Status of the Four Bed Carbon Dioxide Scrubber ISS Technology Demonstration 2022-2023

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The Four Bed Carbon Dioxide Scrubber flight demonstration is presently operating onboard the International Space Station. After being launched in August and activated in September 2021, the system has been removing metabolic CO_2 from the cabin as a supplement and replacement for other CO_2 removal systems, specifically the two Carbon Dioxide Removal Assemblies. This paper describes on-orbit operations and changes (including installation of the Calnetix blower) during 2022 and early 2023. Performance of the system especially as affected by changes in the on-orbit configuration will be described. System reliability, software changes, and ongoing efforts will be summarized.

Nomenclature

ASV	=	Air Selector Valve
BER	=	Basic ExPRESS Rack
CHX	=	Condensing Heat Exchanger
CCAA	=	Common Cabin Air Assembly
CDA	=	Carbon Dioxide (Adlink) Sensor
CDRA	=	Carbon Dioxide Removal Assembly
CNX	=	Calnetix Technologies LLC
CO_2	=	Carbon Dioxide
dP	=	Differential Pressure
ECLSS	=	Environmental Control and Life Support System
EMC	=	Electromagnetic Compatibility
EMI	=	Electromagnetic Interference
FBCO2	=	Four-Bed Carbon Dioxide
HC	=	Half-Cycle
HWI	=	Honeywell International
ISS	=	International Space Station
MCA	=	Major Constituent Analyzer
NASA	=	National Aeronautics and Space Administration
RFP	=	Request for Proposal
RTD	=	Resistance Temperature Detector
rpm	=	Revolutions Per Minute
SBS	=	Side-by-side

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SCFM = Standard Cubic Feet per Minute
TAS = Thermal Amine Scrubber
TC = Trace Contaminant
TVSA = Thermal and Vacuum Swing Adsorption

1. Introduction

THE Four Bed Carbon Dioxide (FBCO2) Scrubber has been developed as a technology demonstration flight system for the purpose of evaluating its potential as a carbon dioxide removal technology for future missions including a Mars transfer vehicle. It was launched to the International Space Station (ISS) in August 2021 and activated in September of 2021.

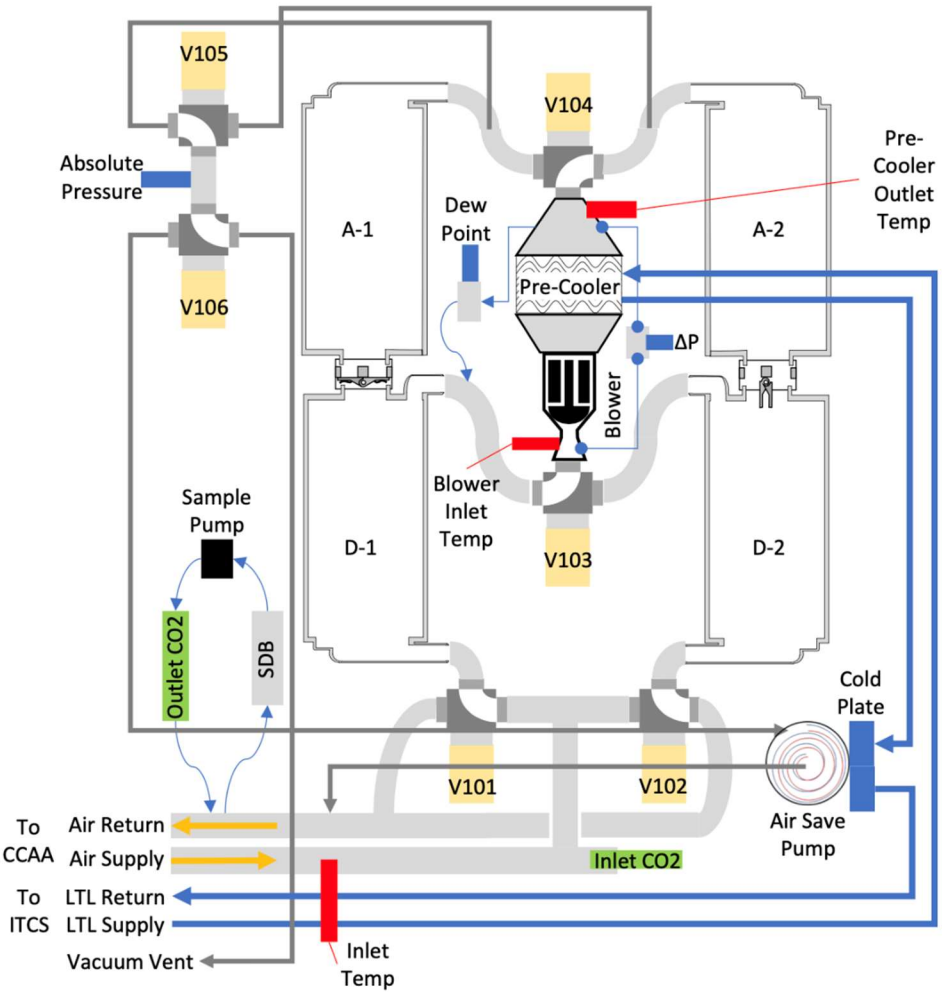


Figure 1. FBCO2 scrubber schematic.

A schematic of FBCO2 is shown in Figure 1 as if it was 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 works[1-7]. 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 half-cycle 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 was hot from the previous cycle and that heat is used to push moisture out of bed D-2. Half-cycle 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 half-cycle. 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 (RTD).

2. Calnetix Blower

A. Description

A long-life, magnetically levitated blower was developed by Calnetix Technologies, LLC (CNX) as part of the FBCO2 development program (Figure 2). Since the development of the Calnetix blower was not completed in time to be incorporated in the initial FBCO2 flight hardware delivery to ISS, a Carbon Dioxide Removal Assembly (CDRA) heritage Honeywell International (HWI) airfoil bearing blower was used as a stop-gap solution. The HWI blower is no longer being produced so is not an option for use in future exploration missions.

Extensive testing of the CNX blower was conducted at MSFC to characterize its performance and verify compliance with ISS requirements, including Electromagnetic Compatibility/ Electromagnetic Interference (EMI/EMC), acoustic emissions, and power surge tolerance. The performance testing is addressed in a companion paper[8] and is summarized below.

The initial flight version of the CNX blower was delivered to MSFC in the fall of 2020 and operated to obtain acoustic emissions measurements. During this testing, it was noted that the flow vs. blower differential pressure (dP) relationship for the CNX blower was markedly flatter than the HWI blower (Figure 3). Operationally, this means that a change in system differential pressure will result in a greater change in flow rate for the CNX blower than for the HWI blower. During a normal FBCO2 Scrubber cycle, significant changes in system differential pressure are observed due to large changes in the sorbent bed temperature. Since large flow rate changes are undesirable from a process control standpoint, an effort was undertaken to redesign the CNX impeller (or wheel). Ultimately, however, this redesign effort produced a wheel with an even flatter flow vs. dP curve. The interim solution was to return to the initial wheel design. Variations in flow rate over a cycle for the current CNX and HWI blower are shown in Figure 4.

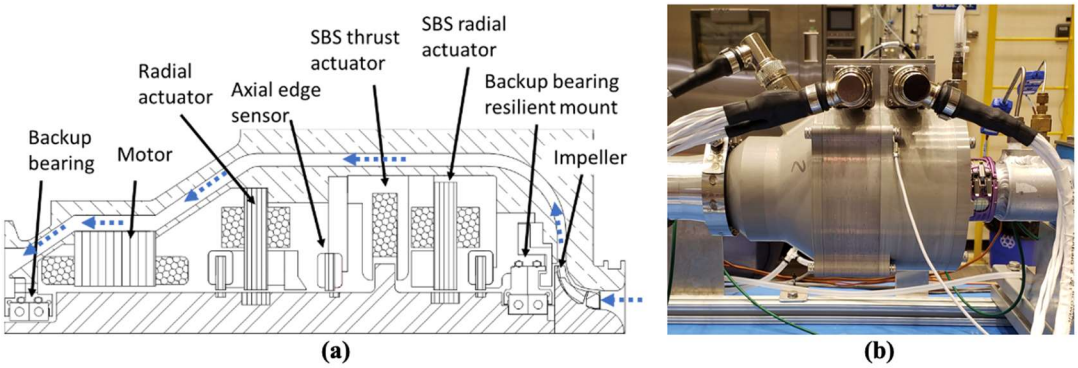


Figure 2. Calnetix magnetically levitated blower for FBCO2. (a) Layout of Calnetix blower highlighting major components and its airflow path and (b) an image of the blower installed into the performance test stand.

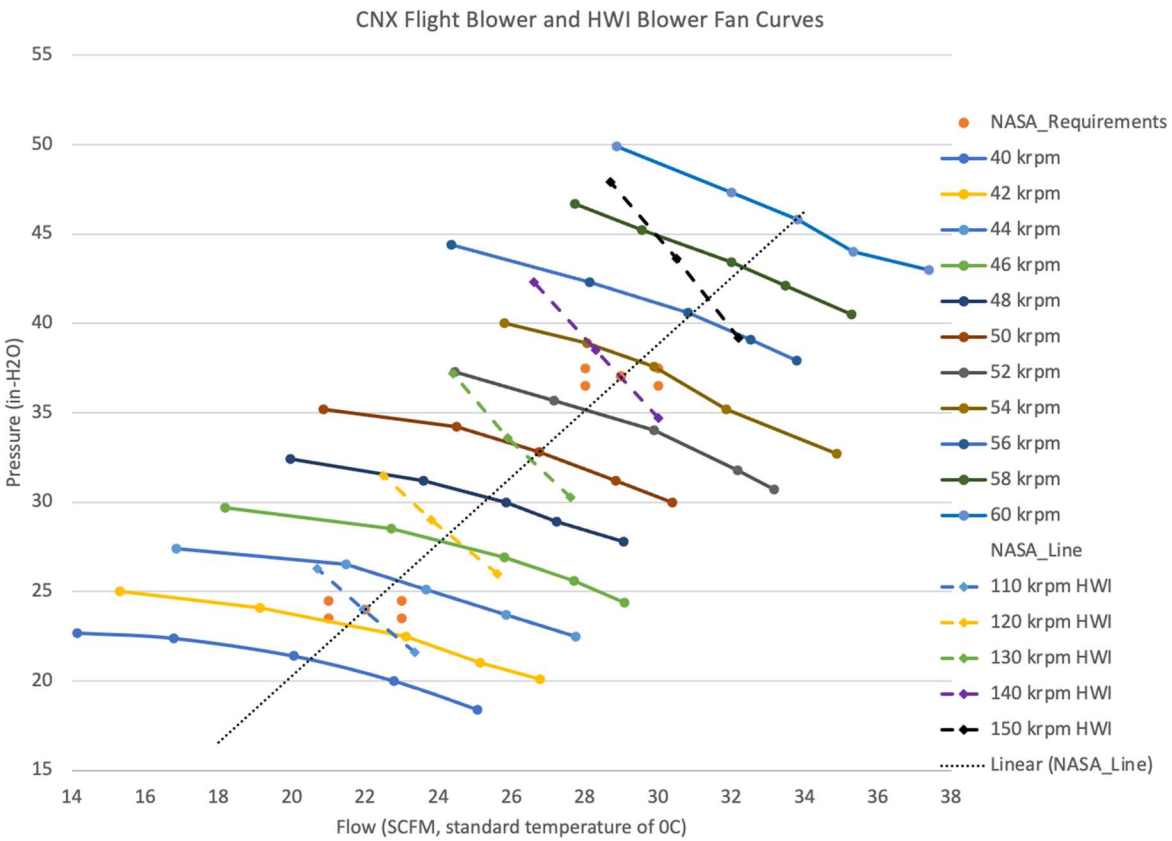


Figure 3. Overall Calnetix blower and Honeywell blower performance. Beige dots are NASA requirements; solid lines connect CNX blower test points, and dashed lines connect HWI blower test points. The black dotted diagonal line passing through all blower curves approximates the FBCO2 system differential pressure drop.

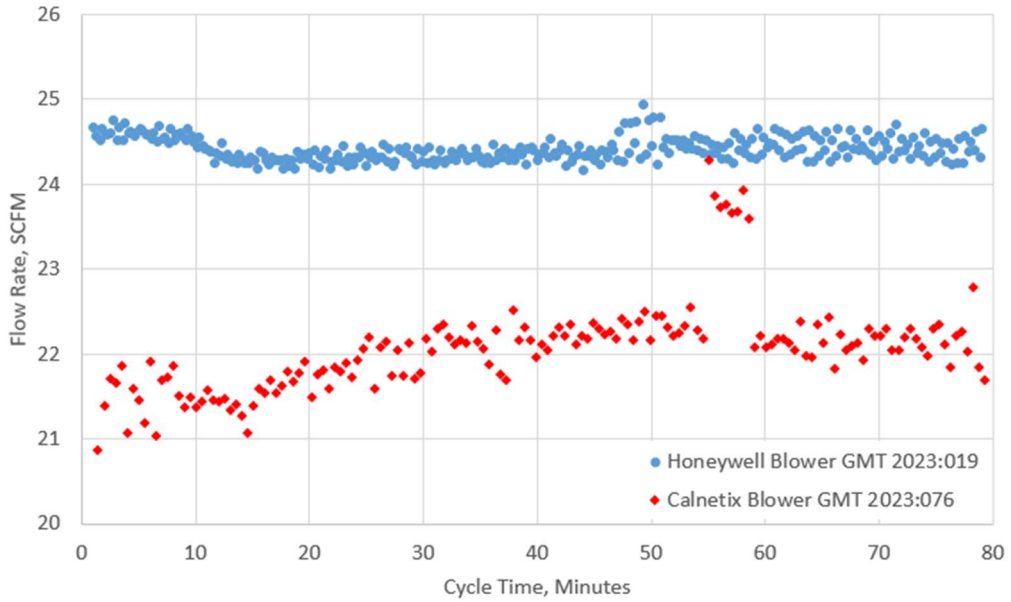


Figure 4. Flow rate variations over a half-cycle for the HWI and CNX blower under similar ISS configurations. The HWI blower (blue circles) is at 130,000 rpm, while the CNX blower (red diamonds) is at 54,000 rpm. After software adjustments described below, the CNX blower rpm will be increased to 56,000.

B. CNX Blower Installation

The CNX blower was installed on the FBCO2 Scrubber on Feb. 13 and 15 of 2023. This was a complex operation that included removal of the FBCO2 Scrubber from the Basic Express Rack (BER), securing it to a rack face, and replacement of multiple electrical and tubing components to accommodate the new blower. The complex operation was accomplished with only minimal difficulty, with the crew even dedicating some of their personal time to complete the installation. Some of the key aspects of the installation and subsequent blower operation are discussed below.

1. Acoustic Emissions Concerns/Acoustic Blanket

Based on the acoustics emission measurements taken for the flight CNX blower, the ISS Acoustics Office was concerned that the CNX blower would exceed ISS acoustic emission requirements once operational on the ISS. Due to this concern, an acoustic blanket was fabricated, launched, and installed as part of the CNX blower installation. Following installation, an acoustic survey was conducted immediately after the blower was operational on Feb. 15, 2023. The overall results of the survey cleared the CNX blower for operation at the chosen nominal speed of 56,000 rpm. A full cycle was run at this rpm before experiencing the high voltage fault summarized below.

2. Software Error

Two faults occurred during the initial operation of the CNX blower. One was a somewhat obscure software error where the arming of a fault was not cleared properly, later resulting in an inappropriate evaluation of vacuum vent pressure at the wrong point in the cycle. This will be corrected in a future software upgrade. A temporary solution is to power cycle the FBCO2 Scrubber controller to clear the arming of this fault. This fault occurred during initial blower operation.

3. High Voltage fault

The second fault occurred during a half-cycle change. Here the CNX controller reported a high voltage fault during spin-down from 56,000 to 30,000 rpm. The rpm is reduced to reduce stress on the blower while the FBCO2 valves are in transition and partially deadheading the blower. At the time of this writing, it is believed that back electromotive force (EMF) being generated during the blower spin-down results in a high voltage fault. Calnetix is investigating potential options to prevent this occurrence.

4. High Differential Pressure Near Miss

Although no fault occurred, the CNX blower differential pressure was observed to closely approach the fault value following half-cycle transition as it spun up to 56,000 rpm. Some increase in dP is expected at HC transition; however, the CNX blower developed greater dP than the HWI blower at 130,000 rpm. The specific ISS configuration with the Lab CDRA operational results in higher FBCO2 blower dP and flow reduction in general. This will be discussed later in the System Performance section.

5. Temporary Adjustments in rpm

The approach taken to prevent a high differential pressure fault was to reduce the high rpm value from 56,000 to 54,000 rpm. This was successful in preventing the dP from getting close to the current high dP limit. To avoid the high voltage fault during blower spin-down, the low rpm value was increased from 30,000 to 47,000. With these two temporary adjustments in place, the blower has operated without fault for two months as of this writing. However, as an undesirable side effect, a flow rate lower than that experienced with the HWI blower was observed, and as expected lower CO_2 removal rate. Obviously, the long-term goal is to increase the blower flow rate and thus the CO_2 removal rate to meet the exploration objective of 4-crew equivalent at a cabin pressure of 2 torr. Work is currently ongoing to remediate the conditions causing the high voltage fault and thus allow higher flow rates.

6. Rack Slider Mount Installation

The anomaly with the rack slide mount interference, as described in Cmarik 2022[2], was fixed during the CNX blower installation. A new rack slide mount was fabricated, launched, and successfully installed, allowing for the FBCO2 Scrubber to easily slide out of the rack as originally designed.

7. Blower Commanding Issues

The HWI blower speed command issue was never successfully resolved through software means. As reported last year, a nuisance fault was observed where the blower controller did not change the blower speed when commanded. A software change applied a potential solution using a command repeat, but the nuisance fault persisted. Since initial installation, this nuisance fault occurred over 90 times.

During initial operation of the Calnetix blower, the commanding issue was not encountered. Continued operation will determine if, as expected, this issue is no longer of concern.

3. System Performance

A. 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 accommodates increased number of crew, which is of importance during temporary periods such as crew changeouts where as many as 11 crew (vs. 7 nominally) are onboard the ISS. The FBCO2 Scrubber removal performance is summarized in Figure 5. Here each point represents the removal rate for a single half-cycle. The different colors are described in the following sections.

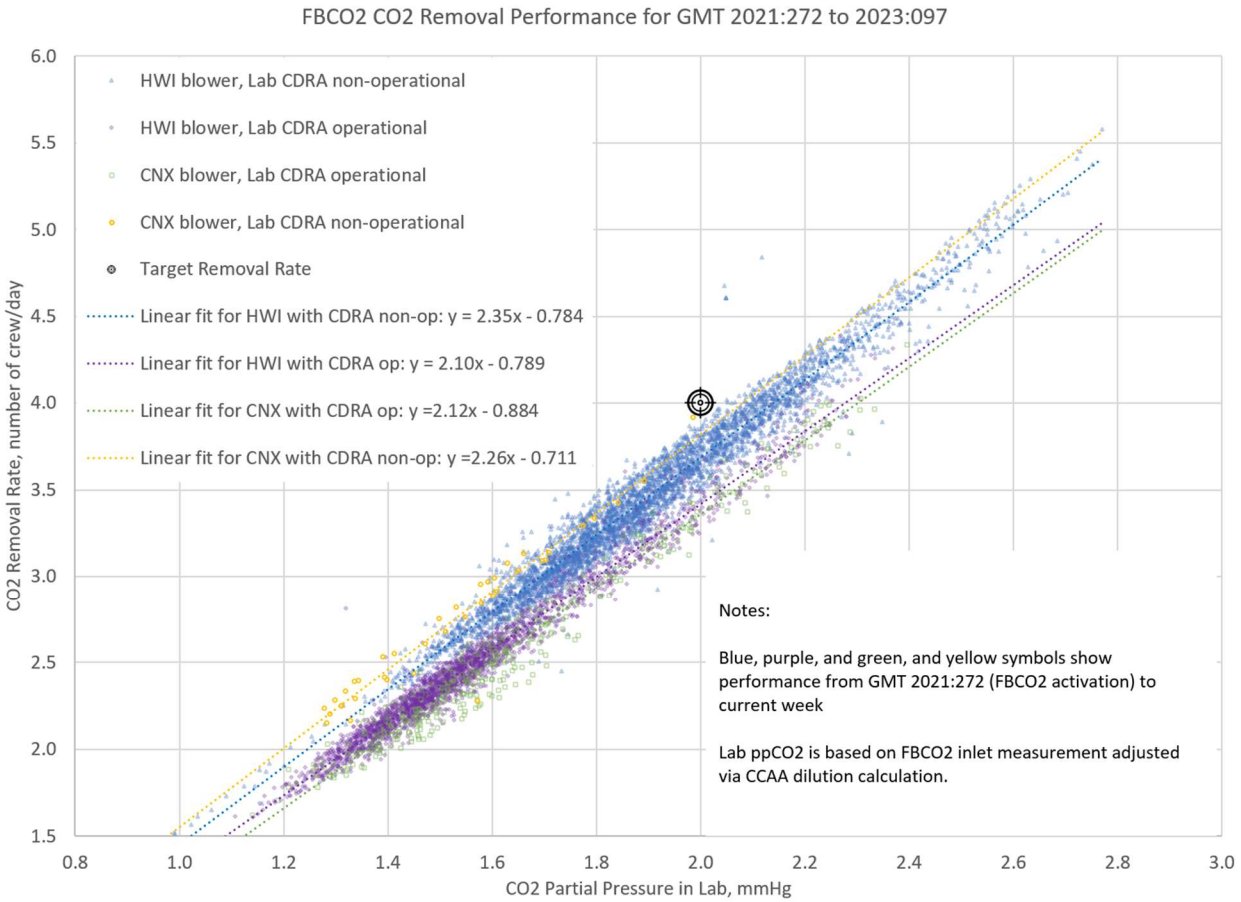


Figure 5. FBCO2 Scrubber removal performance since activation. Operation with the HWI blower and the Lab CDRA non-operational is shown in light blue. Operation with HWI blower and the Lab CDRA operation is shown in purple. Operation with the CNX blower and the Lab CDRA operational is shown in green. Operation with the CNX blower and the Lab CDRA non-operational is shown in green. The dashed lines are linear fits of the performance.

B. 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 the FBCO2 Scrubber is a tube at the exit of the condensing heat exchanger (CHX) that is part of the Common Cabin Air Assembly (CCAA). When the FBCO2 Scrubber was activated, the Thermal Amine Scrubber (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 Scrubber pulling from 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.

C. Reduction of Removal Rate

As shown in Figure 5, removal performance is markedly influenced by the Lab CDRA operation. The specific impact is provided in Table 1. It is evident that the Lab CDRA operation has the most influence on removal rate for the CNX blower, which increased 14% compared to 8% for the HWI blower. Without the Lab CDRA operating, the removal rate approaches within 5% of the target of 4 crew equivalent. Upon increase of the CNX blower speed from 54,000 to 56,000 rpm, the target removal rate should be nearly if not actually achieved.

Table 1. Removal Rates for Different Configurations.

Blower	*Lab CDRA Status*	*RPM*	*Slope*	*Intercept*	*Lab ppCO2 mmHg*	*Removal Rate #crew*
HWI	Non-Op	140K	2.24	-0.784	2	3.69 (8% change)
HWI	Operational	140K	2.10	-0.789	2	3.42
CNX	Operational	54K	2.12	-0.884	2	3.36
CNX	Non-Op	54K	2.26	-0.711	2	3.82 (14% change)

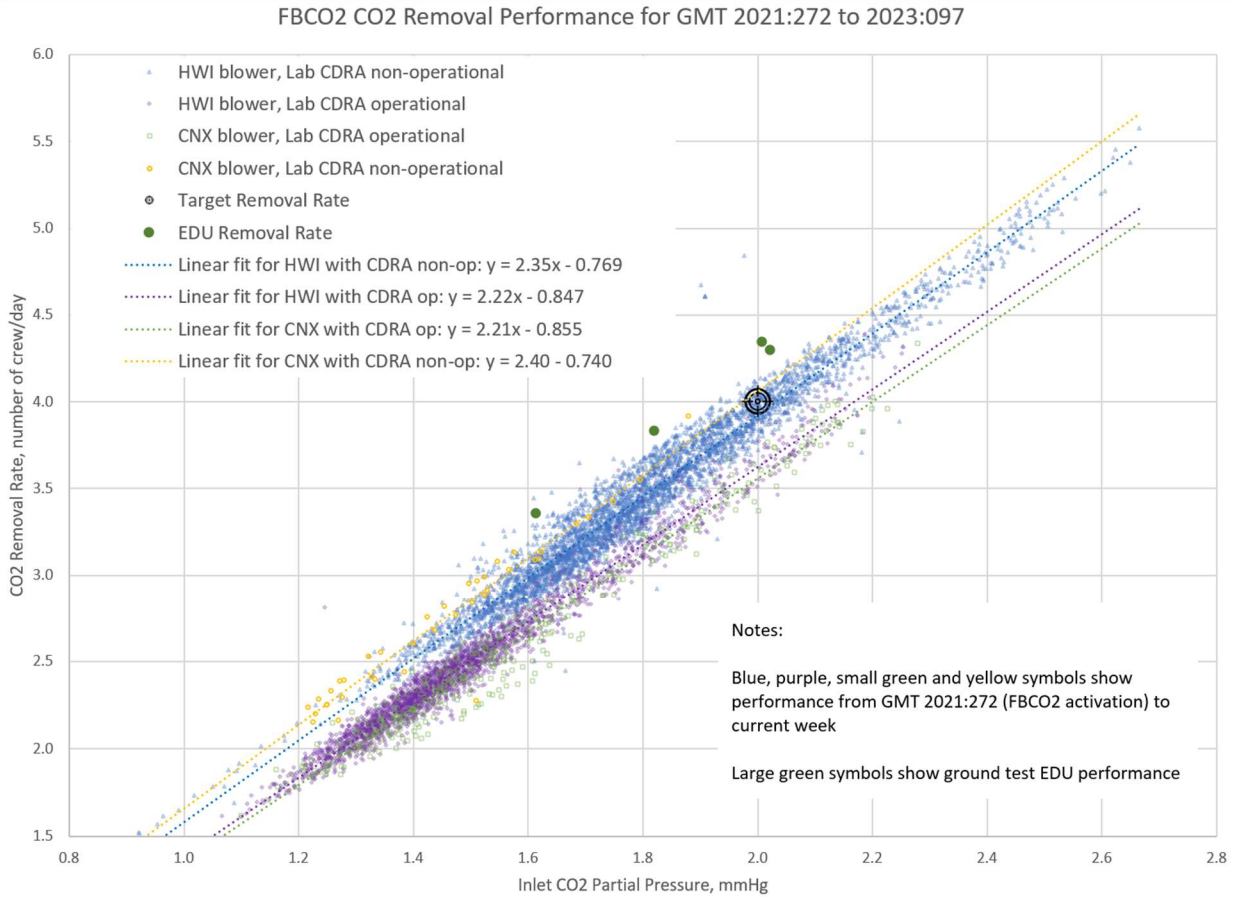


Figure 6. Comparison of FBCO2 Scrubber performance with the ground test unit. Operation with the HWI blower and the Lab CDRA non-operational is shown in light blue. Operation with HWI blower and the Lab CDRA operation is shown in purple. Operation with the CNX blower and the Lab CDRA operational is shown in green. Operation with the CNX blower and the Lab CDRA non-operational is shown in green. The dashed lines are linear fits of the performance.

D. Comparison with Ground Testing

Figure 6 provides a comparison of the ground test FBCO2 scrubber with the ISS flight demonstration hardware. In this case the inlet CO_2 partial pressure is plotted instead of the Lab partial pressure, as the ground test unit is operated open loop. From the figure, the lower CO_2 removal rate of the flight unit is evident although the flow rates are virtually the same.

Of the number of possible causes for this difference, reduced heater power is perhaps the most plausible. As described by Cmarik 2022[2], due to susceptibility to power transients, a resistor was installed in the power feed of the FBCO2 Scrubber that feeds the adsorbent bed heaters. As discussed in Knox 2021[4], ground testing has shown that for higher heater powers, even if the same bed temperature is reached by the end of the cycle, greater desorption occurs. The underlying physics is not completely understood but is likely tied to the larger pressure spike and thus greater flowrate out of the desorbing adsorbent bed in the case of higher heater power.

E. Lack of Dusting Indications

During the design of the FBCO2 Scrubber, special attention was paid to the remediation of dust production. These design improvements are described in numerous papers; measurements based on ground testing indicated that dust production had been reduced to 1% of that experienced by CDRA[6].

However, the critical test of the FBCO2 Scrubber is in long term testing in the ISS environment. In Figure 7, the half-cycle average blower differential pressure is plotted for two configurations, with and without the Lab CDRA operational. The Lab CDRA operation begins sporadically at 4500 half cycles and is marked by higher dP. Continuous Lab CDRA operation begins at about 5100 hours. Here the relatively constant dP for both cases indicates that the amount of dust produced by the FBCO2 Scrubber after 1.2 years of operations is insufficient to cause retainment screen blockage. Minor changes in dP can be correlated to external conditions such as Lab total pressure as shown in Figure 7. Longer operational durations will of course be required to demonstrate applicability of the current system to longer duration missions such as a 3-year Mars transit mission.

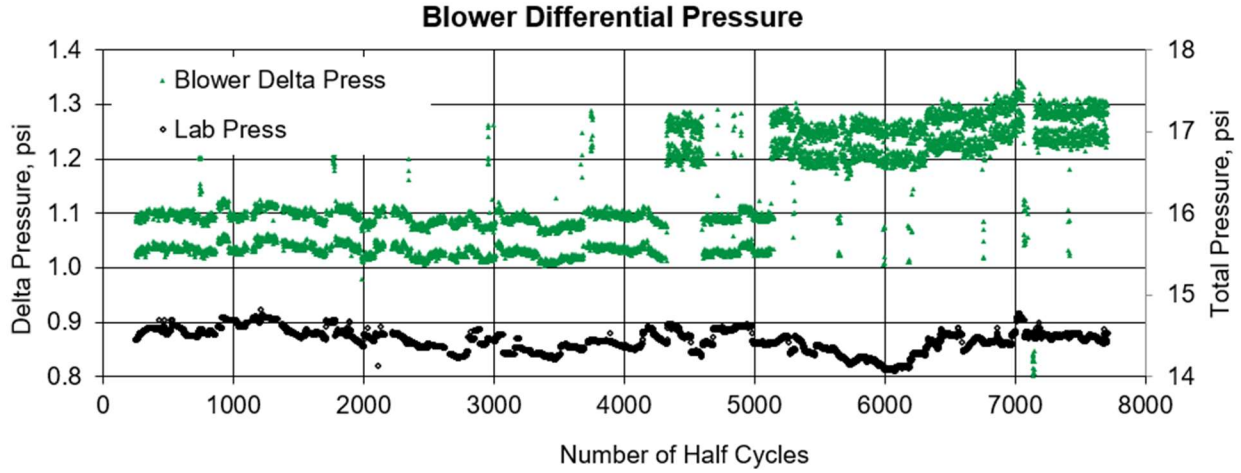


Figure 7. Blower differential pressure. Green triangles show the blower delta pressure. Black circles show the Lab module total pressure.

F. CO2 Purity Results

FBCO2 is required to produce CO_2 with less than 1% O2 and less than 2% N2 in the vented gas. Gas samples have been collected from the FBCO2 vent during special procedures conducted once every 6 months. The collected gas samples are analyzed by the Toxicology and Environmental Chemistry Lab at Johnson Space Center. The analysis is particularly challenging due to the nearly pure CO_2 contents. As a result, the analysis peak cannot be quantified and thus not included in Table 2.

Table 2. CO_2 Purity Results

Sample IDs	O2 (%)	N2 (%)	H2O (ppm)
1102 and 1105	0.74	2.47	n/a
1045 and 1050	0.29	0.84	n/a
1052 and 1056	0.24	0.72	n/a
1076 and 1072	2.99	9.62	n/a
1077 and 1074	<0.3	<1.0	n/a

Three out of 5 samples indicate that FBCO2 is exceeding the required specification, while two others present a wholly different result. The consistency of the three positively indicating samples indicates they are more likely accurate while the other two may have had sampling or storage errors prior to test.

In all cases, the water content could not be quantified. Other gas samples from other systems have successfully quantified H2O, thus it can be inferred that the water content is nearly zero. Extremely dry readings at the FBCO2 desiccant bed exit dew point sensor indicates that virtually no water vapor will be found in the CO_2 product stream.

Trace contaminant (TC) analysis was also conducted on these samples, but the full reports are too extensive for this forum. In summary, the larger adsorption pores of the 13X zeolite used in FBCO2 results in the capture and venting of various TCs which show no interaction with CDRA, TAS, or other CO_2 removal systems. The outcome is that certain TCs are entering the vented product gas which may cause concern for future storage and CO_2 reduction hardware.

G. Air Save Pump Performance Degradation

The air-save pump draws down the pressure in the adsorbent beds prior to exposure to space vacuum to reduce air losses, and in the case of integration with a downstream CO_2 reduction system, to increase CO_2 purity. The two-stage, sliding vane air save pump in the heritage ISS CDRA was replaced with the smaller Scroll Labs SVF-50 pump. The Scroll Labs pump showed better performance in that the final pressure attained in the 10-minute air save segment was below 10 torr compared with approximately 50 torr for the two-stage sliding vane pump.

As shown in Figure 8, after over nearly 8000 half-cycles of operation, the final pressure in the air save segment has begun to show excursions up to 15 torr (not including the out-of-family data). The inverse correlation with the FBCO2 inlet CO2 partial pressure is evident in Figure 8, though it does not account for the increasingly high values of pump pressure. These are still well below the 50 torr level for the CDRA pump but may indicate gradual bearing wear. Pump performance is still acceptable; however, it is noted that the current run time is nearly 1300 hours vs. the recommended bearing regreasing period of 10,000 hours. The pump performance will be closely monitored to understand ultimate pump life and sparing requirements for future missions.

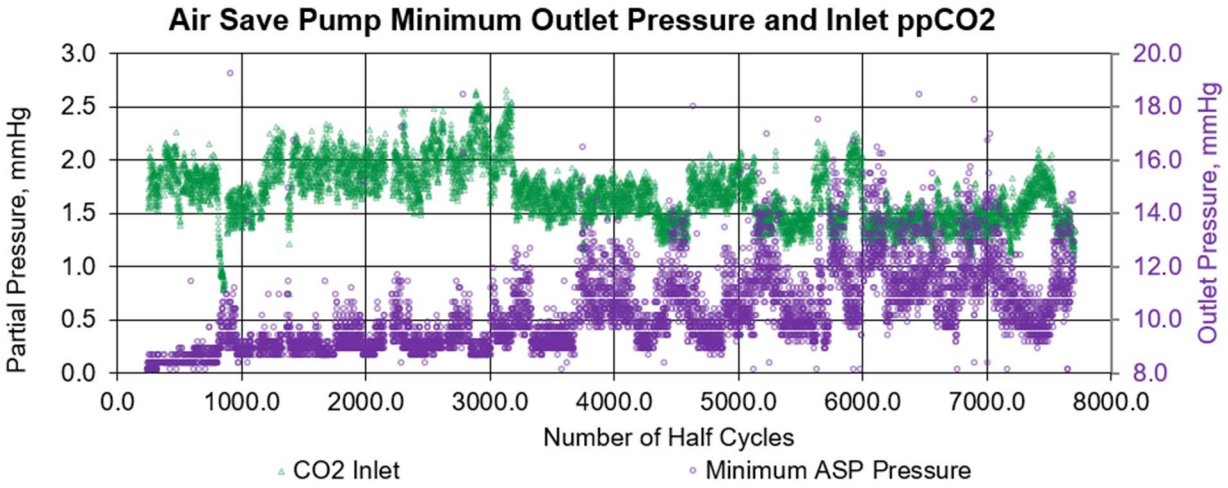


Figure 8. Air Save Pump performance degradation. Purple circles show minimum air save pump pressure. Green triangles show FBCO2 inlet CO_2 partial pressure.

4. Observations

The FBCO2 Scrubber has operated for approximately 1.2 years, and as of this writing, has had no mechanical issues requiring maintenance. The blower differential pressure has not shown any increase that would indicate zeolite dust is building up on the retainment screens. Although performance is lower than the requirement presently, the magnetically levitated blower installed this year is expected to enable greater flow rates. As a result, CO_2 removal rates are expected to meet or exceed the requirement.

5. Conclusions

The FBCO2 Scrubber technology demonstration has been successful during the first year of operation with respect to its primary objective, that is, to require minimal maintenance. Current data shows no indication of excessive dust generation, though continued operation period will be required to establish long term maintenance-free operation. Operation of the Calnetix blower at the intended flow rate is expected to provide required CO_2 removal rates. Thus, continued operation of the FBCO2 Scrubber is anticipated to establish its suitability for long-term missions such as part of a Mars Transit mission.

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