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CDRA-4EU Testing in Support of ISS

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NASA's Marshall Space Flight Center (MSFC) recently conducted tests on two desiccant beds of the four-bed molecular sieve carbon dioxide removal assembly (CDRA) returned from the International Space Station (ISS). MSFC had previously characterized the relationship between CDRA-4EU inlet conditions and the dewpoint at the desiccant bed exit as well as between the compressor and accumulator that make up the Carbon Dioxide Management Assembly (CDMA). MSFC installed the flight desiccant beds into the existing Exploration Test Chamber (E-chamber) using a suite of instrumentation not available on orbit to investigate the orbital performance of the desiccant beds. Test objectives, facility design and test results are presented.

Nomenclature

AES = Advanced Exploration Systems
ARREM = Atmosphere Resource Recovery and Environmental Monitoring
4BMS = Four Bed Molecular Sieve
CDMA = Carbon Dioxide Management Assembly
CDRA-4 = Carbon Dioxide Removal Assembly, Revision 4
CDRA-4EU = Carbon Dioxide Removal Assembly, Revision 4 Engineering Unit
CHX = Condensing Heat Exchanger
CO_2 = Carbon Dioxide
CHX = Condensing Heat Exchanger
HEO = Human Exploration and Operations Directorate
ISS = International Space Station
LSSP = Life Support Systems Project
MSFC = Marshall Space Flight Center
$ppCO_2$ = Partial Pressure of Carbon Dioxide (Pascal)
SLPM = Standard Liters per minute

I. Introduction

BY February of 2015, the maximum flow through the Laminar Flow Element of the Sabatier reactor used on the International Space Station (ISS) had decreased over time, indicating a blockage in the system. When the Laminar Flow Rod element was removed from the Sabatier reactor, the crew found liquid water. Liquid water not only reduces flow to the Sabatier, but could also damage the Carbon Dioxide Management Assembly (CDMA) which compresses the CO_2 removed from the Carbon Dioxide Removal Assembly, Revision 4 (CDRA-4). Although the team investigated several possible sources of moisture, they were unable to close all legs of the root cause analysis with available flight instrumentation. After the beds were returned from orbit in mid-2015, they were sent to the NASA Marshall Space Flight Center (MSFC) for performance evaluation in the Carbon Dioxide Removal Assembly, Revision 4 Engineering Unit (CDRA-4EU) flight-like test system described below.

Under the Atmosphere Resource Recovery and Environmental Monitoring (ARREM) Project operating

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under the Human Exploration and Operations (HEO) directorate[1], a 4-Bed Molecular Sieve (4BMS) ground test system named CDRA Dash 4 Engineering Unit (CDRA-4EU) was developed to more closely mimic the current CDRA-4 configuration on ISS[2-4]. The CDRA-4EU configuration, which is located in the MSFC Environmental Test chamber (E-chamber) is used to develop technology for advanced exploration, and also to support on-orbit anomaly investigations as needed.

II. Objectives

1. Using desiccant bed outlet dewpoint and CDMA outlet dewpoint measurements, determine if the flight beds transmit moisture at rates higher than the CDRA-4EU system hardware.
2. Determine if the pressure drop, possibly caused by a blockage or excess moisture, of the flight desiccant beds is higher than the CDRA-4EU system hardware.

III. CDRA Hardware and Test Facility

The CDRA, built by Honeywell (formerly AiResearch and Allied Signal) uses a fully regenerative thermal/pressure swing adsorption process to remove CO_2 from the ISS cabin air. The CDRA operates cyclically and employs two desiccant beds and two adsorbent beds. As one desiccant bed and one adsorbent bed operate in adsorption mode, the other two beds are desorbing (regenerating). Half-way through a cycle, the beds switch modes, providing continuous CO_2 removal capability.

CDRA-4EU (figure 1) is located in the E-Chamber located in the MSFC ECLSS Development Facility. The E-Chamber provides the capability to replicate and control dry bulb temperature, CO_2 partial pressure, humidity, airflow and trace contaminant levels. The CO_2 that exits CDRA during the desorbing (regenerating) cycle is directed to either a space vacuum simulator, or the flight-like CDMA Compressor (light blue box) located in the bottom right hand side of figure 2.

Figure 1. CDRA-4EU

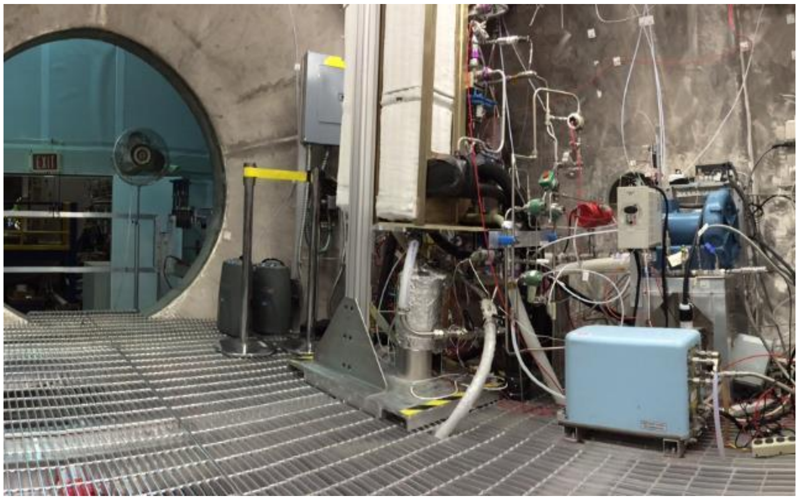

Figure 2. E-Chamber

The CDMA is a facility replication of the ISS CO_2 compressor using a flight spare unit from Southwest Research Institute (SwRI) and an accumulator consisting of several small tanks with a combined volume of 20 Liters. The CDRA-4EU system and E-Chamber facility uses a full suite of instrumentation to define the environment of the CDRA system. Dewpoint sensors were located downstream of the desiccant bed (inside of the CDRA system) as well as downstream of the CDMA compressor and are noted in figure 3. For this test program, CDRA-4EU was operating in standalone mode, with direct injector of CO_2 into the CDRA-4U inlet and temperature and humidly controlled by the condensing heat exchanger (CHX).

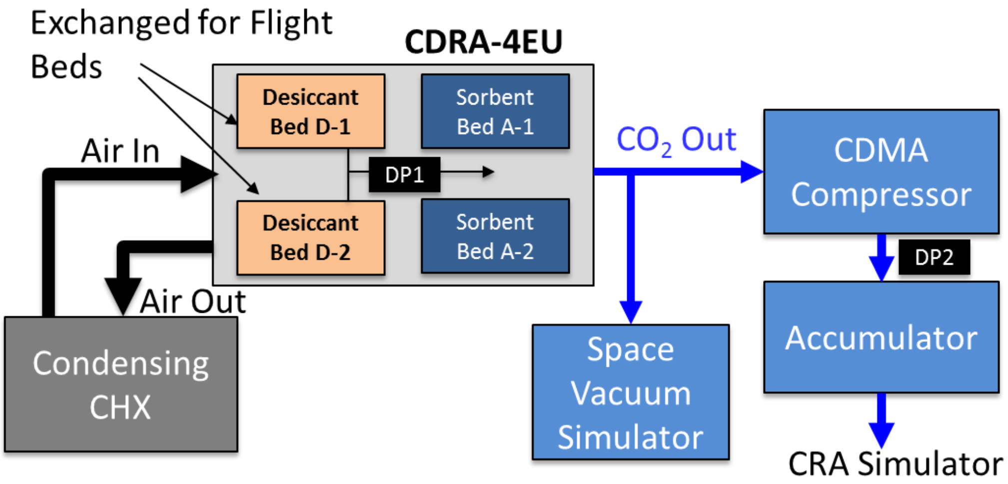

Figure 3. Dewpoint Sensor Locations (DP1, DP2)

IV. Test Sequence

The test series consisted of four phases described below.

1. Develop baseline dewpoint measurement values using the development desiccant beds tested at ISS inlet conditions listed below.
2. Partially dry the flight beds to reduce the effect of moisture that could have been adsorbed during transport from orbit to MSFC. Subject the beds to a GN_2 drying cycle at 38°C prior to installation into CDRA-4EU. The low temperature bake-out allows moisture removal without driving off possible (but unconfirmed) Siloxane substances.
3. Determine flight desiccant bed outlet dewpoints after installation into CDRA-4EU. Perform stand-alone testing without the compressor to protect it from possible liquid water damage. Test at the same conditions used in orbital operations and in the baseline performance tests described in step 1.
4. Operate with the compressor using high moisture inlet conditions to investigate the dewpoint at the exit of the compressor in simulated worst case conditions after the results of Step 3 indicate that excessive H_2O transmittance was not indicated in the desiccant bed exit dewpoint.

V. Test Conditions

Open-Loop Test Conditions

496 SLPM	System Inlet Flowrate
400 Pa	CO_2 Injection partial pressure ($ppCO_2$) at CDRA inlet
10-25-109	Half Cycle Segment durations (minutes) [Segment A1, Segment A2, Segment A3]
4.4°C	Low Temperature Loop (LTL) (temperature of water delivered to the condensing heat exchanger)
5 °C	Dewpoint at CDRA inlet

Closed Loop Test Conditions

710 SLPM	System Inlet Flowrate
307 Pa	CO_2 Injection partial pressure ($ppCO_2$) at CDRA inlet
10-124-10	Half Cycle Segment durations (minutes) [Segment A1, Segment A2, Segment A3]
8.3°C	Inlet Dewpoint
0.182 kg/hr	Sabatier Simulator Flowrate
620-690 kPa	Compressor Pressure Limits

Half Cycle segments: A1-Airsave: A2- sorbent bed A2 adsorbing and sorbent bed A1 desorbing to compressor, A3- sorbent bed A2 adsorbing and sorbent bed A1 desorbing to vacuum,

VI. Open Loop Test Results

The Flight desiccant beds were tested at the conditions exhibited at the time they were shut down on orbit. Because we did not have a measurement of the moisture content of the beds, we vented the CO_2 adsorbed into the beds to vacuum rather than through the compressor, which could have been damaged by the presence of liquid water. The test operated for two days, beginning on October 19th, 2016. The test data is separated into two sections, Day 1 and Day 2 for trend analysis, but they were run continuously with no break in operation.

Parameter	Target	Ground Development Bed Baseline	Flight Bed Test Day 1 (10/19/15)	Flight Bed Test Day 2 (10/20/15)
$ppCO_2$ (Pa) at CDRA Inlet	400	400	397	399
Flowrate (SLPM)	496	497	483	493
Half-cycle (minutes)	144	144	144	144
LTL Temperature (°C)	4.4	4.4	4.5	4.4
Inlet Temperature (°C)	10	12.2	9.9	9.7
Inlet Dew Point (°C)	5	6.9	3	4.5
Des. bed outlet Dew Point (°C)	n/a	-82.2	-79.4	-85.6
CO_2 Removal Rate (kg/day)	n/a	4.81	4.94	5

Table 1. Open Loop Performance Comparison

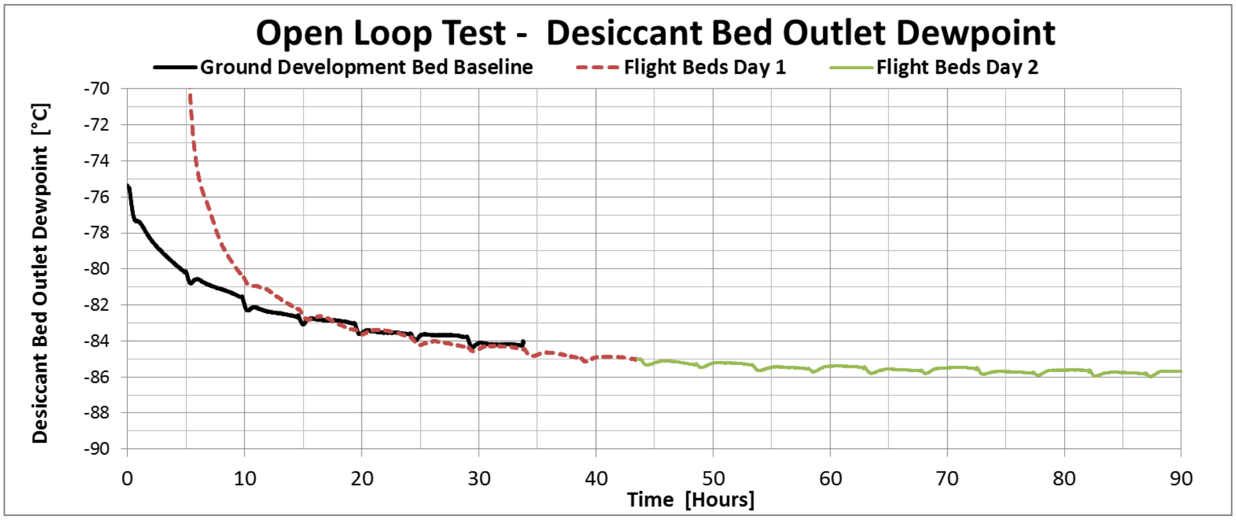

Figure 4. Open Loop Desiccant Bed Outlet Dewpoint Comparison

The dewpoint started relatively high at the beginning of the test due to moisture intrusion during installation of the beds and the drying time of the chilled mirror dewpoint measurement device. After 15 hours, the flight desiccant bed outlet dewpoint matched that of the development test hardware and remained stable for the remainder of the test duration. A Desiccant Bed outlet dewpoint measured at -86°C corresponds to less than 1 part per million (ppm) water vapor. The difference between the desiccant bed outlet dewpoint measurements is smaller than the accuracy of the precision chilled-mirror dewpoint measuring device.

VII. Closed Loop Test Results

The development desiccant beds were tested using high moisture-content inlet conditions (warmer temperature and higher dewpoint) to evaluate the effect of dewpoint on CO_2 exiting the compressor. The flight beds were tested using a CDMA pressure range between 620 kPa and 690 kPa, and Sabatier simulator rate of 0.18 kg/hr, consistent with ISS conditions and the baseline created for this comparison. The average input test parameters and output measurements for this test are summarized in Table 2, and represented in graphical format in Figure 5. and Figure 6.

Parameter	Ground Development Bed Baseline	Flight Bed Test
$ppCO_2$ (Pa)	305	303
Inlet Flow rate (SLPM)	699	699
Half-cycle (min.)	144	144
LTL Temperature (°C)	8.44	7.33
Sabatier Sim. Flow (kg/hour)	.18	.18
Inlet Temperature (°C)	12.6	11.2
Inlet Dew Point (°C)	8.7	7.1
Des. Outlet Dew Point (°C)	-88	-88
CO_2 Removal Rate (kg/day)	4.6	4.7

Table 2. Closed Loop Performance Comparison

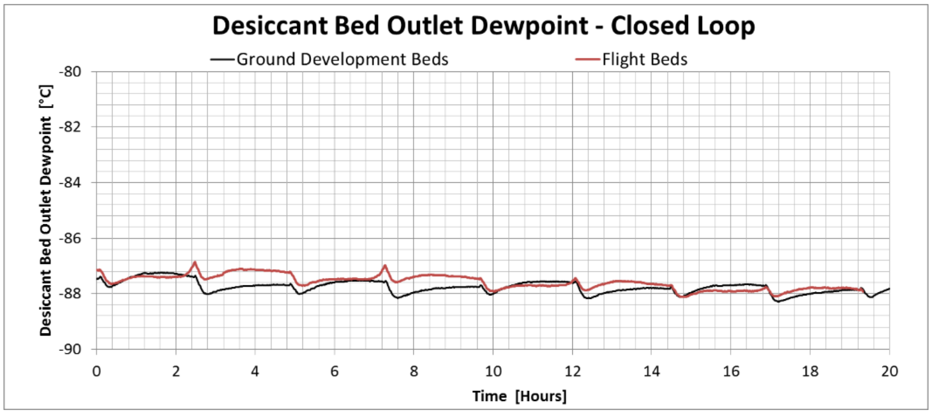

Figure 5. Closed-Loop Desiccant Bed Outlet Dewpoint Comparison

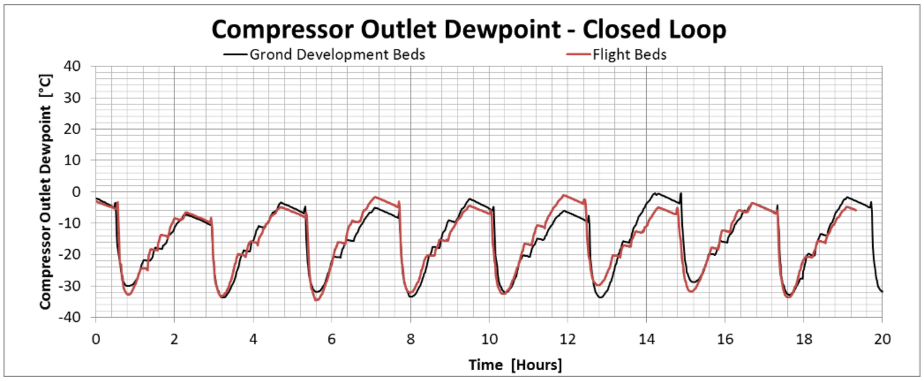

Figure 6. Closed-Loop Compressor Outlet Dewpoint Comparison

Observations:

1. Similar to the open loop testing, closed loop desiccant bed outlet dewpoint measured -88°C and corresponded to less than 1 ppm (part per million) water vapor. This difference is smaller than the accuracy of the precision dewpoint measuring device.
2. The dewpoint measured at the exit of the compressor did not exceed 0°C, which is 16°C below the threshold for forming liquid water.
3. The compressor exit dewpoint increased sharply during compressor operation (as seen in the ratcheting, positively-sloped regions), declined weakly during CO_2 desorption with the compressor off, and declined dramatically when the compressor was off and the CO_2 accumulator mass was reduced using the Sabatier simulator.
4. These tests did not produce data that indicates the flight desiccant beds performed differently than the development desiccant beds.

VIII. Desiccant Bed Pressure Drop

If excess water had existed in the CDRA-4 desiccant beds on ISS, the excess water could have accumulated in the desiccant bed zeolite material, causing attrition of those particles and an increased pressure drop. Because the desiccant beds had not been completely disassembled prior to CDRA-4EU testing, there was no visual inspection of the internal desiccant bed materials that could have indicated dusting. While testing CDRA-4EU, we used internal instrumentation to measure the ΔP across the desiccant beds and manipulated the following pressure measurements (figure 7) to calculate the effective ΔP across the desiccant beds during operation.

- Pressure downstream of Precooler measured by ΔP to atmospheric pressure (accuracy = 6.7 Pa)
- Precooler pressure drop assumed Zero (actual value is believed small and consistent between experiments)
- Blower ΔP (accuracy ~ 13 Pa)
- Inlet Pressure (accuracy ~ 0.267 kPa)
- The graphs in figure 8 were plotted with a 15 point sliding average for clarity due to noise in the ΔP measurement.

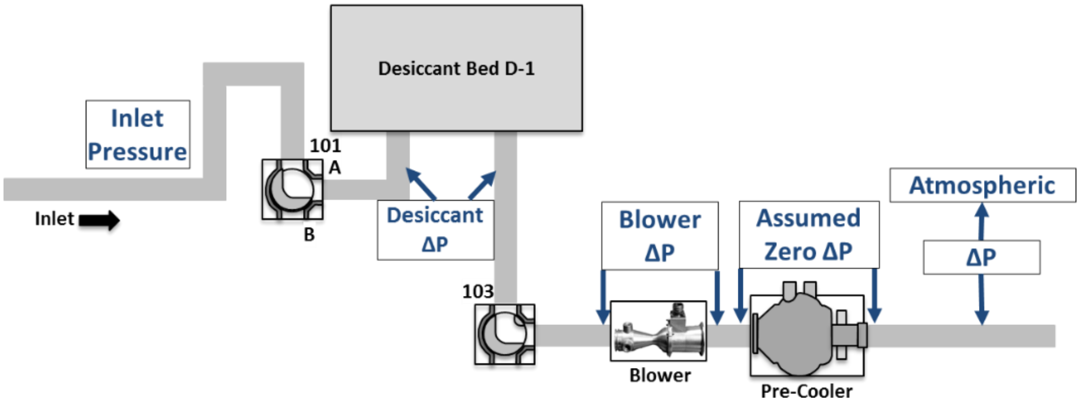

Figure 7. ΔP Measurement Diagram

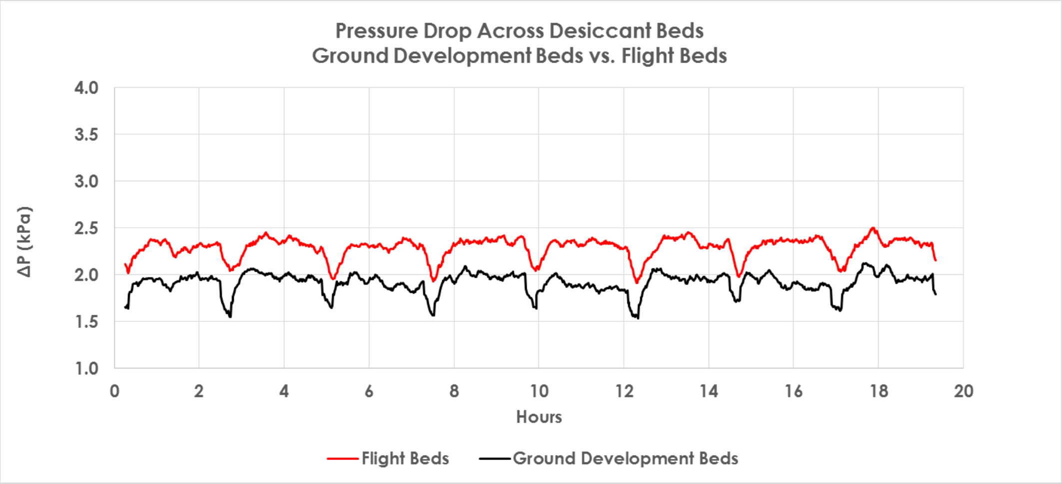

Figure 8. Calculated Desiccant Bed Pressure Drop

Because we lacked a dedicated pre-cooler ΔP measurement and were limited by the resolution of the inlet pressure measurement (ranged for atmospheric pressure), only the relative difference can be quantitatively assessed in this test. The flight beds exhibited ~20% higher pressure drop than the CDRA-4EU beds used as a reference. We performed breakthrough testing in a follow-on program using more precise instrumentation. In those follow-on tests, the flight beds exhibited 22% higher pressure drop than the baseline development desiccant beds, confirming the relative ΔP result measured in this CDRA-4EU experiment. The increased pressure drop on its own cannot prove or disprove the existence of excess water in the flight beds. But the additional measurement may correlate to the visual inspections when the beds are disassembled and analyzed at a later date.

IX. Conclusions

When tested in the CDRA-4EU system using simulated flight conditions, as well as worst case inlet dewpoint conditions, the flight desiccant beds produced dewpoint measurements comparable to the development desiccant beds at the desiccant bed outlet and CDMA outlet. While we could not determine the residual amount of water in the desiccant beds at the initiation of testing, the desiccant bed exit dewpoint measurement did not indicate that excess moisture was transmitted through the beds during nominal operating conditions, and is not a likely candidate (when considered in isolation) for the water found in the Sabatier on ISS.

X. References

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