Status of the Four Bed Carbon Dioxide Scrubber ISS Technology Demonstration 2024-2026

Lyndsey Winslette[1]
NASA Marshall Space Flight Center, Huntsville, AL, United States 35812

James C. Knox[2]
Knox Analytical Solutions Inc., Lacey Springs, AL, United States 35754

Kagen Crawford[3]
NASA Marshall Space Flight Center, Huntsville, AL, United States 35812

The Four Bed Carbon Dioxide Scrubber (FBCO2) is presently operating as a primary carbon dioxide (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 continues to supplement or fully replace heritage systems. This paper describes the past two years accomplishments and forward outlook. The performance of the system at increased blower speeds, addition of an inlet air flow sensor, removal and replacement of the air save pump and adsorbent bed filters, as well as efforts related to the transition to an ISS system will be summarized.

Acronyms and Nomenclature

ASP	=	air save pump
ASV	=	air selector valve
CCAA	=	Common Cabin Air Assembly
CDRA	=	Carbon Dioxide Removal Assembly
CHX	=	condensing heat exchanger
CNX	=	Calnetix Technologies LLC
CO_2	=	carbon dioxide
CV	=	check valve
ECLSS	=	Environmental Control and Life Support System
FBCO2	=	Four-Bed Carbon Dioxide
HC	=	half-cycle
ISS	=	International Space Station
JSC	=	NASA Johnson Space Center
LON	=	launch on-need spare
LTL	=	low temperature loop
mmHg	=	millimeters of mercury
MOOS	=	minimum on-orbit spare
MSFC	=	NASA Marshall Space Center
NASA	=	National Aeronautics and Space Administration
ORU	=	orbital replacement unit
PAR	=	parameter
RBB	=	resistor bypass box
REA	=	resistor enclosure assembly
rpm	=	rotations per minute
µm	=	micrometer

[1] Sustaining Engineer, ECLSS Development Branch, Mail Stop: ES62, MSFC, AL 35812.
[2] FBCO2 Subject Matter Expert, ECLSS Development Branch, Mail Stop: ES62, MSFC, AL 35812.
[3] Project Manager, Exploration Projects and Integration Office, Mail Stop: HP30, MSFC, AL 35812.

I. Introduction

THE Four Bed Carbon Dioxide Scrubber (FBCO2) was developed as a technology demonstration to evaluate its potential as a carbon dioxide (CO_2) removal technology for advanced exploration systems. A primary design objective was to provide the CO_2 removal equivalent to a 4-crew capacity, or 4.16 kg/day at a cabin CO_2 partial pressure of 2mmHg. FBCO2 is a four-bed molecular sieve system that uses thermal and vacuum swing adsorption to scrub CO_2 by utilizing a 13X zeolite sorbent with water and air save capabilities.

Activated in September 2021, FBCO2 reached its technology demonstration goal of 3 years of operational run time in late February 2025 with minimal unplanned maintenance events and exceeding its CO_2 removal goal. Due to its on-orbit performance and reliability FBCO2 transitioned to an International Space Station (ISS) system in July 2025 and is on track to reach 4 years of operational run time in March 2026. FBCO2 is currently being operated as the prime CO2 scrubber within the United States Orbital Segment, playing a vital role in atmospheric revitalization for the ISS. The ISS Program is planning for the continued use of FBCO2 at 100% duty cycle through the end of ISS life in 2030.

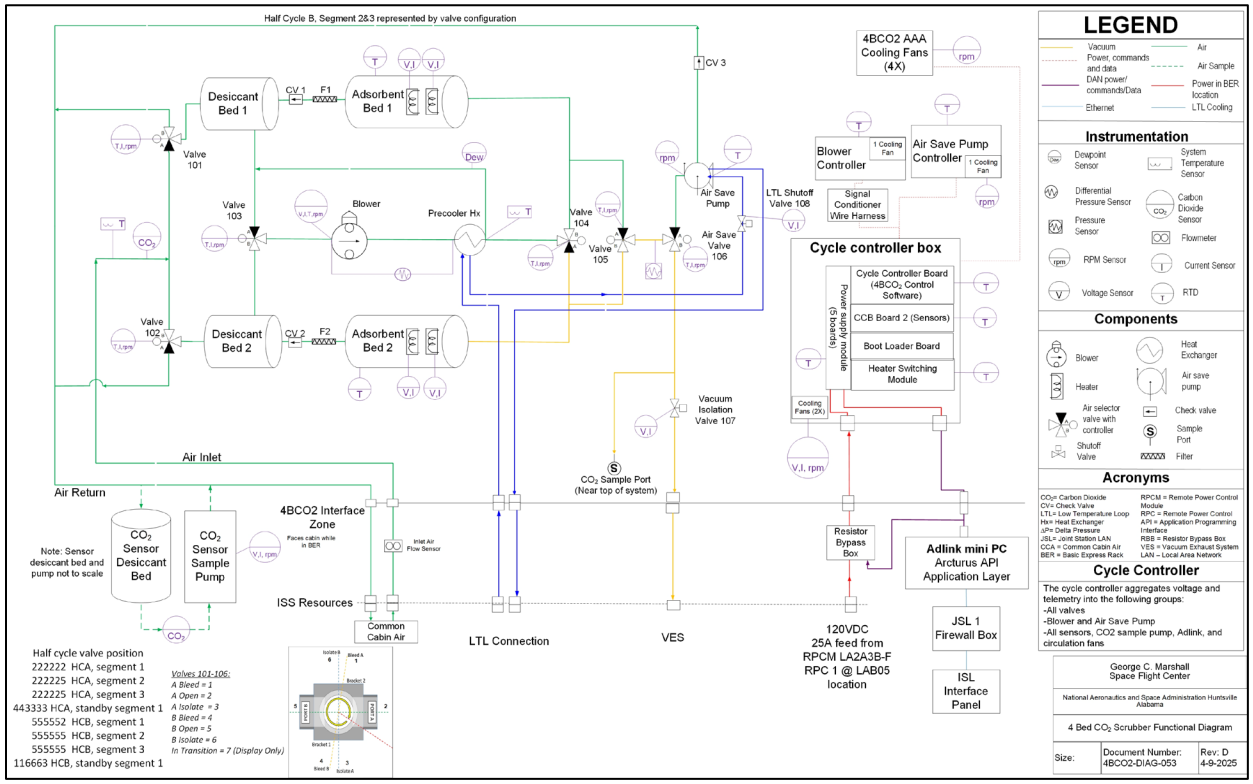


Figure 1. FBCO2 Scrubber flight hardware diagram.

A diagram of FBCO2 is shown in Figure 1 above. Core features and functions of the system have been described in greater detail in previous papers [1-3]. In summary, conditioned air from the Common Cabin Air Assembly (CCAA) is drawn into FBCO2 by the suction generated by the air blower. Four of the six air selector valves (ASVs) direct the air flow path. For Half Cycle A (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 adsorbent 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, with the beds changing from adsorbing to desorbing. The remaining two ASVs connect bed A-1 to an air save pump (ASP) 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, and to desorb H_2O from the downstream desiccant bed in the subsequent HC. Sorbent bed heating is achieved by embedded heaters controlled to a setpoint temperature via internal resistance temperature detectors.

II. System Performance

A. CO_2 Removal Performance

CO_2 removal performance is the primary performance metric. 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 community. Higher CO_2 removal rates can also accommodate larger crew complements, which is important during temporary periods such as crew handovers. Notably, in February 2025 the ISS accommodated 12 crew during a changeout period while maintaining the average 1-hour CO_2 partial pressure below 3.0 mmHg. In February 2026, FBCO2 served as the sole CO_2 removal system during a period of 7 crew.

1. Comparison of CO_2 Removal Performance with Measured Flow

Previous software issues described by Knox 2023 [1] and Winslette 2024 [3] prevented the CNX blower from operating at the desired nominal speed. In September 2024, CNX software updates were deployed and allowed for an increase of the blower speed from 56k rpm to 58.5k rpm. In March 2025, a resistor bypass box was installed to provide adequate, stable voltage to the blower and allowed for an increase to 60k rpm, resulting in an increased flow, and therefore a higher CO_2 removal rate.

As discussed in previous papers [2,3], FBCO2 contained no flow measurement device when it was launched to the ISS, so data from other sources was used to estimate flow rate. On GMT 2025 093, an inlet air flow meter was installed to provide a direct measurement of the inlet air velocity to enable refined flow measurements and CO2 removal rates. At a blower speed setpoint of 60K rpm the flowrate has been measured between 30.0 – 33.0 standard cubic feet per minute. Figure 2 below summarizes CO_2 removal performance at 60k rpm with estimated flow shown in purple and measured flow shown in green, with Lab CDRA non-operational. The current preferred nominal operating condition remains at a blower speed of 60k rpm. Each point represents the removal rate for a single HC.

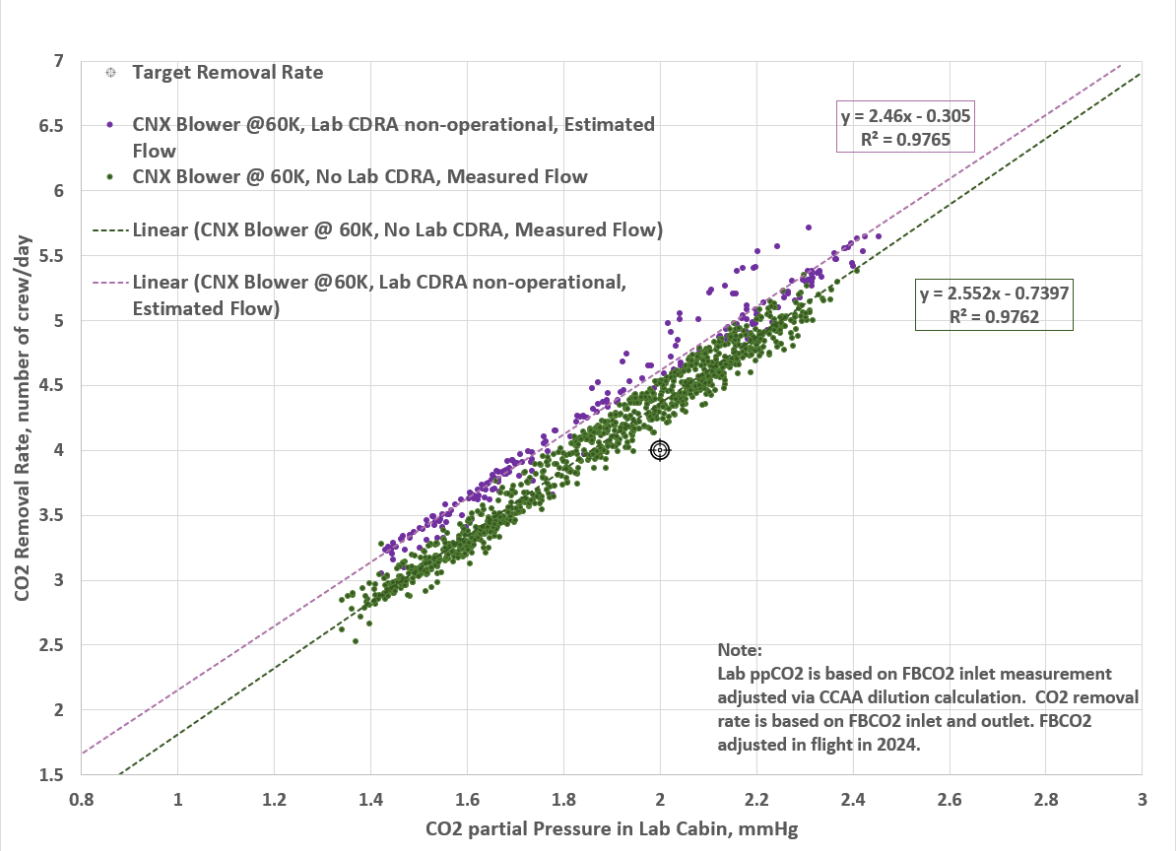


Figure 2. FBCO2 Scrubber CO_2 Removal Performance at 60k rpm and no Lab CDRA operation. Operation with estimated flow shown in purple. Operation with measured flow shown in green. FBCO2 inlet sensor used for CO_2 partial pressure measurement and FBCO2 internal CO_2 sensor used for FBCO2 outlet measurement.

2. Influence of Lab CDRA Operation on CO_2 Removal Performance

FBCO2's removal capability is impacted by the operation of Lab CDRA due to the competition over a single air supply source. With both Lab CDRA and FBCO2 pulling air through the same tube at the exit of the CCAA's condensing heat exchanger (CHX), the total pressure is reduced at the inlet of the blowers for both systems. A reduction in total pressure reduces the performance of the blower and the flow rate, and consequently results in a reduced CO_2 removal rate. Figure 3 below shows a comparison of CO_2 removal performance at 60K rpm blower speed with Lab CDRA non-operational, shown in green, and Lab CDRA operational, shown in yellow. Each point represents the removal rate for a single HC using measured flow rates. While data at 60K rpm and Lab CDRA operational is limited, the observed performance decrease is consistent with previous comparisons [1,3] of data at 54K rpm and 56K rpm impacted by the operation of Lab CDRA.

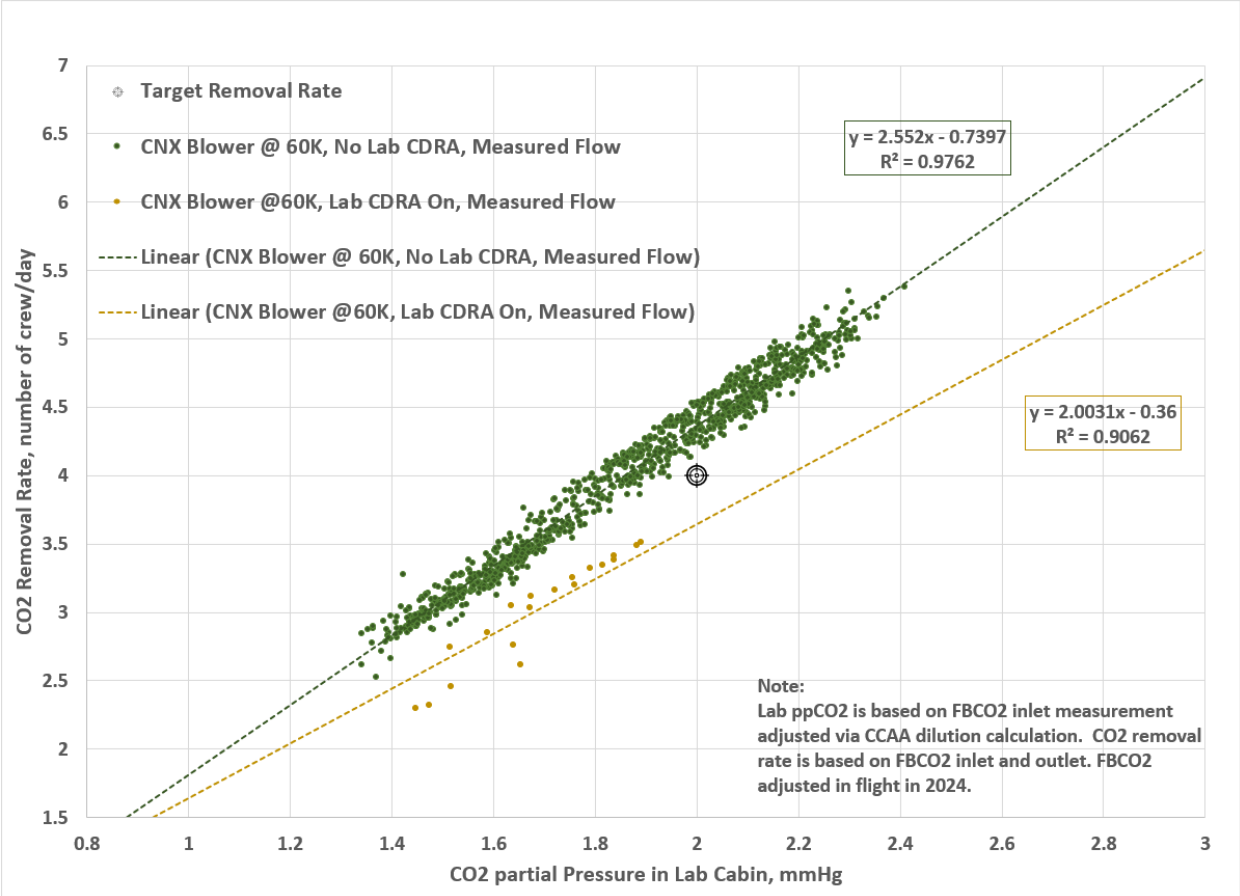


Figure 3. FBCO2 Scrubber CO_2 removal performance 60k rpm with measured flow rate. Operation with Lab CDRA non-operational shown in green. Operational Lab CDRA operational shown in yellow. FBCO2 inlet sensor used for CO2 partial pressure measurement and FBCO2 internal CO2 sensor used for FBCO2 outlet measurement.

3. Influence of ISS Lab Module Internal Thermal Control System on CO_2 Removal Performance

Thermal Control Systems are used to maintain payloads and equipment within their required temperature ranges, by collecting, transferring, and rejecting heat. FBCO2 interfaces with the Low Temperature Loop (LTL) supplied by the Lab Module's Internal Thermal Control System. The LTL line nominally operates at setpoints of 4.5°C and 9.4°C, however other setpoints may be used as needed to meet desired cabin air conditions. These nominal setpoints result in the vast majority of coolant temperatures in the range of 4.5 ± 0.4 °C and 9.4 ± 0.4 °C.

FBCO2's air save pump (ASP) has a thermal strap mounted to the surface of a cold plate for thermal control. LTL water flows through the internal structure of the cold plate and transfers heat through conduction to keep the ASP within a desired temperature range. The FBCO2 precooler heat exchanger also utilizes the LTL to remove heat added

to process air by both the blower and the desiccant bed due to the heat of adsorption of water vapor. As the precooler outlet air temperature decreases, the sorbent bed inlet air temperature decreases, increasing the CO_2 capacity of the zeolite in the CO_2 sorbent bed and the overall system CO_2 removal.

The CHX within the CCAA also relies on the LTL to effectively condense water vapor from the cabin air for humidity and temperature control. FBCO2 receives air at the exit of the CCAA CHX and is subject to variations in inlet temperature and dewpoint, resulting in variations in mass flow rates into the system. Blower flow rate combined with CO_2 concentration at the system inlet and outlet are used to calculate CO_2 removal and system performance. Figure 4 below shows CO_2 removal performance at 60K rpm blower speed with measured flow and Lab CDRA non-operational. Performance with the LTL temperature above 7°C is shown in blue. Performance with the LTL temperature below 7°C is shown in green. Each point represents the removal rate for a single HC. Data shows that higher LTL temperatures translate to higher CO_2 removal performance. At higher temperatures the mass flow rate is reduced due to less dense gas, yet performance increases. This increase is believed to result from reduced CO_2 absorption in the desiccant bed 13X at higher temperatures.

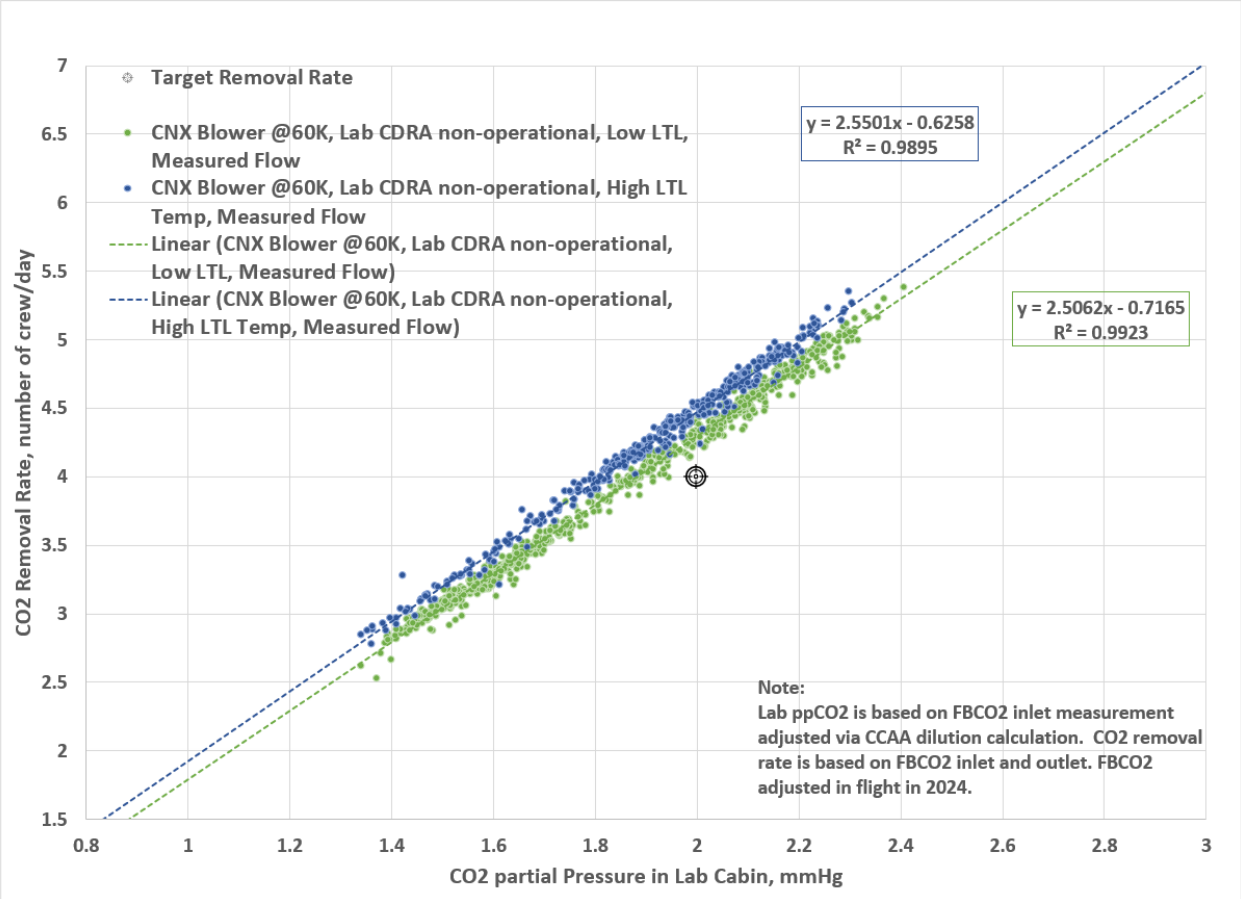


Figure 4. FBCO2 Scrubber CO_2 Removal Performance at 60k rpm with Lab CDRA Non-operational and measured flow. Operation with Low Temperature Cooling Loop below 7 °C shown in green. Operation with Low Temperature Cooling Loop above 7 °C shown in blue. FBCO2 inlet sensor used for CO2 partial pressure measurement and FBCO2 internal CO2 sensor used for FBCO2 outlet measurement. measurement.

B. Zeolite Dusting Laboratory Analysis

In early 2024, the adsorbent bed filters were removed to verify the effectiveness of the design updates used to mitigate the recurring zeolite dust problems seen in CDRA. As discussed elsewhere [3,4], dust generation can be

attributed to abrasive interaction of the zeolite pellets during rapid bed repressurization, high compressive forces, and poor hydrothermal stability of certain zeolites.

In FBCO2, the zeolite 13X adsorbent material was chosen for its high hydrothermal stability. Additionally, the system's cylindrical bed shape and open heater configuration allow for maximum visibility during packing and full compaction without void spaces. Finally, the valves were designed to limit repressurization air velocity to industry standards. The pleated filter element (35µm absolute rating) was designed to increase dust capacity and reduce pressure drop.

Both filters were returned on the SpaceX Cargo Resupply Services Mission 30 flight in April 2024 and were analyzed by Boeing at the Huntsville Central Laboratory for particle size fractioning, particle identification, and contaminant loading. Analysis showed the filters had little to no debris on the filters themselves and much of the dust was found in the sample bag they were returned in. The total mass of dust debris, which contained some contaminants thought to be from the vacuum collection adapter, was 0.03 grams. In comparison to a previous CDRA dust analysis performed in 2014, FBCO2 dust production was found to be reduced by 2 to 3 orders of magnitude over a 2-year operational period. Figures 5 and 6 below show the extreme cleanliness of the screens under microscope analysis with only a few larger particles greater than 300 microns. The particles were found to mainly consist of sodium aluminosilicates, which is the chemical composition of zeolite 13X used in the adsorbent beds and within a portion or the desiccant beds. The zeolite dust size ranged from 5-59 µm, with larger particles up to approximately 750 µm lodged in the screen. The FBCO2 team is planning for periodic inspection of the filters to assess the rate of degradation of adsorbent material in these beds over time. The next bed filter cleaning, or if needed, removal and replacement is currently planned for January 2027.

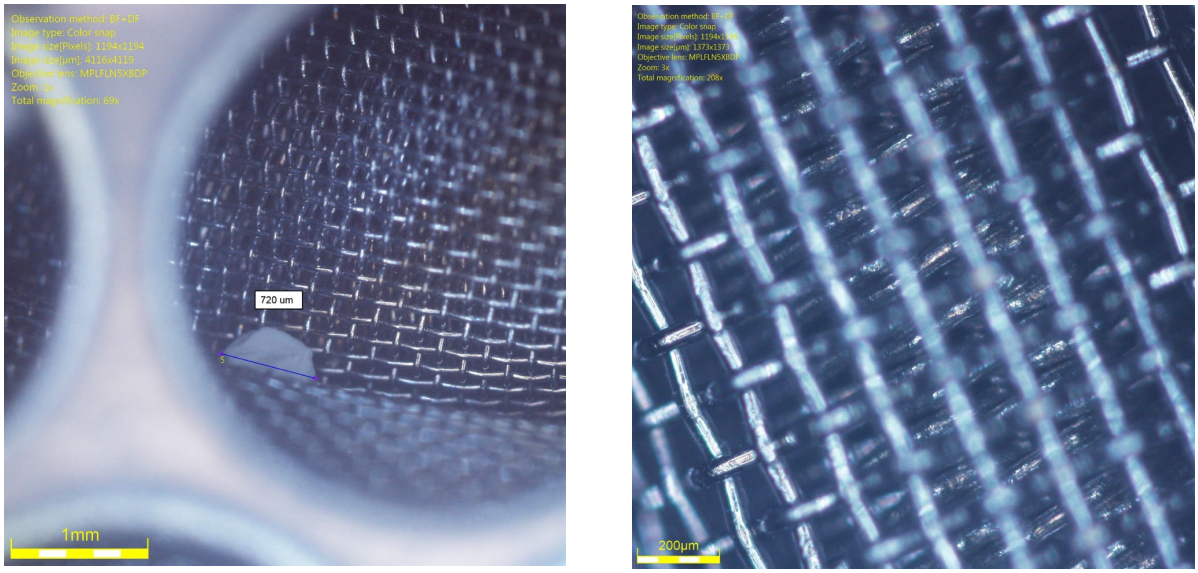


Figure 5 and 6. FBCO2 filter screens analyzed under microscope inspection at Boeing Huntsville Central Lab.

III. Other Activities During 2024/2026

A. Air Save Pump Assembly Replacement

On 2024 GMT 181, while FBCO2 was operating in the air save segment, the ASP was unable to bring the pressure down to the desired level. This led to a fault being triggered that sent the system to a non-operational configuration. NASA Johnson Space Center (JSC) console operators cleared the fault, restarted FBCO2 and completed the half cycle; however, upon entering the following half cycle (HC-B), FBCO2 experienced an equivalent fault. The team put FBCO2 in a safe standby configuration and convened a Failure Investigation Team to review available data and determine a path forward. While most telemetry was within family, the vent line pressure during Segment 1 in the half cycles leading up to the fault showed the maximum pumping ability was quickly degrading. The team determined the best path forward was to remove and replace the failed ASP with the on-orbit spare. The commercial off the shelf ASP

accrued approximately 2,700 operational hours at the time of failure. The cause of the pump failure remains unknown, as a tear down and evaluation of the pump has not been performed to date.

On 2024 GMT 205, ISS crew replaced the failed ASP and FBCO2 was reactivated. During activation, the sorbent bed pressure increased whenever the ASP turned off. It was soon discovered that the spare ASP did not contain an internal check valve (CV) to prevent the back flow of cabin air after the pump turns off. FBCO2 engineering and flight operations teams were able to develop a workaround using software parameter (PAR) modifications to allow FBCO2 to return to an operational status on 2024 GMT 215. FBCO2 continued to operate with modified PARs until a new CV, external to the ASP, was flown and installed on 2025 GMT 045. While FBCO2 remained operational, significant contributions were made by the flight operators and engineering team to edit and revise many of the procedures required for daily operation. The installation and performance of the external CV is discussed later in this section.

Further investigation revealed that several factors, including manufacturer changes to the ASP configuration, and inconsistencies of the NASA build from the original to the spare pump, contributed to the oversight. The original pump was supplied by JSC, followed by drawing conversions and handovers to produce the spare pump at NASA Marshall Space Flight Center (MSFC). Several lessons learned and recommended actions resulted from the investigation.

B. Check Valve Installation and Return to Nominal Operations

Shortly after the discovery of the CV omission following the ASP replacement and activation, the FBCO2 team pursued plans to install a new CV. After deliberating between several design options, it was decided to permanently locate an independent CV downstream of the ASP, at the opposite end of a ½ inch flex hose that attaches to the ASP outlet. A commercial off the shelf Swagelok CV with a 1.0 pound per square inch differential crack pressure was successfully installed on 2025 GMT 045. The placement did result in the flex hose being raised approximately 4-5 inches; however, the crew was easily able to reroute the hose without issue. A review of telemetry has shown that the new CV is performing better than the previous CV that was located within the ASP. After a thorough checkout and data review on 2025 GMT 045, JSC flight operators were able to return the modified software PARs back to the original values without issue.

C. Resistor Bypass Box Installation

During the ISS transient test for FBCO2, a power spike caused a current surge, which tripped the Cycle Controller Box 120V 12A breaker. To address the current surge, an inline Resistor Enclosure Assembly (REA) was added to FBCO2. When the REA was installed, the electrical current was reduced to a level that would not trip the breaker; however, due to voltage drop across the inline resistor, the blower was not able to reach its desired nominal speed of 60k rpm, limiting CO_2 removal performance.

MSFC engineering developed the Resistor Bypass Box (RBB) to replace the REA to reduce the voltage drop to the system during nominal power conditions. Unlike the REA where the inline resistor was always operational, the RBB only opens to the resistor when a transient is detected and is nominally closed to the bypass. The RBB provides adequate voltage to the blower during nominal conditions and allows the blower to reach its desired speed. Lowering the voltage drop to the system also reduced the thermal energy dissipated into the FBCO2 structure.

The RBB was successfully installed on 2025 GMT 045. Two feed lines supply power to FBCO2. As evidenced from a comparison of the 120V Feed 1 and 120V Feed 2 telemetry seen in the figures below, the RBB is performing as expected. Figures 7 and 8 show the 120V Feed 1 & 120V Feed 2 voltage lines respectively with the previous REA installed during nominal operation. Figures 9 and 10 show the increased stability and lowered voltage drop during nominal operations on 120V Feed 1 & 120V Feed 2 voltage lines respectively with the RBB installed. As previously mentioned, this enabled the blower speed to be increased to 60k rpm on 2025 GMT 064.

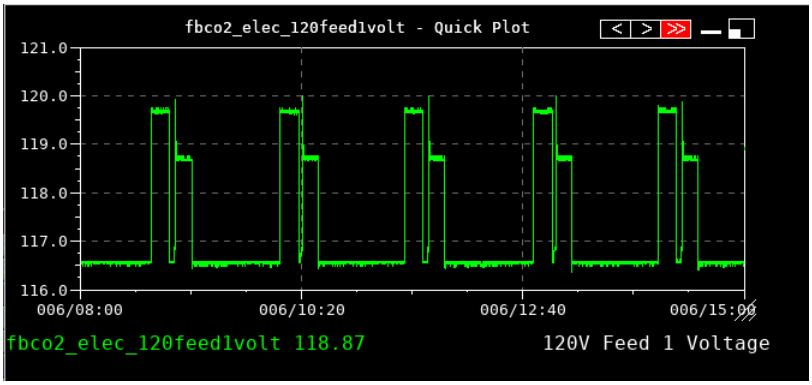


Figure 7. Variations in 120V Feed 1 voltage on 2025 GMT 006 during nominal operations with REA installed.

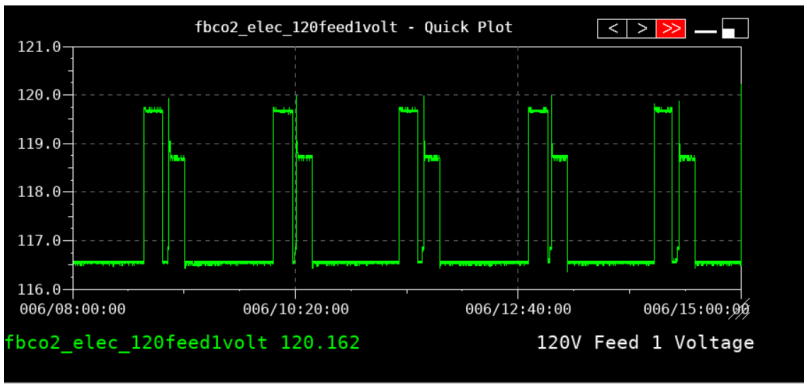


Figure 8. Variations in 120V Feed 2 voltage on 2025 GMT 006 during nominal operations with REA installed.

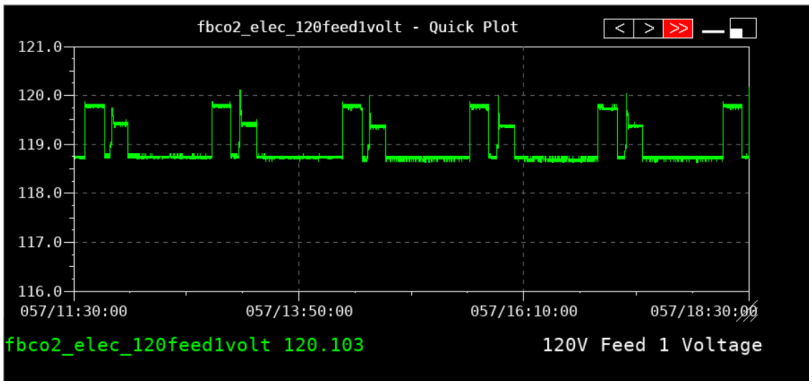


Figure 9. Increased stability and lowered voltage drop in 120V Feed 1 voltage on 2025 GMT 045 during nominal operations with RBB installed.

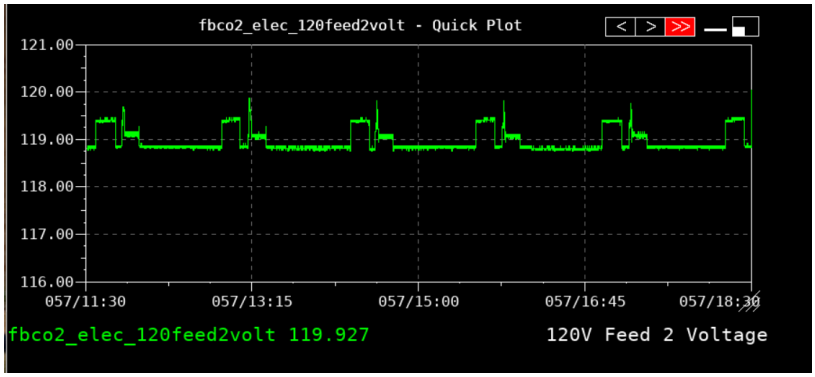


Figure 10. Increased stability and lowered voltage drop in 120V Feed 2 voltage on 2025 GMT 045 during nominal operations with RBB installed.

IV. FBCO2 Ongoing Work and Forward Planning

Forward plans for the US ISS CO_2 management include FBCO2's operation at 100% duty cycle through ISS decommissioning planned for 2030. After achieving the technology demonstration's operational goal in February 2025, it was requested that the system transition to a hardware sparing and maintenance plan in line with other ISS Systems while additionally requesting continued support in analyzing telemetry data for performance optimization opportunities.

The ISS Program's need for an alternative, highly effective CO_2 removal system necessitated the development of a FBCO2 supportability plan, including an assessment of minimum on orbit spares (MOOS) and launch on need (LON) spares to support continued operation. While the MOOS tracks all repairable/replaceable components, traffic models were also created for processing, repairing, and returning certain repairable components. The supportability plan was produced from the team's assessment of all orbital replaceable units (ORUs), including accumulated run time, or cycle time, and estimated life expectancy for each component. The FBCO2 sparing posture prioritizes ORUs that are susceptible to wear over time and are necessary for system operation. This originally meant, for ORUs, there would be enough spares to meet MOOS on-orbit, and one LON spare. There's an exception for the Air Selector Valve (ASV) and Pleated Filter (PF) given their use in multiple unit operation locations on FBCO2. The inlet and outlet CO_2 sensors were deemed non-critical for operation and will have one on-orbit spare, but no LON spare. Due to potential launch limitations, the sparing strategy has shifted towards flying all LON spares to the ISS in the event that future flights may be limited or unavailable. Figure 11 below shows the current sparing posture as of February 2026.

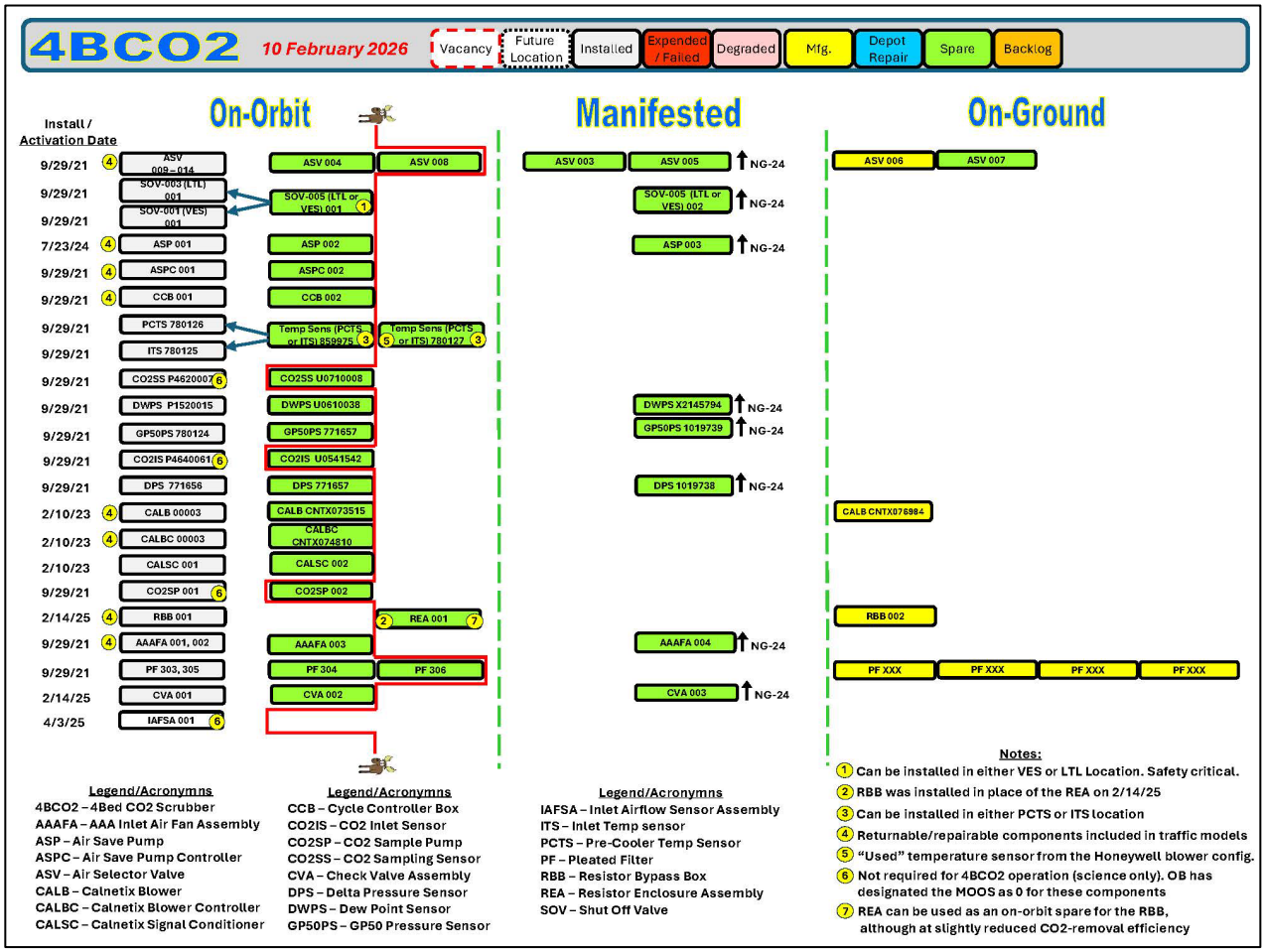


Figure 11. FBCO2 Sparing plan as of February 2026.

In 2024, the FBCO2 team successfully built, tested, and flew the resistor bypass box and check valve assembly. In 2025, the FBCO2 team successfully built, tested, and delivered 11 pieces of flight hardware including: an inlet

airflow sensor assembly, a refurbished ASP, a solenoid shut-off valve, a CO_2 sample pump, two avionic air fan assemblies, a CNX blower signal harness, a third ASP, a dew point transmitter, a shutoff valve, and a check valve assembly. Thus far in 2026, the FBCO2 team has completed the testing, verifications, labeling and shipping of 5 pieces of flight hardware including: two air selector valves, a delta pressure sensor, an absolute pressure sensor, and an avionic air fan assembly. Remaining hardware to be completed in 2026 include a spare RBB and a Calnetix blower which are planned to fly in fall 2026.

Looking forward to 2027 and beyond, the risk of reduced flights to the ISS has been mitigated. The FBCO2 team is resetting the sparing strategy, due to completed work and reduced urgency, and is transitioning to a sustaining-focused role. The increased focus on sustaining is a sign of successful engineering implementation of a highly effective CO_2 removal system. Stepping back on sparing allows the ISS Program Office to more effectively balance funding across vehicle priorities as the ISS Program funding is reducing annually, approaching decommissioning in 2030. The sustaining effort includes efforts to track on-orbit CO_2 removal data and operational data to determine system operation status, and determine the need for unplanned sparing, maintenance, or repairs.

The sparing plan for FBCO2 in 2027 will rely on using the team's traffic model and hardware life expectancy calculations to predict failures of ORUs within the year. If ISS flights continue to be available, the intent is to cycle repairable hardware to the ground for repair as needed, predicted by life expectancy, and to ensure, for non-repairable COTS hardware, that one ORU over MOOS is sustained on the ground or on-orbit.

V. Conclusion

All goals of the FBCO2 technology demonstration that were established at the onset of the project have been successfully and comprehensively met. As of March 2026, FBCO2 has achieved four years of operational time with negligible dust generation and minimal unplanned maintenance. Notably, FBCO2 continues to achieve greater than the 4 crew/day at 2 mmHg $ppCO_2$ removal performance goal and serves as a primary CO_2 removal system for the ISS. The unexpected omission of an internal CV in the ASP challenged the team to establish new operating norms and software workarounds to keep FBCO2 operational in July 2024. Meanwhile, the engineering team successfully met the challenge of incorporating an external CV into the system to restore FBCO2 to its nominal functionality in February 2025. Continued operation will further inform and optimize system operation and supportability plans to enable the use of FBCO2 technology in future exploration missions.

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, 52nd International Conference on Environmental Systems. 2023, International Conference on Environmental Systems: Calgary, Canada, 2022.

[2] Knox, J.C., G.E. Cmarik, and J.D. Garr, Performance of the Four Bed Carbon Dioxide Scrubber ISS Technology Demonstration, 51st International Conference on Environmental Systems: St. Paul, Minnesota, 2023.

[3] Winslette, L., J.C. Knox, T. Giesy, J. Williams, and J.D. Garr, Status of the Four Bed Carbon Dioxide Scrubber ISS Technology Demonstration 2023-2024, 53rd International Conference on Environmental Systems: Louisville, Kentucky, 2024.

[4] Knox. J.C, Winslette, L., Adnvances in Zeolite CO2 Removal System Design for Dust Mitigation, 55th International Conference on Environmental Systems: Rio Grande, Puerto Rico, 2026.