J. C. "Predictive Modeling of the CDRA 4BMS," *46th International Conference on Environmental Systems*. Vienna, 2016.
[19]Coker, R. F., Knox, J. C., Schunk, G., and Gomez, C. "Computer Simulation and Modeling of CO2 Removal Systems for Exploration," *45th International Conference on Environmental Systems*. SAE, Bellevue, Washington, 2015.
[20]Coker, R., Knox, J. C., Gauto, H., and Gomez, C. "Full System Modeling and Validation of the Carbon Dioxide Removal Assembly." 2014.
[21]Schunk, R. G., Peters, W., and Thomas, J. T. "Four Bed Molecular Sieve – Exploration (4BMS-X) Virtual Heater Design and Optimization," *47th International Conference on Environmental Systems*. Charleston, 2017.
[22]Afandizadeh, S., and Foumeny, E. A. "Design of packed bed reactors: guides to catalyst shape, size, and loading selection," *Applied Thermal Engineering* Vol. 21, No. 6, 2001, pp. 669-682.
[23]Perry, J. L., and Kayatin, M. J. "The Incidence and Fate of Volatile Methyl Siloxanes in a Crewed Spacecraft Cabin," 2017.