NASA Exploration Toilet On-orbit Results and Impact on Future Missions

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The Universal Waste Management System (UWMS), which has the ISS operational nomenclature "Toilet", was initially installed on the International Space Station (ISS) in 2020 with final installation completed in 2021. Technical progress continued to be made with each on-orbit operation that culminated in additional crew use of the UWMS on ISS. Additional problems were evaluated during troubleshooting and testing with the UWMS hardware using water and pretreat to simulate crew use. This paper summarizes the additional testing, troubleshooting and the results as well as characterizes the additional data obtained and summarizes the interpretation of the data to characterize the hardware's operational nuances. Use of the hardware by crew is planned and will also be summarized. The paper will also describe the additional portions of the technology demonstration that were completed and the benefits 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
DFS = Dual Fan Separator
ECLS = Environmental Control and Life Support
ECLSS = Environmental Control and Life Support System
EDU = Engineering Development Unit
FY = Fiscal Year
ISS = International Space Station
JSC = Johnson Space Center
LED = Light Emitting Diode
LR = Logistics Reduction

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NCR = Non-conformance Report
NASA = National Aeronautics and Space Administration
OBF = Odor Bacteria Filter
SpX = Space X
TIH = Toilet Integration Hardware
TD = Technical Demonstration
UPA = Urine Processor Assembly
UWMS = Universal Waste Management System
WHC = Waste and Hygiene Compartment
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 project builds on previous toilet designs and delivered a toilet for ISS and the first crewed Orion mission. Delivery of the Orion toilet (seen in Fig. 1) was in December 2019 and the unit was installed into the Artemis-2 vehicle in March 2021 for launch in 2023. The ISS unit, seen in Fig. 2 along with the Toilet Integration Hardware, launched to ISS in October 2020. The ISS unit is awaiting final installation and nominal operations on ISS in Node 3. A limited checkout was performed in October/November 2021.

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 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 panel that initiating the unit either with removal of the urine funnel or lifting the commode lid. Pretreatment of the urine is performed in both units to stabilize the urine for processing on ISS or venting on Orion. 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 can be found in a previous paper [1].

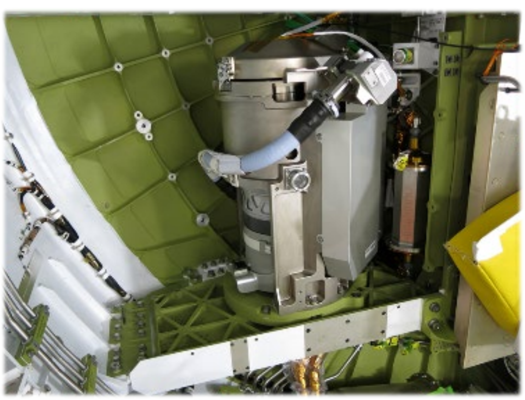

Fig. 1. Orion UWMS installed in Artemis-II Vehicle.

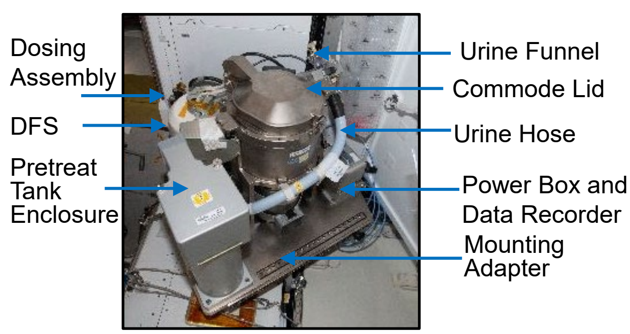

Fig. 2. ISS UWMS with Toilet Integration Hardware in Node 3, ISS.

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 yielded insight into the system's operations key to future use and also provided information needed for the Orion Artemis-2+ missions. Several efforts were made to go back into operational status with additional technical challenges arising along with technical data allowing better understanding of the Toilet and support systems as well as the impact on downstream hardware. Each time the system is operated, understanding grows on what is actually a nominal operational mode and what procedures are needed to maintain that mode.

III. Pressure Transducer Fault

A paper was written on the ISS Toilet for ICES 2022 ICES-2022-073 which included some background on limited crew operations of 2021 and what was known about the pressure transducer fault at that time. The purpose of this sections is to update the reader on the latest conclusions.

The fault tree remains open,but has been narrowed down to two possible causes: 1) Blockage, most likely in the pitot [location of smallest diameter], or 2) Dynamic fluid response where natural frequencies of the fluid – gas expansion/contraction – came into alignment with either the sensor mechanical frequencies, or the electrical reading frequencies of the controller. The latter issue is supported as a potential by hand calculations, but given the duration of the anomalous response, ~17 seconds, which occurred through then entire toilet spin down (i.e. over motor speed 0-7700 rpm), this is unlikely. Which lead to a primary or leading cause, Blockage, albeit unverified.

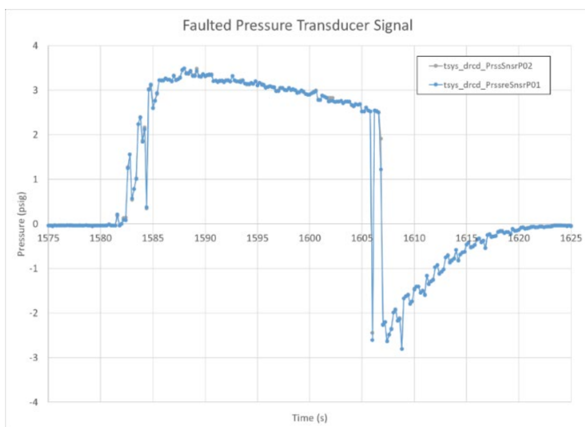

Figure 3. Pressure Transducer data plot.

Furthermore, additional evidence has come to light which supports blockage recurrence during operations in 2022. While not exactly the same signal which caused the fault circa 2021, two times on two separator occasions toilet has come out of dormant periods and shown a disconnect between the separator liquid volume and the pressure transducers readings. Such signal is a good indication of blockage at the pitot – between the separator and transducers. Both times, additional water was added to generate higher separator pressure, and the Toilet was operated to induce a series of urine outlet valve cycles to encourage clearing the suspect blockage. Both occurrences succeeded in a recovery of nominal pressure transducer signals and a clearing of the liquid in the separator. Activities which followed these occurrences showed nominal toilet performance with respect to pressure signal, response, and clearing of liquid. These occurrences strongly support the possibility of pitot buildup, but also show that recovery from such anomaly is also possible.

With respect to build up being possible, this suggests that pretreat may not be adequately mixed with the urine from the crew. A major requirement in design of the dose pump and toilet was mixing pretreat to ensure a mostly homogeneous output product of pretreated urine. The current mixing program has two pulses of pretreat first a pre-dose which occurs ahead of any urine addition, and second a main dose which is intended to mix with the urine as it is coming into the separator. Toilet successfully passed dose mixing acceptance tests with small, medium, and large urine profiles, however, the human element in real time operations adds much unknown variability in a micturition profile. There are two lines of thought that could result in improper pretreat mixing, but both involve timing. Simply put, too much pretreat at the beginning leaves higher untreated urine in the finish or conversely, lower pretreat at the beginning leaves too much pretreat at the finish. We focus on the finish of a use because that residual is left in the Toilet liquid gas separator between uses. Low or high pretreat can lead to the generation of solids from breakdown or evaporation. At this time studies into this level of detail have not been complete but are recommended for future fine tuning of Toilet operations.

IV. Dormancy Period 1

One of the objectives of the Exploration Toilet is to be able to go into and come out of quiescent periods. In other words, periods without use are a planned part of future exploration missions. Therefore, the need for Toilet to go into Dormancy and subsequently return to operation via a post dormancy activation and checkout is vital. A dormancy procedure was created to achieve a specific sequence of events to safely put Toilet into a dormant state. The sequence included:

1. Acid flush – to ensure stabilization and protection from any urine that was not properly treated
2. Water flush – to push all acid and urine out of Toilet lines and hoses
3. Separator Rinsing – to fully coat the separator internals with a light pretreat, and
4. Dilution – to leave the hardware with only water and a light acid content (sometimes called pretreat lite) for the duration of the non-operational period

This sequence and version of Dormancy procedure was executed on ISS in November of 2021. After subsequent findings – release of pretreat into the cabin, discovered March 2022 – changes were made based on the failure investigation.

V. Pretreat Solution Release

After investigation of the Pressure sensor fault, which occurred during limited crew operations in October to November of 2021, a plan to continue data gathering with Toilet use was proposed for March of 2022. The plan was set in motion and started with the Toilet Air filter (TAF) Remove & Replace (R&R) procedure. During the removal, corrosion was found at the top of the TAF and the underside of the commode cover. Based on photos taken from the crew, the conclusion was that pretreat, and water escaped the toilet system during the Dormancy procedure. Seen in Figure X, liquid was present and evident in the post dormancy photos (taken 5 hours after the activity) matching a corrosion location and size observed in later photo documentation after discovery.

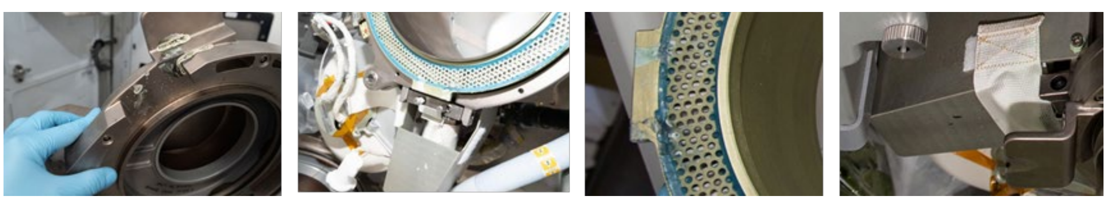

Figure X. Dried residue from pretreat and water solution release on UWMS commode top, access door pins and OBF.

The dried evidence kicked off a new failure investigation for pretreat in the cabin. That failure was further split into two parts: 1) Liquid bypass of the separator and 2) liquid breakthrough of the TAF. The latter is discussed as part of the TAF design. The primary issue or cause of pretreat in the cabin is a failure in containment or separation of the liquid by the liquid-gas separator. Figure X has a Fault Tree of the condition for liquid bypassing the separator. Open legs can be reorganized into some combined buckets for discussion purposes. Table X shows this regrouping.

Table 1. Fault Tree Legs.

	Fault Tree Leg	Comments
Liquid migration (non-operating)	2.1.1.1, 2.1.2.2, and 2.1.2.3	
Maze Seal Bypass (operating)	2.1.1.2	
Overflow/Carryover		
Incorrect Pressure Readings	2.1.3.1.4.1 Pitot flaw/crack 2.1.3.1.4.2 Blockage	
Large Micturition or Slug	2.1.3.3	
Entrainment in air stream	Not in fault tree	

By grouping as such, mitigations, controls, and risks can be discussed and quantified in order to substantiate further use of toilet while managing safety concerns. The UWMS nominally safes itself when an error condition is seen. The system will flag a shutdown fault, then remove and inhibit power to the rotary components. Risks to the hardware from the fault tree is the same for all fault legs, pretreated urine outside the separator which could dry and cause a mechanical bridge between the rotating items and the static housing. A dried bridge can be cleaned and refurbished on the ground but does require on-orbit R&R and return to ground facilities.

Table 2. Comments on safety risks, mitigations, and controls.

	Risk	Mitigations or Controls
Liquid migration (non-operating)	PTU in the cabin	- Residual pretreated urine in separator is generally low [35±15 mL]. Only a fraction would be able to escape during standby
Maze Seal Bypass (operating)	PTU in the cabin	- Monitor toilet use for power increases as this indicates 30-50 mL between the housing and separator
Overflow/Carryover	PTU in the cabin	See Below
- Incorrect Pressure Readings	PTU in the cabin	- Regular toilet use decrease likeliness of build up or blockage from non-homogeneous pretreated urine - Controls include creating a blockage clearing and checkout procedure
- Large Micturition or Slug	PTU in the cabin	- Use notched funnel to eliminate possibility
- Entrainment in air stream	PTU in the cabin	- None, low risk due to very low volume (micro droplets <0.2 mL), TAF can contain such low volumes

Additional controls for all PTU in the cabin cases include taping a mitt used for cleanup of pretreat spills over the suspect air outlet to capture and liquid that might escape and to regularly monitor the condition of the mess up mitt. A single sheet of the mitt has a capacity of around 100 mL, and thus should be able to contain any carryover and breakthrough of liquid on the order of magnitude of 10-20 mL or less. To this point only once has liquid made an external escape of pretreat and that volume was estimated to be around 10 mL. In its use thus far on ISS, toilet has processed between 30 and 40 Liters of total liquid volume of which over 11 Liters was urine from crew operations in 2021.

VI. Dormancy Period 2

The UWMS is currently in dormancy to allow the team to evaluate data and recommend an operational path as well as allow hardware updates for operations of the conductivity sensor and acoustics. A proposed additional checkout is in consideration. Completion of a working conductivity sensor as well as acoustics modifications are currently in work. The conductivity sensor will likely impact a return to nominal operations as well as mitigations for acoustic levels. This work likely will push the schedule of operations for completion of the tech demo into 2023; however, additional checkout operations may occur late in 2023.

VII. Odor Bacteria Filter

The first R&R of the TAF – prior to limited crew use in 2021 – allowed small carbon particles to escape into the cabin. These particles are the adsorbent within the filter bed used for odor control. The filter outlet utilizes a pleated membrane filter that prevents any dusting or particles from escaping, but the inlet to the filter has no such membrane. The beds are held by a course stainless wire mesh. The unidirectional air flow during operation generally sets and maintains the bed from the inlet side. On the other hand, ground packaging includes a plug that installs in the inlet to retain any free particles inside the filter during any processing and handling. The whole TAF is then double bagged for flight, see Figure x.

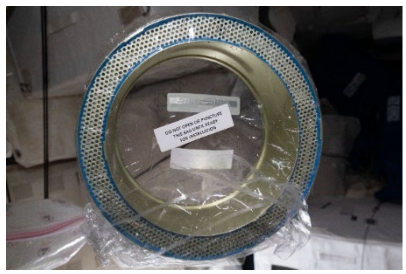

Figure X. Toilet Air Filter (Odor Bacteria Filter)

After the particle release, all the air filters on ISS were inspected inside their packaging. Of the 12 filters on orbit, 6 (half) had no evidence of particles in the packaging, 4 has very few particles and 2 had many particles. A procedure update was developed to minimize risk of particle escape and protect the crew during the R&R. Appropriate PPE was added to protect crew from any inhalation hazard and a vacuum would be used to safely collect any particles inside the bag before removing the filter. Incidentally, one of the two filters with the highest number of particles was chosen and used in the new filter R&R procedure in March of 2022 and showed successful particle collection/containment and crew protection. Thus, at this time, the team believes the procedure updates have adequately put controls in place for managing this risk/issue.

A separate issue was noted during the second filter R&R – after limited crew operations in 2021. The crew had not fully opened the filter access door during the first filter R&R which led to the face seals on the TAF to be scrunched and folded. Figure x shows at least one of the two seals was fully compromised and the second seal may also have been compromised during the 16 days of crew operation. This might explain the crew complaint of odor *during* UWMS use (i.e., when air was flowing). Further testing is needed to verify. The crew procedure was updated to give a caution note and explicitly direct the crew to open the filter access door to the *open* and *locked* position. Recurrence of the filter seal issue has not yet been seen.

Figure X. One of two seals folded.

The final known issue with the TAF is the containment of liquid. During development and qualification, the filter was intended to be a barrier to liquid, specifically pretreated urine, from escaping into the cabin. The primary failure mode expected would be solenoid valves failing open and allowing the Urine Processor Assembly's (UPA) Wastewater Storage Tank Assembly (WSTA) to backflow into Toilet hardware. The WSTA is a metal bellows that exerts positive pressure on the liquid side of operations. Such risk poses substantial hazard to the crew were they to come into direct contact with the pretreat. As part of the investigation for the pretreat in the cabin, a sub failure was performed at the last line of defense, the TAF, and an inability to contain the pretreated urine. Ground testing target the membrane material and time to effect of pretreat breakthrough. The test conditions simulated the WSTA backpressure expected (0.6 psig) onto the filter over time. A static test with no additional air flow or motive force applied. In this testing, a column of pretreated urine was allowed to sit on the membrane over the course of several days to understand the breakthrough time. Between 31.5 and 47 hours and 54 to 54.5 hours across two discrete sample sets exhibited pretreat breakthrough. Conservativity, the recommendation was to limit the exposure time to 24 hours and recommend full replacement of the TAF and clean-up of pretreat urine exposed hardware.

While the testing showed containment of a static pressure, dynamic pressure – or pressure with flow – was never tested. It was believed that the worst-case scenario was the *higher* static pressure and that the testing completely enveloped the dynamic case. This turns out to be a poor assumption. As later testing confirms, the introduction of air flow through the membrane drastically impacts the ability to hold back liquid. Simple test setups were undertaken on a downgrade TAF. They were as follows:

1. Static test of TAF flight configuration
    a. Tilt filter to localize liquid collection area in 1g
    b. Add 30 mL water
    c. No leak noted at outer membrane
2. Dynamic test of TAF flight configuration
    a. Connect above test config to the development DFS combined air outlet
    b. Startup dev DFS
    c. Leak noted instantly, essentially 20+ mL in under 2s
3. Dynamic test of TAF flight configuration with lower volume
    a. Using dry TAF, tilt and add X mL water
    b. Startup dev DFS
    c. Leak noted instantly

The testing underscored the difference between the static and dynamic case for the membrane. Given the results, the TAF does not meet its design intent and is not a barrier to greater than 5 mL liquid entrain in airflow. However, a case can still be made for the MSFC testing being representative of the membrane providing a barrier for a static liquid pressure. The primary example of that failure is back flow from the WSTA which, as a bellows design has a constant pressure associate the level of fill it maintains. In this case, the collapsed bellows position being neutral stress, means a positive pressure constantly applied back towards the UWMS. Software is in place such that most back flow conditions which result in slow but continual reduction in WSTA pressure would be flagged sch that appropriate crew action could take place.

VIII. Impact on 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 missions, planned for 2024, is finalizing stowage quantities that directly affect ballast and heat shield design decisions. Information gleaned from the previous Limited Checkout x 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 successful operations by the crew.

A single fecal canister was returned from the ISS for evaluation by the engineering team as seen in Figure x. This canister was examined externally for damage, odor and weight before opening and showed that although the canister was in good physical shape, there was odor coming from the assembly of the Fecal Canister and Lid. Further study revealed that the gasket material between the two components was an open-cell foam which allowed odor to escape. Additional evaluation, testing and redesign of the gasket material are currently in work. See Figure x for Fecal Canister and Lid Assembly.

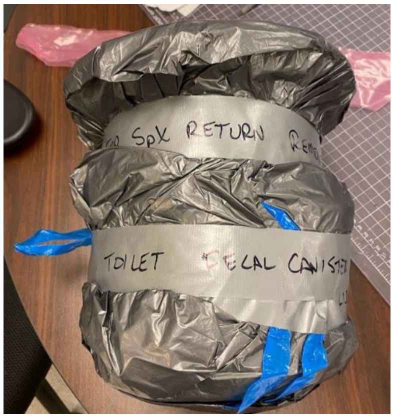

Figure x, Returned Fecal Canister

Figure x. Returned Fecal Canister

Figure x. Fecal Canister X-ray and Lid Assembly

The Fecal Canister was x-rayed before it was opened as well, see Figure x. Compaction efficiency studies have been performed using ground prototypes and fecal simulants to estimate the quantity of fecal deposits that could be expected in the fecal canister volume. Validation of this ground testing with actual micro-gravity cases was needed. The returned fecal canister provided the first insight into the ability of the crewmembers to compact deposits and also how actual fecal material, flight fecal bags and use of on-orbit available wipes and gloves impacted the number of deposits contained in the canister. The x-ray showed good fecal compaction, however, more compaction plates than expected were seen.

Figure x. Deposit in Fecal Bag

Finally, excavation of the canister was performed in a lab under an exhaust hood. Each compaction plate and deposit package was removed individually from the canister. Each deposit was weighed and then opened to reveal the contents. Separation of the wipes and gloves from the deposit was done to obtain data on usage of wipes and gloves for each deposit. Wipes used by the crew included Huggies Wet Wipes, Russian Dry Wipes and an antibacterial wipe.

Results of the excavation showed that the canister contained 13 deposits, significantly less than ground testing and design calculations had shown at 20 per canister. Full and complete compaction was seen with no appreciable void spaces noted. Six compaction plates were used by the crew at varying intervals. This operation is left to crew discretion and varies based on fecal deposit size, consistency, number of wipes and gloves in each deposit. Also noted that crew preferred the Russian Dry Wipes with more used and the Huggies Wet Wipes. Antibacterial wipes were not used in high numbers. See results in Table 1.

Figure X.

Table 1. Results of excavation of fecal canister used on ISS by 2 crewmembers in Limited Checkout and returned for ground evaluation.

# Toilet Uses	# Fecal Bags Used	# Compaction Plates Used	US Dry Wipe	Gloves	Russian Dry Wipe	US Wet Wipe	Disinfectant wipe	Fecal Deposit Average Weight (lbs)	Overall Average Weight (lbs)
	13	6	0	12	46	64	3		
Sub D (male)	6	total	0	0	11	25	0		
		avg per use	0	0	1.83	4.17	0.00	0.221	0.420
		mass per use (lbs)		0.00	0.04	0.21	0.00		
Sub C (female)	7	total	0	12	35	39	3		
		avg per use	0.00	1.71	5.00	5.57	0.43	0.427	0.503
		mass per use (lbs)		0.02	0.12	0.28	0.02		
Overall	13	total	0	12	46	64	3		
		avg per use	0.00	0.92	3.54	4.92	0.23	0.333	0.490
		mass per use (lbs)		0.01	0.08	0.25	0.01		

The Orion program is assessing the results of the excavation with expectation that an additional two fecal canisters will be returned for evaluation when the UWMS technology demonstration is completed. The results of the single fecal canister used by two crewmembers indicates that additional fecal canisters would be needed for the Artemis-2 mission. An Artemis-2 Demo consisting of 12 days with concurrent use by 4 crewmembers is planned and is pending scheduling of available crew time. This demonstration is meant to mimic the Artemis-2 mission in duration and crew size and will provide details on overall UWMS system use in a prolonged and higher use frequency period as well as additional details on needed numbers of fecal canisters. The Orion program is not manifesting the Russian Dry Wipes and during this Artemis-2 demonstration, crew has been asked to limit use of wipes that are available. Data is needed to define manifesting of wipes as well.

IX. Other Testing with UWMS on ISS

A. Collapsible Contingency Urinal (CCU)

The Collapsible Contingency Urinal (CCU) was developed for use in microgravity as a backup urine collection system in the event of a UWMS failure and resulting loss of mission. After a UWMS failure, the Orion vehicle would begin its return flight to Earth. The CCU would be used during the return flight.

The CCU consists of a plastic bag for containment, lined internally with hydrophilic vanes that use capillary action to wick the fluid to the bottom of the bag. A drain port is located at the bottom of the bag for urine to be drained via venting to space, allowing the CCU to be used again. The hydrophilic vanes also stabilize fluid against perturbations, reducing the risk of urine exiting the CCU during handling. A male and female version of the CCU was developed to accommodate different anatomy.

During development, four CCU designs were tested by crew on the International Space Station. There is no ground-based substitute for testing microgravity urine collection, so the opportunities to test and refine the CCU on International Space Station were crucial to the development of this hardware. Male and female crew members tested each design during urination-only and simultaneous urination-and-defecation events ("dual operations"). During the dual operations test, the test subjects defecated into the UWMS at the same time as urinating into the CCU with UWMS in the off condition. This important test allowed the CCU team to understand the ergonomics, logistics, and acceptability of the CCU design for the dual operations use case. The test subjects indicated that the CCU as designed was acceptable for use during dual operations.

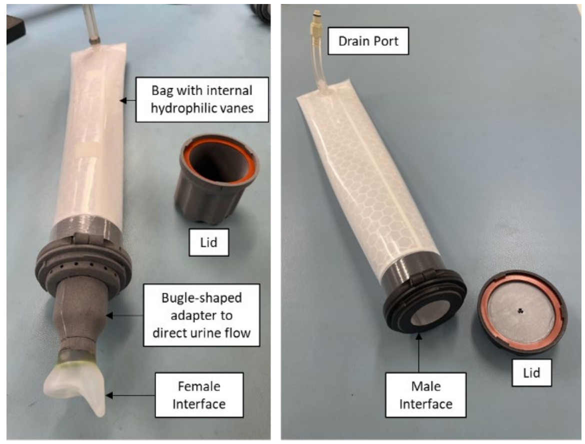

Figure x. Collapsible Contingency Urinal, female and male.

X. Hardware Redesigns and Upgrades

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 are being addressed, both in mitigation efforts and hardware redesigns and the pretreat quality monitoring concerns are in work crew interface equipment being redesigns or just waiting for crew inputs on current set

A stop-gap effort with a NASA Marshall Space Flight Center delivered a new conductivity sensor (inductive-based) as a temporary monitor while teams developed a drop-in, permanent replacement later in 2023. This temporary sensor uses a COTS toroidal sensor in a custom manifold block to strategically reduces the overall sample volume but not interfere with the sensor's electromagnetic field effects. In October 2022, the COTS sensor was installed; however, upon initial activation there appears to be significant interferences caused by bubbles that resided in the hardware due to weeks of dormancy. Attempts to clear these potential bubble interferences have not been effective. Upcoming Toilet operations will not rely on this sensor but rather using the pressure transducer data; however, troubleshooting will still be pursued in hopes of sensor recovery.

The permanent sensor drop in design efforts are in works – parallel paths considering new sensor approaches (colorimetric/inductive properties) and redesigning the baselined conductivity sensor (electrode based) to mitigate known failure modes. The down select and flight hardware delivery is expected to be mid-late 2023.

XI. Conclusion

Completion of the technology demonstration of the UWMS on ISS is paramount to informing explorations 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.

Acknowledgments

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