Performance of the Four Bed Carbon Dioxide Scrubber ISS Technology Demonstration

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Introduction

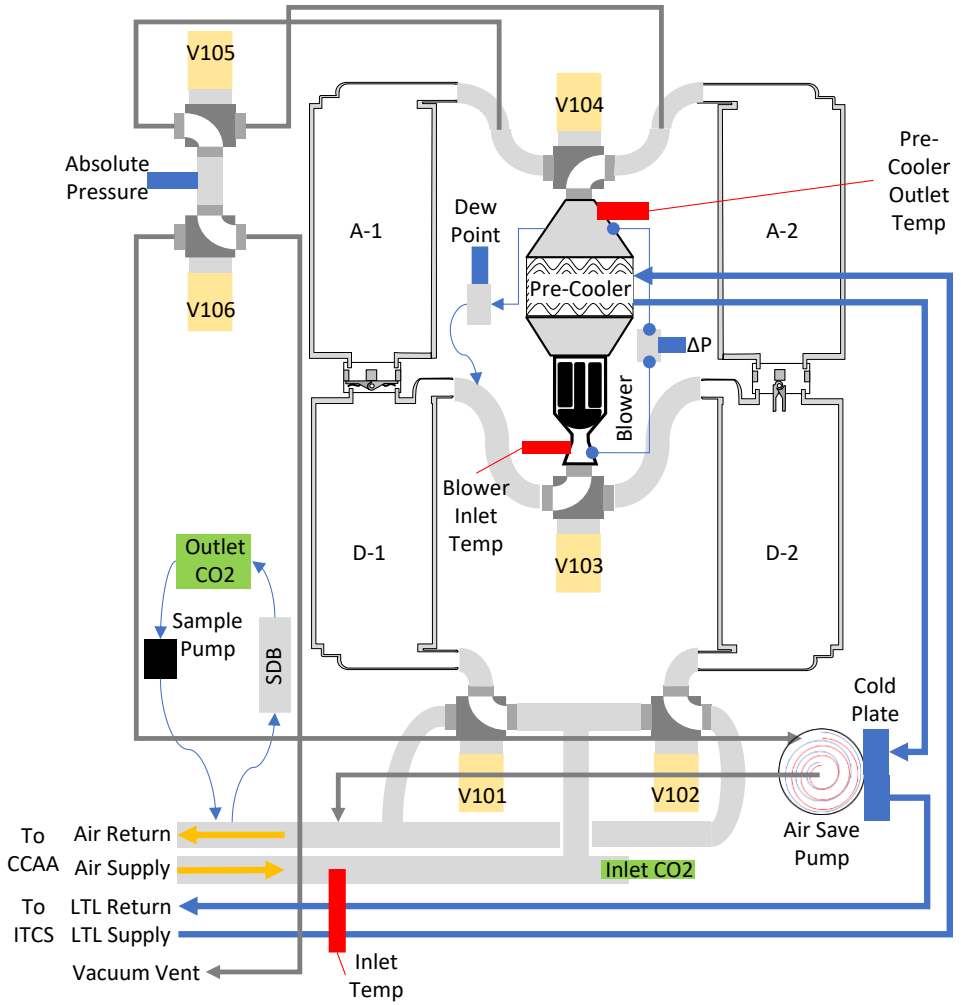
- Four Bed Carbon Dioxide Scrubber (aka FBCO2, 4BCO2)
  - Technology Demonstration – CO_2 removal for ISS
    - Primary goal – uninterrupted operation for 20,000 hours
  - Activated onboard ISS September 2021





Background – Operation relative to CDRA

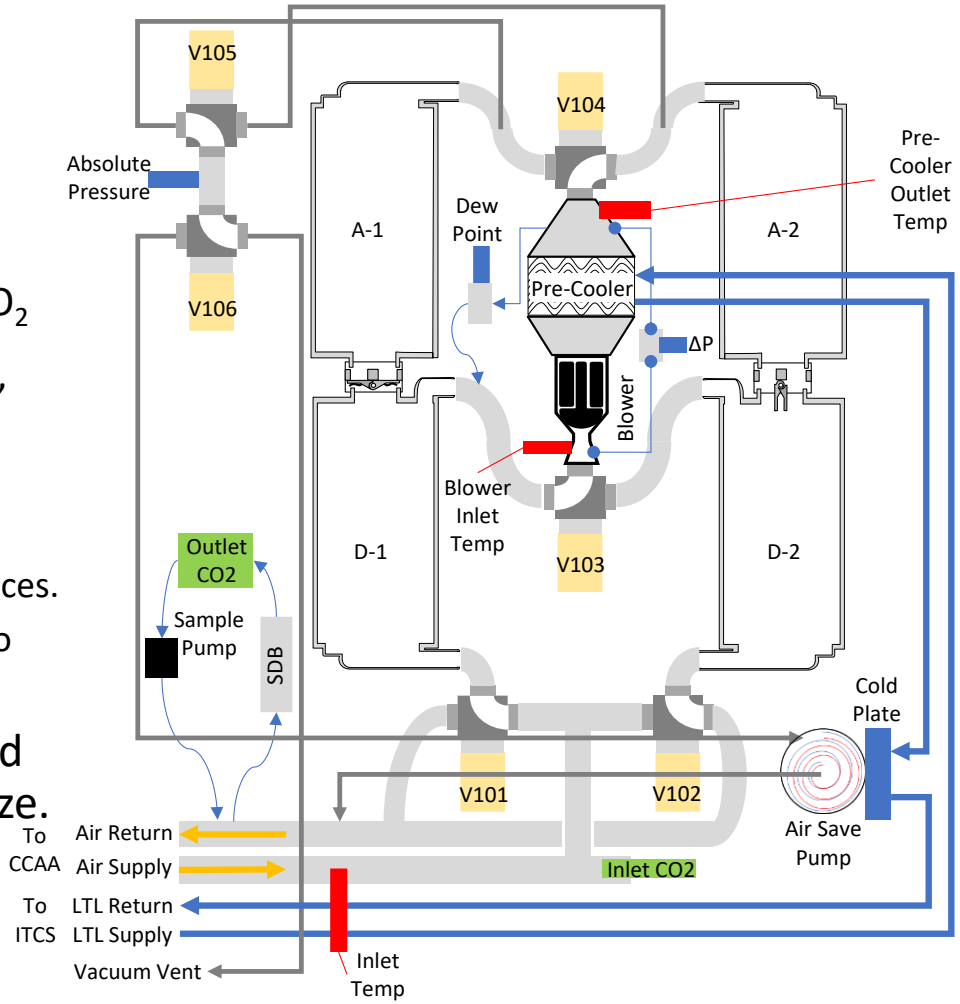
- 6 valves
  - New valves, same flow paths
  - Bleed port allows gentle repress
- 8 sensors
  - Similar T, P measurements
  - Direct measurement of inlet and outlet CO_2 %
  - Direct measurement of dew point after desiccant beds
  - Direct measurement of blower/PC dP
- Similar functional components but new hardware in most places
  - Heritage air blower



Operation of a four-bed CO_2 scrubber

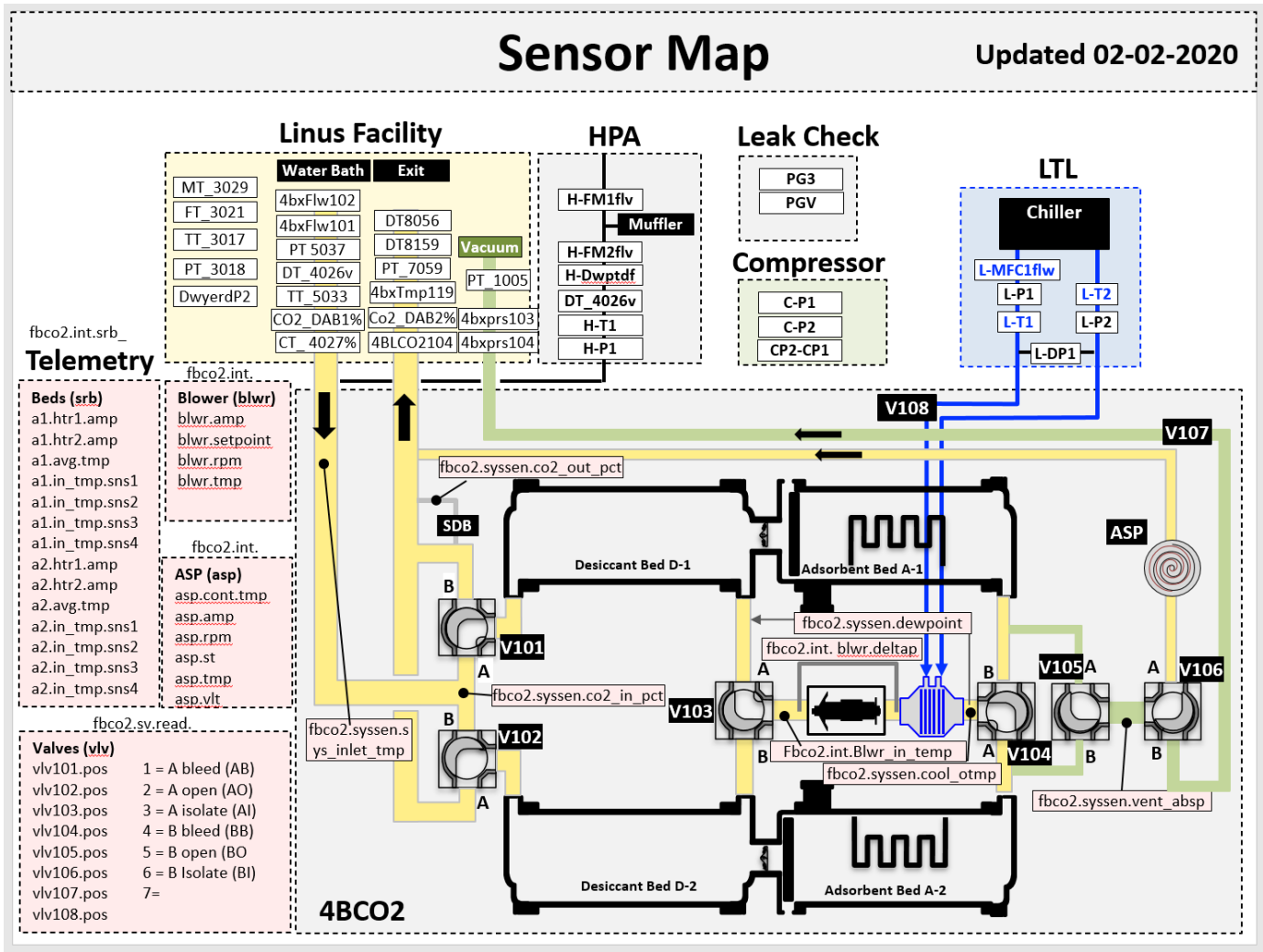
- Operations are split into half-cycles (HC) A and B
  - These are mirrors of each other, schematic shows HC A
- Tracing the flow path through valves:

1. Air is pulled from cabin air system (CCAA). Air contains O_2/N_2, H_2O, and CO_2
2. Air flow path is supply duct, V101, bed D-1, V103, blower, precooler, V104, bed A-2, bed D-2, V102, return duct
   1. In this path, D-1 is scrubbing H_2O, but CO_2 and O_2/N_2 pass.
   2. Then, A-2 is scrubbing CO_2, but O_2/N_2 pass.
   3. Finally, the air returning to cabin retakes H_2O from D-2 to maintain mass balances.
   4. While this is happening, A-1 is heated and connected to vacuum to vent CO_2 to space through V105 and V106. This heat will be used to dry D-1 next cycle.
3. Half-cycle time is part of design process and can be adjusted based on volume of air flow, humidity at supply, heating rate, and bed size.
4. At end of HC A transitioning to HC B, all 6 valves rotate.
   1. V106 links the Air Save Pump to the now-desorbing bed A-2 to recover O_2/N_2 trapped in voids of ducts and bed.
   2. Once air save is complete, A-2 is linked to space vacuum to vent CO_2



Ground Testing of FBCO2

- Additional sensors were available for ground test operations
- Inlet and outlet CO_2 sensors were used for corrections to flight sensors, which were found to have offsets
- The inlet temperature sensor also found to have an offset
- Since there is no flight flow measurement, facility flow measurement is used to estimate on-orbit flow rate via blower power

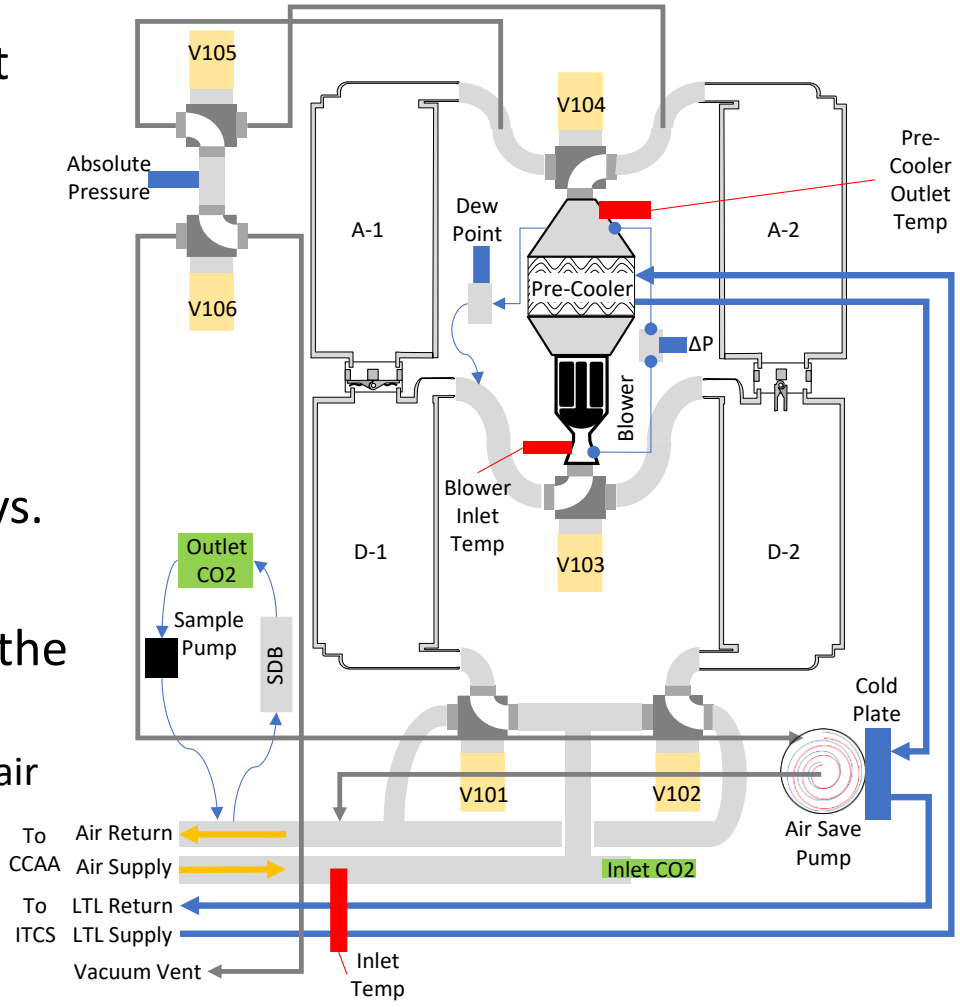


On-orbit performance calculations

- On-orbit performance calculation includes FBCO2 inlet and outlet partial pressure CO_2 ($ppCO_2$) and mass flow rate

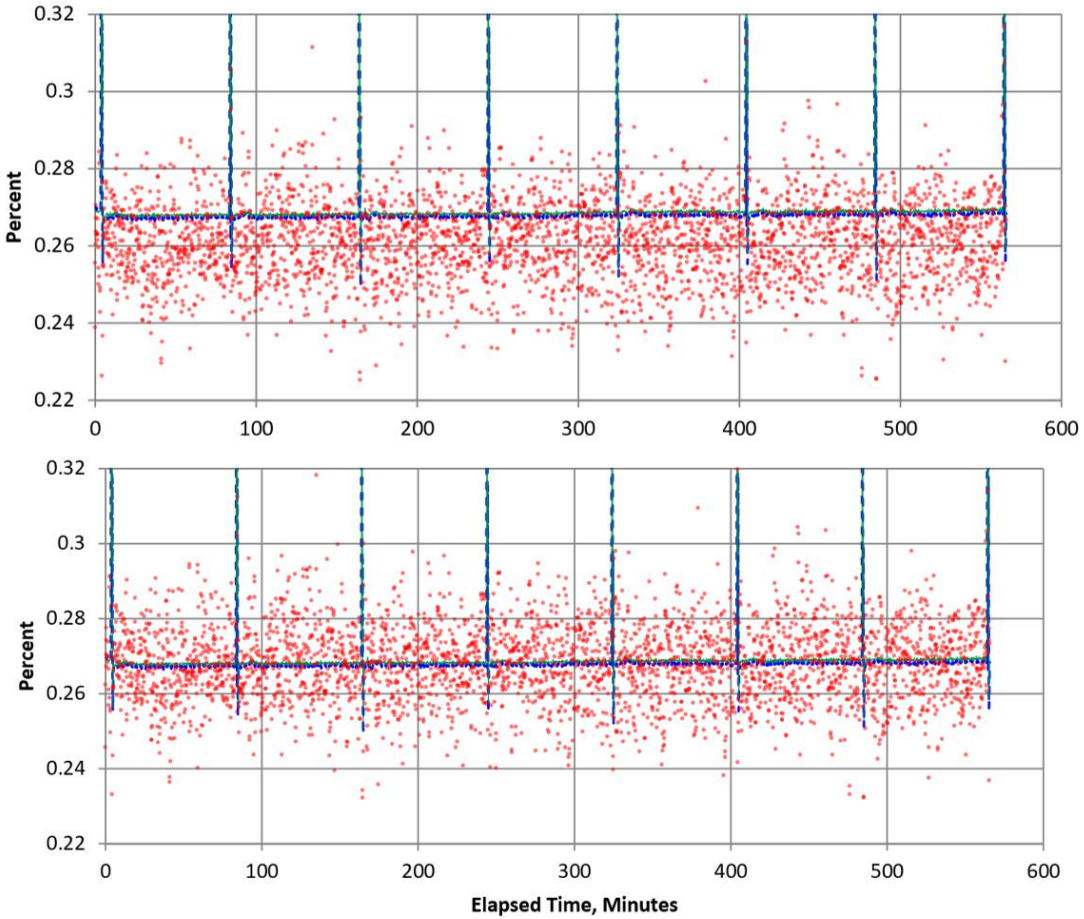
$$\dot{m}_{CO2} = \frac{P_S M_{CO2}}{\bar{R} T_S} \dot{V}_S \left(X_{CO2_{IN}} - X_{CO2_{OUT}} \right)$$

- The performance evaluation metric used during ground testing is CO_2 removal rate vs. inlet $ppCO_2$
- The on-orbit performance evaluation metric is CO_2 removal rate vs. ISS Laboratory $ppCO_2$
- Independent calculation of the Lab $ppCO_2$ requires estimation of the CCAA flow rate, as:
  - The FBCO2 effluent contains essentially no CO2, and mixes with the ISS Lab air to become the FBCO2 influent
  - Thus the FBCO2 influent $ppCO_2$ is diluted compared to the Lab $ppCO_2$
- *This paper describes the corrections and estimations required to calculate performance during ground testing and on-orbit*



Inlet CO_2 Sensor Corrections

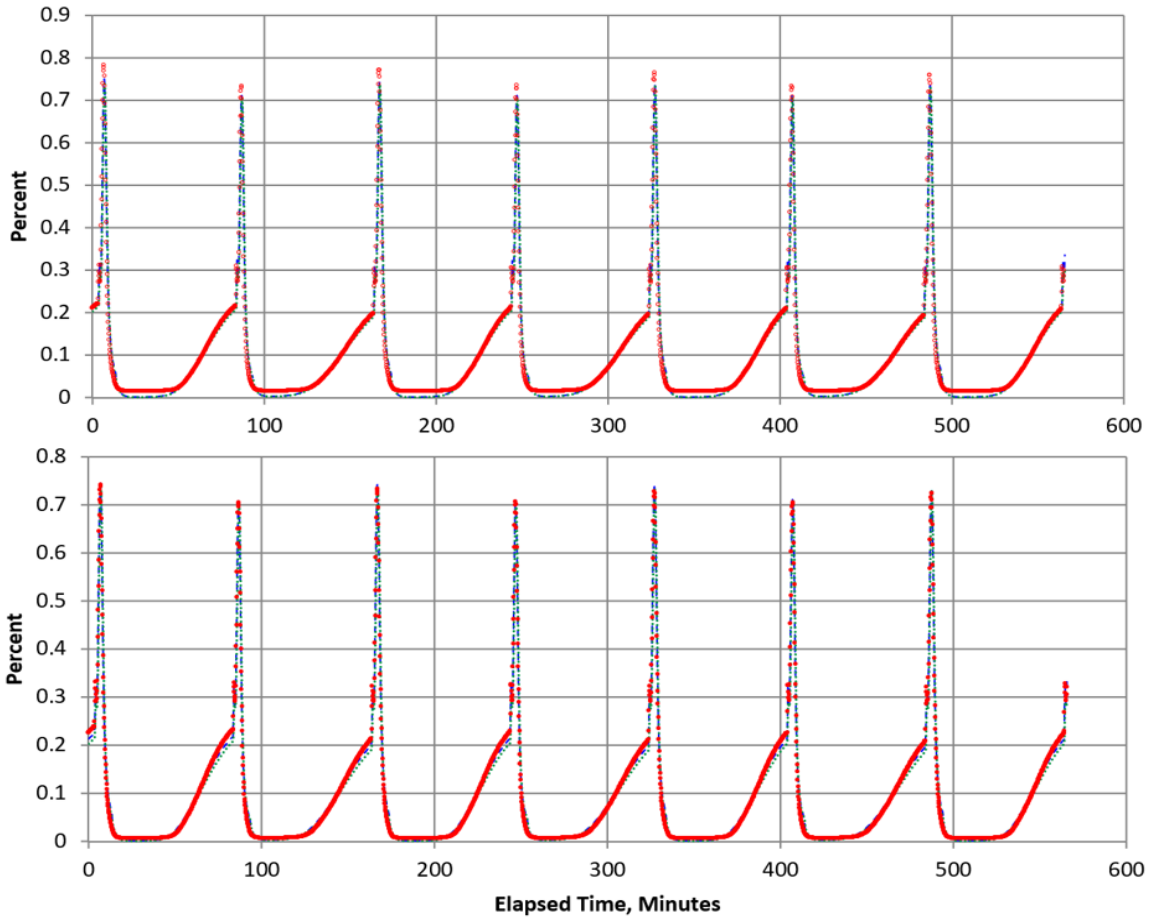
- Simple adjustment to flight sensor (red) removes sensor offset
- Average results correlate well with facility sensors (green and blue overlapping lines)
- Also, good correlation with other flight sensors as seen on later slide
- Similar approach used for inlet temperature sensor



Flight inlet CO_2 sensor compared with facility sensors. Y-axis is percent volume CO_2. Top: prior to offset adjustment. Bottom: after offset adjustment. Red dots are flight sensor measurements; green lines and blue dashed lines are Sable CA-10 facility sensor measurements.

Outlet CO_2 Sensor Corrections

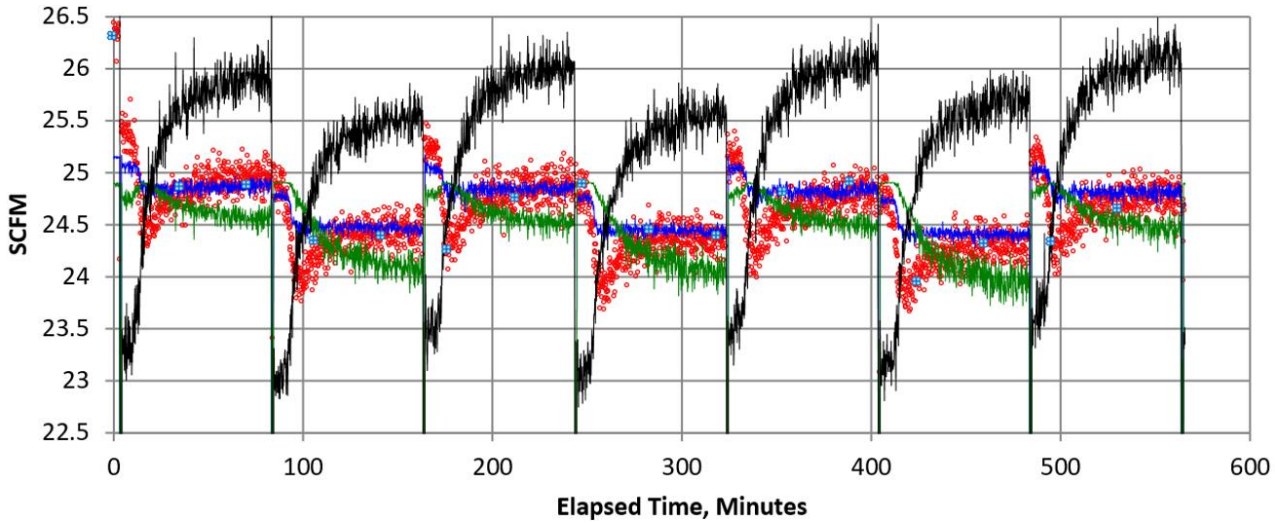
- Quadratic fit with smallest SSE used to remove low offset of flight sensor (red)
- Facility sensors are overlapping blue and red lines
- Small resultant change in middle portion of curves
- Overall error for averaged CO_2 removal rate less than 1%



Flight outlet CO_2 sensor compared with facility sensors. Y-axis is percent volume CO_2. Top: prior to adjustment. Bottom: after adjustment. Red dots are flight sensor measurements; green dots and blue dashed lines are LI-COR LI-850 and Sable CA-10 facility sensor measurements respectively.

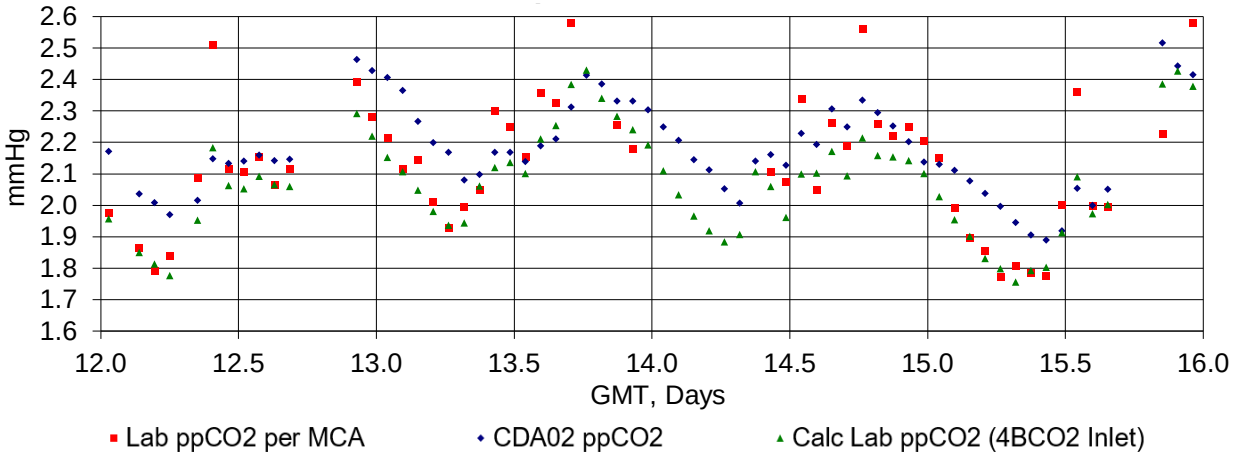
Process Air Flow Rate

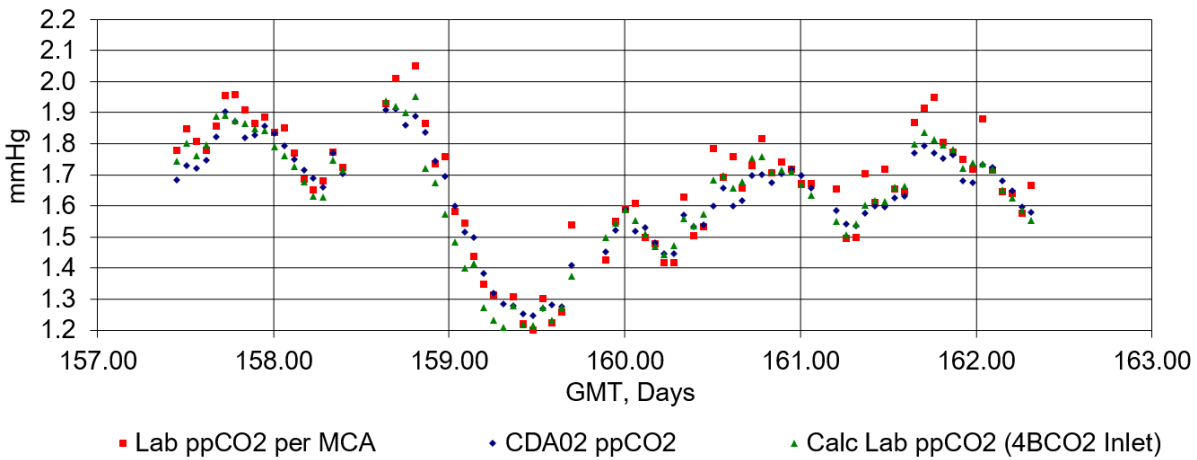
- During FBCO2 ground testing, a mass flow meter was installed upstream of the FBCO2 inlet
- Correlations to various measurements were evaluated:
  1. Blower inlet power
  2. Blower controller inlet power
  3. Blower delta pressure
  4. Fit based on independent bench test data and blower delta pressure
- No measurement tracked actual flow rate completely
- Blower inlet power was chosen as most representative
- Bench testing with actual system conditions in process for next generation (magnetically levitated)
- Results should provide better estimations for next generation blower



Comparison of approaches to estimate FBCO2 flow rate. Red dots are facility flow measurements (Sierra QuadraTherm® 780i); blue line is estimated flow rate based on blower power measurement; green line is estimated flow rate based on blower delta pressure measurement; and black line is flow rate based on independent bench test data and blower delta pressure.

ISS Laboratory CO_2 Partial Pressure Comparison

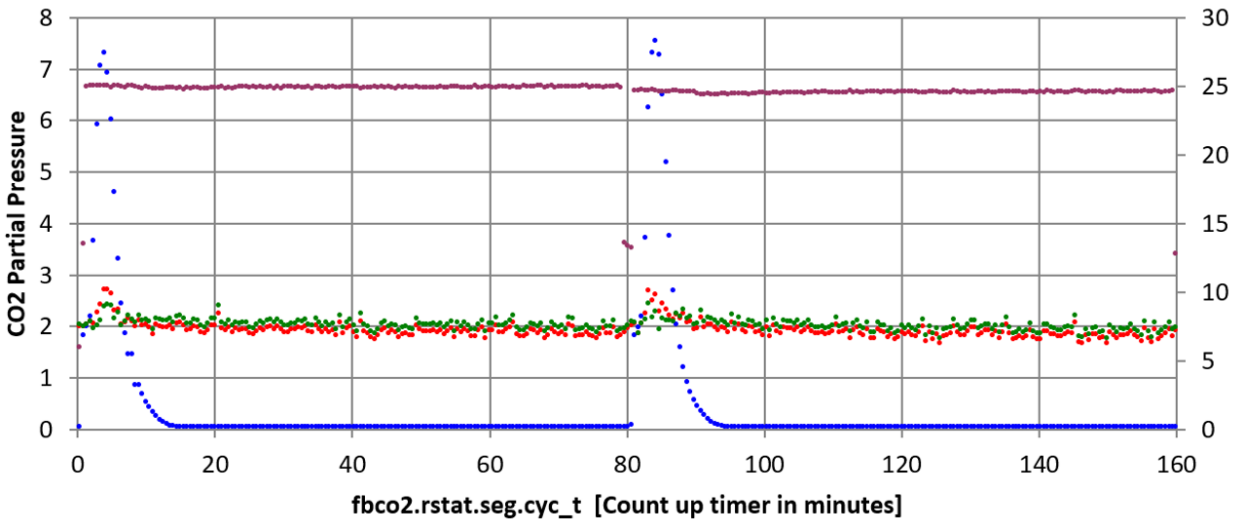




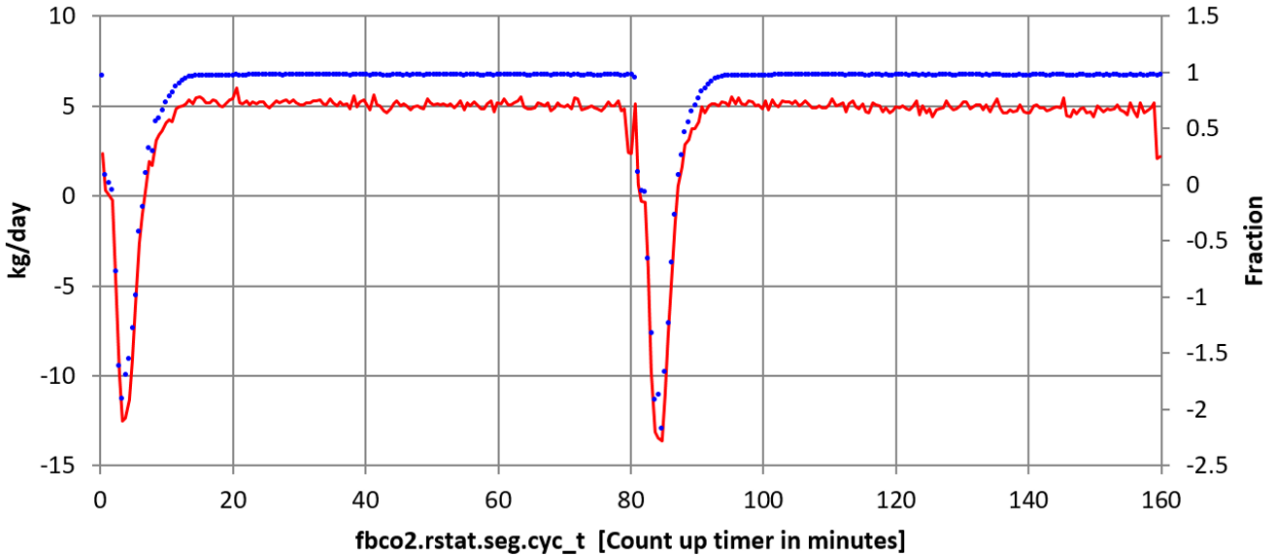
- Plots show Lab $ppCO_2$ measurements for early and mid-2022
- MCA samples all ISS modules: Lab sampling is not aligned with FBCO2 cycles
- Early 2022 plots show greater differences in CDA02 and MCA
- Mid-2022 plots are after CDA02 calibration
- Calculated Lab $ppCO_2$ is conservative, and was used for FBCO2 performance
- FBCO2 $ppCO_2$ calibration via MCA is planned, though large changes are not expected

Corrected On-Orbit Cyclic Measurements

- Average removal rate achieved target performance based on inlet ppCO2
- Target performance slightly low using Lab ppCO2 basis
- Ground test hardware performance higher at similar conditions, cause for difference presently unclear



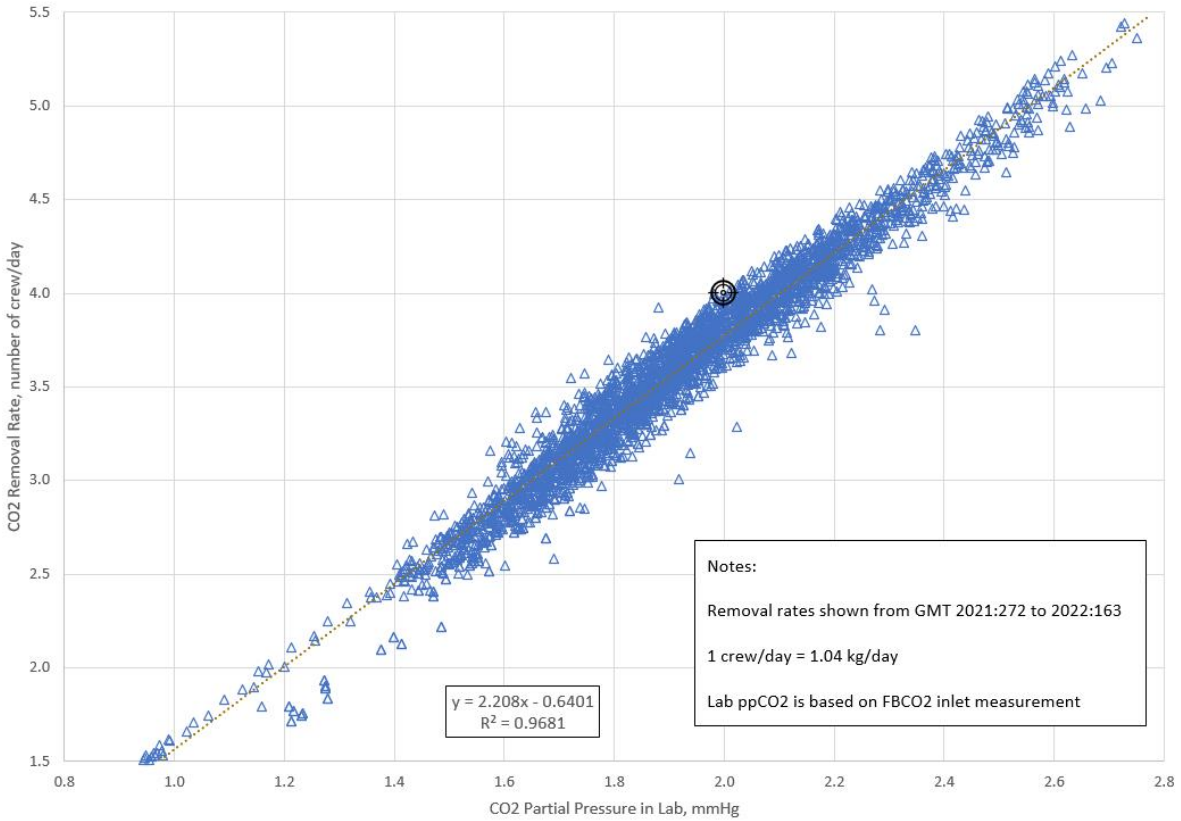
Adjusted measurements used for CO_2 Removal Calculation. Y-axis is partial pressure of CO_2 in mmHg. Red dots are inlet $ppCO_2$, green dots are Lab ppCO2, blue dots are outlet $ppCO_2$, and purple dots are flow rate. X-axis is FBCO2 cycle time.

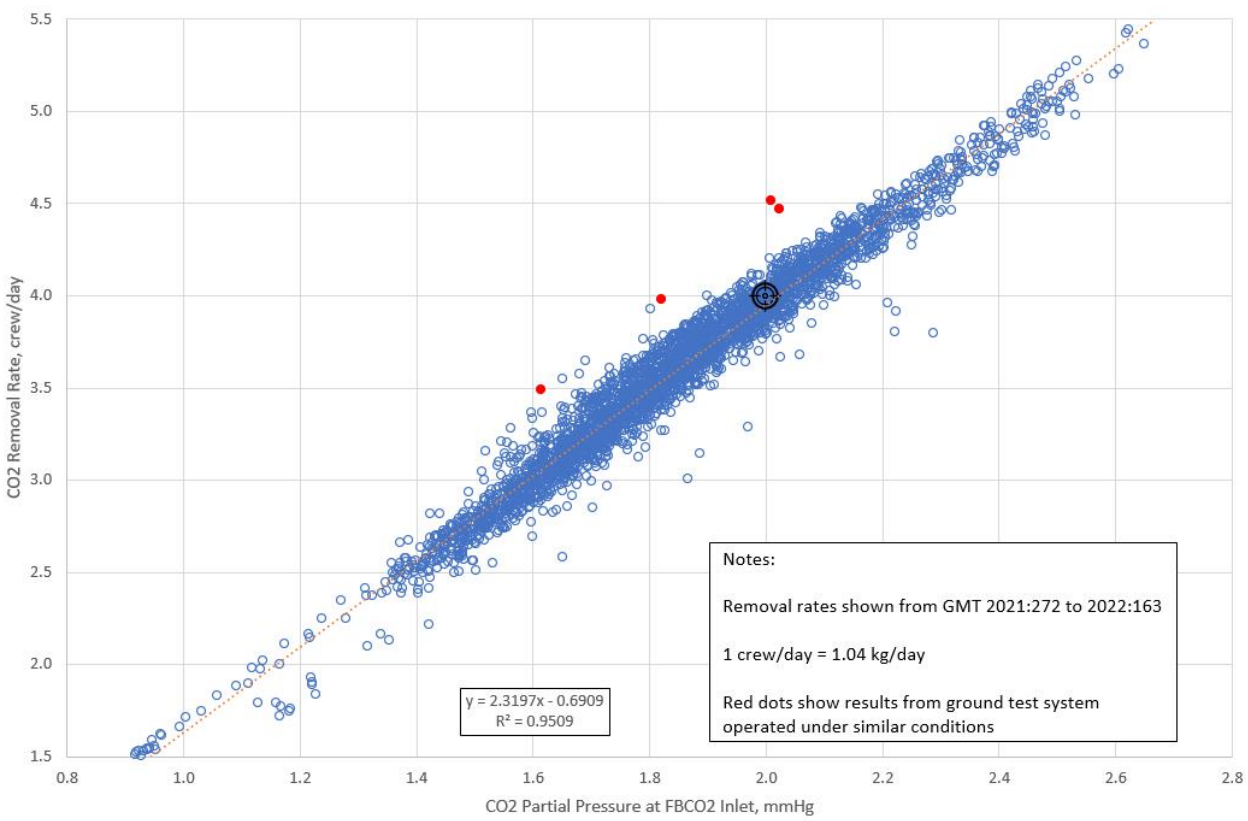


CO_2 removal rate and removal fraction. Red line is CO_2 removal rate; blue dots are CO_2 removal fraction. X-axis is FBCO2 cycle time.

Performance Calculations

- Average removal rate achieved target performance based on inlet ppCO2
- Target performance slightly low using Lab ppCO2 basis
- Ground test hardware performance higher at similar conditions, cause for difference presently unclear





Conclusions

- Methods developed to obtain accuracy in on-orbit FBCO2 performance measurements despite known inaccuracies in $ppCO_2$ sensor readings and the lack of an air flow rate sensor
- Method developed to obtain an estimate of the CCAA flow rate such that the Lab ppCO2 could be calculated from the FBCO2 inlet $ppCO_2$ sensor
- Resulting FBCO2 performance meets the target performance as a function of the inlet $ppCO_2$ (how performance was evaluated during ground testing)
- Performance is about 5% below the target when the influence of CCAA dilution is considered
- CCAA dilution imposes a CO_2 removal performance penalty of over 6%
- Installation of next generation magnetically levitated blower will allow for greater flow rates, overcoming current performance deficit
- FBCO2 performance will be sufficient to meet the NASA requirements for a future exploration mission such as a Mars transit mission