NASA Exploration Toilet Hardware Technical Challenges and Accomplishments

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The Universal Waste Management System (UWMS), ISS operational nomenclature "Toilet" was initially installed on the International Space Station (ISS) in 2020 with final installation completed in 2021. Technical progress continues to be made with each on-orbit operation and will ultimately culminate with nominal US crew use of the hardware on ISS.

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During 2024, another attempt was made to perform the Artemis II Demonstration on ISS with a re-flight of the Dosing Assembly using original components. This paper discusses the issues encountered when the Dosing Assembly failed to dispense pretreat as well as a subsequent failure to start of the UWMS and the on-orbit troubleshooting resulting in the removal and return of the controller. A summary of ground troubleshooting of the controller (which is the Orion common controller used in the Orion vehicle for numerous systems) as well as planned repairs is discussed. An updated design of the commode seat and fecal bag for Artemis-2 UWMS was demonstrated on ISS and a summary of the hardware, results and selection of seat for use on Artemis-2 is included in the paper. Details of air flow of each option of the updated seat, original seat along with permutations for original UWMS Fecal Bag, Updated Fecal Bag and current WHC ACY Insert (Russian design Fecal Bag) are described as well as crew feedback on the evaluation. Implications for all work on Orion missions will be detailed.

Nomenclature

AES	=	Advanced Exploration Systems
ACY Insert	=	Russian designed fecal bag
ARED	=	Advanced Resistive Exercise Device
COTS	=	Commercial-Off-The-Shelf
CCM	=	COTS Conductivity Monitor
DFS	=	Dual Fan Separator
ECLS	=	Environmental Control and Life Support
ECLSS	=	Environmental Control and Life Support System
EDU	=	Engineering Development Unit
EEE	=	Electrical, Electronic and Electromechanical
FPGA	=	Field Programmable Gate Arrays
FY	=	Fiscal Year
GMT	=	Greenwich Mean Time
GSFC	=	Goddard Space Flight Center
HLS	=	Human Landing System
ISS	=	International Space Station
JPL	=	Jet Propulsion Laboratory
JSC	=	Johnson Space Center
LED	=	Light Emitting Diode
LOO	=	Lavatory On Orbit
LR	=	Logistics Reduction
MCO	=	Mars Campaign Office, AESMD
NCR	=	Non-conformance Report
NASA	=	National Aeronautics and Space Administration
NESC	=	NASA Engineering and Safety Center
OBF	=	Odor Bacteria Filter
PEEK	=	Polyether Ether Ketone
RTRC	=	Raytheon Technology Research Center
SpX	=	Space X
TAF	=	Toilet Air Filter
TIH	=	Toilet Integration Hardware
TD	=	Technical Demonstration
UPA	=	Urine Processor Assembly
UWMS	=	Universal Waste Management System
WHC	=	Waste and Hygiene Compartment
WMS	=	Waste Management System on Orion

I. Introduction

NASA contracted Collins Aerospace to develop an updated toilet for use in exploration missions. It is desirable to have a common core hardware assembly that only requires modest modifications for adaption to multiple exploration microgravity missions. The goal of the new system is to reduce mass and volume, both of which are key objectives of successful hardware used for long-range missions. Additionally, the new toilet has the goal of improving usability for female crewmembers. The Universal Waste Management System (UWMS) project built on previous toilet designs and delivered a toilet for the International Space Station (ISS) and the first crewed Orion mission.[1] The operational nomenclature (Op Nom) of both units is Toilet and, in this paper, UWMS (the contract name) and Toilet are used interchangeably. Delivery of the Orion Toilet (Figure 1) was in December 2019 and the unit was installed into the Artemis-II vehicle in March 2021 for launch in 2026. The ISS unit, seen in Figure 2 along with the Toilet Integration Hardware[2], launched to ISS in October 2020. The ISS unit was installed and is awaiting the start of nominal operations on ISS in Node 3 pending resolution of technical issues. A limited checkout was performed in October/November 2021[3] and an Artemis-II Demonstration (meant to mimic the Orion Artemis mission in length and number of crew) was started in January 2023 but was stopped after 3 days due to a failed dose pump.[4]

Figure 1. Orion UWMS installed in Artemis-II vehicle.

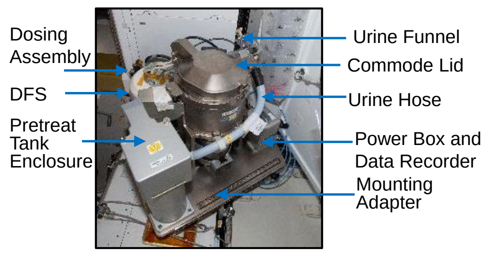
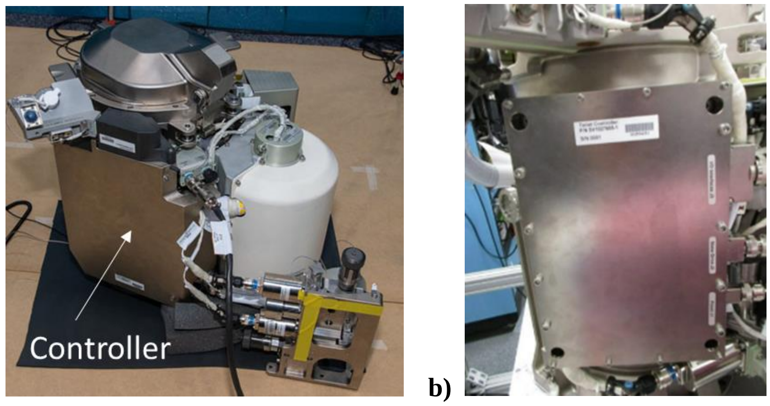


Figure 2. ISS UWMS with Toilet Integration Hardware in Node 3, ISS.

The UWMS project's two toilet units have key goals for a reduction in mass and volume over previous toilets used in space vehicles. The ISS UWMS (Toilet) is 65 percent smaller and 40 percent lighter than the current ISS toilet used by US crew in the Waste and Hygiene Compartment (WHC.) The Orion UWMS (Toilet) is 61 percent smaller than the toilet used on Shuttle missions. Air flow to aid in the collection of urine and fecal material and odor control is provided by a dual fan separator (DFS) which also serves to remove air from the urine/pretreat stream. Combining the two fans used in previous toilet designs into a motor arrangement with a single fan housing (separate impellers) provides much of the resultant reduction in mass and volume. The unit uses a simple startup operation with no need for an external control panel that turns on the unit either with removal of the urine funnel or lifting the commode lid.

The UWMS project adopted the Orion "common controller" for use in both the ISS and Orion units, seen in Figure 3, a) and b). In this system, power conditioning, control, failure detection & notification, and data processing are performed by a single controller. There is a RS-422 serial interface which contains UWMS health and status data. per Collins document #an19-093A, "Controller Behavior for the Universal Waste Management System"

"The UWMS Controller determines the actions that the system takes and controls the responses and indications required by the user. It is therefore a key part of the system's fault detection, isolation, and indication scheme. There are two UWMS configurations: the -1 configuration which is the ISS unit, and the -2 configuration which is the Orion unit. The Controller Field Programmable Gate Arrays (FPGAs) differ for the two configurations; version -006 is the ISS FPGA, while version -004 is the Orion FPGA." Both UWMS Units share many common controller circuits with only minor differences. Because of this, the issue seen on the ISS unit has potential implications for the Orion Artemis-II unit.



a) b)

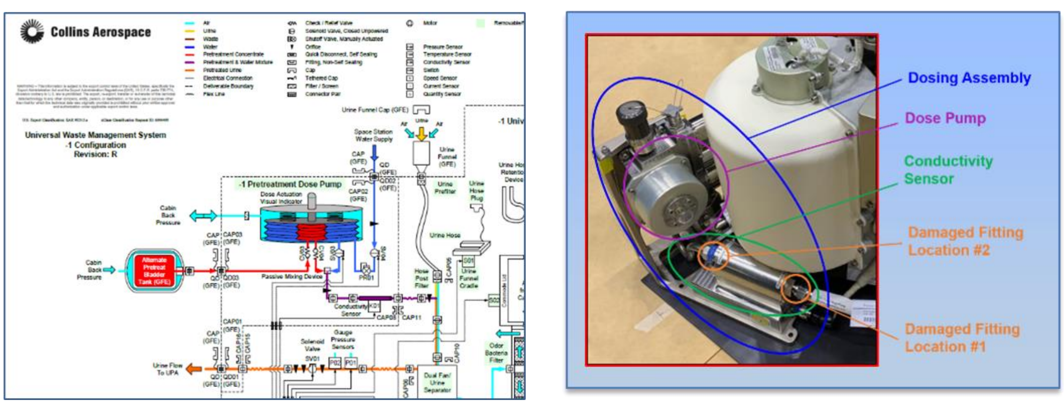
Figure 3. a) and b). Controller location on UWMS, a) shows controller on UWMS during environmental testing, b) closeup view of controller on UWMS.

II. Second Attempt of Artemis II Demonstration on ISS

NASA's need for additional data for the Orion Artemis II mission drove the use of UWMS on ISS to mimic crew use on Artemis II for a duration of 10.5 days and crew size of four. The Artemis II Demo was attempted in 2023 and problems were found with the dosing assembly. Operations of UWMS on ISS were limited by the non-functional dosing assembly, currently in redesign on the ground. Because of the need for these, NASA attempted a second demonstration on ISS using a spare dosing assembly with the same configuration as the original hardware. A verify operational status test was performed in January 2024 and toilet performed nominally.

III. Dosing Assembly

Pretreatment of the urine is performed in both units to stabilize the urine for processing on ISS or venting on Orion. Orion uses Oxone, a heritage solid form for urine treatment used on Shuttle for short mission durations such as also planned for Artemis-II. For the ISS unit, a strong acid solution of phospho-chromic acid is used in liquid form. A nested bellows pump uses ISS water bus pressure to expand the bellows which draws pretreat concentrate solution in as the water bellows fills. Actuation of the dose pump dispenses both fluids, water and pretreat concentrate, into



a) b)

Figure 4. a) UWMS flow path for urine and pretreatment, b) UWMS dosing assembly hardware.

the urine stream. See Figure 4, a) flow path and b) for dosing assembly hardware identification.

A. Re-flight / Launch of Spare Dosing Assembly

The Orion program needs data on consumable use rates, reliability of components, and input from the ISS crew on the user interfaces before launch of Artemis II.[5] To meet the need for data, NASA launched the spare dosing assembly that is in the original configuration to ISS to attempt another Artemis II demonstration on ISS of the UWMS hardware with crew usage. Assembly and testing were started in late calendar 2023 and the hardware was delivered to NASA on February 14, 2024 (Figure 5) for launch to ISS.

Figure 5. UWMS spare dosing assembly.

B. Discovery of Issue

In preparation for the start of the second attempt for the Artemis-II Demo on ISS, on-orbit functional testing was performed in mid-May 2024. Procedures included dispensing of multiple manual doses (made up of pretreat concentrate and water as previously described) to purge the new pretreat hose and internal UWMS piping of a diluted pretreat concentrate, pretreat lite, that the hardware was filled with for launch only. It was estimated that a total of 51 doses of 3.3ml each would be needed to fully purge the system and begin acceptable dosing with the mixture of pretreat concentrate and water, as shown in Figure 6.

Color	Part	Volume	mL Per Dose	# of Doses
(light blue)	PT Hose	153 mL	3.3 mL	~46.4
(green)	Dose Pump Inlet	10.96 mL	3.3 mL	~3.4
(purple)	Dose Tube and Conductivity Sensor	20.43 mL	55.7 mL (52.4+3.3)	~0.37
(red)	CCM to Fill Sensor Manifold	69.62 mL	55.7 mL	~1.25
Total		254.01 mL	--	~52 doses

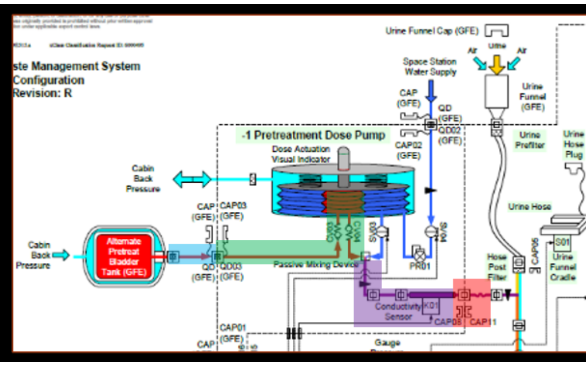


Figure 6. Volume and number of doses needed to purge UWMS of pretreat lite.

Two indicators were used to evaluate when purging was completed, and dosing started. An updated COTS Conductivity Monitor (CCM) was installed which indicates the conductivity of the pretreat solution at the outlet of the dosing assembly. Also, during the manual doses a comparison is done using the pre-dose pressure with the outlet valve closed. This captures residual bowl pressure and post-dose pressure. The difference in these measurements can be

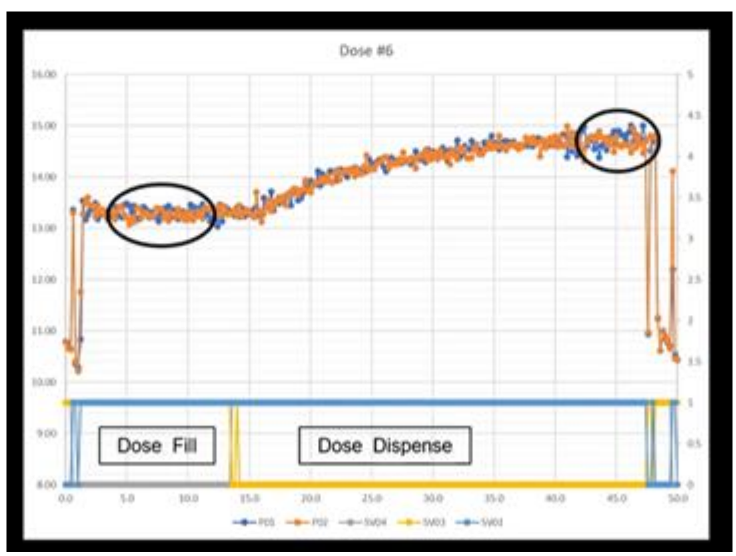


Figure 7. Ideal profile shown from GMT 294, dose 6.

compared to known values based on volume and density of the fluid (noted as the separator delta-pressure). Ideal profile is shown in Figure 7 which shows pressures recorded during dose fill and dose dispense.

After 70 manual doses, the CCM read ~0.0 mS/cm consistently indicating only water in the lines. The separator delta-pressure readings agreed with that condition suggesting only water is entering the bowl. A visual inspection by crewmembers of the Dose Pump Pretreat Hose Quick Disconnect indicated no pretreat was present. Pretreat concentrate (dispensed by dose pump) is a dark orange-red, when diluted with water during dosing, it goes to a dark yellow-orange (pretreat.) Pretreat Lite (used for launch) is a light-yellow fluid. Water has no color which in this case indicated no presence of pretreat solution of any concentration.

The team revisited the fault tree from the previous failure of the dosing assembly for potential causes listed below in Table 1.

Table 1. Fault Tree Potential Causes

Anomaly	Resulting Condition	Toilet Response
CV03 Failed Closed	Blocked Pretreat Path	No Pretreat in Dose.
CV04 Failed Closed	Blocked Pretreat Path	No Pretreat in Dose.
CV03 Failed Open	Pretreat Bellows Breathing into and out of PT Tank	No Pretreat in Dose
CV04 Failed Open	Pretreat Bellows Breathing into and out of Dose Tube/ Conductivity Sensor	No Pretreat in Dose
CV03 Leak	Pretreat Bellows Breathing into/out of PT Tank	Lower Pretreat in Dose
CV04 Leak	Pretreat Bellows Breathing into/out of Conductivity Sensor	Lower Pretreat in Dose
Pretreat Bellows Failure	Pretreat Bellows fills with water	No Pretreat in Dose Separator Fill Outside of Fill Phase
Gas Trapped in Bellows	Lower Bellows Pretreat volume	Up to10% decrease in PT volume
Pretreat Bellows Leak	Pretreat Bellows fills with water	Lower Pretreat in Dose

Additional troubleshooting on-orbit in 2024 was considered to further identify the cause of the lack of pretreat solution. These tasks were scheduled to begin in July 2024. It was assumed that the lack of dispensing of pretreat was related to a failure of the check valves in the dose pump although it was not clear if the failure was a Fail Open of CV-03, Fail Closed of CV-03 inlet check valve or related to a failed state of CV-04, outlet check valve. The troubleshooting was halted due to the controller technical problem detailed below. The dosing assembly was returned to Earth for further testing.

IV. Air Flow Test of Updated Fecal Bag and Commode Seat

A. Description of New Hardware

Using crew feedback from the aborted Artemis II Demo and previous uses of UWMS, the seat and fecal bag for UWMS were redesigned. The design was based on early designs for the Human Landing System (HLS) Lavatory On-Orbit (LOO) project.[6] The seat allows the fecal bag to be installed over the seat so it can contact the body during use. The new fecal bag is a smaller volume and has a more crew accessible closure method. The redesign and evaluation allow the Artemis II UWMS to be upgraded before launch. Evaluation on ISS will confirm air flow and crew accessibility.

The Russian WHC ACY opening with the seat lifted out of the way is 4" in diameter which is equivalent to the smaller of the UWMS seats provided. Crew uses WHC ACY in this manner to avoid excessive cleaning needed with the ACY seat. UWMS originally included a 4” seat and a 5” seat (referring to the opening size.) The HLS LOO seat is 4.3" in diameter. The updated seat opening matches the current WHC opening (4”) which the crew prefers. Two designs were developed. Both have the same interface and bag attachment. The second design has an extended section to direct air flow down the length of the bag. Seats are seen in Figure 8. Testing is needed to validate which design will be chosen to fly on Orion’s Artemis II mission.

a) b) c) d)

Figure 8. a) Russian WHC use with fecal bag, b) Orion UWMS with original 5" seat and original UWMS fecal bag installed, c) LOO seat design with fecal bag installed, d) Updated seat with updated fecal bag (design #2).

The fecal bag has a significantly reduced volume based on crew comments that the size was too large. The fundamental design change is the location over the seat which mimics the WHC arrangement. The bag also utilizes a drawstring closure which is very similar to the WHC design. These design updates were made at crew request. Fecal bags are shown in Figure 9.

Testing is needed to validate air flow, efficiency, and actual use in micro-gravity with air flow. A "dry" test with only air flow (no crew use) was performed with the hardware to evaluate the updated designs with a follow-on evaluation for crew use to follow.

a) b) c) d)

Figure 9. a) Original UWMS fecal bag, b) Russian ACY Insert, c) LOO fecal bag, d) Updated fecal bag.

B. Testing Plan for On-Orbit Air Flow Evaluation

Testing of the updated designs of the fecal bag and commode seat was done on-orbit using UWMS in June 2024 with UWMS on but was only an air flow evaluation. No actual crew use (defecation or urination) was performed during the evaluation. The crewmember was asked to tape the sides of the seat carrier to force the air inlet down the interior of the seat/bag combination. The original design bag placement was under the seat and air flow was directed under and above the seat seen in Figure 10 a). The updated design attaches the fecal bag around the top of the seat with an elastic closure. The seat is grooved to hold the bag in place.

a) b) c)

Figure 10. a) Original 5" Toilet Seat, b) 4" Toilet Seat, Grooved with Tube, c) Overhead view showing tape locations and placement of tissue for test.

Testing was done with the following iterations (shown in Table 2.) Two new designs were evaluated (4" Grooved Seat and 4" Grooved Seat with Tube) as well as the original seat designs (4" Toilet Seat and 5" Toilet Seat) and a test with no seat, bag only. The original Fecal Bag, the Russian ACY Insert and the updated design, Fecal Bag, Elastic, 7" were tested. The crew member provided a video of the testing along with commentary. As noted, the ACY Insert (Russian bag used on the Russian toilet) compared favorably with the updated design combination of the 4" Toilet Seat, Grooved with Tube and Fecal Bag, Elastic, 7". The Orion program does not have access to Russian hardware, so the ACY Inserts are not available for use on Artemis II.

C. Results of On-Orbit Test

Results are shown in Table 2. The crew member performing the test used a balled-up tissue to simulate a fecal solid. The 4" Toilet Seat, Grooved with Tube and the Fecal Bag, Elastic 7" was the most favorably viewed by the crew member performing the test and another crew member who was asked for opinions. The crew member concluded that the ACY Insert (Russian version of the fecal bag with solid sides and holes in the bottom) is ideal with or without the tube and with the air inlets taped off. Other combinations of bags and seats all had some degree of bouncing/ricochet of the fecal simulant (balled up tissue) within the bag. Test #3 with the taped openings, 4" grooved seat with tube, and elastic bag did have "good results" with some bouncing and seemed to get the best review other than the ACY Inserts.

Table 2. On-Orbit Airflow Test Results with Updated Seat Design.

Test	Seat	Fecal Bag	Fecal Bag Placement	Crew Feedback / Observations
1	No Seat, Bag Only	Fecal Bag (old)	n/a	tissue goes to bottom, some but not much bouncing
2	4" Toilet Seat	Fecal Bag, Elastic, 7"	Over Seat	tissue goes to bottom, bounces up, does not stay at bottom
3	4" Toilet Seat, Grooved with Tube	Fecal Bag, Elastic, 7"	Over Seat	tissue goes to bottom, stays at bottom "sucked it right down—it sits there"
4	4" Toilet Seat, Grooved with Tube	ACY Insert (WHC)*	Over Seat	tissues goes down fast, stays at bottom
5	4" Toilet Seat, Grooved	Fecal Bag, Elastic, 7"	Over Seat	tissues goes to bottom, bounces up, does not stay at bottom
6	4" Toilet Seat, Grooved	ACY Insert (WHC)*	Over Seat	tissues goes down fast, stays at bottom
7	4" Toilet Seat	Fecal Bag (old)	Under Seat	tissue stays at top attaches to seat, does not go down
8	4" Toilet Seat	Fecal Bag (old)	Over Seat	overwrap makes hole shallow, bounces at the bottom
9	5" Toilet Seat (old)	Fecal Bag (old)	Under Seat	goes down, bounces, does not settle, significant bouncing
10	5" Toilet Seat (old)	Fecal Bag (old)	Over Seat	tissue goes down slowly, does not settle, some bouncing

D. Down Select and Comments from Stakeholders

Results of the on-orbit testing were shared with the crew community at the Artemis crew tag-up. Crew member who performed the test spoke with Artemis II prime crew members who concurred with using the recommended seat selection as indicated from the on-orbit testing results, 4" Toilet Seat, Grooved with Tube and the Fecal Bag, Elastic 7".

E. Status of New Hardware for Artemis II

Based on crew opinion detailed above, the Orion program is building replacement fecal bags and seat in these updated designs for Artemis II. The hardware is in production and delivery is planned for April 2025. The seat will be installed into the Artemis II UWMS unit prior to launch and the fecal bags will be stowed in place of the original fecal bags currently manifested. Final acceptance by Orion includes a slight mass increase of the seat shown in Table 3.

Table 3. Increased mass for Orion UWMS with updated seat and fecal bag designs.

Component	Mass (grams)
UWMS 5" Seat	463.57
4" Grooved Seat	421.07
4" Grooved Seat with Tube	649.15
UWMS Fecal Bag	9.98
Updated Fecal Bag	9.98
UWMS Seat + Bag	472.98
Updated Seat + Bag	659.13
Increase in mass	***186.15***

V. Controller

A. Discovery of Fail-to-Start Condition on UWMS

Additional troubleshooting of the dosing assembly was planned in July 2024 after completion of the air flow test described above. Unrelated maintenance in Node 3 on July 5, 2024, necessitated removal of the Toilet System (including UWMS and Toilet Integration Hardware (TIH)) from the Toilet Stall and temporary stowage elsewhere. Attempts were made to start Toilet on July 9, 2024, with no luck. The Toilet failed to start despite multiple attempts and indicated a Pressure Sensor Shut Down Fault. When the toilet task was started, the dual fan separator did not activate. Toilet showed a shutdown fault which appears to be related to invalid signals from both pressure sensors. Power cycle did not clear the fault.

B. On-Orbit Troubleshooting

Because the Toilet System was removed from connections to the ISS for power and data, those connections were immediately suspected. Testing of various connectors and power availability was done and showed nothing anomalous. Troubleshooting included checking for connections at all harnesses and connectors as well as integrity of wiring and connections that may have been disturbed during removal of Toilet System from Node 3 location for unrelated maintenance. Further tasks include measurements of continuity and voltage at various points in the system. The efforts to troubleshoot the dose pump failure to dispense were not successful and the Dose Pump was returned on SpX-31 in October as dosing was not operational. The Toilet Data Recorder (TDR, Toilet Integration Hardware) was removed from the circuit to determine if a transient was causing the shutdown fault. A spare pressure sensor and TDR are currently on-orbit. A spare controller is awaiting completion at the Collins facility. If the UWMS was returned to service, troubleshooting of the dose pump fail to dispense pretreat was planned to continue.

Toilet operations showed lower than expected voltage readings on the pressure sensor circuit at the controller. The readings were reported as 1.478 and 1.48 Volts with an expected voltage of 15.0 Volts. This appears to indicate that the current limiter in the controller tripped. Further testing of resistance on those circuits appeared to show a short but will be validated on the ground with the development controller. Results pointed to an issue with the controller.

Further testing included testing to ensure power was being applied to the pressure sensor circuit. During the start-up sequence, power was not seen going to the pressure sensors. Testing with the sensor removed from the circuit had no impact on the conditions, prompting the conclusion that the sensors themselves were not causing the trip. (See

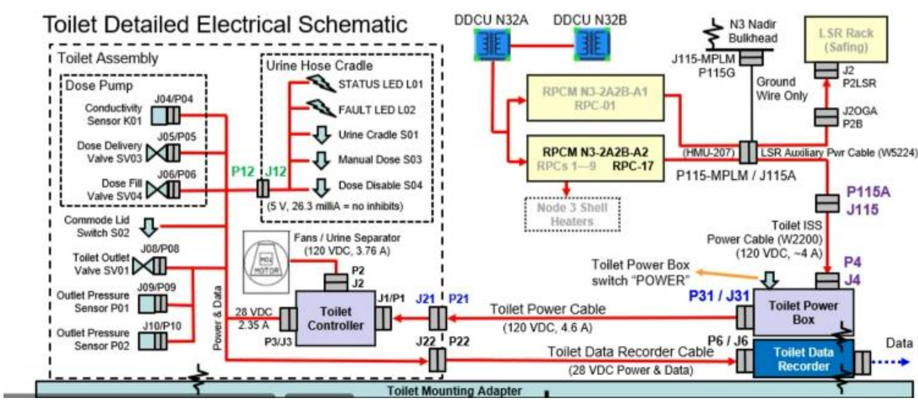


Figure 11. Toilet schematic from JSC's training materials.

circuit of interest in Figure 11).

Collins presented results of ground testing with the development controller. The results validated the voltage readings when the controller current limiter tripped. The resistance results are inconsistent with the on-orbit readings posing the question as to whether the resistance readings were taken on the correct pins. The conclusion from Collins is "that the failure is occurring internal to the UWMS controller, upstream of the Pressure Sensor Excitation Circuit."

A theory that other effectors in the schematic might be causing an impact resulted in attempting startup testing with the effectors removed from the circuit. All but the motor effectors were removed with no impact. And finally, all including the motor were removed with no impact. Additional UWMS troubleshooting repeated readings made during previous troubleshooting. Resistance readings did show low resistance (~8.7, 9.3 k-ohms) which was 0.01k-ohms previously. Voltage readings were 1.47 Volts on the circuit with all effectors (pressure sensors, cradle, and conductivity sensor) removed and only the motor in the circuit. Measurement of resistance was then repeated with all effectors including the motor removed and the readings were essentially the same. This indicates an issue in the controller in the pressure sensor excitation circuit. Testing on the ground is needed to determine root cause, see Fault Tree in Figure 12.

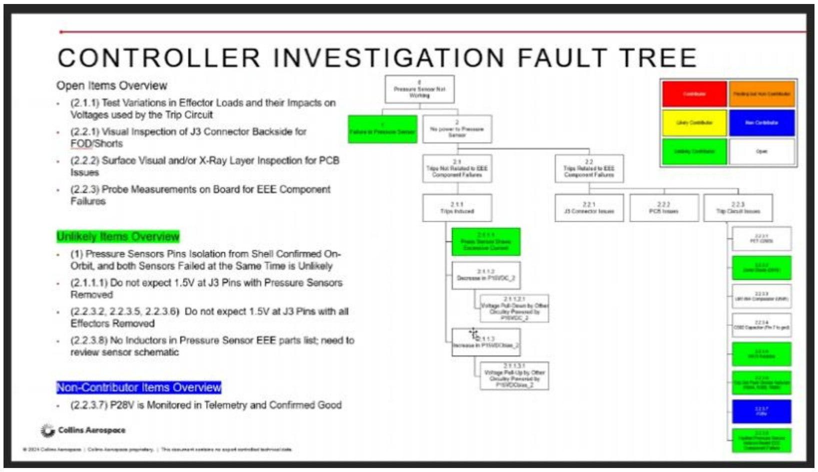


Figure 12. Fault Tree developed by Collins for the controller failure on ISS UWMS.

At this point it was considered that the cause of the shutdown was in the controller. The controller was removed from the UWMS and prepared for return on Crew-8. Crew-8 departure from ISS was delayed due to weather in Florida as was the docking of the boat with the cargo including the controller. The controller was received at the Collins Windsor Locks, Connecticut facility November. The Orion UWMS currently installed in the Artemis-2 vehicle contains the same circuit. This unit is powered up and the fan started on a quarterly schedule.

C. Ground Troubleshooting / Testing at Collins Windsor Locks Facility and Goddard Space Flight Center (GSFC)

The UWMS pressure sensor circuit operates in a mode where the voltages sensed by the comparator and the supply to the comparator are too close together and can cause the comparator to trip the circuit off cutting power to the pressure sensors. This can cause a system fault and shuts down the UWMS. This was a known issue with the Orion common DMC circuit (as of 2022) but was accepted for the UWMS since the voltages appeared to have enough margin between them. This initially led to theories of this circuit operation inducing a part failure OR a part failure causing the trip.

Testing on the circuit board showed a current backflow towards the comparator which should not be occurring. The comparator was suspected as being failed and causing a current leakage. Circuit analysis simulation models by the NASA Engineering and Safety Center (NESC) understand why the comparator could fail came up with 3 theories, 2 of which based on the test data were ruled out. #3 was to be checked after part removal. The flight controller was received at the Collins Windsor Locks facility in mid-November 2024. A Tiger Team convened at the facility to begin troubleshooting to determine the root cause of the failure. The cover was removed to reveal the secondary side. Photos were taken of the board and then a visual inspection was completed, with no findings (Figure 13).

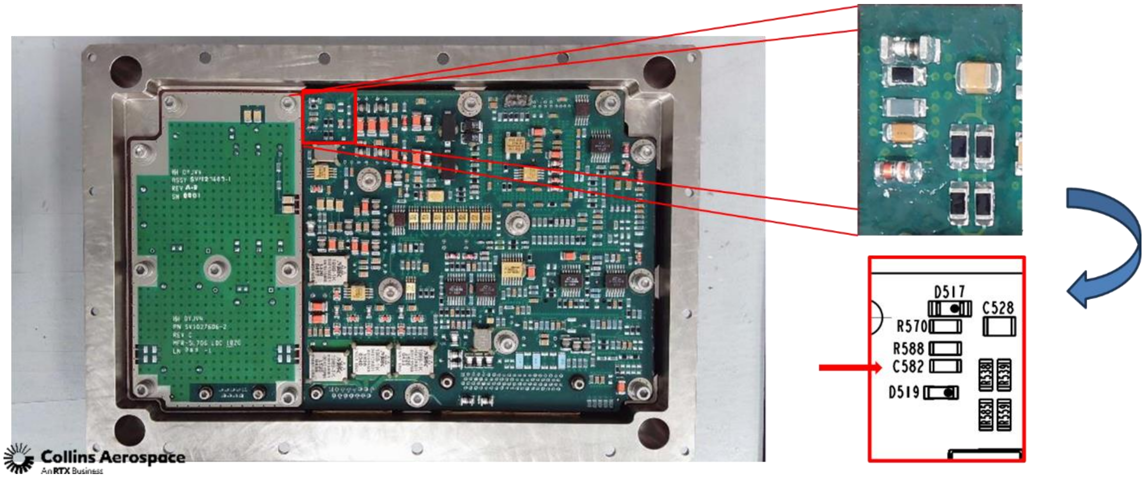


Figure 13. Photos taken of the UWMS Controller Board (at Collins Windsor Locks facility). No anomalies identified.

Conformal coat was removed and powered voltage measurements were performed on the board. Testing showed a repeat of the findings on-orbit with the shutdown fault in place. Conformal coating was removed from the area of the pressure sensor shut down circuit. After the overnight period, the controller powered on the circuit nominally, however the data did not look correct per the expected operation of the comparator. Similar measurements were made on the development controller at Collins Houston and showed as expected results.

During measurements of the controller circuit, it again reverted to the faulted state, but the data appeared correct (true to design). Operations to confirm whether the change could be recreated were not successful and the system was seen to be still faulted in a latched state (remains in this faulted condition). It was observed that during start up, nominal voltage is seen for several seconds before the circuit faults and latches. Measurements of the conductivity sensor circuit output and hot probing on the board with an oscilloscope to take measurements in an energized state showed no anomalies. No components were seen to be loose or not secure with pressure. Testing at Collins Windsor Locks facility showed anomalous leakage current in the Pressure Sensor limiter circuit that seemed to show that the comparator part on the UWMS-1 (ISS) Controller pressure sensor circuit likely has an issue.

Testing of another circuit with the same design in the controller, the conductivity sensor circuit, showed nominal performance of the comparator. Testing confirmed the pressure sensor excitation output current limiter trip is occurring because the comparator circuitry internal to the controller consistently and erroneously causes a trip. After isolating the false trip to the comparator circuitry, subsequent testing has focused on isolating the erroneous operations to an Electrical, Electronic and Electromechanical (EEE) part failure or an unstable operating mode of its comparator given the design operates the part outside of datasheet recommendations (input voltages too close to rail voltage).

Testing appeared to confirm a damaged comparator part was causing the shut-down fault trip; however, the root cause of the failure within the part was unknown. Additionally, the use of the comparator part outside the data sheet recommended range of operations was reviewed for potential impacts on the part.

Testing was also done on the controller using a flight GP:50 pressure sensor. Previously, testing was done with a simulated load from a break-out box. This testing was being done to ascertain if transients from the pressure sensor contribute to the damage to the comparator and showed the GP:50 COTS pressure sensor was not back-feeding into the circuit to damage the comparator.

Texas Instruments said that when the comparator is operated outside the data sheet, the comparator fails to operate properly. This can result in degrading outputs, damage to the part and generally a lack of ability to perform as a comparator is designed to operate. This is in line with the testing performed at Collins WL and the behavior exhibited to date. Discussions with Texas Instruments and further review of the fault tree analysis continued because it was not clear if the common mode operation of the circuit is the root cause. If all causes for comparator damage could be removed except single/random part failure, that would help indicate a part failure rather than a design cause. If it is not a random part failure and not caused by the common mode operation of the circuit, changing the circuit to the updated version on Artemis-3,4 and the ISS spare would not correct the issue.

The Comparator was removed from the board for further testing at GSFC. Testing included:

- External Visual Inspection
- Radiographic Inspection
- Electrical Testing
- Scanning Acoustic Microscopy as applicable
- Decapsulation/Disassembly
- Internal Visual Inspection
- SEM-EDS as necessary
- Failure Localization as necessary
- And a written report with photographs and determination of the root cause of the failure.
- Destructive testing will be performed if the cause cannot be determined by other means.

Optical and x-ray tests were completed and didn't show anything "too terribly anomalous." Electrical testing of the comparator at GSFC showed nominal performance compared to a pristine part and is not manifesting the problem seen on shutdown (Figure 14.) There was slight damage noted on one of the pins. Based on the testing it was determined the comparator LM139A, U505 was not the source of the excess current through the 1kΩ resistor R570.

Testing of the controller board at Collins WL showed leakage current was still present with the comparator removed indicating the comparator was not the source of the leakage. Testing isolated the source to a capacitor in the circuit. Collins testing of the capacitor showed leakage current of 270 microamps.

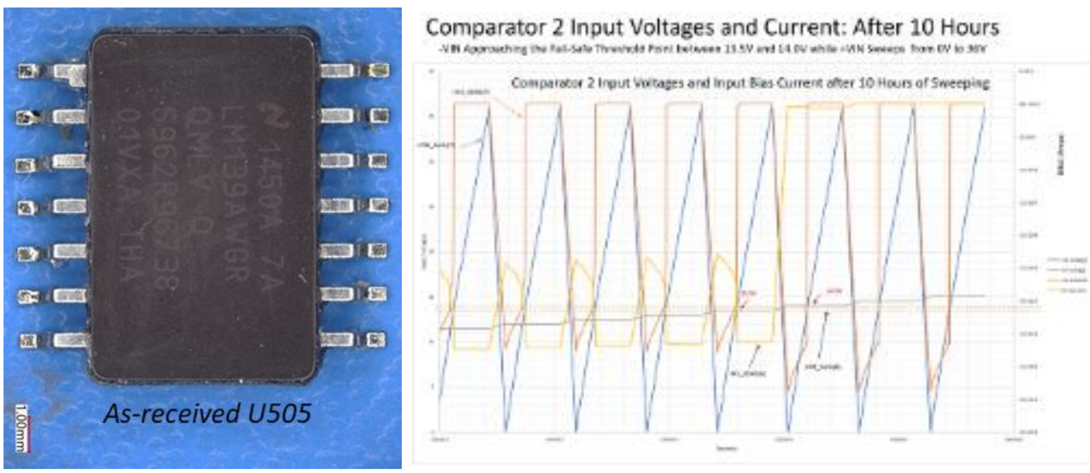


Figure 14. Comparator 2 input voltages and current after 10 hours.

The subject matter expert at GSFC provided details on what could be causing leakage current to increase voltage to the comparator causing a trip. Dendritic growth could be providing a media for current to flow thru. This could be at a crack in the capacitor or in the board itself. The crack may be a defect or could have been a workmanship issue caused by rework on the board during testing in 2019. The C582 capacitor was sent to GSFC for failure analysis, and it was shown to have off-nominal leakage current, indicating a low/unstable insulation resistance, see Figure 15. Removing C582 from the circuit showed the leakage was no longer present.

Electrical testing, biased infrared, X-ray and acoustic microscopy (AM) were all consistent with an internal leakage path associated with suspected delamination/cracks inside capacitor. Monitored leakage current test confirmed unstable, high leakage current 70 to 90 micro amps @15V: >1mA @ 50V or ~40kΩ to 240kΩ instead of 100GΩ per specification. Destructive analysis via cross section identified a very large internal delamination constrained within the ceramic between two closely spaced/dual electrodes with cracks extending from the delamination that span between opposing electrodes/terminations. The locations of these cracks are consistent with features detected via AM, X-ray and infrared hot spots.

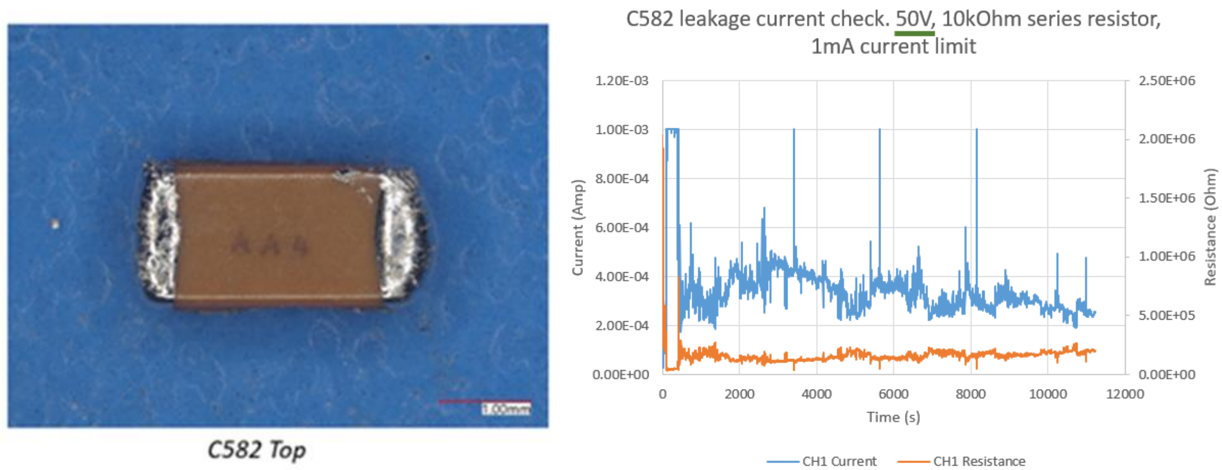


Figure 15. C582 leakage current check.

The GSFC team concluded via acoustic microscopy and sectioning of the capacitor that the internal delamination is most likely a pre-existing defect as-received from capacitor manufacturer. NOTE: Acoustic Microscopy is not a required screen for "CDR" capacitors. Per GSFC SME experience/feedback, even nominal stresses associated with part assembly, thermal and mechanical environments, and voltage application, may contribute to a delamination becoming an internal crack in the ceramic dielectric material spanning between opposing electrodes/terminations.

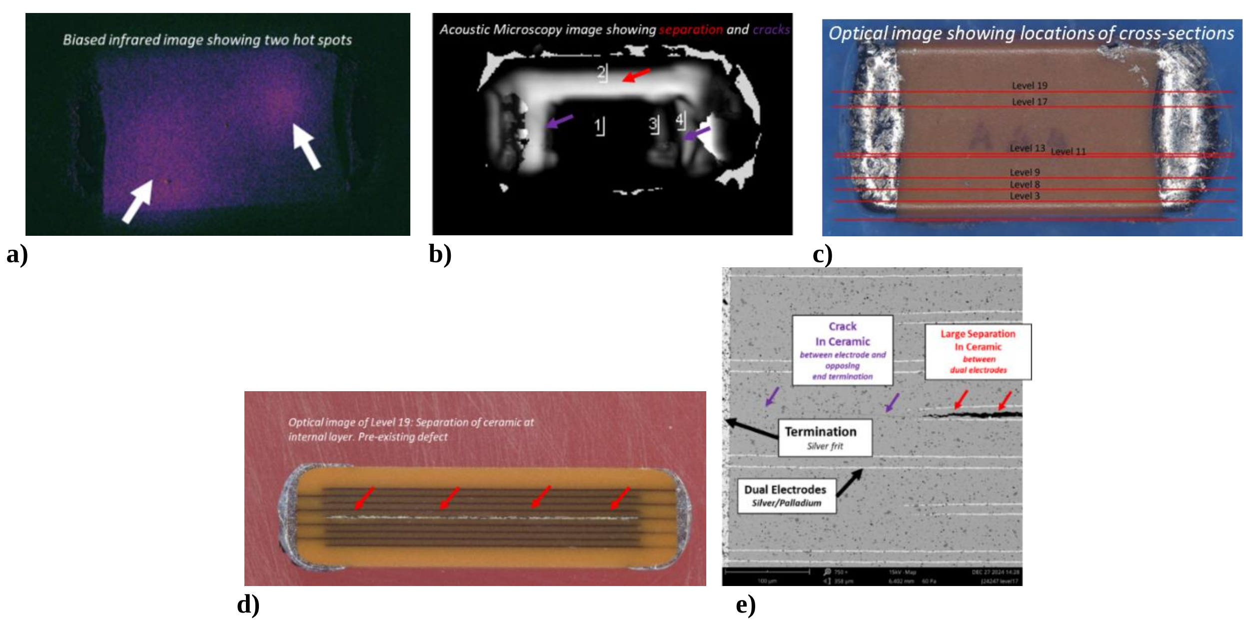


Figure 16. Details of testing of C582 at GSFC, a) Hot Spots during infrared testing, b) acoustic microscopy showing separation and cracks, c) cross-sections, d) details of separations of ceramics at internal layer, e) scanning electron microscope image at level 17 of a crack.

Biased operation over time most likely lead to electrochemical migration (ECM) of silver from the electrode and/or termination metals in the form of "dendrites" along the crack surfaces. Dendrites develop erratically leading to variable and generally decreasing insulation resistance failure modes. Figure 16 shows the results of the testing at GSFC.

D. Discussion of Lot Date Code and Locations/Criticality

The lot date code of the failed capacitor was identified and 61 remaining parts from that lot were in inventory. Jet Propulsion Laboratory (JPL) performed acoustic microscopy on these parts and revealed an internal separation (void and/or delamination) defect in one of the parts, see Figure 17. Investigation showed that a total of 1914 parts were received by Collins from this lot. The parts were located on the ISS UWMS, Orion Artemis-2 board and other hardware on the Artemis-2 vehicle supporting life support hardware.

Investigation is in progress on the locations within these boards and potential impacts of a similar outcome as the capacitor on the ISS UWMS board. Corrective actions are currently to be determined based on conclusion of the evaluation of the probability and impact of the capacitor failures. Root cause of the “failure to start” event of the ISS UWMS was determined to be a single part failure (capacitor) in the controller and although the defect rate for the lot was higher than expected, a higher failure rate was not seen.

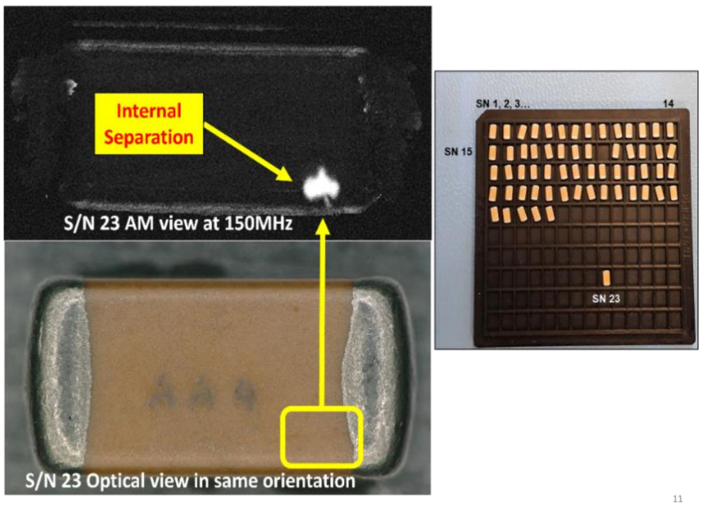


Figure 17. Testing at JPL of remaining parts in the lot.

VI. Conclusion

Completion of the technology demonstration of the UWMS on ISS is paramount to informing exploration missions including Orion program milestones. The demonstration will provide details of consumables usage, ability of the crew to perform simultaneous urination and defecation operations, and overall information on use of a compact toilet in micro-gravity. Scheduling this work using available data and further learning of the operational performance is advantageous while also pursuing component modifications. At the time of this writing, corrective actions for the controller and the dosing assembly are in work. Upon determination of these actions, re-flight and resumption of on-orbit testing will be scheduled. Discovery of issues such as the capacitor vulnerability in shut down circuits on the ISS UWMS highlight the advantage of performing a technology demonstration on ISS prior to exploration missions such as Orion and further Lunar/Mars programs.

Acknowledgments

This paper summarizes work that was performed by numerous NASA and contractor engineers, analysts, functional specialists, technicians, and crewmembers. While NASA programs MCO, ISS and Orion provide significant funding of the activities discussed, NASA recognizes the significant contributions of commercial partners, small businesses, and academic institutions. The failure investigation of the controller and the Tiger Team members included participation from the Mars Campaign Office, NASA Programs – Orion and ISS; contractors at Collins Aerospace – Houston and Windsor Locks, Lockheed Martin; the NASA Engineering and Safety Center; 6 NASA Centers _ Glenn Research Center, Goddard Space Flight Center, Jet Propulsion Laboratory, Johnson Space Center, Langley Research Center, and Kennedy Space Center. Thanks to all the many subject matter experts for their assistance.

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