48th International Conference on Environmental Systems
8-12 July 2018, Albuquerque, New Mexico
ICES-2018-180

EMU METOX Performance Testing

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The NASA Extra-Vehicular Mobility Unit (EMU) has two methodologies for CO_2 removal. The EMU Contamination Control Cartridge (CCC) containing LiOH has been largely phased out in favor of a regenerable silver oxide system known as Metal Oxide (METOX). In 2016, observed decreased performance of the METOX system during Extra-Vehicular Activities (EVAs) led to a Space Station Program to investigate the cause of the performance decrease. The team decided to use a test system originally developed by the Crew and Thermal Systems Division (CTSD) at NASA's Johnson Space Center to support a life extension effort of the LiOH CCCs to support the investigation of decreased METOX performance due to age or usage. This paper will cover the results of this testing and discuss the impact on the future use of CO_2 removal technologies on the EMU and other life support systems.

Nomenclature

ACFM = Actual Cubic Feet per Minute
BTU = British Thermal Unit (~1055 Joules)
CCC = Contaminant Control Canister
CEM = Controlled Evaporative Mixer
CTSD = Crew and Thermal Systems Division
EMU = Extra-Vehicular Mobility Unit
EVA = Extra-Vehicular Activity
g/hr = Grams/Hour
HMS = Human Metabolic Simulator
ISS = International Space Station
JSC = Johnson Space Center
LiOH = Lithium hydroxide
METOX = Metal-Oxide
PLSS = Portable Life Support System
SLM = Standard Liters/Minute
S/N = Serial Number
W = Watts

I. Introduction

The Extra-Vehicular Activity (EVA) program office at NASA's Johnson Space Center initiated an internal investigation in 2016 to determine potential causes and explanations of an observed performance decrease of the CO_2 removal canisters onboard the Extra-vehicular Mobility Unit (EMU) during spacewalks (EVAs) on the International Space Station (ISS). The system in question is known as METOX (Metal Oxide), which consists of a silver oxide sorbent packed into a metal canister. During nominal operation, the system can absorb more than 1.6 lbs. (0.72 kg) of CO_2 (8000 BTU or 8440 kJ metabolic equivalent) during the course of an EVA, keeping the CO_2 partial pressure of the EMU ventilation loop within allowable limits through the course of an EVA. The system also includes a charcoal filter for absorption of trace contaminants within the ventilation loop. The METOX system is regenerable onboard the space station using high temperature gas system to desorb CO_2 from the sorbent bed.

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The METOX system was implemented as a replacement for the Lithium Hydroxide (LiOH) Contaminant Control Cartridges (CCCs) beginning in 2001[1]. The CCCs are required to be repacked on the ground after every use. The desire for greater reusability and self-sustaining operations aboard the ISS drove the development of the METOX system. In operation, the METOX system has less CO_2 absorption capacity than the LiOH system, which was capable of capturing in excess of 2.0 lbs. (0.90 kg) of CO_2 (10000 BTU or 10550 kJ metabolic equivalent) under optimal conditions. The reduction in effective capacity meant that the METOX system often became the limiting consumable during ISS operations. Flight controllers on the ground monitor and track CO_2 partial pressure in real-time throughout the course of an EVA for signs of "breakthrough" which is generally referred to as the time upon which the rate of CO_2 absorption of the canister no longer matches the output of the human, leading to increasing CO_2 levels in the suit. Flight controllers monitoring the trends use simple calculators to predict the EVA time remaining to hit certain CO_2 levels based on past canister performance. In various EVAs leading up to the investigation, canisters exhibited signs of breakthrough sooner than expected, leading to sooner than expected terminations of EVA activity.

The EVA program office tasked JSC's Crew and Thermal Systems Division (CTSD) with performing ground testing of the METOX canisters to aid in the investigation. CTSD used the EMU CCC Ground Test System to perform simulated metabolic profile tests. This system was a modified configuration of the PLSS Development Test System that was already in use supporting a life-extension effort for the LiOH CCCs. Because the CCCs and METOX canisters share a common interface, the system was used without modification. The goal of the testing was to quantify any performance degradation of METOX canisters as seen in the on-orbit hardware and aid in determination of root cause. Potential causes of reduced performance include life-based degradation, contamination due to the on-orbit environment, and on-orbit regenerator performance.

II. Test System Description

The EMU CCC Ground Test System was used to load the METOX canisters with CO_2 by performing a simulated EVA. This system consisted of a ventilation loop that circulated nitrogen at representative EVA pressures, temperatures, and flow rates while adding CO_2 and water vapor in a manner that simulated a crew member's metabolic performance. Figure 1 depicts the general configuration of the test system.

Each canister was mounted in a small vacuum chamber and connected to the EMU CCC Ground Test System using an interface plate that represents the geometry of the METOX/PLSS interface. The test system provided inlet and exit temperature measurements to the CCC test article, as well as over-pressure and negative pressure protection local to the CCC test articles inside of the chamber.

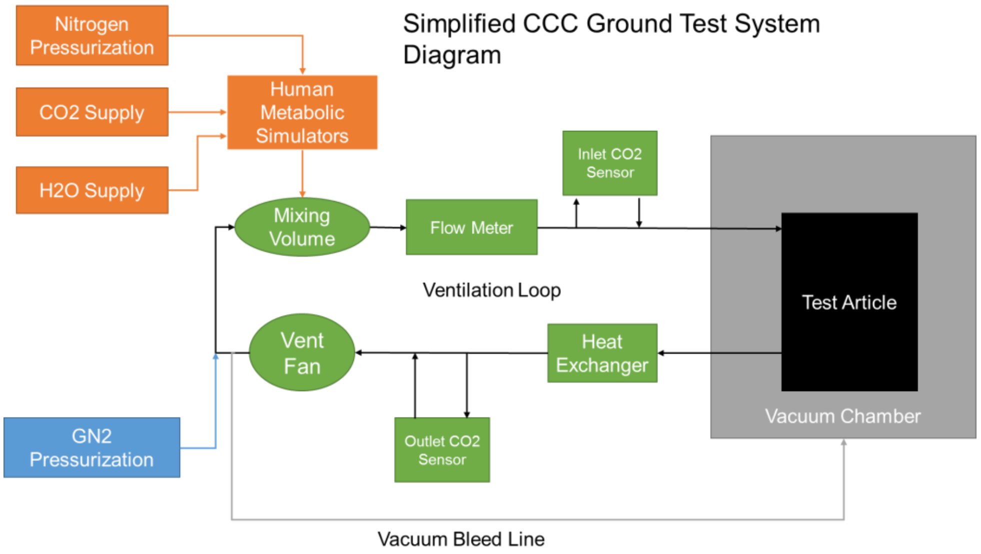

Figure 1: Diagram of the CCC Ground Test System showing the layout of the major components

Outside the chamber, the simulated suit ventilation loop included isolation valves and a pressure drop measurement across the test article. Carbon dioxide sensors and humidity sensors measured test conditions at the inlet and exit of the CCC test article. Other key components included V-cone flow meter, an oxygen sensor, a modified circulating fan, a mixing volume to inject simulated human metabolic products, and a shell and tube condensing heat exchanger. The heat exchanger also featured a condensate collector to assist with a water mass balance calculation.

Pressure control of the loop was achieved through the use of a developmental PLSS regulator and a controlled bleed through a rotameter and metering valve.

Simulated metabolic products, carbon dioxide and water vapor, were injected into the loop through the use of Bronkhorst flow controllers and controlled evaporation mixers (CEMs). These units have successfully demonstrated in recent years of PLSS development the ability to control, measure, and deliver precise amounts of carbon dioxide and water vapor to ventilation loop tests. Data collection was performed through a Labview-based data-acquisition system. All instrument data was logged at 1 Hz intervals and saved to a text database file.

III. Test Profile and Performance Calculation

Each METOX canister was tested using a simulated metabolic profile that averaged 850 BTU/Hr with two brief 10-minute spikes to 2000 BTU/Hr. At the conclusion of the profile, the metabolic rate was held at a simulated 850 BTUs/Hr until the target CO_2 partial pressure was met. Beyond simulating the metabolic output of a human during an EVA, the test profile was also intended to mimic the test profile the METOX system was originally certified to, in order to have a better chance at comparing historical performance data. Figure 2 visually depicts the as-tested profile.

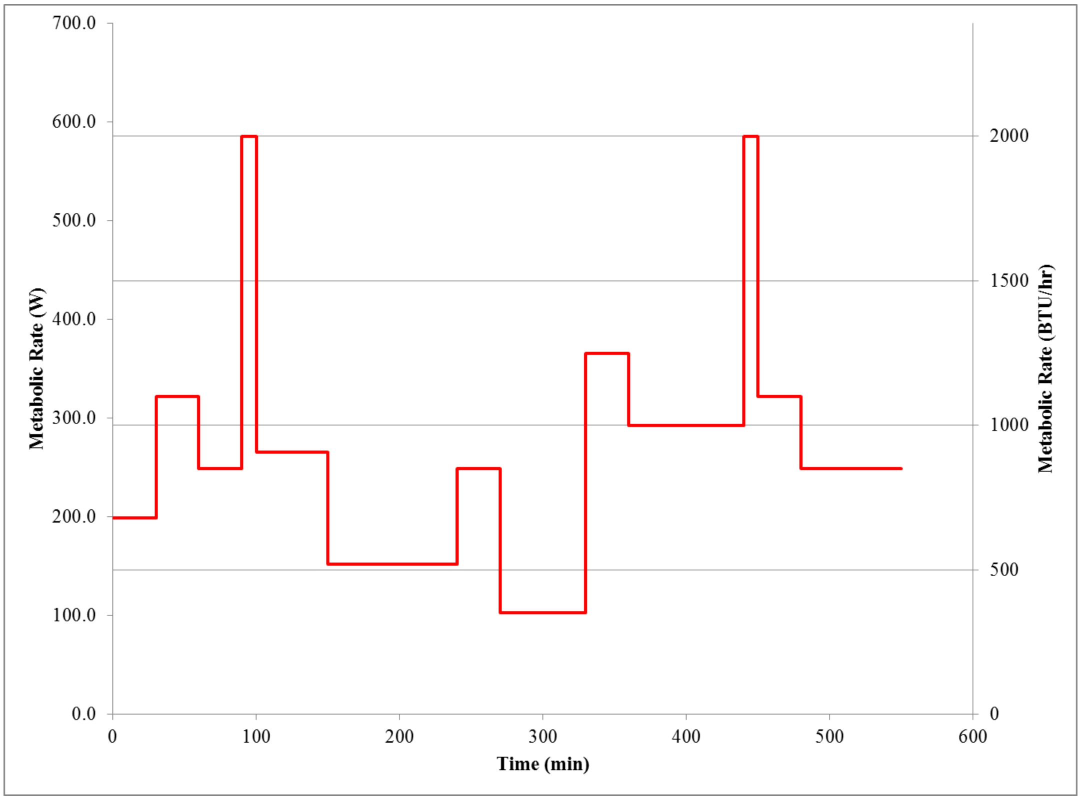

Figure 2: Metabolic Profile for METOX Testing

Table 1 describes the test settings and inputs of the system during the execution of the test profile. Note that while CO$_2$ injection was constant at each setpoint (value given in Standard Liters/Minute) the water vapor injection was varied in real time to maintain an inlet dew point of 50 ± 5 °F (7.2 to 12.7 °C) because the METOX system requires some amount of water to function. Flow rate indicates the gas flow rate of the entire test loop and the chiller cart setting regulates the temperature of the water within the condensing heat exchanger.

Table 1: Test Settings and inputs for profile execution

Test Time (h:mm)	Duration (min)	Qmet (W)	Qmet (BTU/hr)	CO$_2$ (SLM)	Flow rate (ACFM/*ASLM*)	Chiller Cart Setting (°C)
0:00	30	199.1	680	0.520	6.5 ± 0.5 *184 ± 14*	10
0:30	30	322.1	1100	0.842		
1:00	30	248.9	850	0.650		
1:30	10	585.6	2000	1.530		
1:40	50	265.3	906	0.693		
2:30	90	152.3	520	0.398		
4:00	30	248.9	850	0.650		
4:30	60	102.5	350	0.268		
5:30	30	366.0	1250	0.956		
6:00	80	292.8	1000	0.765		
7:20	10	585.6	2000	1.530		
7:30	30	322.1	1100	0.842		
8:00		248.9	850	0.650		

ICES-2018-177[2] describes the how the water and CO$_2$ balance calculations were performed from the raw data for the LiOH CCC ground tests on the same system. This calculation methodology was used in the same manner to produce the final results from the METOX testing.

IV. Results and Discussion

Ten METOX ground tests were performed in total. The tests were performed with four different canisters, and the canisters differed in their processing and usage histories. Canisters S/N 0004 and 0018 were METOX units used in ground testing of the EMU systems. These canisters were tested prior to being flown to ISS to replace canisters S/N 0015 and 0021, which had been used on the ISS for EVAs. These on-orbit canisters were tested on the test system after being regenerated with the on-orbit regenerator as well as twice after being regenerated on the ground.

Table 2 summarizes the results from these tests. Note that many of the tests did not have measurable amounts of condensation collected and that there were scale measurement discrepancies. The pre-test, or initial mass, for canister S/N 0004 was determined to be erroneous and the post-regeneration weight prior to testing was used instead.

Table 2: METOX Testing Summary

	S/N 0018	S/N 0004	S/N 0021 On-orbit Regen	S/N 0021 Ground Regen	S/N 0021 2nd Ground Regen	S/N 0015 On-orbit Regen	S/N 0015 Ground Regen	S/N 0015 2nd Ground Regen
Cycles	37	35	42	43	44	40	41	42
Initial Mass (kg)	13.83	*14.02*	14.24	14.22	14.22	14.17	14.15	14.15
Final Mass (kg)	14.65	14.81	14.97	14.97	14.96	14.89	14.91	14.90
Change in Mass (kg)	0.82	0.79	0.73	0.75	0.74	0.72	0.75	0.74
Condensate Collected (kg)	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Profile Check Points								
Time to 0.426 kPa (h:mm)	8:39	8:34	7:39	7:55	7:51	7:21	8:00	8:00
kJ to 0.426 kPa	7411	7321	6478	6772	6744	6044	6893	6932
Time to 1.0 kPa (h:mm)	9:02	8:55	8:17	8:35	8:28	7:52	8:27	8:27
kJ to 1.0 kPa	7742	7611	7104	7356	7313	6730	7282	7313
Time to 2.0 kPa (h:mm)	9:15	9:05	8:37	8:52	8:46	8:13	8:41	8:41
kJ to 2.0 kPa	7917	7763	7380	7606	7574	7073	7484	7522
Calculated Values								
Total CO_2 Absorbed (kg)	0.68	0.67	0.64	0.65	0.65	0.61	0.64	0.65
Total CO_2 Injected (kg)	0.71	0.69	0.66	0.68	0.67	0.63	0.67	0.67
CO_2 Mass Balance Agreement (%)	*3.3*	*4.1*	*3.6*	*3.5*	*2.8*	*3.0*	*3.5*	*2.8*
Total H_2O Absorbed (kg)	0.10	0.10	0.08	0.09	0.09	0.09	0.10	0.10
Canister Mass Agreement (%)	*3.9*	3.4	*2.5*	*1.1*	*0.6*	*3.1*	*0.8*	*-0.4*

The first notable result is that none of the tested canisters approached the original certified METOX CO_2 capacity figure of 8000 BTUs (~8440 J). In general, good agreement is shown for these test results across different, independent calculations. A CO_2 mass balance was performed on the system where the amount absorbed by each canister based on CO_2 sensor readings was compared to the amount injected into the system via the Human Metabolic Simulators. These system CO_2 balances were in agreement within 4.1% on all of the tests performed, with some tests having as low as 2.8% differences. Canister mass balances were the change in mass taken from the scale readings compared to the CO_2 absorbed and water absorbed (based on the humidity sensor readings) calculations. These also showed good agreement with a maximum difference of 3.9% and a minimum of -0.4%.

These results clearly indicate that the ground canisters performed better than the on-orbit canisters and that the individual canisters performed better after being regenerated on the ground. Canister S/N 00015 improved by approximately 400 Btu (422 kJ) capacity (or 0.08 lbs. (0.036 kg) of absorbed CO_2) and S/N 0021 improved by approximately 200 Btu (211 kJ) capacity (or 0.04 lbs. (0.018 kg) of absorbed CO_2). These improvements could be predicted by the pre-test masses as each canister weighed less after the ground regeneration than it did after the on-orbit regeneration. It should be noted that these results only include a small sample size of two canisters and the values of these differences noted are on the order of the experimental uncertainty of the test set up.

In addition to these trends based on canister history, these tests showed good repeatability on both the test system and canisters when the canisters were treated in the same manner. The table compares the canister results between tests after the first and second ground regenerations. These comparisons show excellent repeatability with most comparisons being less than 1% different. Any parameter with more than 1% difference is due to comparing very small measured values. For example, the scale used to measure the canisters only had a resolution of 0.02 lb (0.01 kg). When comparing 1.66 and 1.64 lbs. canister masses, this difference is equal to the resolution of the instrument. Also, the difference between 0.20 and 0.19 lbs., may be 5.67%, but this is a very small actual mass difference.

Figure 3 shows the breakthrough curves for all of the METOX tests. This is the carbon dioxide level at the exit of the canister as read by the CO_2 sensor. As shown in the previous summary table, it is evident that the ground canisters held the most CO_2 and lasted the longest. The green and burnt orange arrows show the shift, or increase, in performance after canisters S/N 0015 and 0021 were regenerated on the ground.

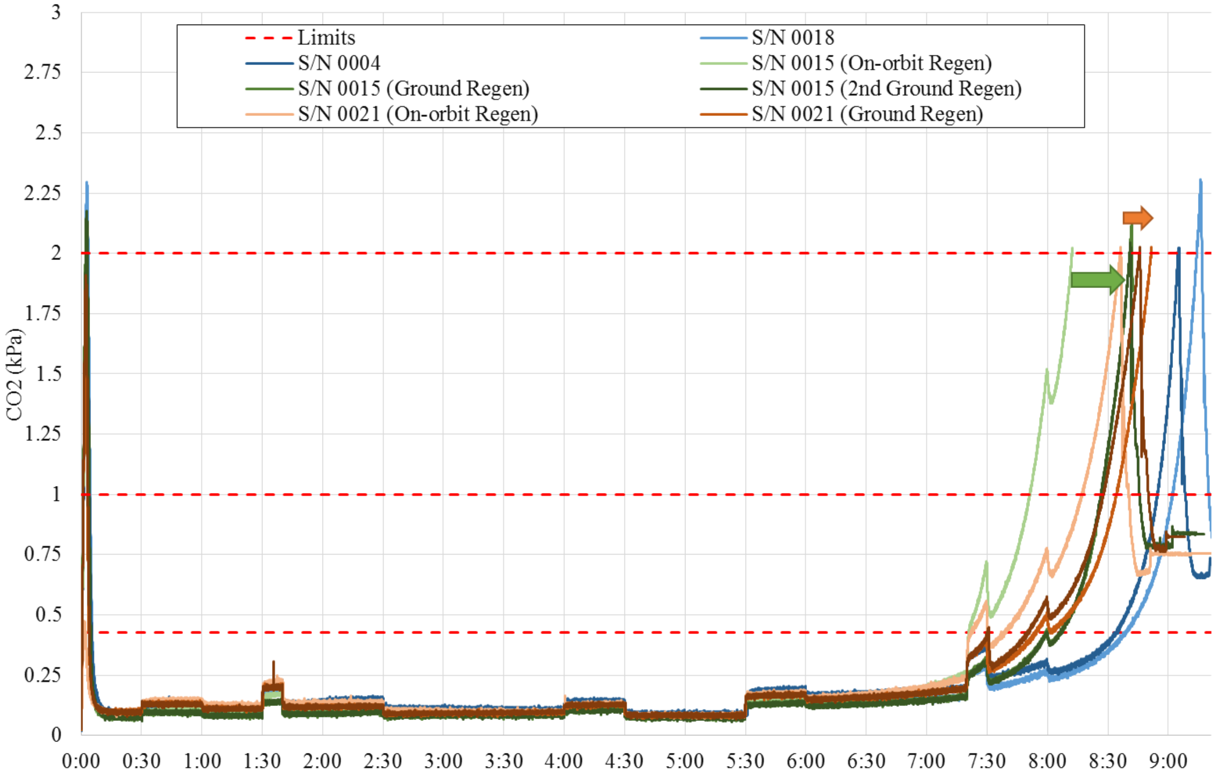

Figure 3. CO_2 Breakthrough Curves for All Tests

These graphs clearly show the improved performance of the canisters from the ground regeneration. They also show the repeatability of the canisters and test system. Both tests using canister S/N 0015 after ground regeneration were so identical that it is difficult to see both curves. The S/N 0021 curves for the ground regeneration are believed to be a slightly different due to minor human error in entering the metabolic profile into the carbon dioxide injection mass flow controllers. Figure 4 shows a comparison of the capacity of each canister in each test.

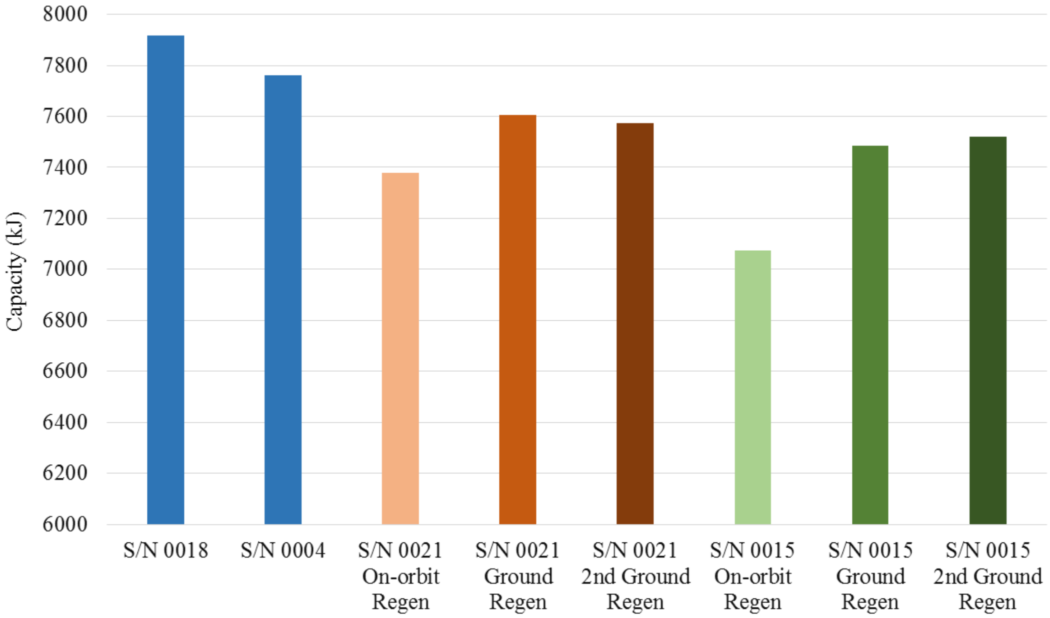

Figure 4: Canister capacity comparison

Again, the ground canisters are better by between approximately ~300 to 800 BTUs (315 to 850 kJ) than canisters that have been on-orbit, even after ground regeneration. The ground regeneration provided 200 – 400 BTUs (~210 to 420 kJ) improvement from on-orbit regeneration. It does not appear that there is any additive benefit for repeated regeneration cycles on the ground and the canister capacity between the two ground regenerations was -0.5% and 0.4% in agreement for canisters S/N 0015 and S/N 0021, respectively. Previous analysis of METOX regeneration performance indicates that the difference may be due to the higher background concentration of CO_2 in the heated air that is used in the regenerator when the canisters are on-orbit. The ISS atmosphere does operated at elevated CO_2 levels as compared to normal lab conditions on Earth and ambient air is used in the regeneration process. It should also be noted that the performance improvement between the ground and on-orbit regeneration does not account for all of the performance degradation that has been seen in the METOX fleet, which has been on the order of 1000 BTU (~1050 kJ) of capacity. Based on the data collected in this test series, post-regeneration mass appears to provide an indication of capacity of each canister.

Figure 5 shows a linear trend between the starting mass (pre-loading) and the capacity of the canister demonstrated during each simulated EVA profile. The canister S/N 0015 test point from the on-orbit regeneration appeared to be an outlier and was removed from the graph. With that test point removed, the linear relationship has an R^2 value of 0.8. Canister S/N 0015 generally weighed less than canister S/N 0021 and also performed less. Something about this canister's operation on the ISS could have caused this out of family low performance, or the mass discrepancy could have been an undetected scale measurement error.

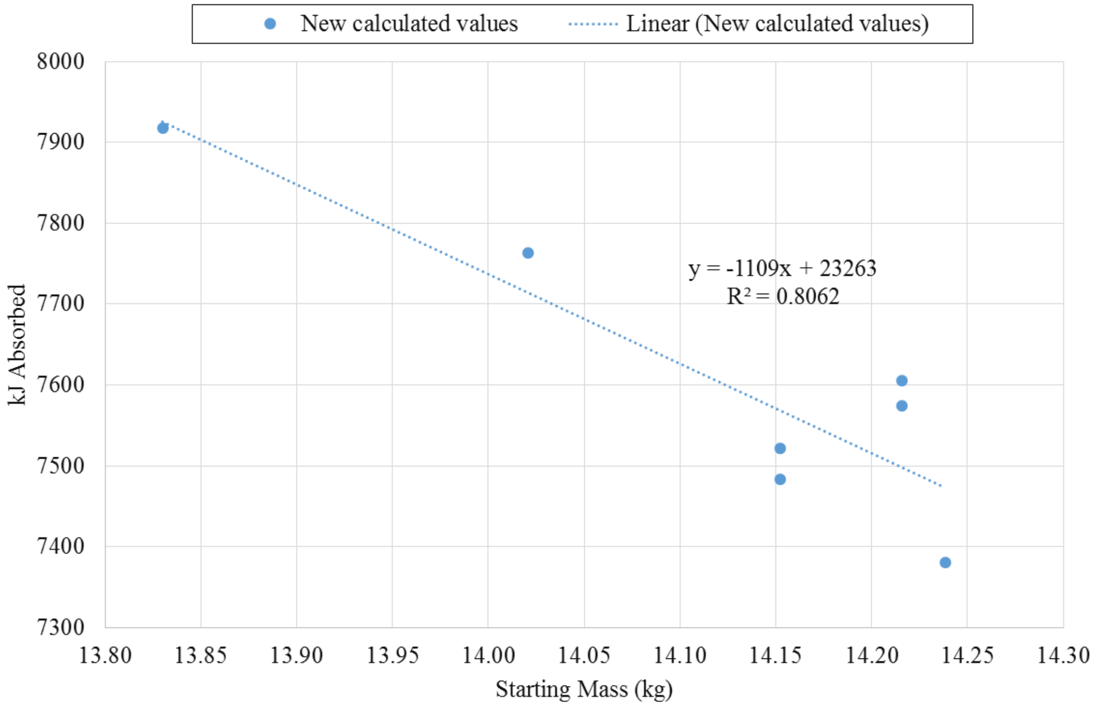

Figure 5: Canister pre-test mass versus capacity to 2.0 kPa CO_2

These trends in performance led to additional analysis of the test results to determine if the data set could provide indications of what was occurring with each canister. Minor changes in the exit temperatures were noticed during testing. Inlet temperatures were steady throughout all of the tests and generally dictated by the temperature of the room surrounding the test system.

Figure 6 depicts the exit temperatures of the gas from the canister, and reveals some interesting patterns. Each metabolic profile consisted of two temperature peaks. The first was during the starting period of the test and the second was shortly after the final 2000 Btu/hr (585.6 W) step in the profile. The graphs shows that during the first temperature peak there are three groups, which directly correspond to the usage history of the canisters. The canisters that were regenerated on-orbit had the lowest capacity and also had the lowest peak exit temperature during the startup portion of the profile. Due to the exothermic nature of the reaction, this may indicate that less of the carbon dioxide and/or water was being absorbed at this time. These canisters absorbed the lowest amounts of carbon dioxide throughout the profile. Next, the ground canisters have a temperature peak that is between the on-orbit regenerated and ground regenerated on-orbit canister test points. These canisters absorbed the highest amounts of carbon dioxide during the profiles. Finally, the on-orbit canisters that were regenerated on the ground showed the highest peak temperatures during the startup portion of the profile. The grouping on this set of tests was very tight for all four tests, which included two ground regenerations on each of the canisters. This first temperature peak for the on-orbit canisters with ground regeneration occurs prior to the maximum CO_2 loading rate per the metabolic profile. This indicates that the temperature is a result of the water reacting with the METOX.

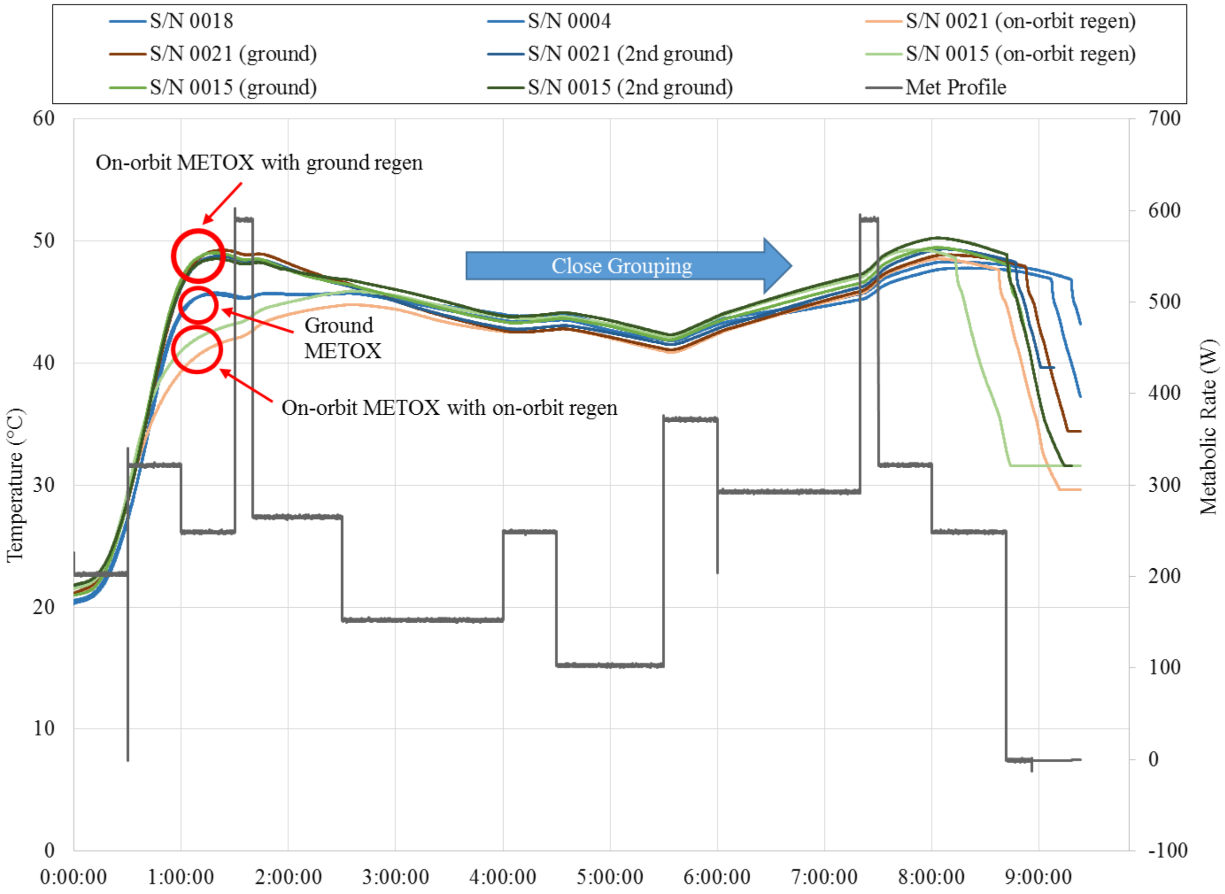

Figure 6: Canister exit temperatures for all tests

A similar grouping was observed for the water absorbed by each canister. Figure 7 shows how much water was absorbed by each canister during each test. The values are shown as negative because this analysis was originally performed on LiOH canisters that produce water instead of absorb water.

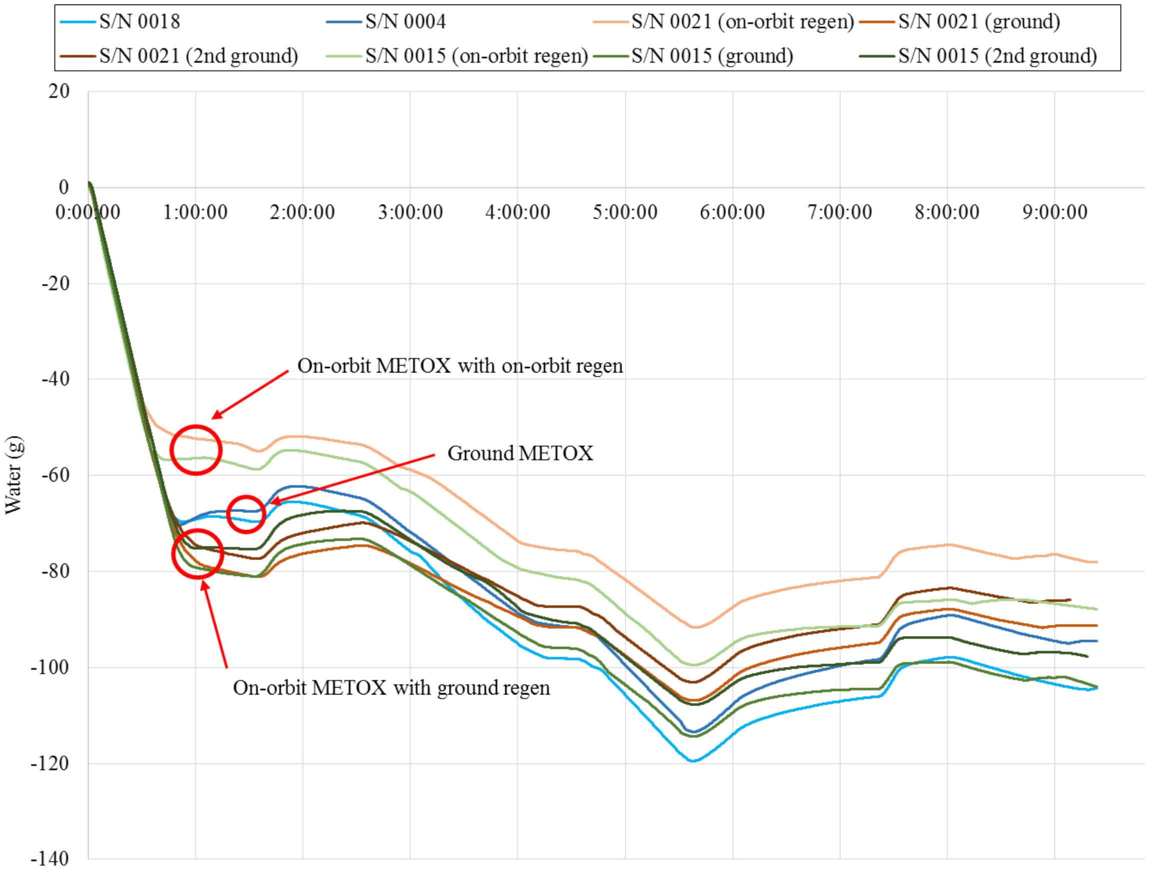

Figure 7: Canister water rejection for all Tests

The on-orbit canister with the on-orbit regeneration absorbed the least amount of water. The ground canisters absorbed more than the on-orbit regenerated canister but less than the ground regenerated canister which in turn absorbed the most water. This trend matches the exit temperature trend based on seeing the highest exit temperatures from the canisters based on the amount of water that was absorbed. This trend is consistent with an exothermic reaction between the water and the METOX sorbent. It is noted that the on-orbit regenerated canisters absorbed less water and less carbon dioxide than the other canisters. However, between canisters S/N 0015 and S/N 0021, canister 0021 absorbed more CO_2 but canister 0015 absorbed more water consistently between all three runs.

Water injection during the test was performed manually to maintain a 50±5°F (7.2 to 12.7 °C) inlet dew point to the canister. Based on this manual and canister performance feedback based method, different amounts of water were injected. These injection patterns also match the temperature and water absorption trends and are depicted in Figure 8.

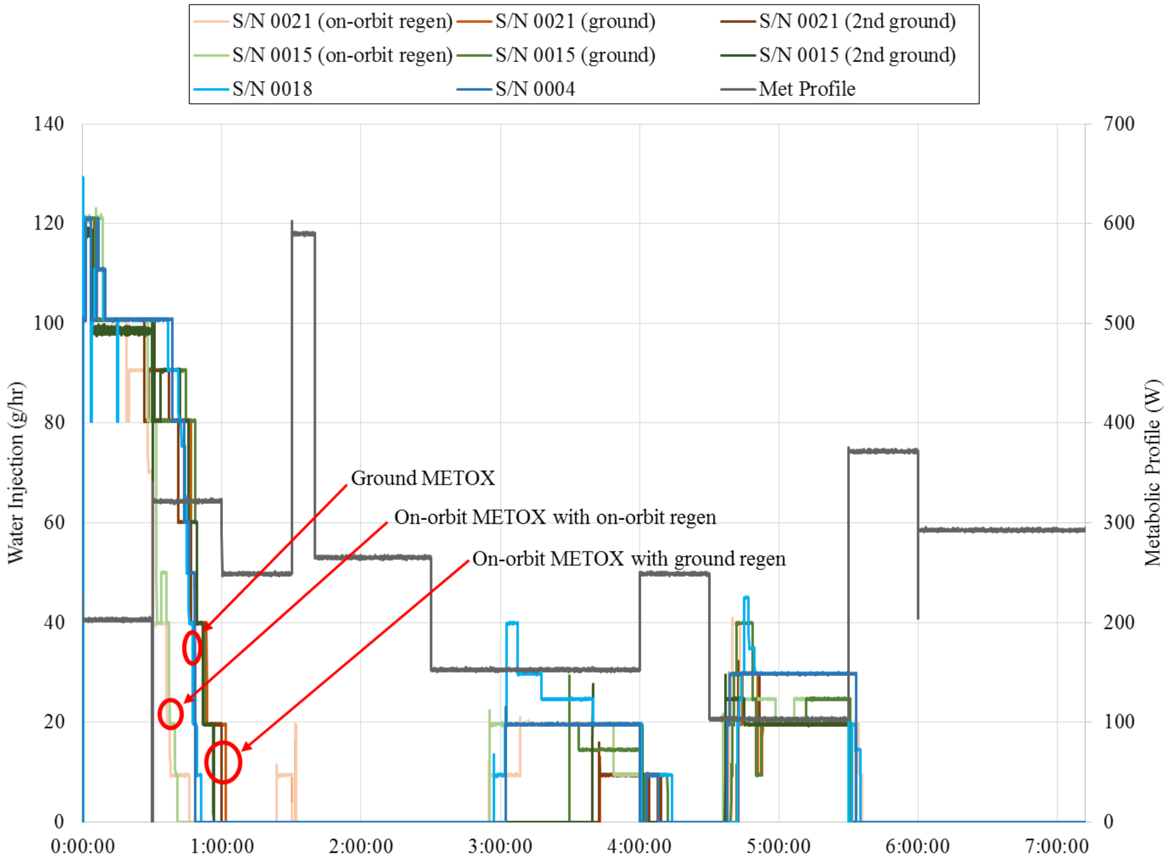

Figure 8: Water Injection for All Tests

Less water was injected at the beginning of the profile for the on-orbit regenerated canisters than the others. The ground canisters were next and the ground regenerated on-orbit canisters required the most water at during start up. Canisters 0015 and 0021 both took on more water at the beginning of the profile, but then needed less water later in the profile to maintain the humidity conditions in the loop.

V. Conclusion

While the results were not conclusive, the testing revealed differences in performance between the METOX canisters used for ground testing and the canisters used on the ISS for EVAs. The reasons for the differences are not clear, but the test demonstrated that the test system can produce repeatable results that corresponded with the observed on-orbit performance. This data was used by the EVA program office as part of the investigation and the test series was also replicated in part at UTC Aerospace Systems with differing results. At the time of writing, the EVA program office was moving to replace the METOX canisters nearing the end of their operational life. Contamination of the sorbent beds, on-orbit CO_2 concentration, and age of the sorbents were considered the most likely causes for the performance reduction by the investigation board.

Acknowledgments

The authors would like to acknowledge Robert Boyle and Mallory Jennings from the Johnson Space Center as the EMU Subsystem Management Team. They provided excellent direction and support to guide the test program requirements as well as aiding in processing the hardware. Victoria Margiott and Tom Chase from United Technologies Aerospace Systems provided technical background and review.

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