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NASA Exploration Toilet Hardware Status and Crew Feedback from ISS Artemis-2 Demonstration

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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. During 2023, the Artemis-2 Demonstration was started, and this paper discusses issues encountered, on-orbit troubleshooting, subsequent ground failure investigation and proposed repairs as well as near-term plans to resume the Artemis-2 demo. Also discussed is an update to the commercial-off-the-shelf (COTS) Conductivity Monitor (CCM) which is planned to be flown for the resumption of the demo along with additional UWMS hardware and Toilet Integration Hardware (TIH). An updated design of the commode seat and fecal bag for Artemis-2 UWMS will be demonstrated on ISS and a summary of the hardware is included in the paper. Use of the hardware during the first days of the aborted demonstration by crewmembers and feedback received is summarized as well as hardware updates resulting from that feedback. The paper will also provide an overview of the demo results to date that inform the Orion-installed UWMS unit and future manifesting of consumables for both Orion and ISS.

Nomenclature

AES = Advanced Exploration Systems
ARED = Advanced Resistive Exercise Device
COTS = Commercial-Off-The-Shelf
CCM = COTS Conductivity Monitor
DFS = Dual Fan Separator
ECLS = Environmental Control and Life Support

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ECLSS = Environmental Control and Life Support System
EDU = Engineering Development Unit
FY = Fiscal Year
GMT = Greenwich Mean Time
HLS = Human Landing System
ISS = International Space Station
JSC = Johnson Space Center
LED = Light Emitting Diode
LOO = Lavatory On Orbit
LR = Logistics Reduction
NCR = Non-conformance Report
NASA = National Aeronautics and Space Administration
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
WSTA = Wastewater Storage Tank Assembly

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 required modest modifications for adaption to multiple exploration microgravity mission elements. 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 builds on previous toilet designs and delivered a toilet for the International Space Station (ISS) and the first crewed Orion mission. Nomenclature of both units is Toilet and, in this paper, UWMS and Toilet are used interchangeably. Delivery of the Orion Toilet (seen in Figure 1) was in December 2019 and the unit was installed into the Artemis-2 vehicle in March 2021 for launch in 2025. The ISS unit, seen in Figure 2 along with the Toilet Integration Hardware, 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 and an Artemis-2 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.

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% smaller and 40% lighter than the current ISS toilet used by US crew in the Waste and Hygiene Compartment (WHC.) The Orion UWMS (WMS) is 61% 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) provided much of the resultant reduction in mass and volume. The unit provides 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.

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

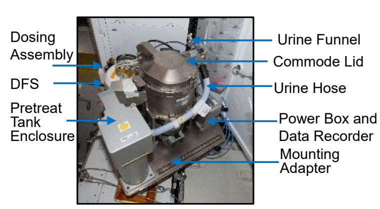


Figure 2. ISS UWMS with Toilet Integration Hardware in Node 3, ISS.

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. 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 solution in. Actuation of the dose pump dispenses both fluids into the urine stream. See Figure 3, a. flow path and b. for Dosing Assembly hardware identification.

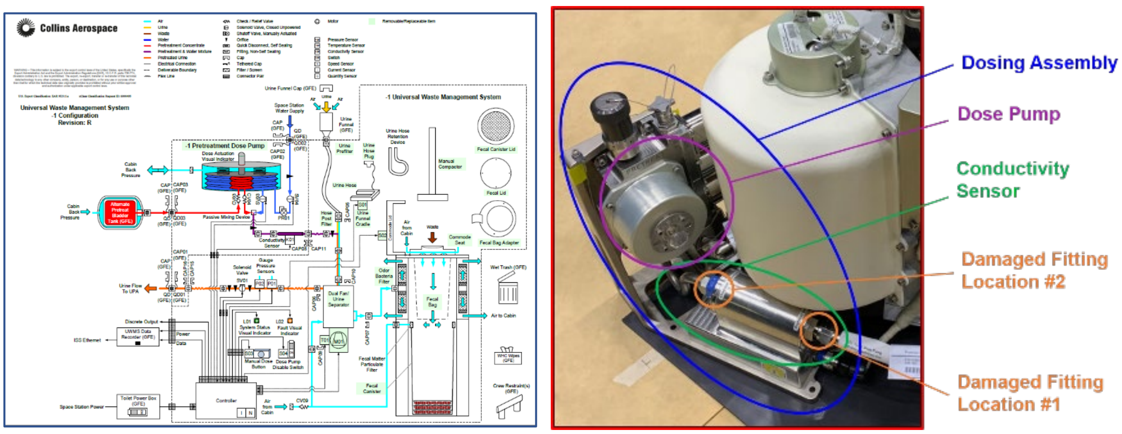


Figure 3, a. UWMS Flow Path for Urine and pretreatment, b. UWMS Dosing Assembly Hardware

A Conductivity Sensor provides measurement of the concentration of pretreat dispensed for the ISS unit. Fecal deposits and consumables such as wipes, and gloves are contained in a hard-sided fecal canister. More details on these items can be found in a previous paper [1].

II. Summary of Past Year's Events

Additional operation of the ISS UWMS on-orbit and analysis of data from the Limited Checkout performed in 2021 and non-crewed operations in 2023 yielded insight into the system's operations. This was key to successful future use and also provided some of the information needed for the Orion Artemis-2+ missions. NASA's need for additional data for the Orion Artemis-2 mission drove scheduling use of UWMS on ISS to mimic use on Artemis-2 in duration and crew size. This demonstration started in February 2023. Issues with the urine pretreat dose pump occurred during the check out and the demonstration was not completed.

The demonstration began February 7, 2023 with use by a female crew member. A male crew member used the UWMS on the following day. Near real time review of pressure sensor data indicated that the urine pretreat solution was not dispensing and the demonstration was halted. A summary of the activities is in Table 1.

Table 1. UWMS Operation by Greenwich Mean Time (GMT) Date

UWMS Operations		
GMT Date	**Activity**	**Notes**
2022-304	CCM Installation	Installed on-orbit inUWMS
2022-305	CCM Checkout	Good Dose Quality Indication from Pressure Readings; CCM readings off-nominal
2022-361	CCM Degas	Inconclusive Quality Indication from Pressuer Readingss; CCM readings off-nominal
2023-038 thru 041	Artemis-2 Demonstration Crew Operations	Bad pretreat Quality indications from Pressure Readings; CCM readings off-nominal

The data used for indication of pretreat had previously been used successfully as seen below in data from the checkout of the COTS Conductivity Monitor (CCM). The pressure data indicated pretreat was successfully dispensed during the CCM Check out as seen in Figure 4. Forty manual doses were dispensed during the checkout of the MSFC supplied CCM to evaluate if pretreat was being dispensed. This was for two purposes; one to evaluate the new CCM operation but also to prepare for additional crew use of UWMS. Pressure readings were similar to previous data seen during the checkout of UWMS in 2021. The average pre-dose pressure was 13.16 psig and the average post-dose pressure was 14.43 psig. The average delta-pressure was 1.27 psig. This indicated that pretreat seems to be present, if possibly 10% low, and crew operations can be started. Pressure readings are compared to previous data on the ground and on-orbit and reflect a comparison to expected differences in specific gravity for water and the pretreat concentrate and water mixture.

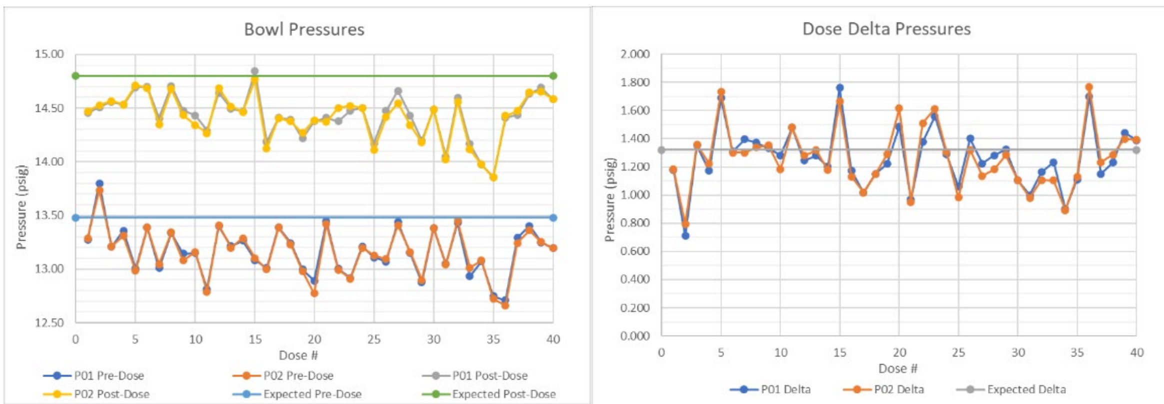


Figure 4. UWMS separator bowl pressure and Dose Delta Pressures during CCM check out operations.

However, there was questionable data in the follow-on attempt to degas the CCM, see Figure 5. Fourteen 'viable' (acceptable amounts of pretreat) manual doses were dispensed during the attempt to degas the inoperable CCM. Pressure readings were similar to previous data seen during the checkout of UWMS in 2021. The average pre-dose pressure was 13.23 psig and the average post-dose pressure was 14.4 psig. The average delta-pressure was 1.15 psig. This indicated that pretreat seems to be present however due to the lower delta-pressure, data is inconclusive on pretreat quality. Crew operations were still possible, however, close monitoring of the quality of the pretreat was necessary.

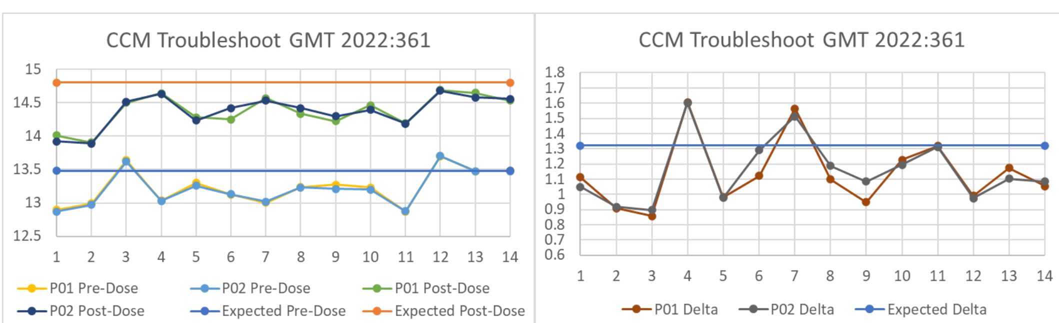


Figure 5. UWMS separator bowl pressures and Dose Delta Pressures during CCM degas operations.

Data summary during the Artemis-2 Demo check out is summarized in Table 2 and can be seen in Figures 6-9. This data shows that pretreat does not appear to be present based on comparison to ground data and previous on-orbit data.

Table 2. Summary of data from Artemis-2 Demonstration Crew Operations

Check #	# Viable Doses	Pre-Dose (psig)	Post-Dose (psig)	Delta-P (psig)	Notes
1	8	13.04	14.1	1.05	Bad Dose - seems like water only
2	8	13.26	14.14	0.19	Bad Dose - seems like water only
3	3	13.56	14.4	0.85	Bad Dose - seems like water only
4	7	13.56	14.32	0.75	Bad Dose - seems like water only indication or partial bellows stroke

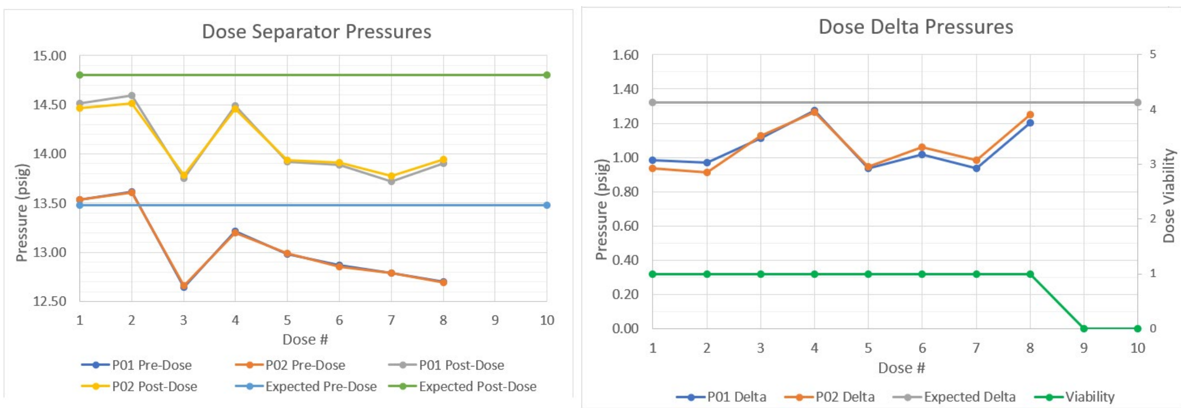


Figure 6. Data from Dose Check #1.

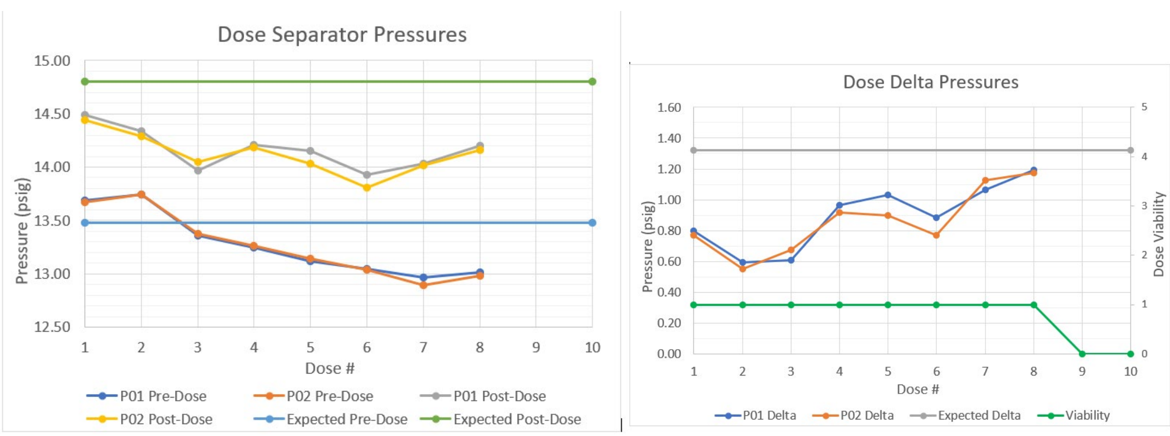


Figure 7. Data from Dose Check #2.

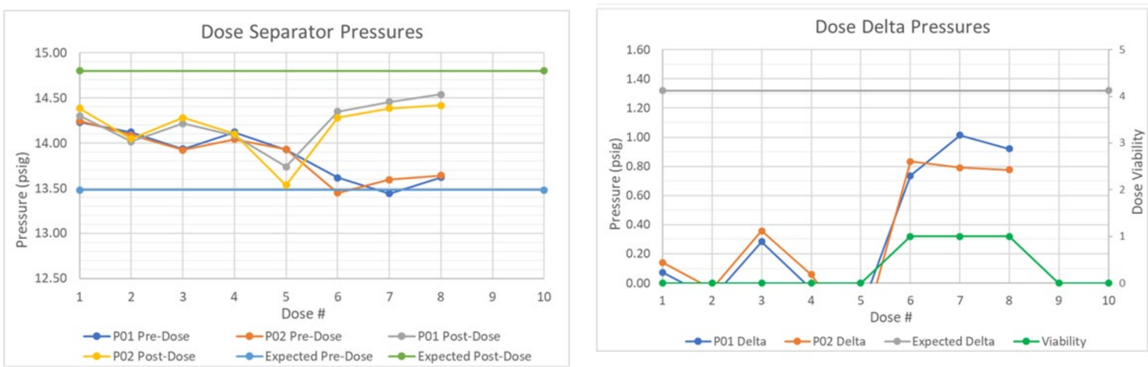


Figure 8. Data from Dose Check #3.

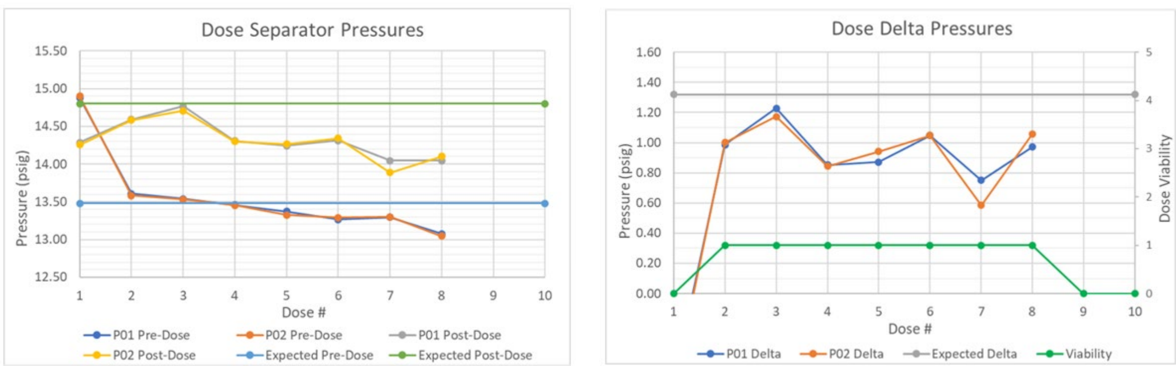


Figure 9. Data from Dose Check #4.

Troubleshooting was performed on-orbit to validate the pressure data and determine if pretreat was not actually dispensing. This troubleshooting included drawing a sample from the base of the urine hose for a color check as seen in the schematic below, Figure 10. Crew reported that the fluid retrieved was a very small sample but very obviously a clear liquid. If pretreat was present the liquid is expected to be some hue of orange because at this point in the schematic the fluid is expected to be pretreat/water only (no urine). This finding supported the pressure data analysis that no pretreat was present. The color of the urine and fluid collected in an external tank was evaluated as well. As seen in Figure 11, the color was seen to be urine only. At this point in the process, the pretreat and urine solution is expected to be a deep green color (changes during oxidation from orange to green.) The color of the collected fluid was seen to be yellow, Figure 11, which also supports the pressure sensor data review.

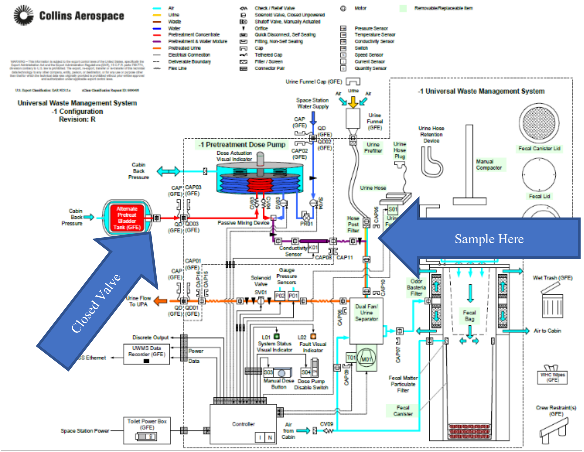


Figure 10. Location of sample taken and valve closed for troubleshooting

Figure 11. Comparison of UWMS filled EDV (Russian tank) and WHC previously filled EDV. Tank on left contains UWMS urine and does not appear to contain pretreat. Tank on right is a previously filled tank used on WHC (Waste and Hygiene Compartment.)

Further testing was done on-orbit to provide insight into the cause of the failure of the dose pump to dispense pretreat solution. The pretreat tank valve was closed (See Figure 10) and dose pump was cycled to inform if the issue within dose pump is with the inlet or outlet check valve, see Figure 12 for details on dose pump and location of check valves. Testing confirmed that it was likely the inlet check valve, CV03, had failed although there was some concern that the outlet check valve, CV04 failed. Ground testing was needed to confirm actual status of these valves.

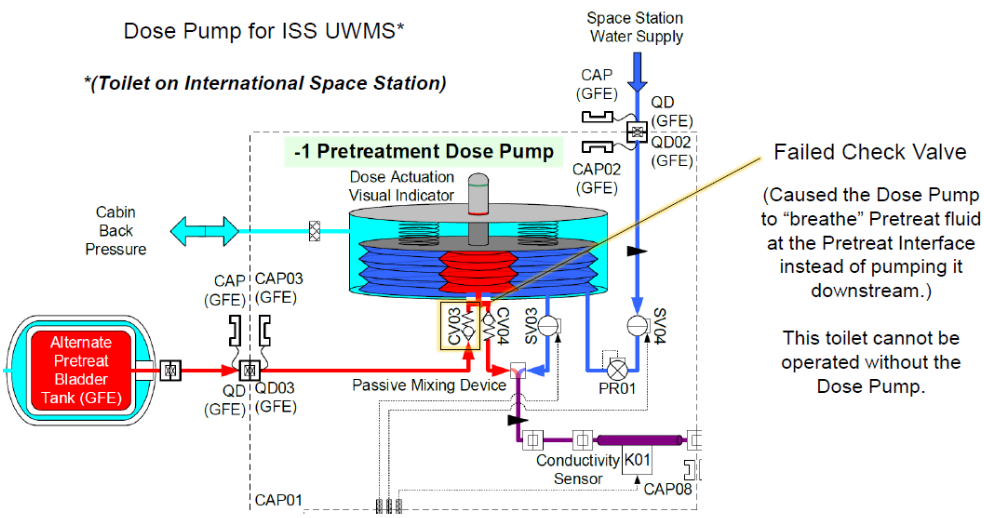


Figure 12. Dose Pump schematic for ISS UWMS

III. Dose Pump Failure Investigation

A. Overview

Based on the pressure sensor data and the testing performed on-orbit a fault tree was developed to guide additional testing. The Dosing Assembly was returned on SpX-28 and was delivered to the Collins Houston lab for evaluation. Testing confirmed that the inlet check valve, CV03, was not operational. Testing on the UWMS failed Dose Pump returned from ISS showed the same results as seen on-orbit with determination that the inlet check valve (pretreat tank side) failed open. Inspection of the check valves after removal from the dose pump showed a piece of the Polyether Ether Ketone (PEEK) shroud from the inlet check valve (CV03) in the inlet side of the outlet check valve (CV04). A photograph of the inlet of CV04, showing the fractured piece of PEEK shroud (approximately ¼ of the total circumference) with pretreat still present is also shown in Figure 13. Subsequent inspection and disassembly of CV03 at the Raytheon Technology Research Center (RTRC) did confirm that the PEEK piece found in CV04 came from the CV03 shroud. Additional fragments were also recovered from the dose pump bellows assembly after flushing operations.

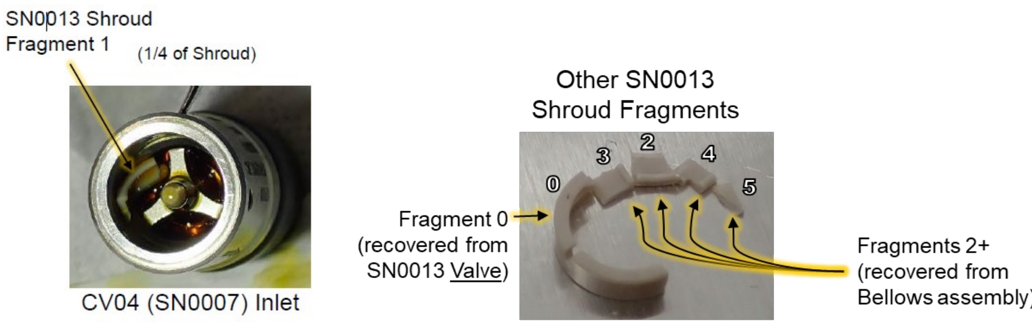


Figure 13. Inlet of CV04 showing fragment of shroud and remaining pieces of shroud recovered.

A fault tree shown in Table 3 was created/updated based on the results showing failure of the check valve and shared with NASA. A high level summary and disposition of the likelihood for each cause is included below. The failure causes that are dispositioned as "Open" are due to the fact that the information desired to verify the likelihood is not available or incomplete. Subsequently, the investigation was placed on hold. For example, the verification of incorrect raw material was pending if the vendor could produce a raw material supplier certification that matched the other certifications to reflect "Victrix supplied" source. But this was not able to be completed before the hold was placed on the investigation. Other items simply cannot be confirmed since evidence from testing or actual measurements are unable to be obtained.

Table 3. Fault tree

Failure	Disposition
Dose Pump lack of pretreat dose	**Open**
1 - Pretreat Flow Restriction	**Unlikely**
1.1 – Blocked Pretreat Path (inlet QD closed, etc.)	Unlikely
1.1.1 – Inlet QD not connected	Non-Contributor
1.1.2 – PT Tank Hand Valve closed	Non-Contributor
1.1.3 – PT Tank empty	Non-Contributor
1.1.4 – Other blockage (blocked/kinked hose)	Unlikely
1.1.5 – PT QD failure	Unlikely
1.2 – Valve time expires before full fill	Non-Contributor
2 - Water Flow Restriction	**Non-Contributor**
2.1 – Blocked Water Path	Non-Contributor
2.2 – Valve time expires before full fill	Non-Contributor
3 – Dose Outlet Flow Restriction	**Non-Contributor**
3.1 – Blocked Outlet Path	Non-Contributor
3.2 – Valve time expires before full dispense	Non-Contributor
4 - Dose Pump External Leak	**Non-Contributor**
4.1 – Dose pushed into Cabin	Non-Contributor
5 - Gas in water Bellows	**Non-Contributor**
5.1 – Lower water in dose	Non-Contributor
6 - CV03 Failure	**Contributor**
6.1 – CV03 Failed Open	Contributor
6.1.1 – FOD	Open
6.1.2 – Corrosion products	Non-Contributor
6.1.3 – Spring failure / jam	Unlikely
6.1.4 – Degradation of Check Valve seal	Unlikely
6.1.5 – Inadequate seal squeeze	Contributor
6.1.5.1 – Shroud failure/shear	Contributor
6.1.5.1.1 – Inadequate Shroud strength	Contributor
6.1.5.1.1.1 – Material strength inadequate (off-nominal)	Contributor
6.1.5.1.1.1.1 – Material property degrad'n in Pretreat (and/or Pretreat Lite)	Contributor
6.1.5.1.1.1.2 – Off-nominal raw material	Unlikely
6.1.5.1.1.1.2.1 – Incorrect raw material	Open
6.1.5.1.1.1.3 – Residual stresses from machining of PEEK components	Open
6.1.5.1.1.2 – Insufficient design margins	Open
6.1.5.1.1.2.1 – Interferences between Shroud & Poppet	Open
6.1.5.1.1.2.1.1 – Unfavorable part tolerance stack-up	Unlikely
6.1.5.1.1.2.1.2 – Shroud & Poppet swelling in Pretreat	Open
6.1.5.1.1.2.2 – Mfg / assembly stresses exceed design allowables	Open
6.1.5.1.1.2.3 – Valve experienced unanticipated back-pressure event	Unlikely
6.1.5.1.1.2.3.1 – Water hammer effect	Unlikely
6.1.5.1.1.2.4 – Baseline design margins incorrect	Unlikely
6.1.5.1.2 – Off-nominal handling of Check Valve	Open
6.1.6 – Degrad'n of O-Ring on Check Valve body (btw. valve body & Manifold)	Unlikely
6.1.7 – Poppet Fracture	Finding, but Non-Contributor
6.2 – CV03 Leak	Non-Contributor
6.3 – CV03 Failed Close	Non-Contributor
7 – CV04 Failure	**Non-Contributor**
7.1 – CV04 Failed Open	Non-Contributor
7.2 – CV04 Leak	Non-Contributor
7.3 – CV04 Failed Close	Non-Contributor
8 – Pretreat Bellows Failure	**Non-Contributor**
8.1 – Pretreat Bellows partially fills with water	Non-Contributor
8.2 – Pretreat Bellows completely fills with water	Non-Contributor
9 – Pretreat Concentrate Internal Leak	**Unlikely**
9.1 – Gas continually pulled into Pretreat Bellows instead of Pretreat Tank	Unlikely
10 – Gas Trapped in Bellows (100% gas in collapsed Bellows)	**Unlikely**
10.1 – Lower Bellows pretreat volume	Unlikely
11 – Regulator Failure	**Non-Contributor**
11.1 – Regulator Failed Open	Non-Contributor
11.2 – Regulator Drift high	Non-Contributor
11.3 – Regulator Drift low	Non-Contributor
12 – SV03 Failure	**Non-Contributor**
12.1 – SV03 Failed Open	Non-Contributor
12.2 – SV03 Failed Close	Non-Contributor
13 – SV04 Failure	**Non-Contributor**
13.1 – SV04 Failed Open	Non-Contributor
13.2 – SV04 Failed Close	Non-Contributor
14 – Electrical Failure	**Non-Contributor**
14.1 – Controller not outputting command signal	Non-Contributor
14.2 – Solenoid valves not receiving command signals or not opening	Non-Contributor

The broken piece of shroud from the failed dose pump check valve was removed and provided to the JSC/Structures and Mechanics Division for analysis.

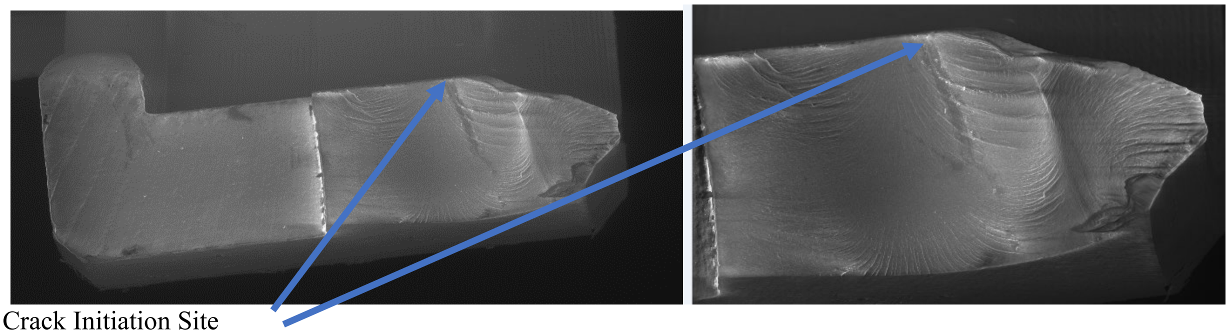


Figure 14. Optical Scans showing cracking of the PEEK shroud from the UWMS Dose Pump Check Valve that failed on-orbit on ISS during preparations for the Artemis-2 Demo

Optical scans in Figure 14 show the crack initiation site which was not at the notch as originally suspected. “The picture below showing the fracture point & the river flow pattern would be the key finding of our investigation,” per Dr. Kim, JSC Structures and Mechanics Division. The photo “is showing a clear crack initiation point. So, it seems like the crack did not start at the corners.”

B. RTRC Testing and Results

The failed check valve (CV03) and the PEEK fragment that was found in the outlet check valve (CV04), as well as the pieces of the shroud recovered from the dose pump bellows, were delivered to the Raytheon Technologies Research Center (RTRC) for further evaluation. Also provided were examples of unused check valves and internal components for comparisons.

The scans taken at RTRC of the fractured part, Figure 15, first recovered showed a likely initiation of the fracture of the check valve PEEK shroud. The fracture initiation site was not at the corner of the notch and is shown in the picture below. Evidence of embrittlement is seen along the fractured edge. This confirmed earlier findings from JSC.

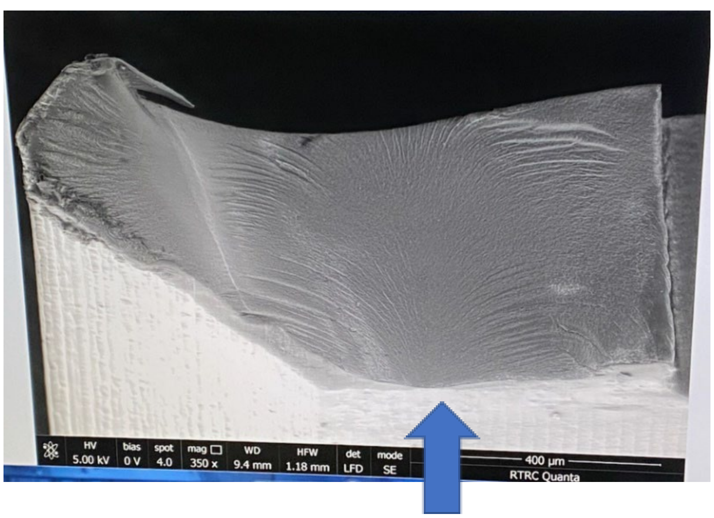


Figure 15. Scans from RTRC of failed shroud.

The poppet was removed from the failed check valve by applying a hot solder edge to the inlet side of the poppet to release the titanium spring retainer. Then, during visual inspection and handling, the topmost edge of the poppet (outlet side) was broken with light hand pressure only, seen in Figure 16. Subsequent investigation of the fracture surfaces showed evidence of brittleness in the failure, similar to the nature of the shroud failure, Figure 17. The images below provide detail views of the broken PEEK poppet. Later investigation and inspection of photographs prior to disassembly of the valve show that this fracture already existed prior to handling and was adjacent to the location of the facture site of the shroud, Figure 18.

Figure 16. Poppet with broken piece

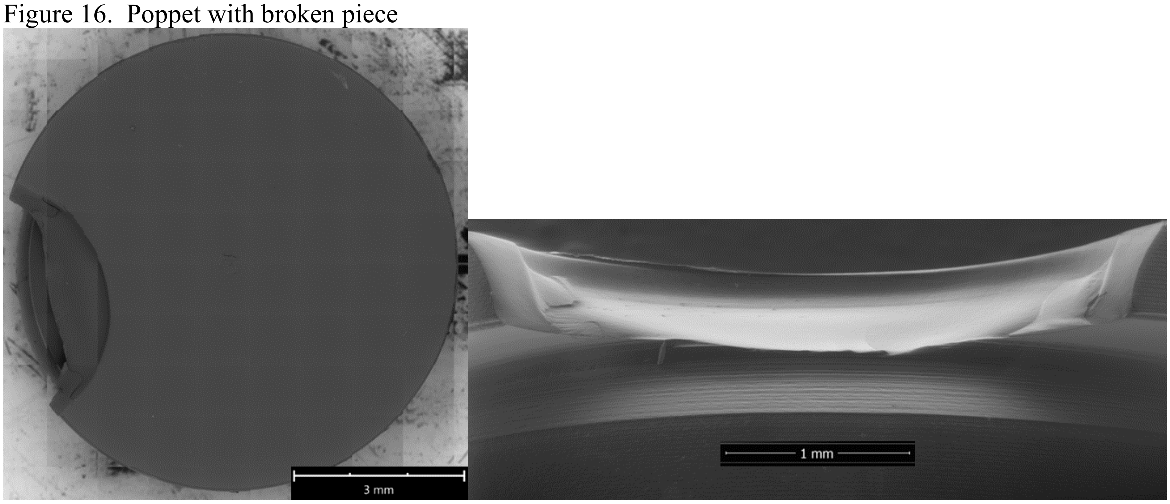


Figure 17. Location of failure in poppet.

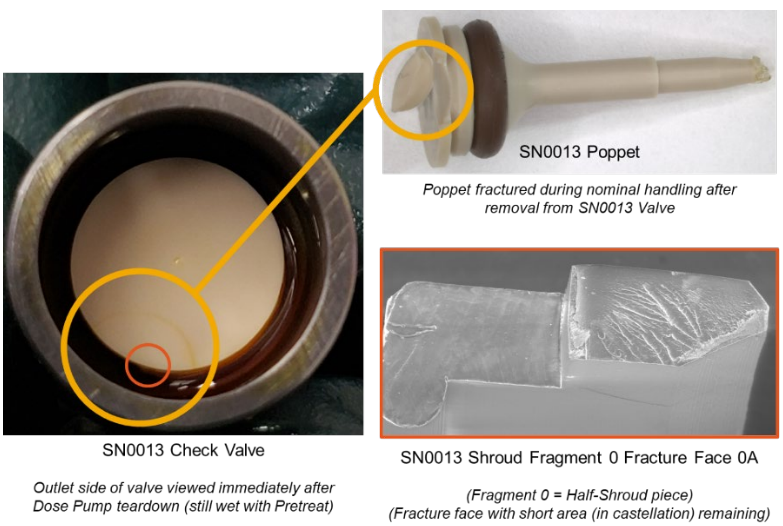


Figure 18. Details of the poppet failure.

Additional observations made by the RTRC team included that the exterior surface of the failed poppet showed evidence of etching and a matte finish as is seen in the comparison photo of both the poppet from the failed check valve and a pristine version supplied by the vendor. The top poppet is from the failed valve (CV03 S/N 0013) that was exposed to pretreat, the bottom poppet is the pristine item that has never been exposed to pretreat. The pristine poppet was noted as having a shinier exterior surface as seen in Figure 19.

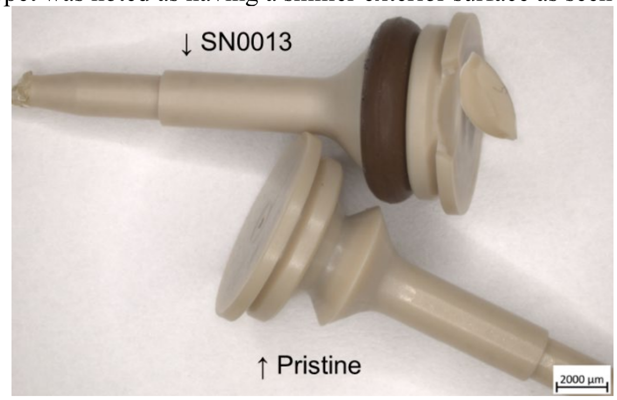


Figure 19. Comparison of failed poppet to pristine unused poppet showing surface etching.

Optical profilometer images, Figure 20 showed a difference in the surface of the PEEK parts indicating the failed part has an altered surface compared to the pristine piece, which also supported the etching theory. This observation was the first to suggest that pretreat affects the surface of the PEEK parts.

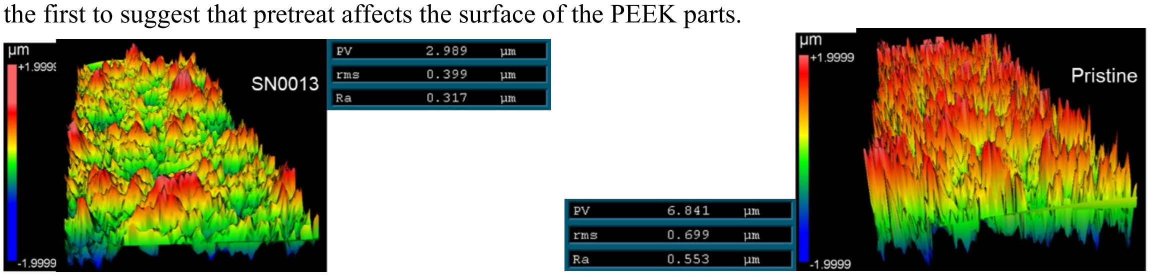


Figure 20. Optical profilometer images of a pristine unused poppet surface and the failed poppet showing evidence of etching.

The theory at this time was that all of the PEEK components had been embrittled by long term exposure (2-3 years) of pretreat lite or pretreat concentrate. PEEK is traditionally very ductile and tough in nature and the brittle fracture surfaces observed on the poppet and the shroud of CV03, combined with the surface etching appearance of the used valve supported this theory initially. However, embrittlement testing of the poppet "shaft" cross section was not successful due to the fact that the rest of the poppet, upstream of the fracture location of the poppet was tough and ductile and required significant force with a sharp tool to cut it. Similar attempts at breaking the shim (sits between the spring and the titanium housing) to evaluate embrittlement were also unsuccessful due to similar observations.

Given these observations, it was suggested by the principal chemist at RTRC to test PEEK components of the failed CV03 check valve, CV04 check valve, pristine PEEK check valve components from stock and raw PEEK bar stock provided by the check valve vendor, with Raman Spectroscopy to analyze the characteristics of the parts/samples that may indicate a susceptibility to chemical attack in acidic environments. Differential Scanning Calorimetry (DSC) also used to evaluate the bar stock samples. The analyses and results of these material evaluations are contained in reports provided to NASA directly[6,7].

In general, the investigation report supports that the prolonged exposure of the PEEK check valve components to pretreat concentrate may have allowed chemical attack of the polymer chains of the PEEK material. If solvents can penetrate the polymer chain spaces of the PEEK material and that solvent can attack the chains (due to being acidic for example), properties of the polymer can change and potentially become embrittled. Removal of such solvent (cleaning and drying) may return some of the properties to original state, which may explain why parts that were previously exposed to pretreat were no longer brittle after being cleaned and dried of pretreat.
The addition of stress to the situation can result in Environmental Stress Cracking (ESC) and eventually fracture. The stress could possibly have come from undetermined amount of PEEK swelling in pretreat combined with small poppet-shroud clearances.

Analysis of two different PEEK trade-name bar stock samples supplied by the vendor (both starting from same NASA directed Victrex 450G resin) provided data that these characteristics can vary between raw materials just due to the differences in material processing. Analysis of different fracture surfaces of the SN0013 shroud vs. finish machined surfaces of the shroud indicate a distinct difference in these characteristics between fractured surfaces (characteristics more prone to chemical attack) and finished/machined surfaces (less prone) as well as between the fractured parts (more prone) and the barstock (less prone). This observation combined with a visible "whiter surface" along the fracture surface areas may be attributed to attack from acidic test solution resulting in polymer chain cleavage. Similar observations were noted on other SN0013 shroud fragments that were flushed from the dose pump bellows (downstream of CV03).

Notable differences between these characteristics were also observed between the two sides of the shim; one side is exposed fully to the test solution (pretreat concentrate) and the interfacing spring while the other side (sheath side) is forced against the titanium housing. The exposed side (inferred from data) had less of the characteristics that resist chemical attack vs. the sheath side against the titanium. These reduced characteristics support the theory that there was some negative interaction of the PEEK with the pretreat concentrate.

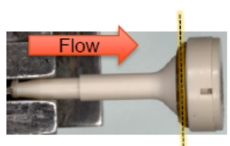
PEEK parts from SN0007 (CV04), downstream of SN0013 (CV03) were also evaluated by Raman spectroscopy. All analyzed components had similar levels of characteristics for resisting chemical attack. Compared to the SN0013 parts, SN 0007 parts have more consistent concentrations of these characteristics. The location of the SN0007 parts may also suggest there is a difference in the characteristics observed due to the chemical environment seen in part of these PEEK parts. This is because the downstream side of the poppet and shroud of CV04 see a lower concentration of acidic solution while the entirety of the CV03 PEEK parts see the pretreat concentrate during use. See Figure 21 for more details.

Ingredient	Nominal Mass Concentration		
	Pretreat (Concentrate)	Pretreat Dose	Pretreat "Lite"
$H_3PO_{4(aq)}$ (85 % H_3PO_4 by mass)	~77.3 %	~7.70 %	~0.08085 %
H_2O	~15.9 %	~91.62 %	~99.91116 %
CrO_3 (>98 % purity)	~6.8 %	~0.68 %	~0.00799 %

(See diagram & schematic)

When pump operates, *Inlet side* sees this. *Outlet side* sees something in between these.

"Inlet Side"



"Outlet Side"

Pretreat Dilution	Estimated pH
Concentrate	~0.5
Dose	~1.2
Lite	~2.4

Figure 21. Details of exposure to pretreat of various locations.

While it is true that thermal processing and machining may impact some differences in these characteristics, the differences observed in the same localized sample area do support a possible interaction of the pretreat concentrate with the PEEK material.

C. Summary of Investigation

Fracture surfaces of Shroud and Poppet from the failed SN0013 CV03 were brittle in nature, as inspected by both RTRC and NASA. Visual and optical profilometer images taken at RTRC after valve disassembly indicate that the PEEK components were etched by the exposure to pretreat (compared to pristine, unused parts). SN0007 (CV04) did not fracture and was made of the same material, which suggests some difference between the environment between CV03 and CV04. Regarding stresses outside of the environment itself, it was also noted that the check valve qual unit underwent >100k cycles in water at the vendor and passed. PEEK barstock manufactured from Victrex 450G base resin (NASA flow down only specifies "Victrex Supplied") show varying differences of characteristics that limit chemical attack. Fractured PEEK parts showed notable differences in characteristics that limit chemical attack compared to the bar stock per Raman measurements, suggesting attack from pretreat solution. Shroud and end of poppet of SN0007 potentially were not fractured due to lower pretreat concentration in the use environment. Attempts to test embrittlement of SN0013 fractured parts showed they were no longer brittle after disassembly RTRC report, which suggested to the chemists at RTRC that rinsing/drying polymers of acidic solutions can reverse the embrittlement effects.

Upon a deeper look at both technical data sheets for the brands of PEEK used in the check valve builds, the information could be interpreted to suggest that use of components made from the 450G resin should not be used or is cautioned in highly acidic environments (pretreat pH ~1).

D. Failure Cause Stack–Chain of Most-Suspected Causes as of 2023-08-22.

- Dose Pump Pretreat delivery failure caused by degraded CV03 internal leakage performance (in backflow direction).
- Degraded CV03 performance caused by irregular valve O-Ring seating.
- Irregular valve O-Ring seating caused by Shroud failure/fracture.
- Shroud failure caused by environmental stress crazing/cracking (ESC).
- ESC caused by PEEK interaction with Pretreat+ persistent tensile stresses in Shroud. Persistent tensile stresses possibly caused by Shroud-Poppet interference due to a small Shroud-Poppet clearance + undetermined PEEK swelling in Pretreat.

IV. CCM Updated Hardware and Bubble Diverter

The pretreat quality device originally supplied by Collins was non-functional during the activities described above as was the CCM. A revised design with platinum probes is expected to be provided in 2024. A replacement of the stopgap CCM is also expected to be provided early in 2024 for possible use in a rescheduled Artemis-2 demonstration. This demonstration is planned for mid-2024 and will include the updated CCM design including a bubble diverter and a return of the Dosing Assembly with the original configuration of check valves with the PEEK materials. This also includes replacement of Toilet Integration Hardware items Pretreat Hose, Pretreated Urine Hose, EDV Adapter and spare fasteners for Dose Pump installation on Mounting Adapter.

V. Plans to Provide Data for Orion's Artemis-2 Mission

Detailed information is needed from the ISS on-orbit technology demonstration to inform essential packing and manifesting decisions for the Orion program. Specifically, the Artemis-2 mission, planned for 2025, is finalizing stowage quantities that directly affect ballast and heat shield design decisions. Information gleaned from the previous Limited Checkout provided valuable data on performance of the UWMS system in a microgravity environment and demonstrated that key functions such as the ability to collect both urine and fecal material were successful as well operations by the crew. Crew feedback from the aborted Artemis-2 Demonstration is also helpful. Crew noted that there was no issue with odor either while using UWMS or when not in use. This confirms the previous theory that odor was caused by a faulty installation of the OBF when the gasket was not in place properly. Feedback of this type continues to be used to make adjustments to the crew interfaces such as the seat and urine hose and consumables such as the fecal bag and canister.

VI. Updated Fecal Bag and Seat Designs

Based on crew feedback from the aborted Artemis-2 Demo and previous uses of UWMS, the seat and fecal bag for UWMS was redesigned 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 fecal bag is a smaller volume and has a more crew accessible closure method. The hardware was delivered in 2023 and an evaluation with UWMS on ISS is planned for 2024. The redesign and evaluation allows the Artemis-2 UWMS to be upgraded before launch. Evaluation on ISS is needed to confirm air flow and crew accessibility. A "dry" test with only air flow (no crew use) will be performed with the hardware to evaluate the updated designs with a follow-on evaluation for crew use to follow. The updated fecal bags and seats launched earlier than the replacement dose pump.

The Russian WHC opening with the seat lifted out of the way is 4" in diameter which is equivalent to the smaller of the UWMS seats provided. The HLS LOO seat is 4.3" in diameter. The updated designed seat matches the current WHC opening which crew says is preferred. 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 22. Testing is needed to validate which design will be chosen to fly on Orion's Artemis-2 mission.

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 23.

Figure 22. Russian WHC use with fecal bag, Orion UWMS with original 5" seat and original UWMS fecal bag installed, LOO seat design with fecal bag installed, updated seat with updated fecal bag (design #2).

Figure 23. Original UWMS fecal bag, Russian WHC fecal bag, LOO fecal bag and updated fecal bag.

Testing on-orbit is needed to validate air flow, efficiency, and actual use in micro-gravity with air flow.

VII.   Technology Demonstration Updates and Accomplishments

There have been significant lessons learned for the current baselined design with each activation of Toilet. Balancing ISS operations, Artemis missions, and continued pursuit of establishing a baseline Exploration Toilet, hardware redesign and stop-gap operations have been in work simultaneously. Acoustics concerns continue to be worked through the toilets provided for Artemis-3 and -4.

Return to the technology demonstration for exploration will recommence when the updated check valves and dose pump are complete as well as the redesigned conductivity sensor. This is likely planned for 2025.

Important insight into the operations of an exploration toilet continues to be obtained as each technical challenge surfaces and is resolved. Learning of materials compatibility issues for long-term exposure to the strong acid used to treat urine is valuable for long range missions to Mars. Use of available data such as from the pressure sensors for evaluation of pretreat presence has been validated and although not the planned use of this data is very useful in evaluation of performance.

VIII.   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.

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