

Four Bed Carbon Dioxide Scrubber Engineering Development Unit Cabin Air Inlet Testing

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This paper reviews a test series conducted on the Four Bed Carbon Dioxide Scrubber Engineering Development Unit, a ground test analog for the Four Bed Carbon Dioxide Scrubber Technology Demonstration currently operating on the International Space Station. For this test series conducted in mid-2022, an alternate FBCO₂ inlet air location (direct from the cabin) was evaluated. This paper presents test results, rationale for observed performance changes, and possible ramifications for the flight FBCO₂ Scrubber.

Nomenclature

CCAA	= Common Cabin Air Assembly
CDRA	= Carbon Dioxide Removal Assembly
CO ₂	= Carbon Dioxide
degF	= Degrees Fahrenheit
dP	= Differential Pressure
ECLSS	= Environmental Control and Life Support System
EDU	= Engineering Development Unit
FBCO ₂	= Four-Bed Carbon Dioxide
HC	= Half-Cycle
ISS	= International Space Station
NASA	= National Aeronautics and Space Administration
ppCO ₂	= Partial pressure of CO ₂
SCFM	= Standard Cubic Feet per Minute
TVSA	= Thermal and Vacuum Swing Adsorption

I. Introduction

THE Four Bed Carbon Dioxide Scrubber Engineering Development Unit (also called the Linus 4-Bed Molecular Sieve)¹⁻³ is a ground test system that was developed and tested as a precursor to the flight FBCO₂ Technology Demonstration^{1,4-6} hardware that is currently operational on the International Space Station (ISS). It is presently being used to conduct long duration testing, test alternate operational modes for the FBCO₂ Scrubber, and test integration with the Temperature Swing Adsorption Compressor (TSAC)⁷.

This report provides information on the Cabin Air Inlet Test conducted from 06/16/22 to 06/27/22. In this test, the performance of the FBCO₂ was evaluated with inlet temperature and dewpoint set as shown in Table 1 to match the average temperature and dewpoint in the ISS Lab module (where the FBCO₂ Scrubber resides). Normally, FBCO₂ Scrubber inlet air is taken from the outlet of the Common Cabin Air Assembly (CCAA) condensing heat exchanger, and thus has reduced temperature and moisture content compared with the cabin air. This reduction in temperature and humidity are advantageous for humidity adsorption in the FBCO₂ desiccant bed. However, a disadvantage of the nominal arrangement is that the FBCO₂ effluent air, which has low CO₂ content, is mixed with the cabin air in the CCAA return line. Thus, in the current flight arrangement, the FBCO₂ inlet air has reduced CO₂ content compared to the cabin air. For the current CCAA and FBCO₂ flow rates, the difference is slightly more than 4%. In future cabin

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air inlet tests, the FBCO₂ inlet partial pressure CO₂ (ppCO₂) should be increased by 4% over the baseline conditions to accommodate this.

All other test conditions except inlet air temperature and dew point were set the same as the baseline conditions. The FBCO₂ system CO₂ removal rates were measured at a range of ppCO₂ levels during this test and will be compared with removal rates obtained for the baseline configuration. In the baseline configuration, inlet temperatures and dew points are set consistent with the FBCO₂ inlet being taken from a port downstream of the CCAA condensing heater exchanger.

Table 1. Operational conditions for cabin air inlet test and for baseline tests.

	Air Flow Rate, SCFM	Total Cycle Time, Min	Inlet Temp., degF	Inlet Dewpoint, degF	P/C In H ₂ O Temp., degF	P/C In H ₂ O flow, GPM	Heater Setpoint, degF
Cabin Air Inlet Test	24.4	160	75	54	49	0.4	408
Baseline Conditions	24.4	160	56	50	49	0.4	408

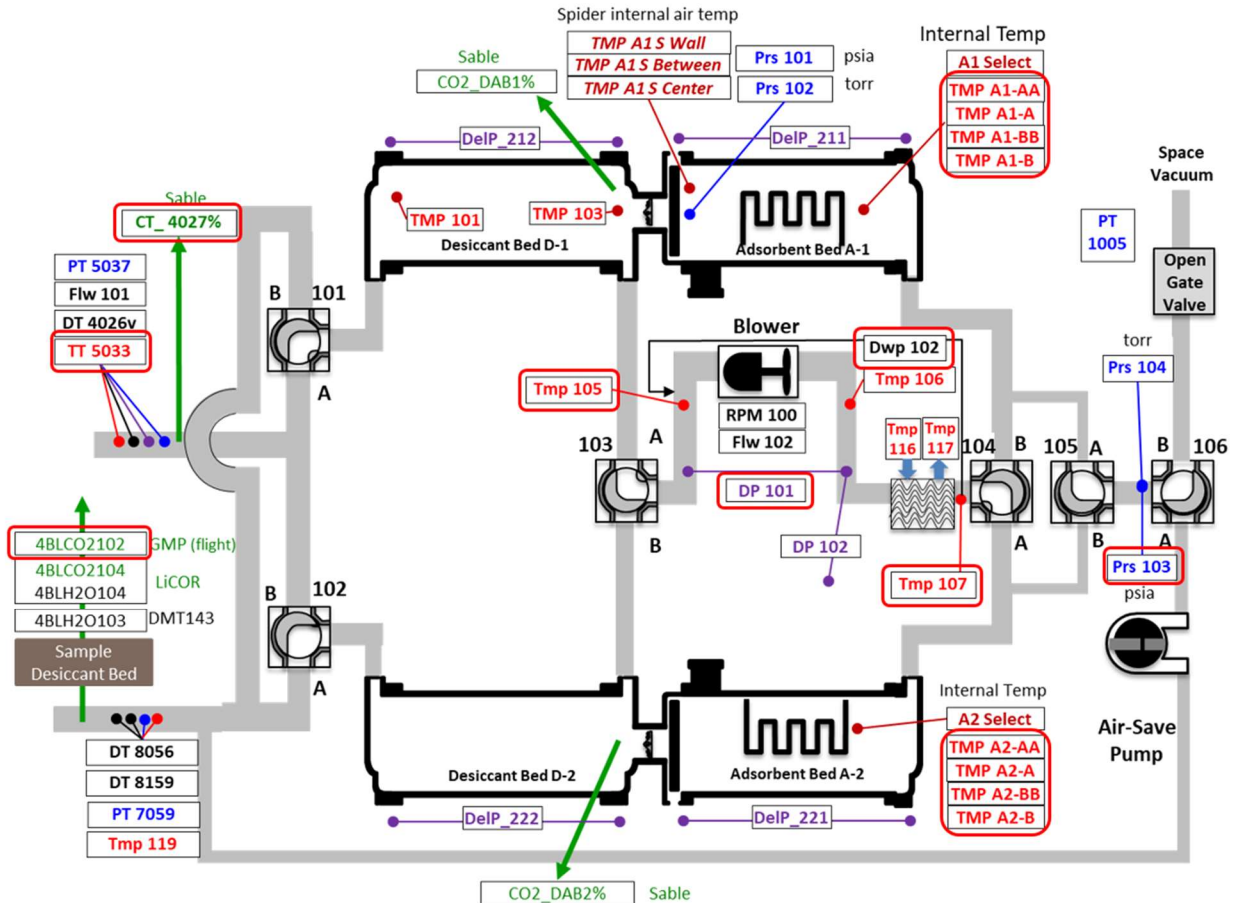


Figure 1. FBCO₂ EDU Schematic. System sensor types retained on the flight system are identified by a red box surrounding the sensor name.

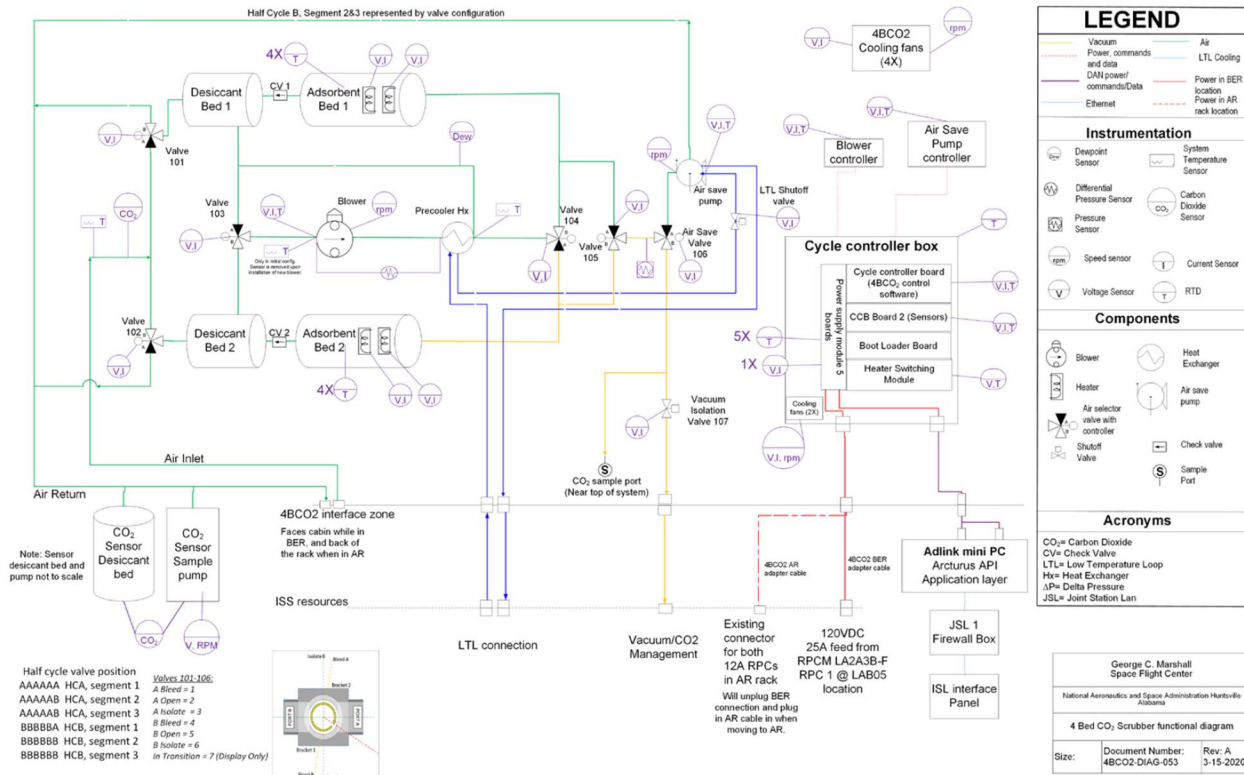


Figure 2. FBCO2 Scrubber flight hardware schematic.

II. Apparatus

The FBCO2 EDU (Engineering Development Unit) schematic is shown in Figure 1. This closely resembles the FBCO2 flight schematic shown in Figure 2. The principal difference is the number of sensors present in the FBCO2 EDU vs. the Flight FBCO2. The reduced sensor set for a flight system is customary, as complexity can be problematic from the standpoint of required flight computing capability and software requirements. For the ground test system, however, an abundance of sensors allows for greater visibility into the intrinsic physics of the complex adsorption process. For example, the ability to sample CO₂ sorbent bed effluent directly (CO₂_DAB1% and CO₂_DAB2%) provides an understanding of CO₂ sorbent bed breakthrough for the FBCO2, whereas the flight system measures only system CO₂ effluent after the influence of the desiccant bed has significantly altered the breakthrough curve².

III. Results and Discussion

The cabin air inlet test series was conducted from Julian day 167 through 175, or 06/16/22 through 06/26/22. Inlet CO₂ partial pressure was varied as shown in Figure 3. Although the original intent was to vary inlet ppCO₂ daily, some issues with programming resulted in the timeline shown.

Desiccant bed outlet dew point over the test series is shown in Figure 4, as well as inlet temperature and dew point, which were essentially constant. These values are averaged over each half-cycle (HC). For the first ~3.5 days, the dew point rises but then steadies out at -120F. After a short shutdown, the dew point rises a bit before dropping to nearly -130F. The change in desiccant bed outlet dew point appears to be influenced by the shutdown/startup event although it is not clear why at this point. In any case, if the dew point can be maintained at the low levels shown in Figure 4 during operation with cabin air inlet, no issues are anticipated with this amount of moisture entering the downstream CO₂ sorbent beds.

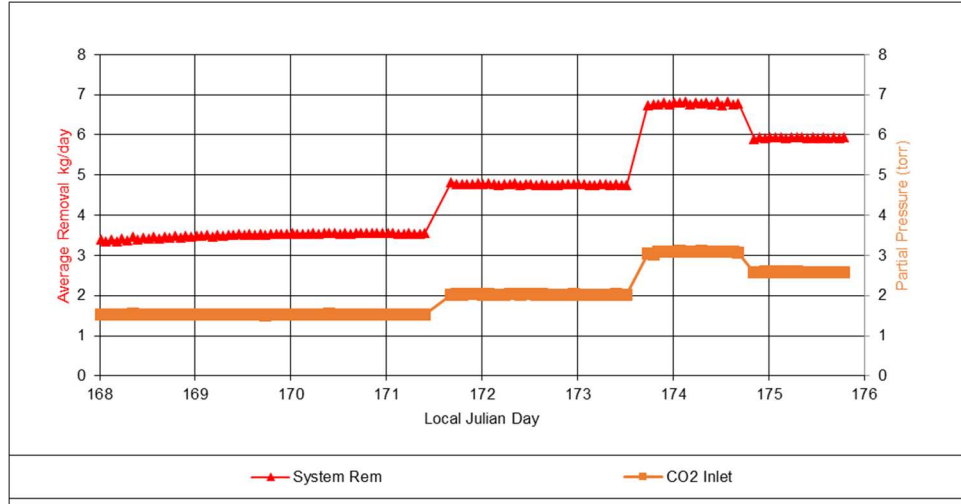


Figure 3. Timeline showing CO₂ inlet partial pressure and CO₂ removal rates over the test series.

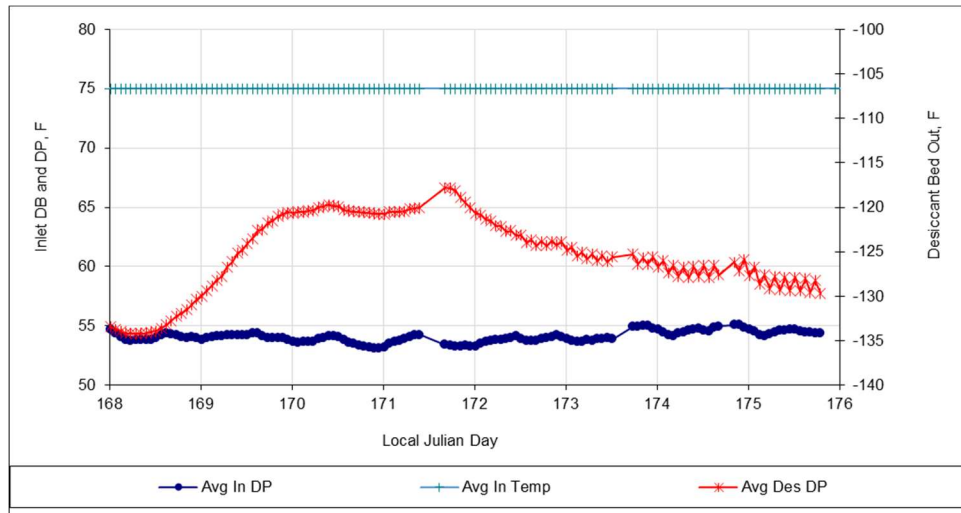


Figure 4. Inlet temperature and dew point and desiccant bed outlet dew point temperature.

Another observation Figure 3 is the gradual increase in CO₂ removal rate over 2 days of operation. The initial CO₂ removal rate at 1.5 mmHg is 3.35 kg/day, slightly above the 3.25 kg/day for the baseline condition. This immediate change from the baseline removal rate is likely due to the higher inlet air temperature, which will reduce the amount of parasitic CO₂ capture on the zeolite 13X in the desiccant beds.

The gradual increase observed up to day 170 is likely to be due to the increased amount of water vapor passing through the desiccant bed up to day 170 as shown in Figure 4. The 13X in the desiccant bed will also capture less CO₂ as the result of increased water vapor loading. These observations will be discussed in greater detail following the next section.

IV. Overall Results and Rationale

Overall performance results from this test series are summarized in Table 2. The baseline results, with nominal inlet temperature and dewpoints, are shown the first three columns. Results from the test points using cabin air conditions are shown in columns 5 through 6. The differences in CO₂ removal are shown in the last two columns. These results were collected from the last full cycle prior to a change in inlet ppCO₂ to obtain cyclic steady-state data. The same results are shown graphically in Figure 5.

Table 2. Baseline and cabin air inlet CO₂ partial pressure and performance.

Baseline Inlet ppCO ₂ , mmHg	Baseline CO ₂ Removal, kg/day	Baseline Removal Efficiency	Cabin Air Inlet ppCO ₂ , mmHg	Cabin Air CO ₂ Removal, kg/day	Cabin Air Removal Efficiency	CO ₂ Removal Increase, kg/day	Percent CO ₂ Removal Increase
1.52	3.21	81%	1.52	3.50	90%	0.29	8.3%
2.03	4.42	84%	2.02	4.77	91%	0.35	7.3%
2.53	5.69	86%	2.58	5.93	89%	0.24	4.0%
3.03	6.72	85%	3.09	6.78	85%	0.06	0.9%

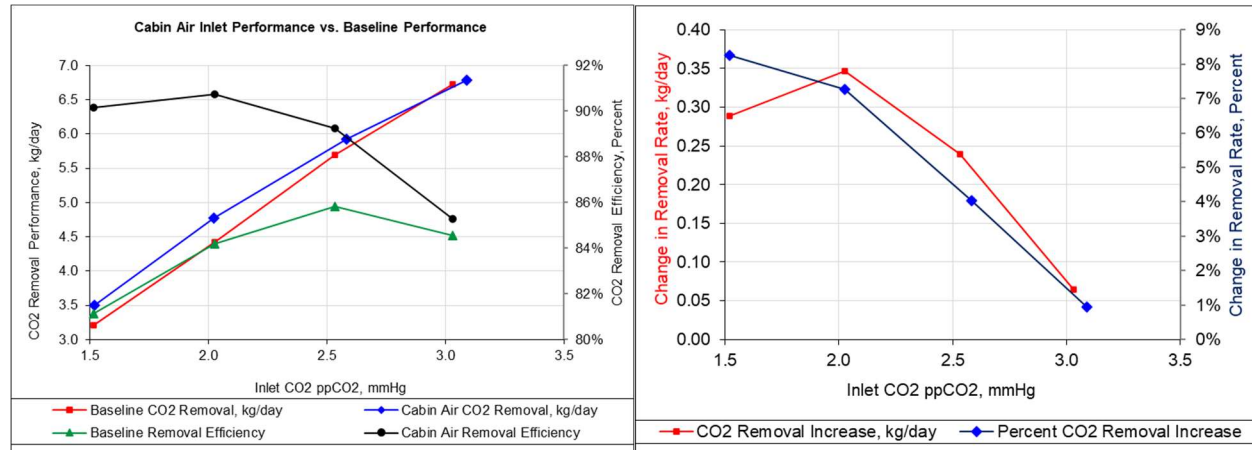


Figure 5. Graphical performance results from baseline and cabin air inlet test points.

To assist in explaining the differences in CO₂ removal performance resulting from changes in inlet temperature and dew point, the transient data shown in the following figures is helpful. These figures depict a full cycle of FBCO₂ operation, or two half-cycles of 80 minutes each.

Figure 6 shows the CO₂ sorbent bed breakthrough curves (CO₂_DAB1 and CO₂_DAB2). Since the flow reverses in alternate half-cycles, these sensors indicate the desiccant bed outlet ppCO₂ on the alternate cycle half-cycle. In this figure, the green trace (CO₂_DAB1) shows desiccant bed outlet ppCO₂ for the first HC and CO₂ sorbent bed breakthrough for the second HC.

Comparing the CO₂_DAB1 curves in Figure 6 and Figure 8, it is evident that the desiccant bed ppCO₂ rises above the inlet condition for the cabin air inlet case only. Differences in exit temperature and dewpoint for the two cases help understand the causes for this change. As seen in Figure 7 and Figure 9, the timing of the CO₂ breakthrough from the desiccant bed corresponds to the timing of thermal wave traveling through the desiccant bed during water adsorption. For the higher inlet temperature in the cabin air test case, the thermal wave has a higher temperature. The result is that more of the CO₂ adsorbed on the desiccant bed 13X is driven off and pushed into the CO₂ sorbent bed.

Increased dewpoint temperature, from 50F in the baseline case to 54F in the Cabin Air Inlet case, also impacts desiccant bed 13X CO₂ capacity. Figure 7 and Figure 9 show the desiccant bed outlet dewpoint for these cases. For the baseline case, very little water vapor is exiting the desiccant bed; the quantity is most likely below the detection limit of the dewpoint sensor. For the Cabin Air Inlet case, it is evident that a very small amount of water vapor is exiting the bed, and thus has broken through the 13X at the highest vapor pressure observed. Although the sensor accuracy is questionable at these low values, it is useful to note that -120F dewpoint corresponds to a very low vapor pressure of 0.25 ppm. However, some 13X CO₂ capacity loss occurs even at very low vapor pressure levels due to the highly competitive nature of water vapor adsorption on zeolite 13X over CO₂ adsorption⁸. This results in the slow increase in CO₂ removal over two days as shown in Figure 3.

CO₂ adsorbed on the 13X in the desiccant bed is returned to the cabin in the subsequent HC, and thus is not removed from the cabin. The blue traces in Figure 6 and Figure 8 reflect the system outlet ppCO₂. The blue spikes immediately after each HC start reflect the CO₂ being desorbed off the desiccant bed 13X. These are higher for the

nominal inlet case, again indicating that more CO₂ is returned to the cabin instead of captured for the baseline inlet case.

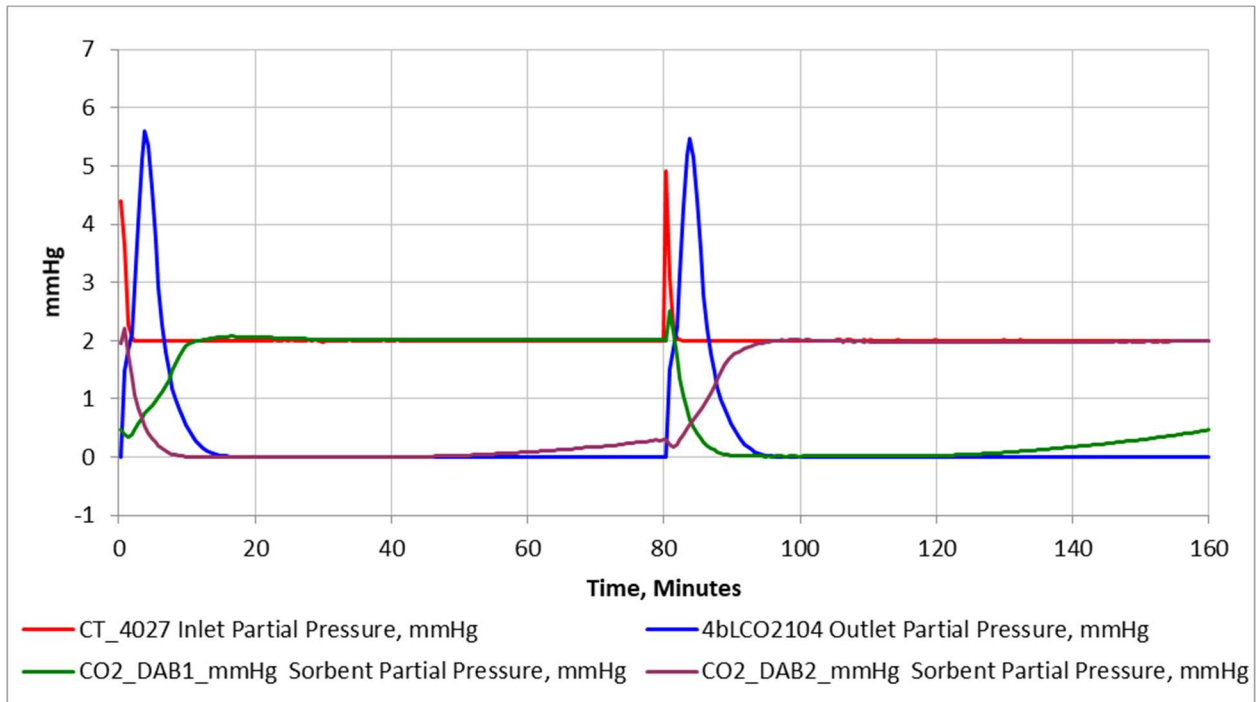


Figure 6. Inlet (red), system outlet (blue), and sorbent outlet CO₂ partial pressures (green and brown) at 2 torr inlet and nominal ISS inlet conditions.

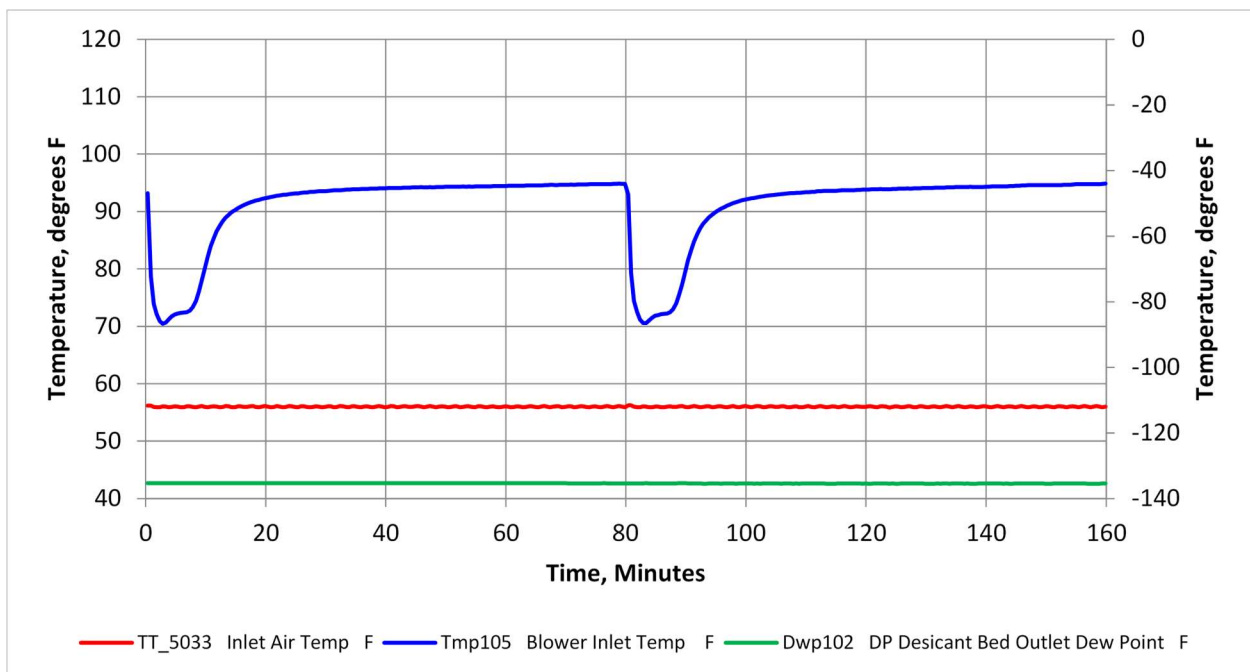


Figure 7. Desiccant bed inlet (red) and outlet temperatures (blue) and outlet dewpoint (green) at 2 mmHg inlet and nominal ISS inlet conditions.

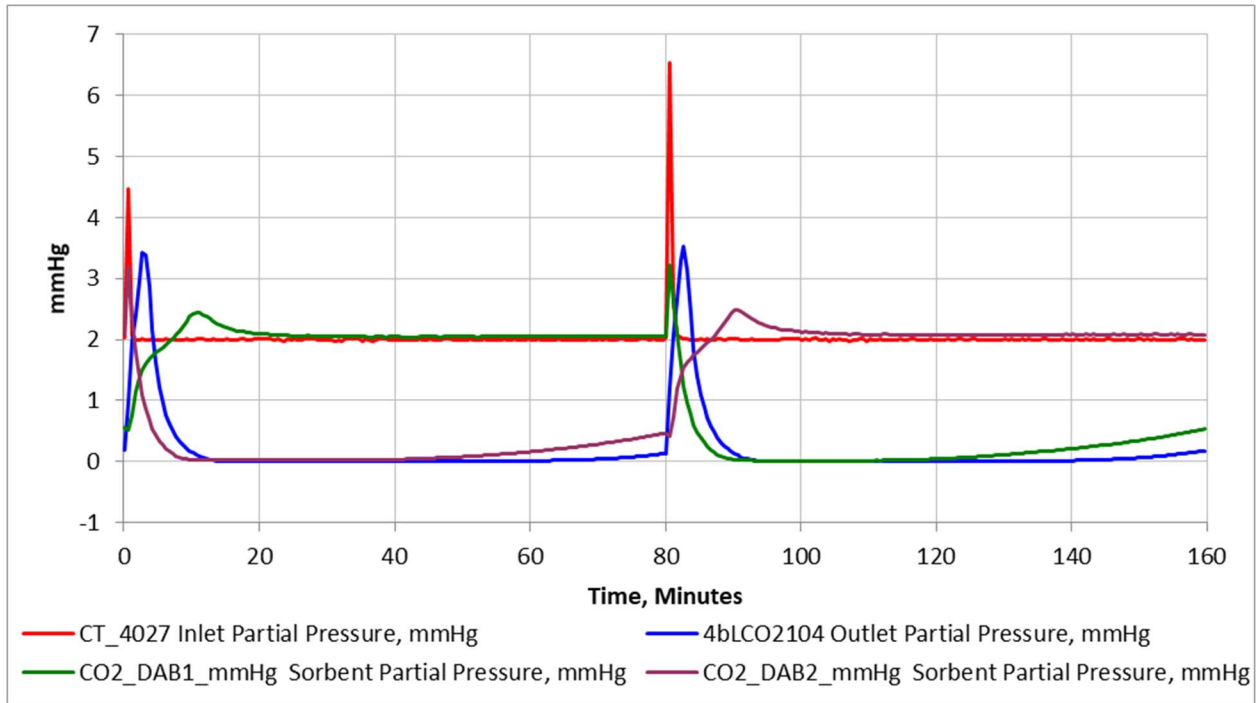


Figure 8. Inlet (red), system outlet (blue), and sorbent outlet CO₂ partial pressures (green and brown) at 2 torr inlet and cabin air inlet conditions

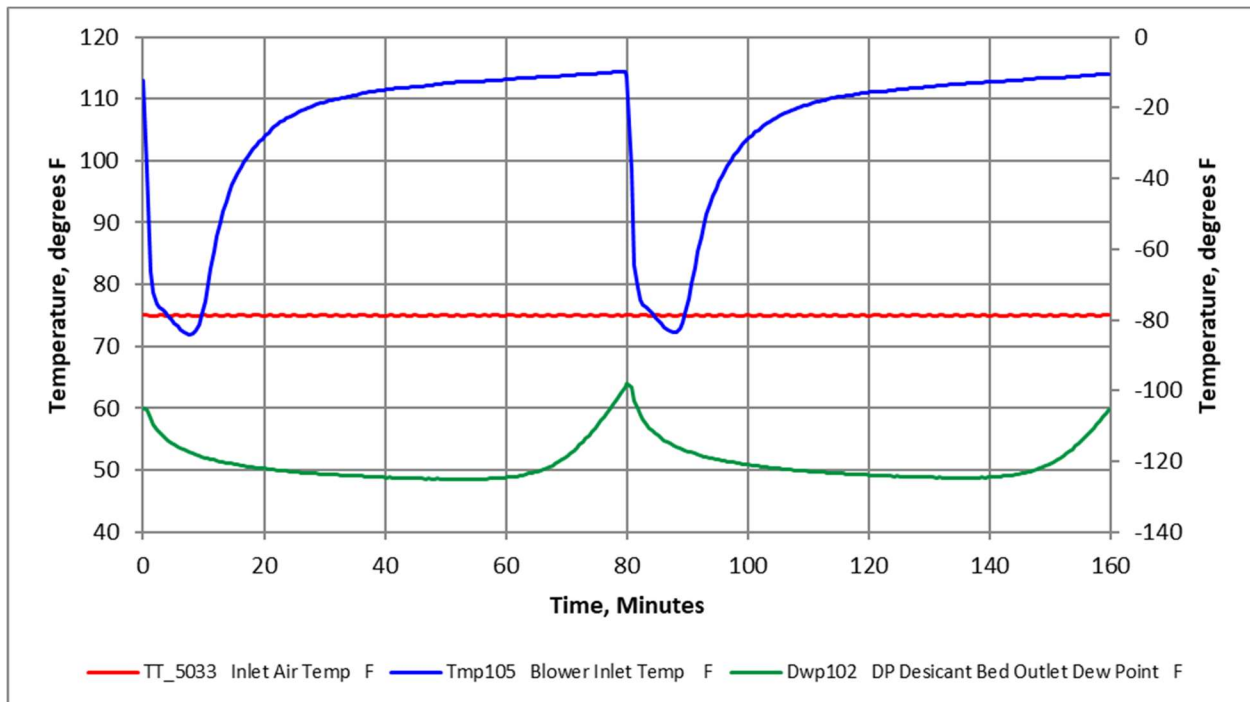


Figure 9. Desiccant bed inlet (red) and outlet temperatures (blue) and outlet dewpoint (green) at 2 torr inlet and cabin air inlet conditions

Comparison of Figure 10 and Figure 11, where the inlet ppCO₂ is now at 2.5 torr, provides a very similar observation: more CO₂ is returned to the cabin for the nominal inlet case. However, though not evident on these plots,

the overall CO₂ removal rate difference is smaller than for the 2.0 torr case because a smaller percentage of the overall mass of CO₂ entering the FBCO₂ scrubber is retained on the desiccant 13X.

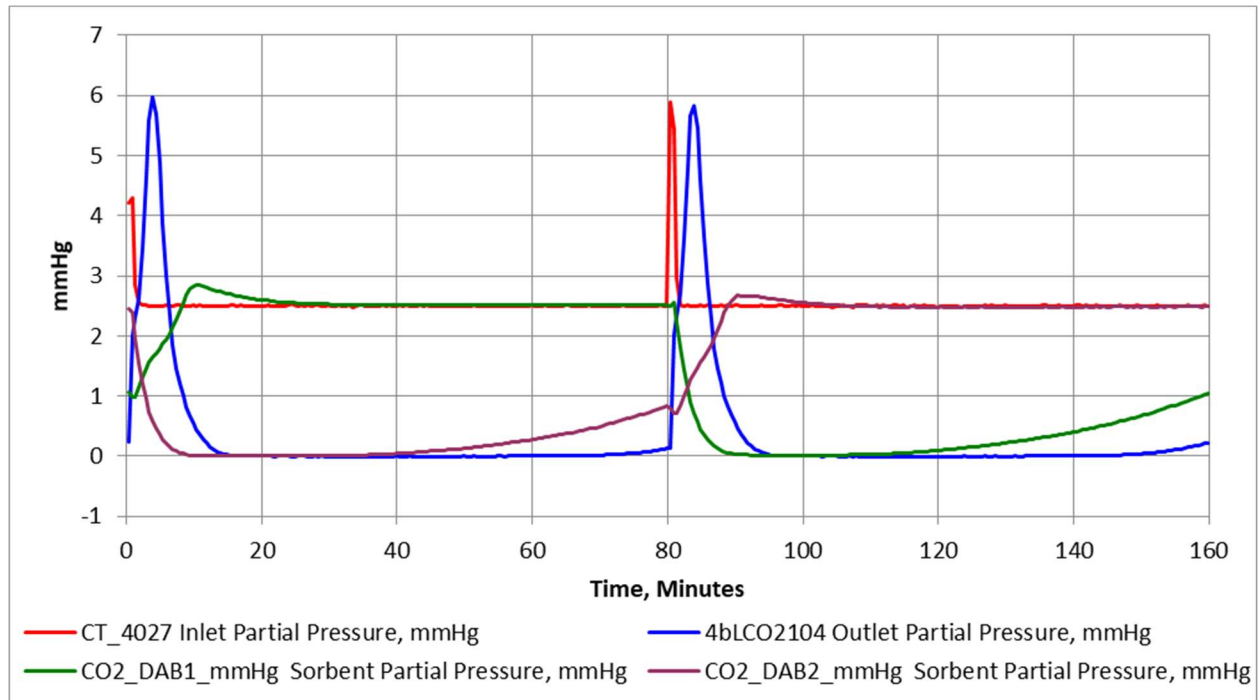


Figure 10. Inlet (red), system outlet (blue), and sorbent outlet CO₂ partial pressures (green and brown) at 2.5 torr inlet and nominal ISS inlet conditions

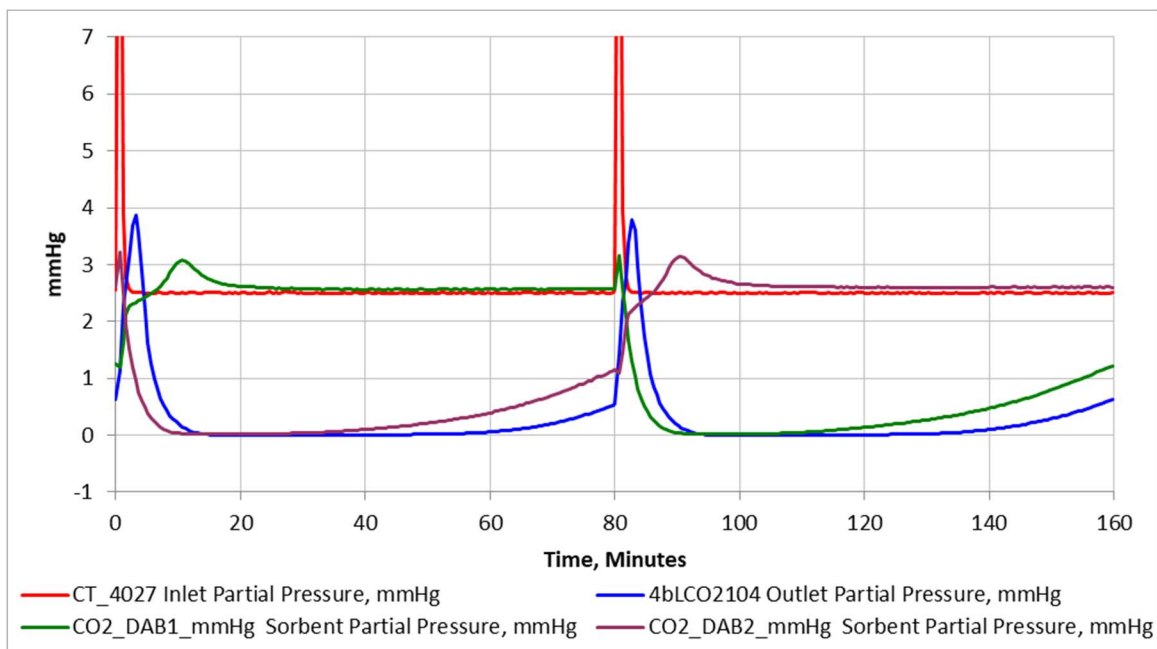


Figure 11. Inlet (red), system outlet (blue), and sorbent outlet CO₂ partial pressures (green and brown) at 2.6 torr inlet and cabin air inlet conditions

The changes in system holdup due to ppCO₂ are provided in Figure 12. Here the holdup and system breakthrough efficiency losses are shown as a percent of the overall inlet CO₂ mass per half-cycle. At lower ppCO₂ levels, the

amount of CO₂ exiting the system is small as nearly all the CO₂ is captured in the CO₂ sorbent bed. As was shown in Figure 5 the reduction in 13X holdup due to higher inlet temperatures results in the highest increase in CO₂ removal rate. However, as inlet ppCO₂ increases, the 13X holdup is a smaller percentage of the overall inlet mass of CO₂. Further, as inlet ppCO₂ increases, the CO₂ sorbent bed captures less of the total CO₂, particularly for the Cabin Air inlet case where less CO₂ is held up on the 13X in the desiccant bed. The combined effect results in only 1% CO₂ removal increase for the case with an inlet ppCO₂ of 3 torr.

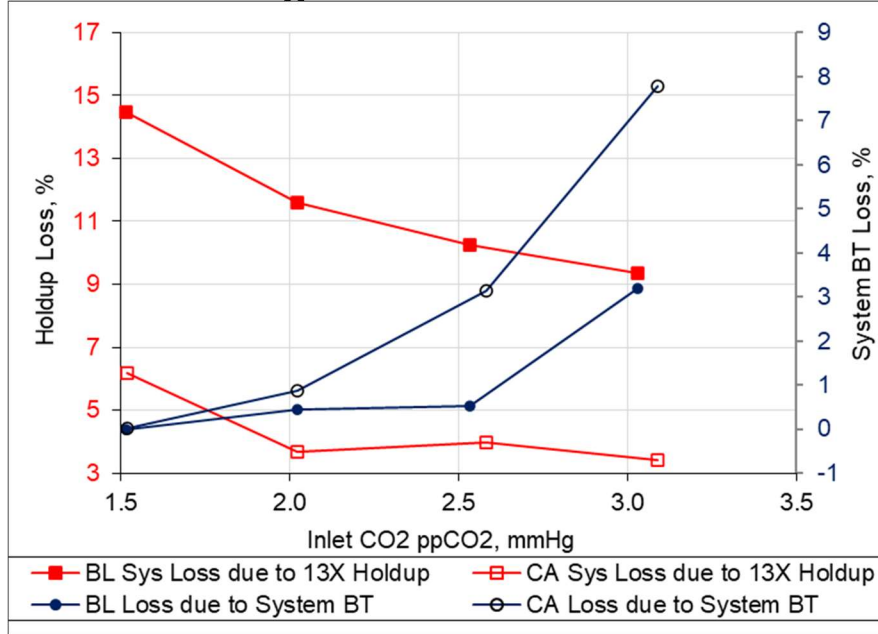


Figure 12. Baseline (BL) and cabin air (CA) percent holdup and system breakthrough losses as a function of inlet pp CO₂.

V. Estimated Impacts of De-Integration from the CCAA on Removal Rate

Results were mixed from this test series. The improvement in CO₂ removal rate had a maximum value of 8% at an inlet ppCO₂ of 1.5 mmHg. For a ppCO₂ level that might be expected during crew changeout (when a high number of crewmembers are present) or 2.5 mmHg, the improvement was only 4%.

However, as noted earlier, this test series did not consider the impact of the dilution of the inlet ppCO₂ when both the inlet and outlet stream is connected to the CCAA. The current performance of the FBCO₂ Scrubber on ISS is provided in a companion paper⁹ and was used to calculate the expected performance if the dilution impact was considered. These results are provided in Table 3. Since the assumption is made that performance increases are additive, these results must be confirmed by actual testing.

Table 3. Predicted cabin air inlet results

Baseline Inlet ppCO ₂ , mmHg	Baseline CO ₂ Removal, kg/day	Cabin Air Inlet ppCO ₂ , mmHg	Predicted Cabin Air CO ₂ Removal, kg/day	Percent CO ₂ Removal Increase
1.52	3.21	1.58	3.65	13.7%
2.03	4.42	2.12	4.97	12.5%
2.53	5.69	2.64	6.18	8.6%
3.03	6.72	3.16	7.08	5.4%

VI. Summary and Conclusions

Testing of the FBMS CO₂ Scrubber EDU with nominal inlet conditions, that is, with air conditioned by the ISS CCAA, and with direct cabin air inlet was conducted to understand potential performance gains. Test results show the

highest gains in CO₂ removal rates (8.3%) are realized at the lowest ppCO₂ of 1.5 mmHg and tail off to 0.9% as the inlet ppCO₂ increases to 3 mmHg.

However, this testing did not consider the impact of dilution of the FBCO₂ inlet ppCO₂ due to integration with the CCAA. If this is considered, an overall gain in CO₂ removal rate of 14% at the lowest inlet ppCO₂ of 1.5 mmHg and 5% as the inlet ppCO₂ increases to 3 mmHg. The combined impact provides a more substantial gain in removal rates. De-integration of the FBCO₂ Scrubber inlet air with the CCAA would also eliminate flow rate limitations due to the pressure drop associated with the ducting from the CCAA to the FBCO₂ inlet, as well as flow rate limitations due to the competition of the Carbon Dioxide Removal Assembly (CDRA) for the same CCAA air supply.

Based on this discussion, further investigation of using cabin air as the inlet to the FBCO₂ Scrubber is warranted. It is suggested that the current test series be repeated with the appropriate inlet cabin air inlet ppCO₂ values shown in Table 3. In addition, the test duration should be extended to determine if increased desiccant bed water vapor breakthrough will occur under these inlet conditions. If the extended test series proves successful, this operational configuration should be considered as part of the ISS FBCO₂ Scrubber Technology demonstration.

References

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