Status of ISS Water Management and Recovery

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Water management on ISS is responsible for the provision of water to the crew for drinking water, food preparation, and hygiene, to the Oxygen Generation System (OGS) for oxygen production via electrolysis, to the Waste & Hygiene Compartment (WHC) for flush water, and for experiments on ISS. This paper summarizes water management activities on the ISS US Segment as of March 2022 and provides a status of the performance and issues related to the operation of the Water Processor Assembly (WPA) and Urine Processor Assembly (UPA).

Nomenclature

AAA	=	Avionics Air Assembly
ARFTA	=	Advanced Recycle Filter Tank Assembly
АСУ	=	Russian Urinal
ACTEX	=	Activated Carbon and Ion Exchange Cartridge
BPA	=	Brine Processor Assembly
CDRA	=	Carbon Dioxide Removal Assembly
CWC	=	Contingency Water Container
CCAA	=	Common Cabin Air Assembly
DA	=	Distillation Assembly
DMSD	=	dimethylsilanediol
EMU	=	Extravehicular Mobility Unit
ЕДВ (EDV)	=	Russian water container
FCA	=	Firmware Controller Assembly
FCPA	=	Fluids Control and Pump Assembly
GLS	=	Gas Liquid Separator
CWC-I	=	Contingency Water Container - Iodinated
ISPR	=	International Standard Payload Rack
IX	=	Ion Exchange
MCV	=	Microbial Check Valve
MLS	=	Mostly Liquid Separator
MF	=	Multifiltration
MTL	=	Moderate Temperature Loop
OGS	=	Oxygen Generation System
ORU	=	Orbital Replacement Unit
PCPA	=	Pressure Control and Pump Assembly
PTU	=	Pretreated Urine
PWD	=	Potable Water Dispenser
PWR	=	Potable Water Reservoir
RHS	=	Reactor Health Sensor
RST	=	Resupply Tank
SPA	=	Separator Plumbing Assembly
TOC	=	Total Organic Carbon
TOCA	=	Total Organic Carbon Analyzer
UPA	=	Urine Processor Assembly
UTAS	=	United Technologies Aerospace
UTS	=	Urine Transfer System
UWMS	=	Universal Waste Management System
WHC	=	Waste & Hygiene Compartment
WRM	=	Water Recovery and Management
WPA	=	Water Processor Assembly
WRS	=	Water Recovery System
WRT	=	Water Resupply Tank
WSS	=	Water Storage System
WSTA	=	Wastewater Storage Tank Assembly

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I. Introduction

THE International Space Station (ISS) Water Recovery and Management (WRM) System insures availability of potable water for crew drinking and hygiene, oxygen generation, urinal flush water, and payloads as required. To support this function, waste water is collected in the form of crew urine, humidity condensate, and Sabatier product water, and subsequently processed by the Water Recovery System (WRS) into potable water. This product water is provided to the potable bus for the various users, and may be stored in water bags for future use when the potable bus needs supplementing. The WRS is comprised of the Urine Processor Assembly (UPA) and Water Processor Assembly (WPA), which are located in two International Standard Payload Racks (ISPR) named WRS#1 and WRS#2. The WRS hardware was delivered to ISS in November 14, 2008 and is located in the ISS Node 3 module.

II. Description of the ISS Water Recovery and Management System

A conceptual schematic of the WRM is provided in Figure 1 and displays the inlets and outlets to both the WRS and Oxygen Generation System (OGS) since both systems are highly interconnected. Crew urine is collected in the Waste & Hygiene Compartment (WHC)[1], which consists of a Russian Urinal system (referred to as the ACY). Presently, strategic water reclamation from fecal waste is not pursued. To maintain chemical and microbial control of the urine and hardware, the urine is treated with an oxidizer and an inorganic acid. The pretreated urine is delivered to the UPA to produce urine distillate and brine. In addition, pretreated urine collected in the Russian Segment may also be manually transferred in Russian fluid container (called ЕДВs) and transferred to the UPA. The recent delivery and installation of the technology demonstration, Brine Processor Assembly (BPA), has allowed further processing of the urine brine, achieving >90% water recovery[2].

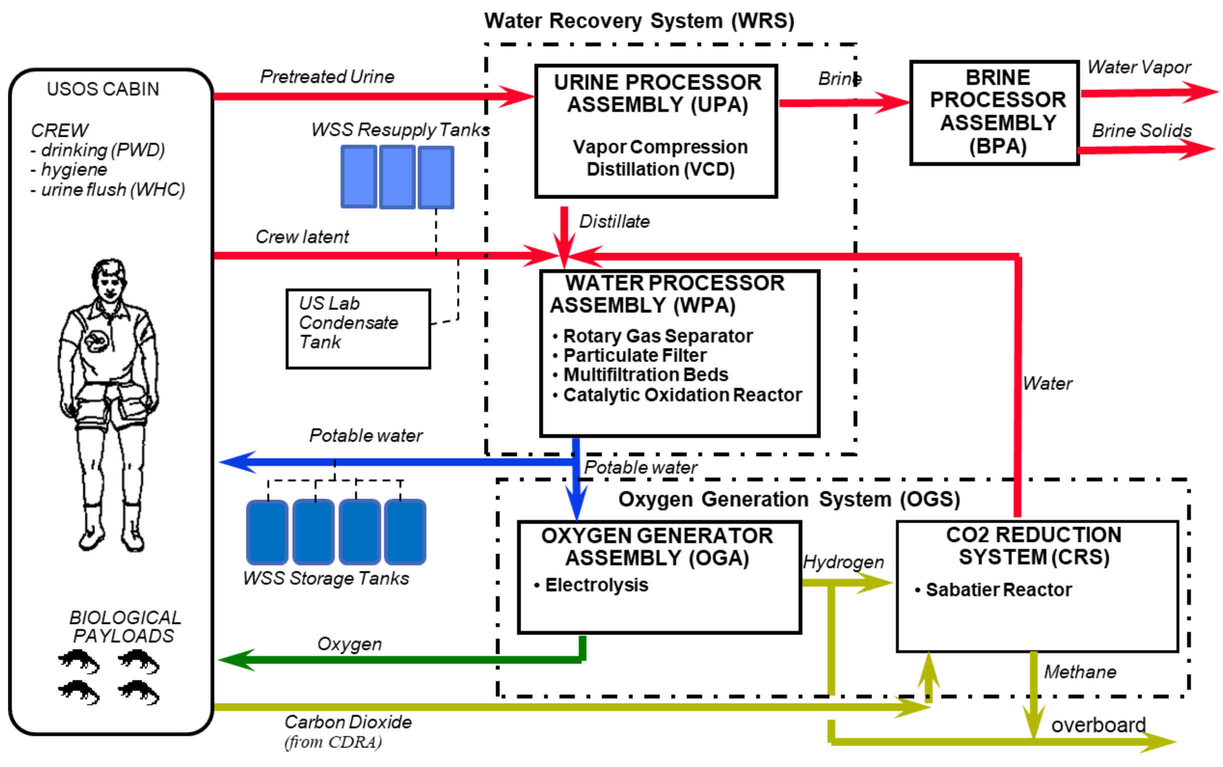

Figure 1. Water Recovery and Management Architecture for the ISS US Segment.

Condensate is collected from the cabin air by the Common Cabin Air Assembly (CCAA) Condensing Heat Exchangers (CHXs). Urine distillate, humidity condensate and Sabatier product water are delivered to the WPA Waste Tank for further processing. However, the Sabatier reactor has not been in service since October 2017 due to a failure of the reactor, though replacement hardware is intended to be delivered to return this capability.

Makeup water from Resupply Tanks (RSTs) launched from the ground is added to the WPA waste tank as required to maintain the water balance. A separate Condensate Tank located in the US Laboratory Module is available as a back-up in the event the WPA Waste Tank is unavailable for waste water collection, or in the past year to provide separate condensate collection and feed to the European Space Agency (ESA) Life Support Rack (LSR), which is a technology demonstration on ISS.

After the waste water is processed by the WRS, it is delivered to the potable bus. The potable bus is maintained at a pressure of approximately 230 to 284 kPa (19 to 26.5 psig) so that water is available on demand for the various users. Users of potable water from the bus include the Oxygen Generation Assembly (OGA), the WHC (for flush water), the Potable Water Dispenser (PWD) for crew consumption, the Extravehicular Mobility Unit (EMU) sublimator and Payloads. Finally, a reserve of a minimum of 818 L (1803 lbs) of potable water is stored on ISS in Contingency Water Containers - Iodinated (CWC-Is), Water Storage System (WSS) Storage Tanks (plumbed directly into the potable bus) and Water Resupply Tanks (RSTs) to maintain ISS operations in response to contingency scenarios.

III. Description of the ISS Water Recovery System

The layout of the two WRS racks is shown in Figure 2, along with the OGS Rack. The WPA is packaged in WRS Rack #1 and partially in WRS Rack #2, linked by process water lines running between the two racks. The remaining portion of WRS Rack #2 houses the UPA.

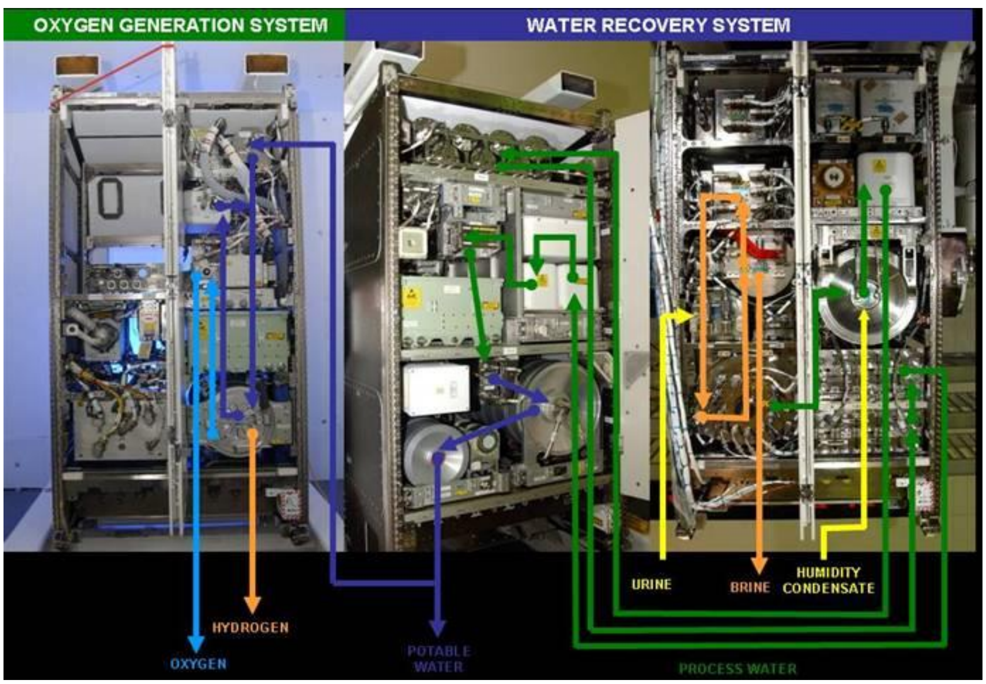

Figure 2. International Space Station Regenerative ECLSS Racks.

The following section provides a description of the WRS, current operational status, and describes issues and lessons learned during the past year. For the prior years' status, see references 1,3-6.

A. Urine Processor Assembly

A simplified schematic of the UPA is shown in Figure 3. Pretreated urine is delivered to the UPA either from the US Segment WHC (outfitted with a Russian urinal) or via manual transfer from the Russian ЕДВ. In either case, the composition of the pretreated urine is crew urine, flush water, and a pretreatment formula containing chromium trioxide and an inorganic acid to inhibit microbial growth and the conversion of urea to ammonia. In the Russian segment, the inorganic acid is sulfuric acid. In the US Segment, the inorganic acid has been switched to phosphoric acid to address precipitation issues with calcium sulfate. The pretreated urine is pumped from the Waste Storage Tank

Assembly (WSTA) into the UPA recycle loop by the Fluids Control and Pump Assembly (FCPA). In the recycle loop, the pretreated urine is recirculated through the Distillation Assembly (DA), the Advanced Recycle Filter Tank Assembly (ARFTA), a brine filter, and back to the DA. Distillate produced in the DA is pumped to the WPA Waste Water Tank. The DA consists of a rotating centrifuge where the waste urine stream is evaporated at low pressure. The vapor is compressed and condensed on the opposite side of the evaporator surface to conserve latent energy. A rotary lobe compressor provides the driving force for the evaporation and compression of water vapor. Waste brine resulting from the distillation process is stored in the ARFTA, which is a bellows tank that can be filled and drained on ISS. When the brine is concentrated to the required limit, the ARFTA is emptied into an ЕДВ. The ЕДВ containers are emptied into the Russian Rodnik tank on the Progress vehicle for disposal. The ARFTA is refilled with pretreated urine to initiate a new concentration cycle. The Pressure Control and Pump Assembly (PCPA) is a four-tube peristaltic purge pump which provides removal of non-condensable gases and water vapor from the DA. Liquid cooling of the pump housing promotes condensation, thus reducing the required volumetric capacity of the peristaltic pump. Gases and condensed water are pumped to the Separator Plumbing Assembly (SPA), which recovers and returns water from the purge gases to the product distillate stream. A Firmware Controller Assembly (FCA) provides the command control, excitation, monitoring, and data downlink for UPA sensors and effectors.

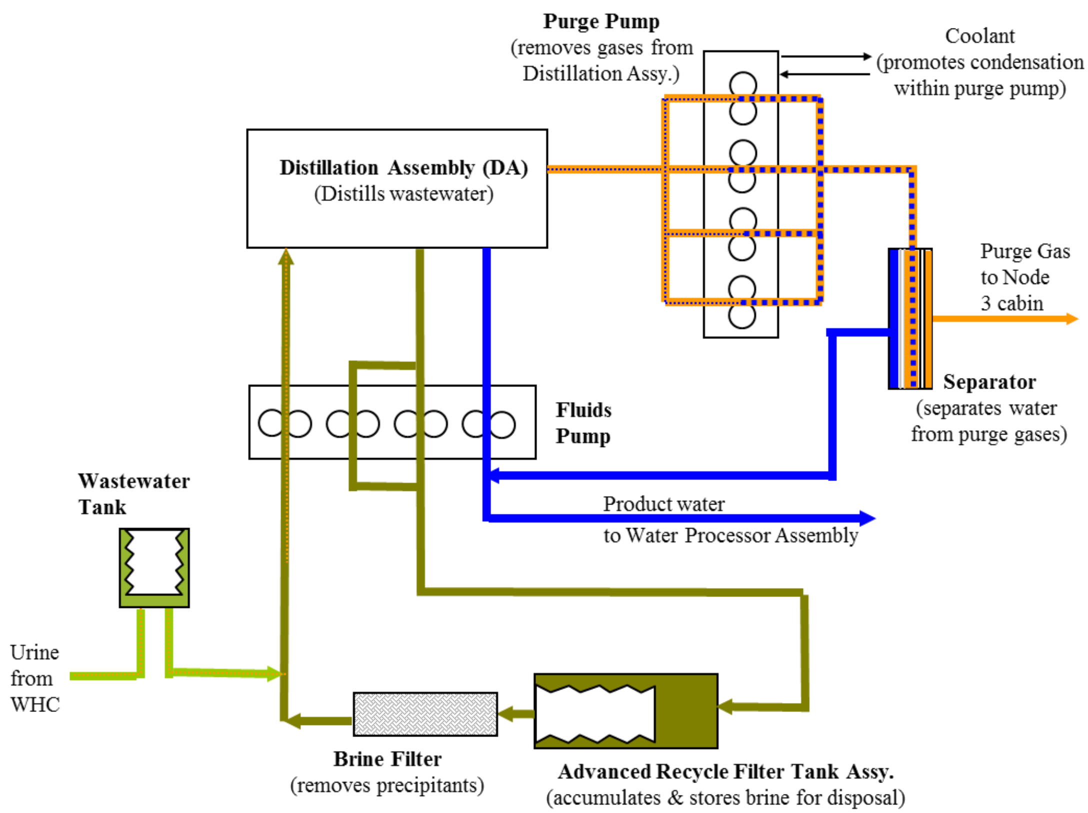

Figure 3. Urine Processor Assembly Schematic.

The UPA was designed to process a nominal load of 9 kg/day (19.8 lbs/day) of wastewater consisting of urine and flush water. This is the expected quantity for a 6-crew load on ISS. The UPA was designed to recover 85% of the water content from the pretreated urine, though issues with urine quality encountered in 2009 required the recovery to be dropped to 75% for the US Segment and 70% for urine collected in the Russian Segment. Implementation of a phosphate-based urine pretreatment[7] in early 2016 allowed the UPA to return to a minimum of 85% recovery of urine collected in the US Segment, though urine recovery from urine collected in the Russian Segment remains at 70% because no changes have been made to the pretreatment in the Russian Segment. Continued assessments of returned brine filter samples have allowed incremental increases of water recovery from US pretreated urine from 85% to 87%.

Targeted final percent recovery from US pretreated urine in the UPA is planned for 90%; however, further analysis of returned samples is required.

B. Water Processor Assembly Overview

An updated simplified schematic of the WPA is provided in Figure 4. The WPA feed water includes humidity condensate, distillate from the UPA, and Sabatier product water when available. Wastewater first passes through a 300 micron External Filter Assembly (EFA) to capture any biofilm from the Waste Water Tank (WWT). The water is initially degassed by the Mostly Liquid Separator (MLS), and then pumped through a 0.5 micron particulate filter, and another EFA, followed by a Multifiltration (MF) Bed containing adsorbent and ion exchange media. Prior to 2019, the WPA used two MF Beds in series but switched to a single MF Bed in July 2019. Volatile organics not effectively removed by the MF Bed are oxidized in the Catalytic Reactor at elevated temperature, which also removes microbial contamination. Excess oxygen and gaseous oxidation by-products are removed by the Gas Liquid Separator (GLS). Dissolved and soluble reaction byproducts are removed by the Ion Exchange Bed, which also adds iodine to the product water as a biocide. Product water is stored in the Water Storage Tank prior to delivery to the ISS potable water bus.

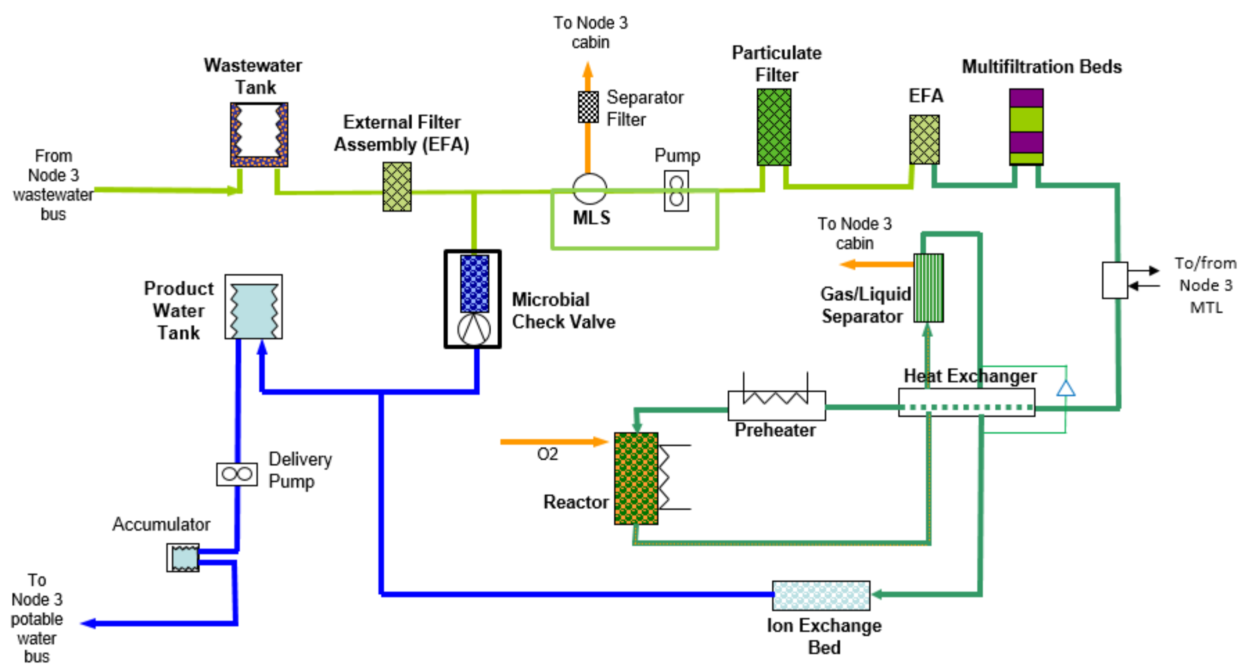

Figure 4. WPA Simplified Schematic.

IV. Water Recovery and Management Status

Between February of 2021 and February 2022, WPA has produced approximately 7,548 L (16,640 lbs) of product water. In addition, 1,200 L (2,645 lbs) of potable water is currently stored on ISS for resupply water and in reserve for contingencies. Management of the water mass balance has improved with the delivery of the Water Storage System (WSS) in the US Segment. This surplus of water in the US Segment is expected to shift with the installation of a replacement distiller for the Russian Segment Urine Processor and a most recent delivery of an additional urine processor in the Multipurpose Laboratory Module (MLM). Installation of the first Urine Processor was completed in 2018, but the distiller failed during initial checkout. Recovery of the system was achieved; however, only for a limited time. Hardware failures and system vacuum leaks have been ongoing challenges for both systems and have been unable to establish a nominal operation frequency. Distillate from the Russian Urine Processors are planned to be used for flush water, feed water to the Russian Elektron, and feed water to their condensate processor pending successful results from analysis of distillate samples returned to the ground.

1. Water Storage System (WSS)

The Water Storage System (WSS) addresses the water management issues associated with water resupply and potable water storage. Potable water storage capacity has increased by launching four tanks recovered from Space Shuttles Endeavor and Atlantis. The former space shuttle tanks are connected to the potable bus with inlet valves that are controlled by ground personnel. Water is transferred (via ground commands) to and from this WSS as needed for the water balance. The additional capacity has greatly increased the WRS's ability to absorb disturbances to the mass balance by adding system capacity and increase the time that ISS crew has to respond to mass balance upsets. The increased time for response will allow ground teams to mitigate mass balance upsets and potentially prevent crew involvement. In addition to assisting with management of the water reserve, the rack incorporates interchangeable 73 L (161 lbs) resupply tanks (RST). The increased size of the resupply tanks and the ability for multiple tanks to be installed into the WSS greatly decreases the frequency and total crew time required to add water to the WRS. The resupply tanks will also provide back-up condensate collection volume in addition to the existing WPA Waste Water Tank and Lab condensate tank. WSS has also received a controllable valve in front of the Lab condensate tank. Previously the condensate tank needed to be isolated from the WPA waste tank because the two bellows tanks have overlapping backpressure. If both tanks are connected to the waste water bus at the same time, the WPA Waste Water tank will push waste water into the Lab Condensate tank. Besides the operational impacts associated with filling the condensate tank, this reverse flow exposes the WPA Waste Water Inlet Valve to the biomass present in the waste tank, thereby increasing the risk of internal blockage.

2. Further Water Management Expansions

Several additional modifications to the ISS water system have been delivered and installed, including a Urine Transfer System (UTS), a Universal Waste Management System (UWMS), and a Brine Processor Assembly (BPA). The BPA increases the total water recovery of water from urine brine generated by the UPA to beyond 95%. Early estimates suggest upwards to 97-98% water recovered from urine. The UWMS, also known as "Toilet," for ISS applications, is a US designed toilet. With increased crew sizes on the ISS, providing additional waste management has been a critical path to ensure crew comfort as well as management the current Waste and Hygiene Compartment (WHC). These systems play a critical role to understand advanced technologies necessary for next generation exploration missions. The UWMS is a new toilet designed by Collins Aerospace (formally United Technologies Aerospace Systems, UTAS). This hardware is planned for use in the Orion vehicle and full demonstration of the hardware on ISS is being pursued.

<u>Urine Transfer System</u>

There were anticipated challenges associated with increased crew sizes, including the introduction and operation of a second toilet into the ELCS systems. To support the operation of two urinals on ISS (UWMS and WHC), a Urine Transfer System (UTS) has been installed on ISS. This hardware automatically manages all inputs (WHC, UWMS, ЕДВ) ensuring that parallel operations do not impact the delivery of urine to UPA. For example, assuming baselined UWMS "Toilet" operations, UTS can divert flow from the WHC to a backup ЕДВ any time pressure sensors indicate the UWMS is also delivering urine to the UPA. This ЕДВ can subsequently be drained to the UPA when neither urinal is in use. As part of the UTS delivery, Boeing incorporated a commercially available compressor that can be used for the same applications as the standalone Russian compressor. The UTS integrated compressor can transfer pretreated urine from ЕДВs to the UPA WSTA and for offloading the UPA brine tank (ARFTA) into the BPA or to brine ЕДВs. This hardware has also reduced the need to manually transfer urine, thus saving crew time spent on system maintenance and operation tasks[19]. Figure 5 showcases the UTS integrated in NOD3. UTS hardware has been installed in June 2020.

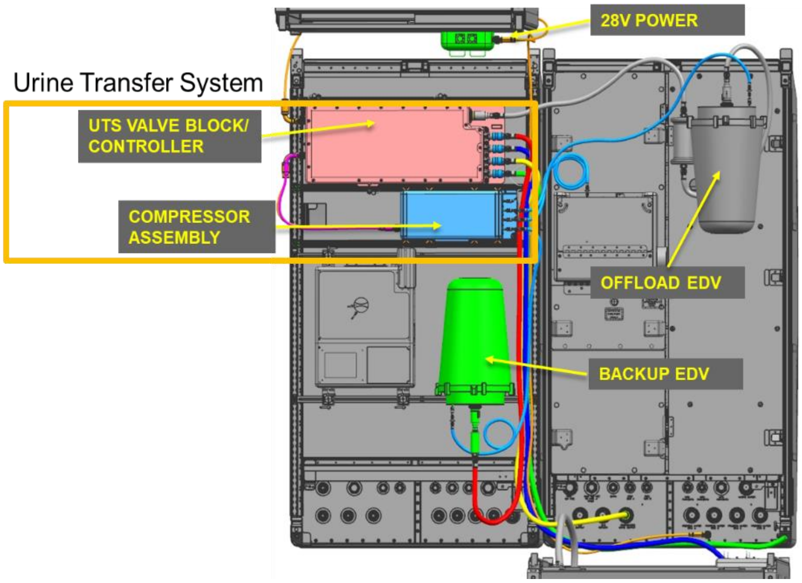

Figure 5. The Urine Transfer System (UTS) integrated in NOD3 on the ISS.

For the past two (2) years, the system has managed to perform nominally with limited, transient anomalies. Current designs of the UTS utilized SD card have experienced occasion corruption and required replacement. The corruption here is within family with other systems using SD cards, and is expected within operations that require re-flashing of the SD (ex: parameter overrides). One other notable anomaly is related with the compressor operations. There have been two instances where the compressor has stayed on when the compressor was expected to turn off. It is believed this behavior is linked to a pressure switch or relay causing a delay in response. Both instances, the system would recover and return to nominal operations.

UWMS, "Toilet"

The ISS saw its first US designed toilet arrive and installed in December 2020. As with most new technology installation, there were notable issues with the UWMS "Toilet" installation and activation[8]. After an initial fitting concern during first installation of a hose, the system was brought online for activation. During first activations of the Toilet, it was discovered that both a locked impeller fan of the dual fan separator prevented initial spin up and a severe conductivity sensor drift in the pretreat dose sensor. The dual fan separator was recovered after a replacement of the ORU, but the conductivity sensor was unrecoverable. This sensor is used to verify proper pretreat dosing of urine. Unfortunately, with the inability to verify proper urine pretreatment, this has prevented full system integration to the Water Recovery System. To accommodate early check-outs of the Toilet, a two-week limited crew operation was completed. These check-outs allow limited crew (1 crew per week) to use the Toilet but in a standalone configuration delivering urine/pretreat/flush water directly into a storage container (ЕДВ). Additional manual pretreat dose activities were utilized in such a way to monitor available pressures sensors in hopes they would offer insights to proper pretreat dose quality. Further details to system issues, modifications, limited check-outs, and accomplishes are provided in a separate conference paper[8]. The limited check out generated pretreated urine that later required additional conservatism with respect to pretreat dosing prior to any UPA processing. Continued efforts to address the recent anomalies are ongoing and hopefully implemented within the coming year.

Brine Processor Assembly (BPA)

The BPA has been installed on the ISS since March 2021. The BPA operates on ISS as a technology demonstration for NASA Exploration missions and processes the brine generated by the UPA to remove water and thereby achieving ~98% water recovery. The system utilizes a specially designed membrane-based bladder that allows water vaper to pass through (membrane distillation) with the aid of heated forced convention. The final step of water reclamation is achieved by established humidity control systems aboard the ISS. The system was delivered to NASA by Paragon Space Development and has since completed seven (7) dewatering cycles as of March 2022. Early dewatering cycles of BPA unfortunately have imparted significant odor impacts to crew. Since the first dewatering cycle, odor mitigation efforts have incorporated a dedicated exhaust filter strategically designed to reduce 'urine-themed' odor generating constituents in the cabin atmosphere. Further details on BPA operations, challenges, and accomplishments can be found in a separate concurrent conference paper[2]. Successful demonstration of this technology is a critical step prior to future manned missions beyond ISS (i.e., a mission to Mars) because of the necessity to recover as much water as reasonably possible (>98% REC) due to the launch costs for water and the absence of resupply capability. With continued success, NASA will continue to use the technology on ISS to reduce the water resupply requirement from earth.

V. Urine Processor Assembly Current Status

The UPA produced 3,857 L (8504 lbs) of distillate at 70% (Russian urine treated with baseline pretreatment) to 87% recovery (US urine treated with alternate pretreatment) from February 2021 to Februrary 2022, completing 34 ARFTA cycles during that time. A graphical summary of UPA production rate and upmass required for ISS operations is provided in Figure 6. In the past year, and 5 brine filters (expected loading) have been replaced to maintain nominal UPA operations.

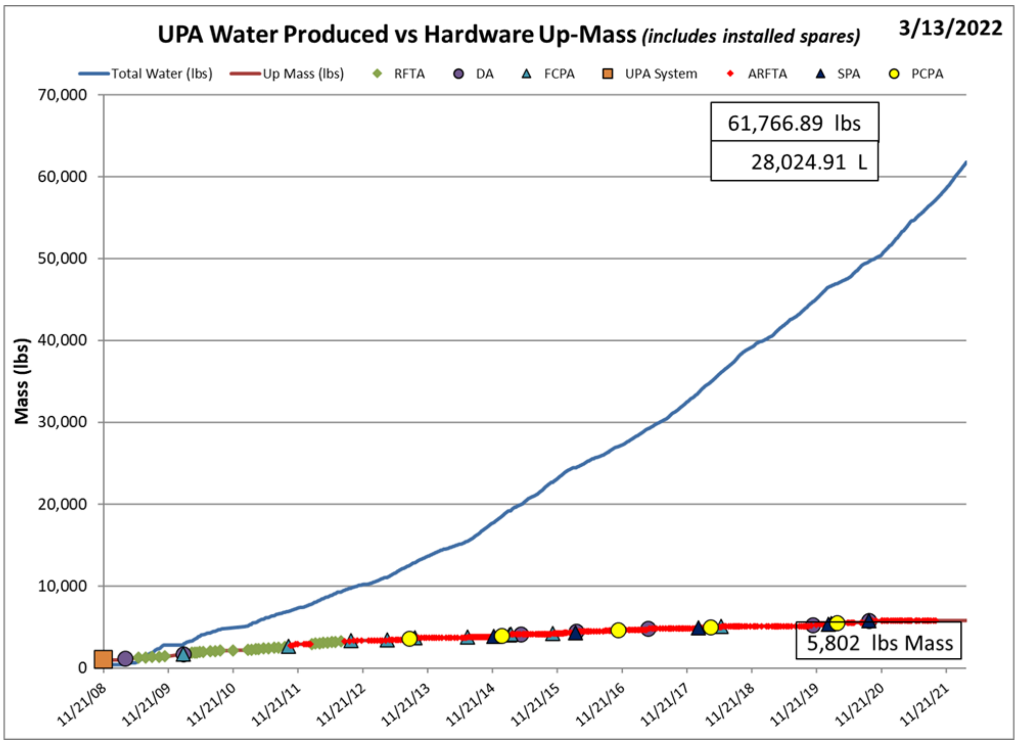

Figure 6. UPA Production and Upmass on ISS.

NASA continued the effort to increase the UPA percent recovery beyond 86%. Increasing the percent recovery is desirable to recover additional water, but primarily to extend the duration of the UPA concentration cycle and thereby reduce crew time required for ARFTA drain and fills. The rationale for increasing the percent recovery is based on previous ground testing that showed the change to the alternate pretreatment would support increased water recovery beyond 85%, potentially up to 90%. This is because the alternate pretreatment eliminated addition of sulfuric acid from the pretreatment, which was contributing to the calcium sulfate precipitation that caused the failure of DA SN 2 in 2010. To further evaluate the viability of increasing water recovery on ISS, brine returned from ISS (in loaded Brine Filters) was analyzed to determine its additional capacity for concentrating calcium sulfate. Based on these analyses coupled with the ground test results, the UPA percent recovery was increased from 86% to 87% in March 2020. Additional analysis will be performed to determine if precent recovery can continue to be incrementally increased.

Since last reporting from 2019, UPA has experienced multiple failures leading to either degraded performance or requiring full ORU replacement. The installation of DA SN004 occurred in October 2019 and at approximately 18 minutes of the initial runtime on this DA, the UPA experienced significant distillate conductivity increase leading to extended reprocessing times. Within the next week of operations; unfortunately, the DA vacuum pressure control sensor used to control vacuum conditions severely offset. This is representative to an earlier DA that exhibited pretreated urine (PTU) crossover into the urine distillate. The current design vacuum pressure sensor is considered non-PTU compatible and is susceptible to diaphragm degradation if exposed to direct PTU/brine directly. This is likely the case for this particular DA SN004. To continue operations of this unit, replicate vacuum sensors located on the purge pump were re-assigned to maintain vacuum control. To facilitate exploration objectives, the Upgraded DA SN002 was installed even though DA SN004 was still operational. Figure 7 showcases the initial severe UPA distillate conductivity on DA SN004 compared to the nominal DA SN002, whose upgrades directly address a primary PTU leak path[10].

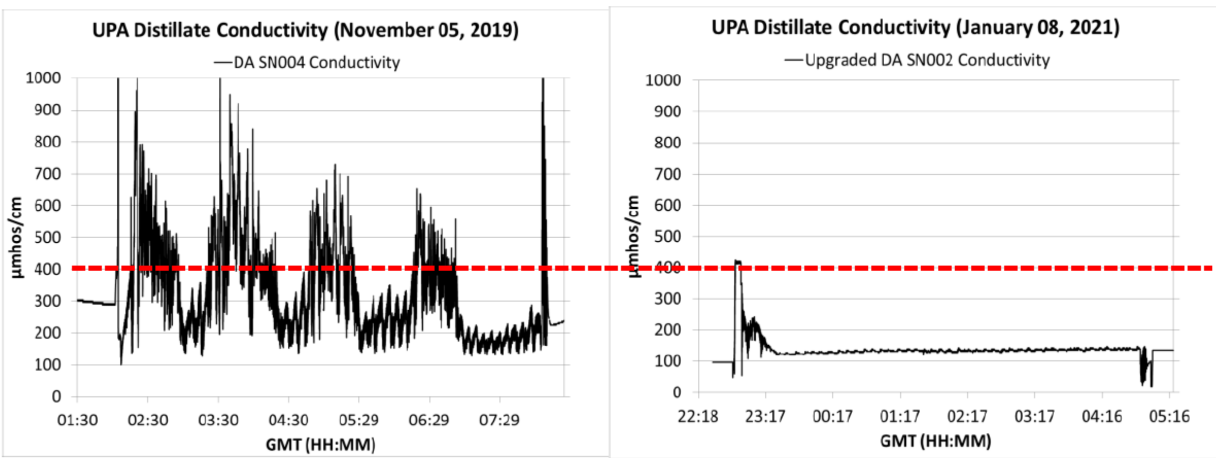

Figure 7. (Left) Example DA SN004 distillate quality signature. (Right) Example Upgraded DA SN002 distillate quality signature.

A notable failure mode for UPA occurred in early 2020 when the system reported significantly lower production rates as well as significant pressure swings (high pressure and low vacuum) at the outlet of the purge pump causing the system to fault. These signatures were unique and were never observed on orbit or during historical ground testing. Exhaustive troubleshooting trying to isolate the fault unfortunately costed an unnecessary replacement of the SPA. All the available telemetry strongly suggested the failure was imparted from degraded pump efficiencies (likely peristaltic tube rupture) of the product water channel of the four-channel peristaltic fluids pump. The fluids pump was replaced with the on-orbit spare and the system was recovered to nominal operations. Unfortunately, this fluids pump has yet to be returned from orbit to confirm the failure mode. Although there are significant telemetry insights to the health of UPA, there are areas of improvement. To that end, an extensive fault isolation and detection study was carried out to elucidate these improvements to better identify system faults as well as opportunities to automate responses. From this study, selected upgrades have been proposed for consideration. This be further described in detail future UPA upgrades papers.

In March 2020, the PCPA failed due to high motor current. This was previously reported in 2021[10] but summarized here for completeness. The unit had logged just over 2300 operational hours on the planetary gear drive system. It's expected the failure mode is similar to the first planetary gear drive FCPA failure; however, this unit has not returned from on-orbit to receive a full ground investigation to confirm the failure mode. Further upgraded planetary gear drives have been completed that directly addresses the known root causes for failure and incorporates further reliability designs. These next generation pump builds are actively being incorporated in available ground ORU spares.

To the credit of upgraded hardware successfully incorporated into UPA, most significantly within the DA[10], UPA has maintained a high level of performance during the influx of crew size and continued processing of Russian urine. UPA has seen significantly more operational run time (>30% increase) in a given year since 2021. A comparison of UPA operations between 2019 through 2021 is presented in Table 1. Despite this increase in duty cycles on UPA, there has been limited issues to report at this time.

Table 1. UPA Metrics Comparing Last Three Years of Operations.

Year	Ave ISS Crew Size	Process Runs	Concentration Cycles	Processing Hours	Total Urine Processed (lbs)
2019	6 (max:9)	277	26	1937	6105
2020	5 (max: 6)	245	25	1657	5355
2021	8 (max: 11)	326	34	2544	8296

VI. Water Processor Assembly Current Status

WPA has processed increasing amounts of wastewater, as average crew size continues to increase on the ISS. Despite the increased throughput, the WPA continues to operate well with only a few notable issues in 2021. Since 2019, WPA has replaced one MF bed, two catalytic reactors, a microbial check valve, a gas liquid separator, and an ion exchange bed. Only two of those replacements were driven by unexpected failures and are discussed below.

The passage of dimethylsilanediol (DMSD) through the WPA has also been closely monitored as it was the leading cause for early MF bed replacements in the past due to organic release downstream. The source of DMSD and its impact on the WPA treatment process has been extensively discussed previously[11-15]. A reprieve of DMSD in WPA product water (<reporting limit) was also observed between 2019 to early 2021 after the installation of siloxane scrubbing air filters and the installation of MF Bed SN21 (single bed operations). This has allowed opportunities to operate the MF beds as originally intended – designed for replacement due to ionic breakthrough before organic breakthrough. The currently installed MF Bed SN7 has since experienced the first and second ionic breakthrough with limited TOC levels observed, well below the potable water requirement (3000 µg/L).

1. Multifiltration Beds Operational Configurations

MF Bed life has typically been dictated by the passage of DMSD through the WPA. There have been 7 instances of increasing Total Organic Carbon (TOC) in the WPA product water due to DMSD. Each TOC trend was initially detected by the TOC Analyzer (TOCA) on ISS, and a summary of the MF bed performances are provided below in Figure 8.

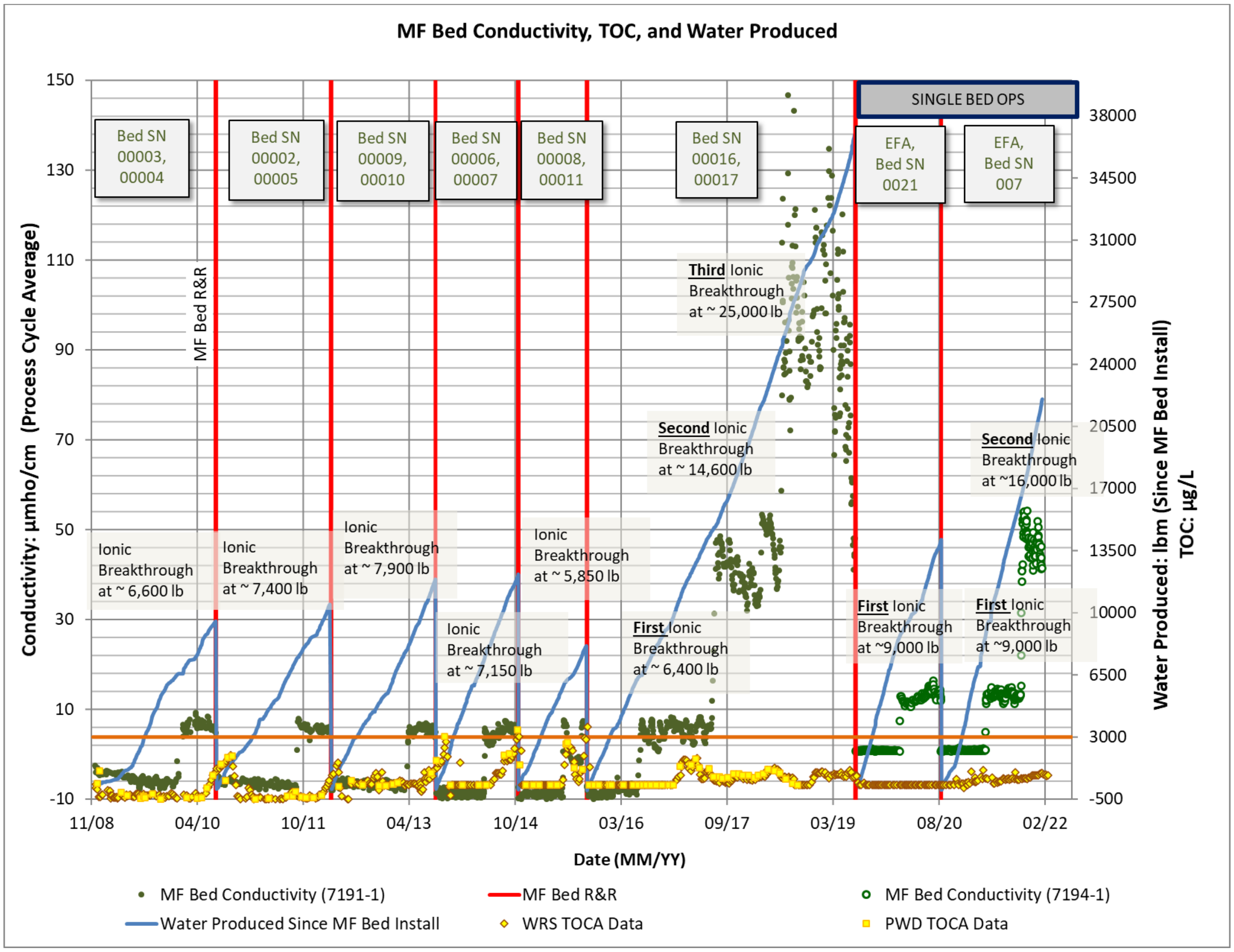

Figure 8. Correlation between Product Water TOC and MF Bed Throughput

In the past, once TOC has been detected by the TOCA on the ISS, it has consistently increased until exceeding the potable specification of 3000 µg/L, necessitating the replacement of both MF Beds. After installation of the MF Beds set in late 2015, the DMSD reached the product water in late 2016. However, the resulting TOC peaked at approximately 1800 µg/L (versus the near 3000 µg/L in years past) before dropping to a steady state condition around 1000 µg/L until the need for replacement due to ionic breakthrough. Engineering personnel believed this lower sustained concentration of DMSD in the product water was an atypical trend, but it was not obvious why DMSD would be at a lower concentration. Possible explanations include a more efficient catalytic reactor, lower precursor volatile methylsiloxane species concentrations known to convert to DMSD in the atmosphere[14] and/or impacts to mass transfer zones of DMSD in the MF beds with reprocessing/processing to address elevated reactor health sensor (RHS) trends.

The lower DMSD concentration trend observed starting in 2016 provided the first opportunity to extend the life of the MF Beds since all previous beds were replaced after approximately one year in operation. Ground testing in tandem with adequate system performance on-orbit confirmed viability of operating MF bed through the second ionic breakthrough but recommends replacement once the third ionic breakthrough occurs[15,16]. To that end, implementation of single MF Bed operations could also be pursued. This reconfiguration also has potential to reduce the severity of the initial DMSD release off the MF beds. DMSD accumulates in the MF beds and is released later on due to saturation and competitive sorption effects. Thus, reducing the maximum release load of DMSD with reduced media volume offers a chance to minimize the initial wave of TOC (primarily from DMSD) released downstream. This offers more favorable conditions feeding the downstream catalytic reactor for maintaining oxidation efficiencies.

As of July 2019, the WPA has implemented single MF bed configuration. This first single bed configuration MF bed performed as expected with no off-nominal behaviors. At the time of its removal, the unit had remaining operational life. This replacement in September 2020, was driven by exploration objectives to begin runtime of the long-awaited upgraded MF bed in the relevant space exploration environment. This upgraded MF bed utilizes a new sorbent media (Ambersorb), replacing an obsolescent media no longer available, and one ion exchange cylinder media has been replaced due to leachate concerns for EMU suit operations. Detailed discussion on the upgraded MF bed media can be found in prior WPA upgrades publications[16,17]. The currently installed MF bed had passed the first ionic breakthrough after about 9,000 lbs of processed wastewater. This trended similarly to the earlier single bed installation. The second ionic breakthrough occurred at approximately 16,000 lbs of processed waste water. Based on ground testing and correlating to earlier two-bed operations, it is projected the third ionic breakthrough will occur after about 25,000 - 30,000 lbs of total wastewater processed. In Figure 9, the upgraded single MF Bed began to indicate DMSD release, observed in returned ground samples approximately 6 months after installation or ~7,000 lbs of waste water processed.

The timing of this DMSD trending correlates to the installation and performance of the Charcoal/HEPA Integrated Particle Scrubbers (CHIPs) filters in 2019. They were deployed to directly scrub the cabin atmosphere of precursors (volatile methylsiloxanes) known to generate DMSD[14,18]. It is likely these filters have now reached a saturation point of volatile methylsiloxanes allowing enough DMSD generation to continue past the current MF Bed during its first ionic breakthrough. Despite detectable DMSD in product waters, levels are significantly lower than pre-siloxane mitigation efforts and, overall, WPA operations have maintained adequate potable water quality. To that end, assuming WPA performance continues to be acceptable, NASA and Boeing personnel intend to operate the MF Beds until the third breakthrough occurs. This will be a *significant increase in MF Bed life* (~30%) and likely establish the expected procedure for loading MF Beds for the remainder of ISS operations. It is estimated this third ionic breakthrough will occur in the coming months.

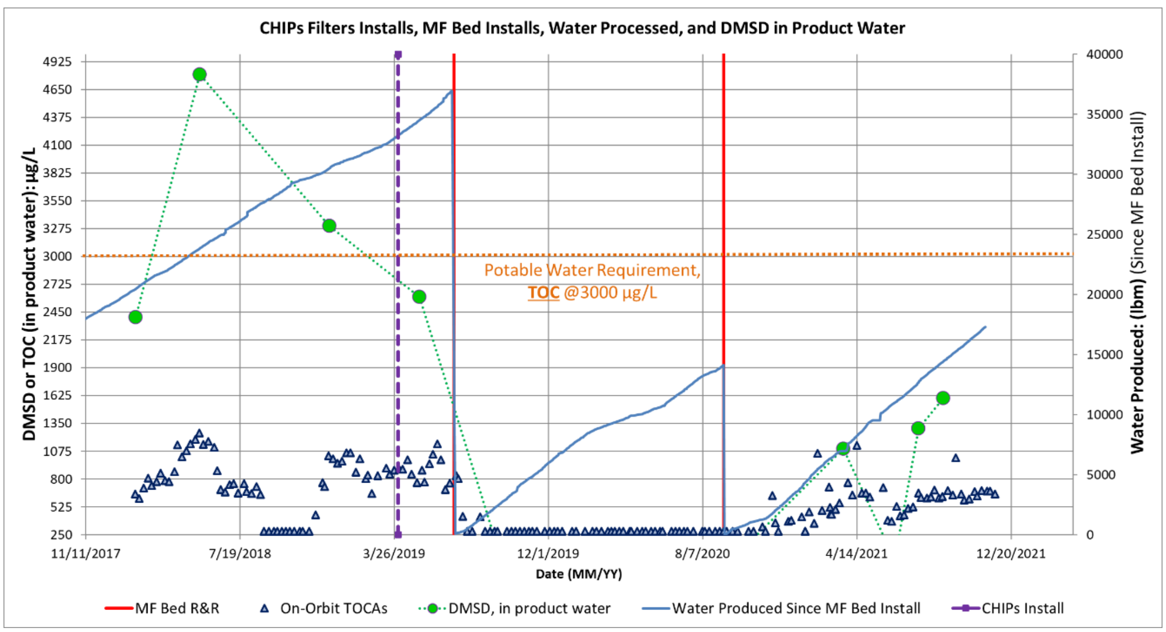

Figure 9. DMSD Responses in Product Water before and after CHIPs and MF Bed Installs. Only reportable DMSD levels are displayed on chart. Note: DMSD reporting limits are 1000 µg/L.

2. *Demonstration Catalytic Reactor*

As an additional effort to reduce DMSD presence in the waste water, NASA has worked with various vendors to develop an improved catalyst for the WPA Catalytic Reactor[13]. This effort identified a catalyst (developed by Collins Aerospace) that showed an increase in DMSD removal efficiency from 75 to 92%. Boeing and Collins have since developed this into Demonstration Catalytic Reactor and has since delivered and installed on the ISS in March 2021. Notable upgrades address known elastomer seal failures and allows for variable oxygen flow controls capabilities. As noted previously[1,4-6], the baseline Catalytic Reactor has been limited to approximately a two year life due to leaking elastomer o-rings. Unfortunately, within the first four (4) days of operations, the Demo Catalytic Reactor failed and was later removed due to an external water leak. This water leak is attributed to the disagreement in upgraded seals (from elastomer to metal) size and accepting gland seal locations. It is projected a rebuilt Demo Catalytic Reactor will be ready by October of 2022 that addresses the ground investigation discoveries. Unfortunately, this has delayed the understanding of how effective this new catalyst addresses DMSD release from MF beds in the relevant environment on the ISS.

3. Gas Liquid Separator

In May 2021, WPA detected a fault when attempting to send WPA to process. The fault indicated a water leak into the air sweep gas side of the Gas and Liquid Separator (GLS) ORU. WPA automatically safed itself to a Standby configuration, which unfortunately left the WPA Avionics Air Assembly (AAA) operating. About eight (8) hours after the initial fault, the AAA power control module tripped due to an overcurrent causing the WPA to become unpowered and losing subsequent telemetry. A likely cause of failure of the AAA hardware was determined to be the GLS ORU water leak traveling through the ducting and plenum reaching the AAA thus causing the trip of the power module. This is the first time a GLS ORU has leaked on orbit in this manner. Ground investigations have not been completed to determine root cause of the on-orbit leak. The full system was later recovered after a replacement of the GLS and WPA AAA with additional inspection and drying activities of the air ducting. Updates to system response to immediately unpower the AAA due to water indications of the GLS was incorporated to operational software to prevent secondary AAA failures from potential water exposures.

VII. Conclusion

Since 2019, the WRS has continued to provide the ISS crew with potable water for drinking, water for electrolysis via the Oxygen Generation System, flush water for the Waste & Hygiene Compartment, hygiene water, and payloads. During this time, the WPA has experienced two significant failures due to external water leaks: Gas Liquid Separator and Demo Catalytic Reactor; however, the system has been providing potable water for use with very little downtime. What downtime has occurred has been easier to manage with significantly less crew time impacts due to the continued operational success of the WSS. The MF Bed operations and configurations have been updated to allow for longer operational install time thanks to the reduction and continued positive trending of overall DMSD concentrations in the water. The Upgraded MF beds are now configured for single bed operations and future replacements are expected to be driven by the third ionic breakthrough.

UPA has historically been affected by elevated conductivity and belt slips; however, the upgraded DA currently installed has significantly reduced or eliminated these concerns. UPA has also seen over 30% increase in operations due to increased crew sizes and continued processing of Russian urine. Despite this increased duty cycle, UPA has managed to operation with limited to no notable issues. This is directly attributed to the years of strategic upgrades to the system to address known failure modes.

The ELCSS communities look forward to future explorations missions. Critical paths of challenging the next generation ELCSS technologies in the relevant space environment are finally being realized. The upgraded MF beds, BPA, UTS, and UPA's DA and planetary gears as found in the fluids and purge pumps have all been integrated on the ISS and are showing exceptional performances. The rebuilt Demo Catalytic Reactor and Toilet hardware updates will get their turn for exploration demonstration, likely within the year.

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References

[1]Carter, D.L. D. Riggle, S. Walker, P. Andreychuk, G. Karaseva, A. Zheleznyakov, L. Bobe, A. Kochetkov, N. Rykhlov, A. Gleich, C. Zahner, K. Spicer, M. Berrill "Operation of the Urine Collection and Pretreatment System in the ISS US Segment Waste & Hygiene Compartment (WHC), presented at the *50th International Conference on Environmental System*, July 2021

[2]Boyce, S.P., Molina, S.,Pasadilla, P., Tewes, P., Joyce, C.J., Harrington, W., et al., "Closing the Water Loop for Exploration: 2021-2022 Status of Brine Processor Assembly", Paper # 2022-317, *51st International Conference on Environmental Systems*, St. Paul, Minnesota, July 2022

[3]Carter, D.L, J. Williamson, C. Brown, J. Bazley, D. Gazda, R. Schaezler, F. Thomas, S. Molina "Status of ISS Water Management and Recovery", Paper # 2019-036, presented at the *49th International Conference on Environmental Systems*, Boston MA, July, 2019

[4]Carter, D.L, J. Williamson, C. Brown, J. Bazley, D. Gazda, R. Schaezler, F. Thomas, "Status of ISS Water Management and Recovery", Paper # 2018-088, presented at the *48th International Conference on Environmental Systems*, Albuquerque New Mexico, July, 2018

[5]Carter, D.L., J.M. Pruitt, C. Brown, J. Bazley, D. Gazda, R. Schaezler, F. Thomas, "Status of ISS Water Management and Recovery", Paper # 2017-036, presented at the *47th International Conference on Environmental Systems*, Charleston, S.C., July, 2017

[6]Carter, D.L. J.M. Pruitt, C. Brown, J. Bazley, D. Gazda, R. Schaezler, L. Bankers, "Status of ISS Water Management and Recovery", Paper # 2016-017, presented at the *46th International Conference on Environmental Systems*, Vienna, Austria, July, 2016

[7]Muirhead, Dean, Evaluation of Alternative Pretreatment Formulations for Minimizing the Risk of Mineral Precipitation During Distillation of Urine, ESCG-4106-12-CHLSS-DOC-0002, January 2012

[8]McKinely, M., Broyan Jr., J.L., Matty, C., Borrego, M., Williamson, J., Garcia, J., "NASA Universal Waste Management System and Toilet Integration Hardware Operations on ISS – Issues, Modifications and Accomplishment", *51st International Conference on Environmental Systems*, St. Paul, Minnesota, July 2022

[10]Williamson, J.P., Carter, L., Hill, J., Brown, A., "Upgrades to the International Space Station Urine Processor Assembly", presented at the *50th International Conference on Environmental Systems*, Virtual. July, 2021

[11]Carter, D.L., B. Bowman, T. Rector, G. Gentry, M. Wilson, "Investigation of DMSD Trend in the ISS Water Processor Assembly", AIAA 1563699, presented at the *43rd International Conference on Environmental Systems*, Vail, Colorado, July 2013

[12]Perry, J., M. Kayatin, "The Incidence and Fate of Volatile Methyl Siloxanes in a Spacecraft Crewed Cabin", Paper # 2017-233, presented at the *47th International Conference on Environmental Systems*, Charleston, South Carolina, July 2017

[13]Muirhead, D.L. and D.L. Carter, "Dimethylsilanediol (DMSD) Source Assessment and Mitigation on ISS: Estimated Contributions from Personal Hygiene Products Containing Volatile Methyl Siloxanes (VMS)", Paper # 2018-123, presented at the *48th International Conference on Environmental Systems*, Albuquerque, NM, July 2018

[14]Stocker, Kelsey, Bonar, B., Siriboe, M., Computational Investigation of DMSD Production from Volatile Methylsiloxanes and Hydroxyl Radicals, presented at the *50th International Conference on Environmental Systems,* Virtual. July, 2021

[15]Carter, D.L., J. Perry, M. Kayatin, M. Wilson, G. Gentry, B. Bowman, T. Rector, J. Agui, R. Green "Design and Delivery of a Filter for Removal of Siloxanes from the ISS Atmosphere", Paper #2016-015, presented at the *46th International Conference on Environmental Systems*, Vienna, Austria, July 2016

[16]Kayatin, M.J., Carter, D.L., Schunk, R.G., Pruitt, J.M., "Upgrades to the ISS Water Recovery System", presented at the *46th International Conference on Environmental Systems*, Vienna, Austria, July 2016

[17]Kayatin, M.J., Pruitt, J.M., Nur, M., Takada, K.C., Carter, L., "Upgrades to the International Space Station Water Recovery System", presented at the *47th International Conference on Environmental Systems*, Charleston, South Carolina, July 2017

[18]Braman, K., Snyder, S.M., "Design and Implementation of Combination Charcoal and HEPA Filters for the International Space Station Cabin Air Ventilation System", presented at the *49th International Conference on Environmental Systems*, Boston MA, July, 2019

[19]Shaw, L., Garr, J.D., Gavin, L.L., Matty, C.M., Ridley, A., Salopek, M., Toon, K.P., "International Space Station as a Testbed for Exploration Environmental Control and Life Support Systems – 2020 Status", presented at the *49th International Conference on Environmental Systems*, Boston MA, July, 2019, *50th International Conference on Environmental Systems*, July, 2020