Status of the Four Bed Carbon Dioxide Scrubber ISS Technology Demonstration 2023-2024

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The Four Bed Carbon Dioxide Scrubber (FBCO2) flight demonstration is presently operating as a primary CO_2 removal system onboard the International Space Station (ISS). After activation in October 2021, FBCO2 has been removing metabolic CO_2 from the ISS cabin where it is supplementing or fully replacing the heritage systems. This paper describes the past year's accomplishments and forward outlook. The performance of the new blower, efforts toward closed-loop operation, and further on-orbit modifications will also be detailed. System reliability, software changes, and ongoing efforts will be summarized.

Nomenclature

ASV	=	*Air Selector Valve*
CHX	=	*Condensing Heat Exchanger*
CCAA	=	*Common Cabin Air Assembly*
CDRA	=	*Carbon Dioxide Removal Assembly*
CNX	=	*Calnetix Technologies LLC*
CO_2	=	*Carbon Dioxide*
dP	=	*Differential Pressure*
ECLSS	=	*Environmental Control and Life Support System*
FBCO2	=	*Four-Bed Carbon Dioxide*
FTIR	=	*Fourier Transform Infrared Spectroscopy*
HC	=	*Half-Cycle*
HWI	=	*Honeywell International*
ISS	=	*International Space Station*
MCA	=	*Mass Constituent Analyzer*
NASA	=	*National Aeronautics and Space Administration*
R-218	=	*Refrigerant 218 or Perfluoropropane*
rpm	=	*Revolutions Per Minute*
SCFM	=	*Standard Cubic Feet per Minute*
SIFT-MS	=	*Selected Ion Flow Tube Mass Spectrometry*

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TAS = *Thermal Amine Scrubber*

I. Introduction

THE FBCO2 Scrubber was developed as a technology demonstration flight system for the purpose of evaluating its potential as a carbon dioxide (CO_2) removal technology for future missions including a Mars transport vehicle. The motivation for and development of the FBCO2 Scrubber has been documented in a series of previous papers.[1-8] It was launched to the International Space Station (ISS) in August 2021 and activated in September 2021. Due to FBCO2's on-orbit performance and reliability, it is operated as much as possible reducing the usage of heritage Carbon Dioxide Removal Assembly (CDRA) life support systems.

Historically, CO_2 levels on the ISS have primarily been controlled by the operation of two CDRAs to maintain ISS ppCO_2 at a 2.8 mmHg US Orbital Segment 24-hour average. As candidates for the next generation of CO_2 control, FBCO2 and the Thermal Amine Scrubber (TAS) were flown on ISS for evaluation and to support increasing ISS crew capacity, which necessitates higher CO_2 removal rates. After approximately 18 months of operation, FBCO2's system performance, among other considerations, had positioned it as the preferred technology for use in future exploration systems and for integration with Sabatier. At the time of this writing, after approximately 2 years and 7 months of operation, FBCO2 is serving as a primary CO_2 removal system and plays an important role in the ISS integrated Environmental Controls and Life Support System (ECLSS) architecture.

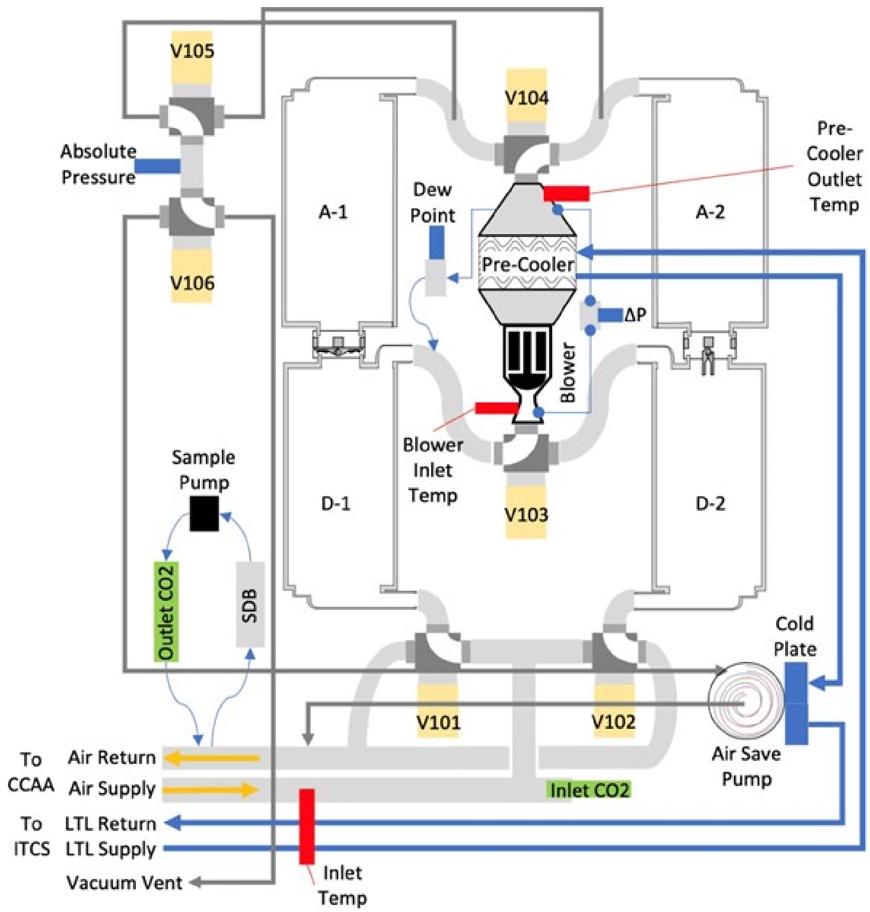

Figure 1. FBCO2 scrubber schematic.

A schematic of FBCO2 is shown in Figure 1 as if it were operating in Half-Cycle (HC) A and venting CO_2 to space. The core features and functions of the system have been described in greater detail in previous papers.[1-8] In summary, conditioned air from the Common Cabin Air Assembly (CCAA) is drawn into FBCO2 by the suction generated by an air blower. Four of the six Air Selector Valves (ASV) direct the air flow path. For HC-A, the flow path is through desiccant bed D-1, then adsorbent bed A-2, and finally through desiccant bed D-2 before returning the air to the CCAA. Water vapor is captured in bed D-1, and then CO_2 is captured in bed A-2. Bed A-2 is hot from the previous cycle and that heat is used to push moisture out of bed D-2. HC-B operates symmetrically, that is, with the beds changing from adsorbing to desorbing and vice-versa. The remaining two ASVs connect bed A-1 to an air save pump for 10 minutes, and then to space vacuum for the remainder of the HC. The sorbent bed is heated to provide a thermal driving force for CO_2 to desorb and vent. Sorbent bed heating is accomplished via embedded heaters, which are controlled to a setpoint temperature via internal resistance temperature detectors.

II. System Performance

A. Zeolite Dusting Mitigation

A recurring problem during CDRA operations has been the generation of zeolite dust in the adsorbent beds. Dust generation can be due to various causes, including abrasive interaction of pellets due to movement where pellets are not closely packed, especially during rapid bed repressurization. Other causes are high compressive forces due to oversized springs in the retention plate and, for some zeolites, poor hydrothermal stability.

In FBCO2, special attention was paid to the remediation of dust production, notably through an extensive screening of commercially available sorbents leading to the selection of a 13X adsorbent material.[7] Other features implemented include a cylindrical bed shape and more open heater configuration to avoid areas with loose packing. Ground testing has indicated that dust production has been reduced by a factor of 100 vs. CDRA.[7] To capture any dust that is generated, the design includes a pleated filter element (35µm absolute rating) and filter slide. The filter pleating increases dust capacity and reduces pressure drop, leading to a high capacity, cleanable dust filter that is easily accessible to crew for maintenance.

Since FBCO2 activation in 2021, there have been no indications in FBCO2 telemetry that zeolite dust or similar particle generation or clogging has become a concern. Due to the non-replaceable nature of the FBCO2 adsorbent beds, which stem from the technology demonstration design, NASA's Space Station Program Control Board recommended inspection of the filters to help verify the effectiveness of the design updates incorporated in FBCO2. Because there are two filters stowed as spares on ISS, the decision was made to return both filters for analysis to determine the level of dust loading, which will help the team extrapolate the estimated lifetime of the non-replaceable beds in FBCO2.

Adsorbent bed filter removal and replacements occurred separately in January and February 2024. Both bed filters were returned on SpaceX Cargo Resupply Services Mission 30 return flight on April 30, 2024; however laboratory analysis has not been completed. Image 1 below shows the removal of a bed filter in January 2024 onboard the ISS. Visual inspection of video recording and still images indicate minimal dust accumulation.

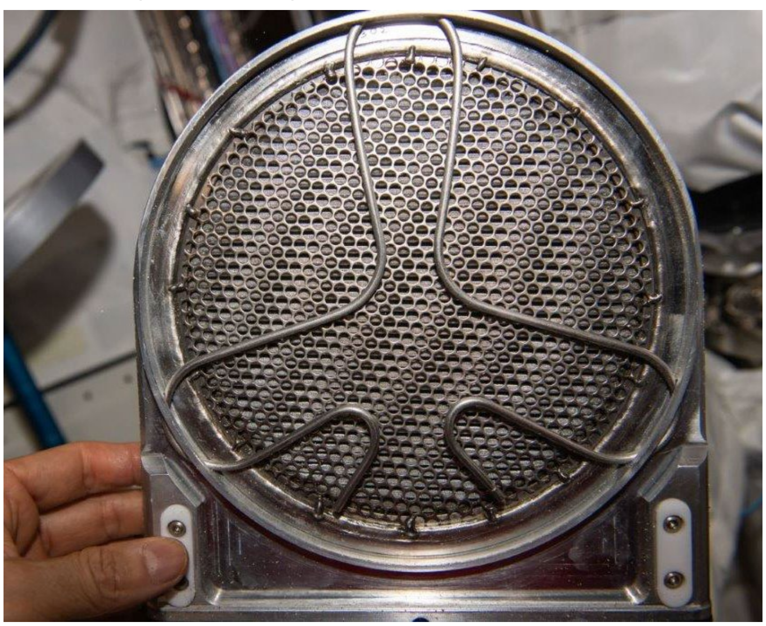

Image 1. NASA astronaut Satoshi Furukawa removing the adsorbent bed filter from FBCO2 Scrubber in Destiny, U.S. Laboratory.

B. CO_2 Removal Performance

The primary performance metric for a CO_2 removal device is the CO_2 removal performance. Higher CO_2 removal performance translates to lower cabin partial pressure for a constant crew load, a condition highly desired by the astronauts and ISS medical community. Additionally, higher CO_2 removal rates accommodate increased number of crew, which is of importance during temporary periods such as crew changeouts where as many as 11 crew are onboard the ISS.

1. *Performance Calculations*

FBCO2 on-orbit performance evaluation requires three key parameters: flow rate and CO_2 concentration at the system inlet and outlet. The inlet and outlet sensors were calibrated on February 27, 2024, using a Mass Constituent Analyzer (MCA). The CCAA was configured for direct cabin inlet without the dilution of the FBCO2 outlet. For the outlet sensor calibration, ASVs 101 and 102 were configured such that inlet flow was redirected to the outlet sensor. The data from this calibration is shown in Figure 2. Here it is evident that the FBCO2 sensors, shown in yellow and blue, had drifted downward significantly over more than two years of operation. The corrections based on this data are used in the performance calculations shown later in this paper.

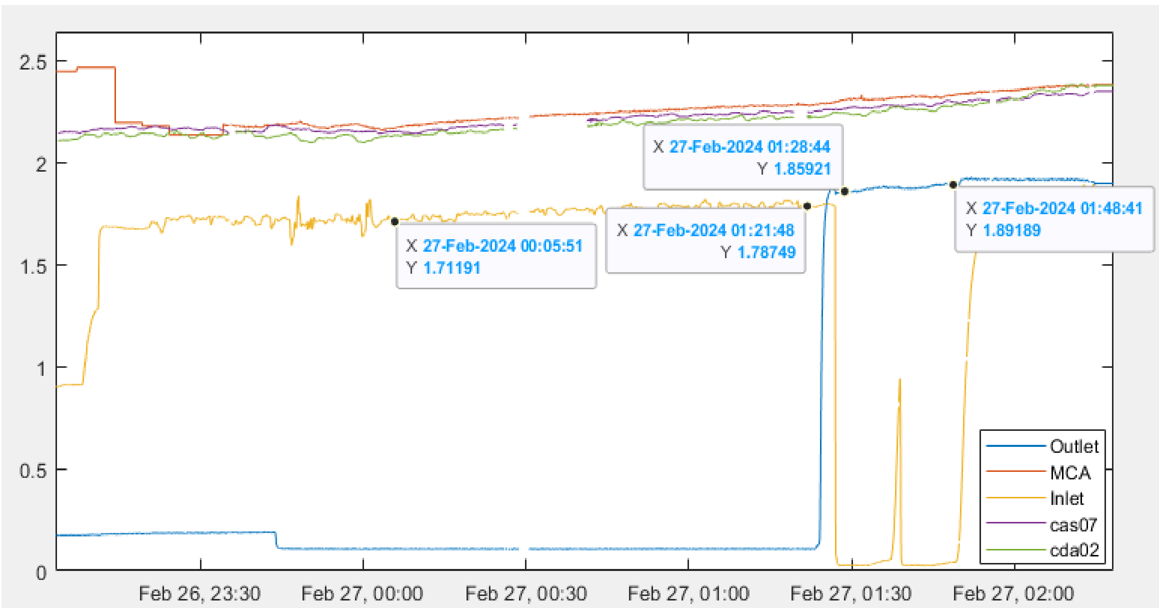

Figure 2. On-orbit calibration of the FBCO2 Scrubber Inlet and Outlet CO_2 Sensors. FBCO2 inlet and outlet sensors shown in yellow and blue, respectively. MCA shown in Red. Additional ISS CO_2 sensors in the US Lab Module include cas07 and cda02.

2. *Flow Rate Calculations and the Influence of Cabin Air Pressure*

Flow rate calculations require an understanding of the influence of boundary conditions on blower performance. Based on data from a year of operation and from ground testing, the CNX blower differential pressure (dP), or delta pressure, appears to be highly sensitive to changes in boundary conditions. The correlation between ISS cabin pressure and blower dP at a blower speed of 56k rpm is presented in Figure 3 below for each HC.

To determine the on-orbit performance of the Calnetix blower, data from the bench testing shown in reference 10 was evaluated as dependent on both differential pressure and blower inlet total pressure. This is shown on the left side of Figure 4, where each of the fit lines represents a specific blower inlet pressure. A multivariate curve fit with R-squared of greater than 0.99 was derived for each RPM setting.

However, a blower inlet pressure value is required to determine flow rate using the above method. Since there is no blower inlet pressure sensor, this value is calculated based on hydraulic equations for each FBCO2 component. Since these calculations require a flow rate value, an alternate method to estimate flow rate based on blower power is used as shown on the right side of Figure 4. The estimated flow rate is then used in the hydraulic calculations to find the blower inlet pressure value required for the multivariate curve fit described previously. Further testing is planned to better understand the scatter in the flow vs. power data such that power can be used directly to determine flow rate.

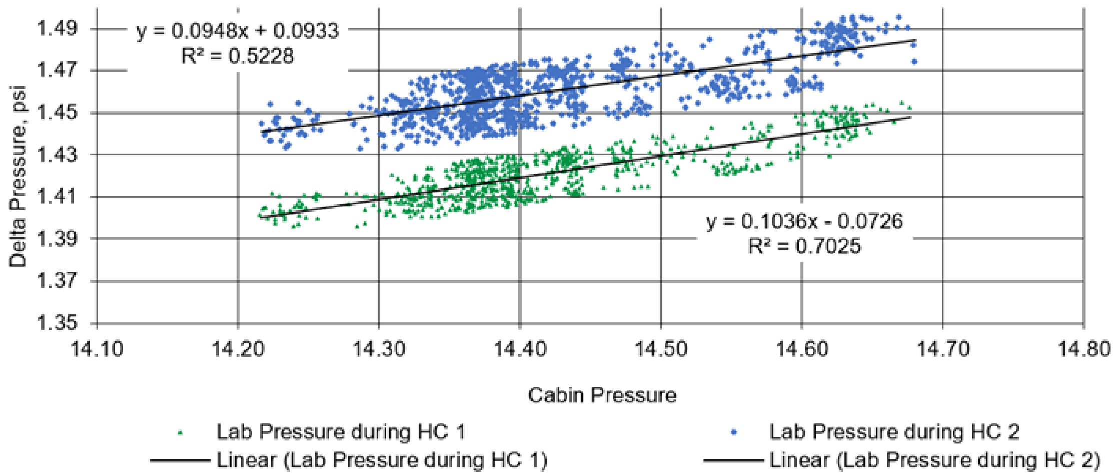

Figure 3. CNX blower differential pressure versus ISS cabin pressure at 56,000 rpm. Half-cycle 1 (HC-A) shown in green. Half-cycle 2 (HC-B) shown in blue.

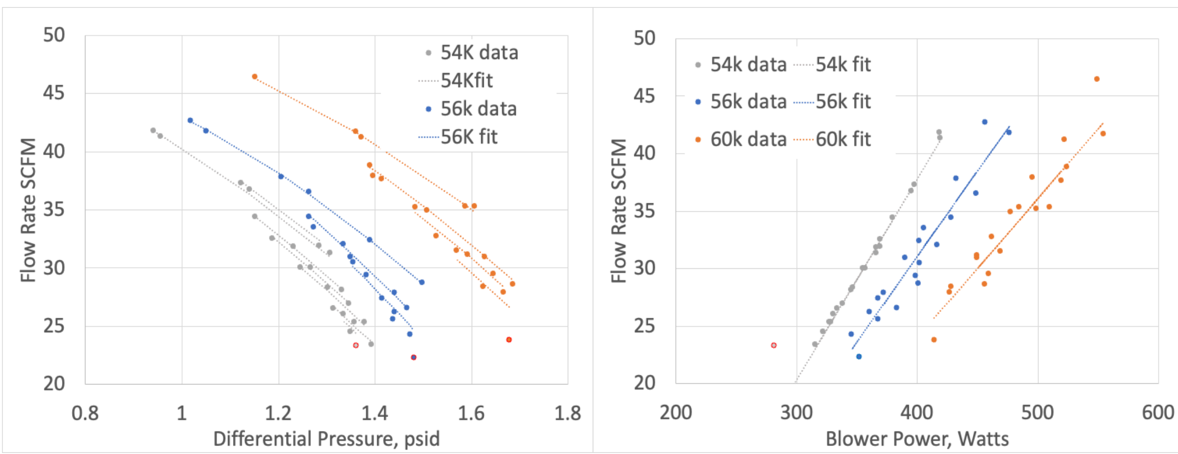

Figure 4. Calnetix blower ground test data at three RPM settings and multiple blower inlet pressures.

3. Influence of CNX Blower RPM on CO_2 Removal Performance

Previous software issues described by Knox 2023[1] prevented the CNX blower from operating at the chosen nominal speed. In May 2023, Calnetix software updates were deployed and allowed for an increase of the blower speed from 54,000 rpm to 56,000 rpm, translating to an increased flow rate and thus a higher CO2 removal rate. Figure 5 below summarizes CO2 removal performance at both 54k and 56k blower speeds. It should be noted that the below figure includes the influence of lab CDRA operation, which is discussed later in greater detail. The influence of Lab CDRA has also been discussed previously by Knox 2023[1]. As evidenced in Figure 5, the current preferred nominal operating conditions include a blower speed of 56k rpm and Lab CDRA non-operational, as shown in blue. Each point represents the removal rate for a single HC.

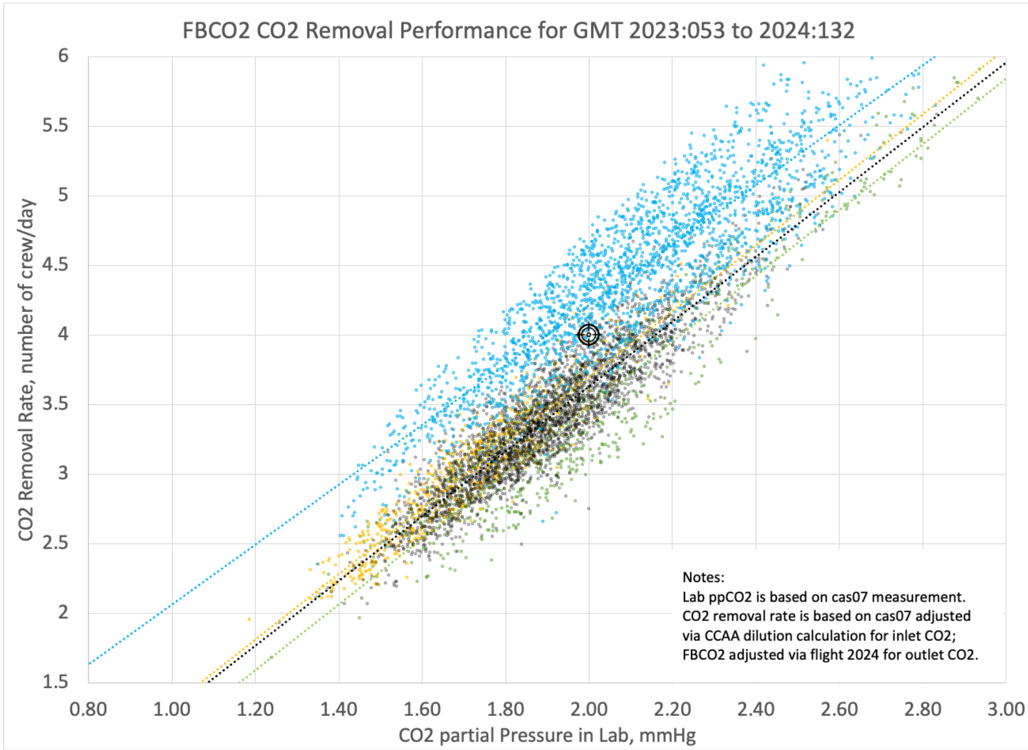

Figure 5. FBCO2 Scrubber CO2 Removal Performance at 54,000 rpm and 56,000 rpm. Operation with CNX blower at 56k rpm and Lab CDRA non-operational shown in blue. Operation with CNX blower at 56k rpm and Lab CDRA operational shown in black. Operation with CNX blower at 55k rpm and Lab CDRA Non-operational shown in yellow. Operation with CNX blower at 54k rpm and Lab CDRA operational shown in green. ISS Lab Module sensor, cas07, used for CO_2 partial pressure measurement.

4. Influence of Lab CDRA operation

The relationship of the operation of the Lab CDRA to the removal capability is due to the competition over a single air supply source. The source of air for both the Lab CDRA and FBCO2 is a tube at the exit of the condensing heat exchanger (CHX) that is part of the CCAA. As previously noted by Knox 2023[1], when FBCO2 was activated, TAS was operational, and the Lab CDRA was not required to maintain ISS CO_2 concentration levels; however, when the TAS failed, the Lab CDRA was activated. With both the Lab CDRA and FBCO2 pulling air through the same tube, the total pressure is reduced at the inlet of the blowers for both systems. This reduced total pressure reduces the performance of the blower and the flow rate, with a resultant reduction in CO_2 removal rate.

TAS was returned to operation in December 2023 and Lab CDRA was deactivated, allowing FBCO2 to operate uncompetitively for air supply. Figure 6 provides a direct comparison of operation with and without Lab CDRA operational. Each point represents the removal rate for a single half-cycle. ISS CO_2 management plans include the continued operation of FBCO2 and TAS as the primary systems during periods of nominal crew size, with Node 3 CDRA providing supplemental removal when larger crew sizes are present.

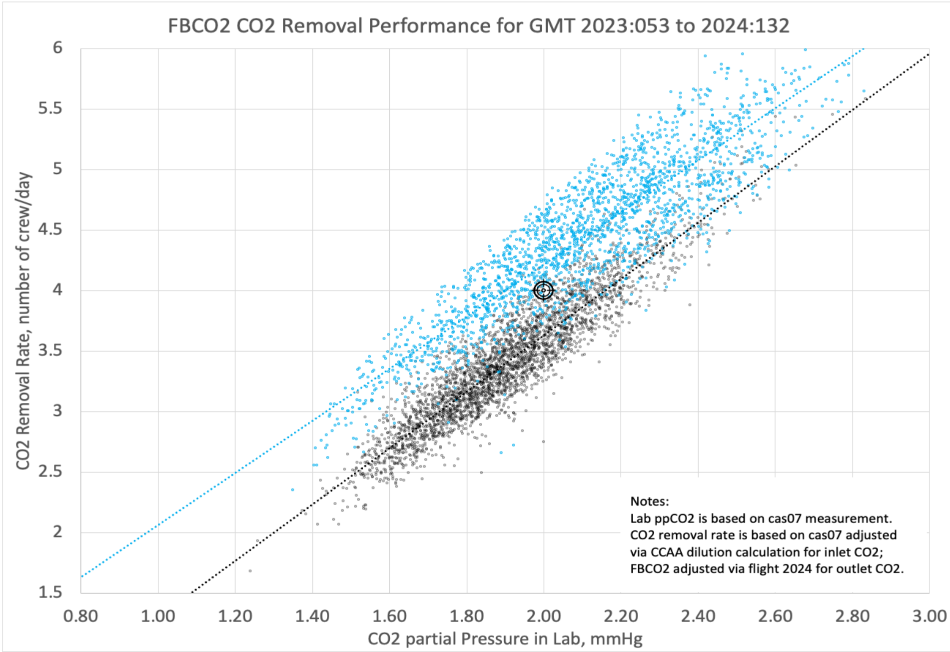

Figure 6. FBCO2 Scrubber CO_2 removal performance 56,000 rpm with Lab CDRA operational and non-operational. Operation with Lab CDRA non-operational shown in blue. Operational Lab CDRA operational shown in black.

III. Other Activities during 2023/2024

A. CNX Blower

In February 2023, a magnetically levitated blower developed by Calnetix Technologies, LLC (CNX) was installed into FBCO2 as part of the FBCO2 development program, as seen in Image 2. FBCO2 flight hardware initially delivered to the ISS utilized a Honeywell International (HWI) airfoil bearing blower, as the CNX blower had not been completed. The HWI blower has a legacy of use in CDRA systems on the ISS; however, the blower is no longer being produced. Extensive testing of the CNX blower was conducted at MSFC to characterize its performance and verify compliance with ISS requirements. While CNX performance has been addressed in previous papers[1,9], the wide variety of conditions experienced on-orbit has identified the need for testing with a wider range of boundary conditions.

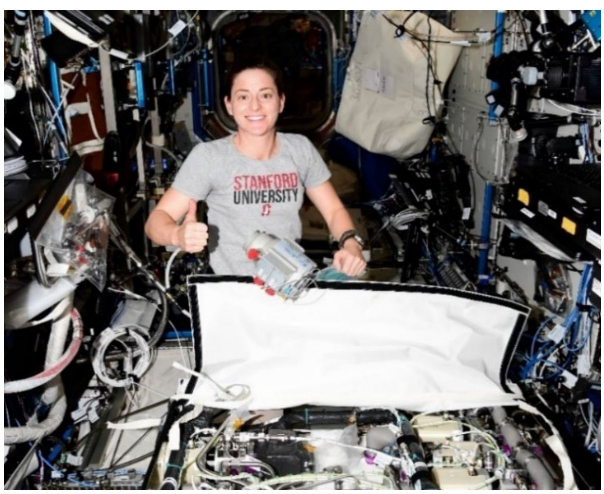

Image 2. NASA astronaut Nicole Mann installing the Calnetix blower on the FBCO2 Scrubber in Destiny, U.S. Laboratory.

As discussed, in May 2023, CNX software updates were deployed and allowed for an increase of the blower speed from 54,000 rpm to 56,000 rpm. Additional software updates are planned for deployment in mid-2024 and are discussed further below. These updates will enable increased commanding to the blower and blower controller, provide increased blower protections, and make available additional parameters to gain further telemetry insight.

In October 2023, FBCO2 experienced an Incorrect Blower Speed fault that resulted in a shutdown. At that time, the blower was spinning at a setpoint of 56K rpm and experienced a low-speed rather than a high-speed drop, indicating that some amount of controlled spin-down was performed automatically. The blower is supported by a 2-axis radial active magnetic bearing (*x1*, *y1*) and a 3-axis (*x2*, *y2*, *z*) combination radial/axial side-by-side active magnetic bearing. These bearings magnetically levitate the rotor and control its position in 5 axes. After reviewing event and fault log data, as well as available telemetry, it was determined that the blower experienced a *y1* Synchronous Vibration Fault triggered via a Synchronous Current Limit exceedance. A later review of (*x1, y1*) and (*x2*,*y2*) synchronous position data indicated that these values experienced a step change from their baseline. The blower was reactivated and commanded to various test speeds to determine if the fault conditions still existed. FBCO2 was brought back to nominal operations after finding the *x*/*y* bearing positions to be in their expected coordinates.

A review of historical bearing synchronous position telemetry revealed that the hardware had entered an unbalanced state previously in June 2023. During this period, the synchronous current and position issues did not escalate to the point of triggering a fault and the bearing positions returned to normal conditions following an extended power down for an unrelated maintenance event. It is unclear if the two anomalies are linked.

There are several potential causes of this recurring bearing unbalance condition that continue to be evaluated. With the data currently available, the leading candidates for a root cause have been narrowed down to the following:

- A structural mode that exists at the nominal 56k rpm blower speed. This mode may either exist between the rotor and the blower housing or between the blower and the internal structure of FBCO2.
- Thermal-related issues that may be causing material changes that affect the spin of the rotor.
- Lower-level electronics or firmware-related issue that incorrectly causes these registers to be flagged.

B. Future Software Updates

Software updates are required to optimize system performance and to provide increased commanding and capabilities. Currently, a software update is being planned for mid-2024. Extensive integrated testing is conducted in Marshall Space Flight Center's Avionics test facility during development. Prior to deployment to FBCO2, formal end-to-end testing and readiness reviews are conducted with NASA Johnson Space Center's ISS operations support teams. The planned updates include:

- Updating the parameter list to support CO_2 Sampling
- Correcting the endianness of blower memory file exports
- Adjusting the timing of blower data requests
- Updating the parameter list to remove the blower inlet temperature sensor that is no longer available
- Updating the parameter list to include a valve closure delay to prevent blower deadheading
- Adding a Blower General Fault to ensure an orderly shutdown upon determination that any blower fault has occurred
- Adding blower Controller Power Command to enable or disable power to the controller
- Adding additional blower telemetry

IV. FBCO2 Ongoing Work and Forward Planning

A. Transition from Technology Demonstration to System

Forward plans for US ISS CO_2 management include FBCO2's transition out of a technology demonstration phase in late 2024 and into an ISS "system" approach for maintenance, hardware sparing, performance optimization, and allocated crew and ground operations support. It should be noted that growth into an ISS system will require a substantial effort to transition. Initial goals of FBCO2 did not include planned maintenance, though ease of maintainability and servicing were thoughtfully considered in the design and have allowed for a blower replacement in 2023 and adsorbent bed filter replacements in 2024. Additional efforts towards the transition include:

- Development of component sparing, stowage, and replacement plans
- Consideration of additional sensors and existing sensor calibration needs
- Increased monitoring of system components for health and trending analysis
- Updated software for improved commanding, system protection, and telemetry

- Development of maintenance procedures and refined maintenance hazard assessments
- Development of hardware and software required for integration with Sabatier
- Increased proficiency of ISS console operators, sustaining personnel, and additional Subject Matter Experts

B. Transition to Closed Loop Operation

In the next few years, FBCO2 will be integrated with the Sabatier Carbon Dioxide Reduction system. This will allow the current CO_2 product stream to be redirected from space vacuum in the current configuration, to a CO_2 compressor and accumulator that will allow a constant flow rate to the Sabatier reactor.

Integration with the Sabatier requires that the FBCO2 product CO_2 stream has a high purity to maintain optimal reaction conditions and avoid degradation of the Sabatier catalyst. In the following sections we discuss purity requirements for N_2, O_2, and H_2O as well as concerns over trace contaminants.

1. CO_2 Purity with Respect to Nitrogen, Oxygen, and Water Vapor

The original FBCO2 system requirements dictate that the CO_2 captured and delivered by the system can have no more than 1% O_2 and 2% N_2 and that it must have low enough humidity to avoid condensation at the outlet of the Sabatier compressor. FBCO2 performance against this requirement is of increasing interest as integration with Sabatier approaches and as valves age, incurring more wear and increasing the likelihood of leaks. Analysis of the O_2 and N_2 composition of CO_2 product samples from FBCO2 have shown inconsistent O_2 and N_2 concentrations, so a plan has been developed to use available leak check procedures to monitor CO_2 product purity more closely.

The contribution of adsorption by the sorbent beds to the O_2 and N_2 concentrations in the CO_2 product can be estimated using single-component isotherm data. Any additional O_2 or N_2 in the CO_2 product is assumed to originate from air leaks into the system. Assuming a 4.16 kg/day CO_2 removal rate, an allowable air leak rate into the CO_2 product can be calculated. An air leak into FBCO2 will cause the 2% N_2 limit to be exceeded before the 1% O_2 limit, so the N_2 requirement is the limiting factor for determining the allowable air leak rate. This allowable air leak rate will produce a certain pressure rise during the existing FBCO2 leak checks. Going forward, leak checks will be executed more frequently, checking the pressure rise against the pressure rise expected for the maximum allowable leak rate to assess O_2 and N_2 concentration in the product CO_2.

Water in the CO_2 product is assumed to originate from water vapor remaining in the CO_2-rich air exiting the desiccant bed. Assuming all water vapor in this stream ends up in the CO_2 product, a maximum allowable dew point in the desiccant bed effluent can be calculated. Going forward, the dew point of this stream will be compared with this maximum allowable dew point to assess water concentration in the CO_2 product. It is worth noting that FBCO2 can tolerate relatively high air leak rates before CO_2 product purity requirements are exceeded, so information from these additional monitoring steps may also be used by the ISS program to evaluate whether $O_2/N_2/H_2O$ loss rates are higher than desirable.

2. CO_2 Purity with Respect to Potential Sabatier Catalyst Degradation Agents

The previous Sabatier experienced catalyst degradation that resulted in the system becoming non-operational. Freon 218 (R-218 or perfluoropropane) has been identified as a possible contributor to Sabatier catalyst degradation. ISS atmospheric monitoring results and the Advanced Multicomponent Air Analyser for ISS (ANITA) results[11] have indicated that FBCO2 removes R-218 from the ISS atmosphere. This results in R-218 being present in the FBCO2 CO_2 product stream which, when integrated with the Sabatier in the future, could result in catalyst degradation. R-218 in the CO_2 product stream has been measured by numerous on-orbit CO_2 product samples as shown in Table 1 below.

Table 1. FBCO2 Scrubber CO2 product samples.

Return	Location	Date	SN	mg/m³ r218	ppm r218	mg/m³ isobutane	mg/m³ carbon disulfide	mg/m³ carbonyl sulfide
SpX-26	Lab	12/12/22	2112	1900	247	21.0	0.79	0.10
SpX-26	Lab	12/12/22	2089	1500	195	18.0	0.43	0.07
SpX-26	Lab	12/26/22	2113	1600	208	26.0	2.80	0.23
SpX-26	Lab	12/26/22	2093	1600	208	26.0	1.70	0.16
SpX-27	Lab	03/28/23	2116	4300	560	3.0	0.47	0.04
SpX-27	Lab	03/28/23	2090	4300	560	2.8	0.40	0.04
SpX-27	Lab	04/04/23	2114	4500	586	5.0	1.80	0.15
SpX-27	Lab	04/04/23	2094	4400	573	5.4	2.80	0.19
SpX-27	Lab	04/04/23	2115	4500	586	4.6	1.20	<0.11
SpX-28	Lab	06/16/23	2062	2800	364	9.6	0.28	<0.043
SpX-28	Lab	06/16/23	2022	3100	403	8.9	0.17	<0.046
SpX-28	Lab	06/27/23	2007	2000	260	9.2	0.68	<0.041
SpX-28	Lab	06/27/23	2009	1900	247	8.2	0.32	<0.044

	mg/m³	ppm		mg/m³	mg/m³	mg/m³
MIN	1500	195	MIN	2.8	0.17	0.041
AVE	2954	384	AVE	11.4	1.06	0.122
MAX	4500	586	MAX	26.0	2.80	0.230
MED	2800	364	MED	8.9	0.68	0.124
	mg/m³	ppm		mg/m³	mg/m³	mg/m³

A review of molecular properties, particularly kinetic diameter and electrostatic properties as shown in Table 2 below, helps to explain why R-218 is captured in zeolite 13X in the FBCO2 Scrubber, though it was not captured in the zeolite 5A in the CDRA. The kinetic diameter of Freon 218 is 6 angstroms, too large to fit in the 5 angstrom pore size of zeolite 5A, but easily fitting in the 10 angstrom pore of zeolite 13X.

Zeolites have a negative charge and attract molecules through electrostatic interactions. R-218 is highly polarizable, leading to it being strongly captured by zeolite 13X. The concentration factor for R-218 is essentially the same as for carbon dioxide indicating the strength of the zeolite 13X/R-218 bond.

Table 2. Molecular properties.

Gas	Formula	Kinetic diameter (A)	Total Dipole (C m x 10^30) (4)	Quadrupole (largest negative) (C m^2 x 10^40)	Polarizability (A^3) (4)	Concentration Factor
Carbon Dioxide	CO2	3.3	0.0	-14.3	2.5	372
R-218	C3F8	6.0	1.1	#N/A	6.3	384
Water	H2O	2.7	6.2	-8.3	1.5	
Isobutane	C4H10	5.3	0.3	1.8	6.0	133
Carbon Disulfide	CS2		0.0	-1.7	8.8	
Carbonyl Sulfide	COS		1.3	-10.0	5.3	
Nitrogen	N2	3.6	0.0	-4.7	1.7	
Oxygen	O2	3.5	0.0	-1.0	1.6	
Zeolite 3A		3				
Zeolite 4A		4				
Zeolite 5A		5				
Zeolite 13X		10				

In February 2024, ground testing at NASA Marshall Space Flight Center was conducted to mimic on-orbit conditions with the injection of R-218 at 1 ppm into the inlet air stream. R-218 evolution from the ground test unit vacuum pump was monitored in real-time using a Gasmet DX4040 Fourier Transform Infrared Spectroscopy (FTIR) with 8 cm^{-1} resolution and a 9.8 m optical path length. A 2 µm Teflon filter was placed in the effluent line between the vacuum pump exit port and the FTIR to remove particulates. An additional pump was utilized to move effluent from the ground test vacuum pump to the FTIR. The ground test effluent was diluted 10-fold with nitrogen so the R-218 concentration would be within the linear range of the FTIR calibration. Bottled effluent samples from the ground test were taken every 6 minutes starting at 14.6 minutes into the half cycle and sent to JSC for gas chromatography mass spectrometry analysis.

The FTIR and GC/MS data demonstrated that R-218 evolved from the ground test adsorbent bed throughout the HC, as shown in Figure 7. The maximum amount of CO_2 exited the ground test unit around 35 minutes into the HC. However, during this time, approximately 400-500 ppm of R-218 also exited the ground test unit. Therefore, there was no opportunity to vent the R-218 overboard without also venting CO_2 under these experimental parameters. A potential solution is to capture the CO_2 in a downstream sorbent system using zeolite 5A. The R-218 would then be vented overboard prior to delivery of the purified CO_2 to the Sabatier.

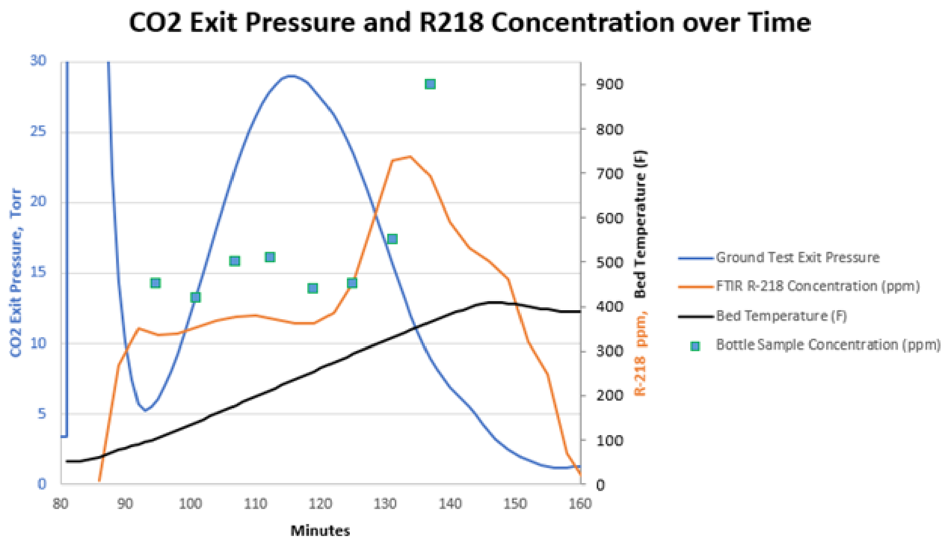

Figure 7. Overlay of CO_2 exit pressure and R-218 evolution from the ground test unit. FTIR data are approximate as method development was underway during the ground test.

V. Conclusions

The FBCO2 Scrubber technology demonstration will reach three years of operation in September 2024 and will transition from a technology demonstration to ISS "system" soon after. While this transition is a significant effort, continued operation of the FBCO2 Scrubber will help to establish its suitability for long-term missions. At the time of this writing, the system has operated with minimal maintenance since activation in September 2021. Integration with Sabatier will be a major achievement towards closing the ECLSS loop on ISS by utilizing carbon dioxide and hydrogen waste streams to produce water.

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References

[1]Knox, J.C., G.E. Cmarik, and J.D. Garr, Status of the Four Bed Carbon Dioxide Scrubber ISS Technology Demonstration 2022-2023, in 52nd International Conference on Environmental Systems. 2023, International Conference on Environmental Systems: Calgary, Canada.

[2]Knox, J.C., G.E. Cmarik, and J.D. Garr, Performance of the Four Bed Carbon Dioxide Scrubber ISS Technology Demonstration, in 51st International Conference on Environmental Systems. 2022, International Conference on Environmental Systems: St. Paul, Minnesota.

[3]Cmarik, G.E., J.C. Knox, and J.D. Garr, Progress of Four Bed Carbon Dioxide Scrubber, in 51st International Conference on Environmental Systems. 2022, International Conference on Environmental Systems: St. Paul, Minnesota.

[4]Peters, W., G.E. Cmarik, and J.C. Knox, 4BCO2 EDU Performance, in 50th International Conference on Environmental Systems. 2021, International Conference on Environmental Systems: Virtual.

[5]Knox, J.C., G.E. Cmarik, and W. Peters, Optimization of the 4-Bed CO_2 Scrubber Performance Based on Ground Tests, in 50th International Conference on Environmental Systems. 2021, International Conference on Environmental Systems: Virtual.

[6]Cmarik, G., J. Knox, and W. Peters, 4-Bed CO2 Scrubber – From Design to Build, in 50th International Conference on Environmental Systems. 2020.

[7]Cmarik, G.E. and J.C. Knox, CO2 Removal for the International Space Station–4-Bed Molecular Sieve Material Selection and System Design, in International Conference on Environmental Systems. 2019: Boston, Mass.

[8]Peters, W. and J. Knox, Four Bed Carbon Dioxide Scrubber System Component Design Guide. 2018, NASA: Marshall Space Flight Center.

[9]Oliver-Butler, K., et al., Test and Evaluation of the Next Generation Blower for FBCO2 Scrubber, in 52nd International Conference on Environmental Systems. 2023, ICES: Calgary, Canada.

[10] Khartri, R., et al., Commissioning and Operational Data of Advanced Magnetic-Bearing-Supported Carbon Dioxide Blower for Space Applications, in 53rd International Conference on Environmental Systems. 2024, ICES, Louisville

[11]Honne, A., ANITA2 – the Advanced Multicomponent Air Analyser for ISS – Gas Measurement Results From the ISS Air in 2022, in 52nd International Conference on Environmental Systems. 2023, ICES: Calgary, Canada.