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
CHX	=	Condensing Heat Exchangers
CWC	=	Contingency Water Container
CCAA	=	Common Cabin Air Assembly
DA	=	Distillation Assembly
DMSD	=	Dimethylsilanediol
EFA	=	External Filter Assembly
EMU	=	Extravehicular Mobility Unit
ЕДВ	=	Russian Water Container
FCA	=	Firmware Controller Assembly
FCPA	=	Fluids Control and Pump Assembly
GLS	=	Gas Liquid Separator
CWC-I	=	Contingency Water Container – Iodinated
ISS	=	International Space Station
ISPR	=	International Standard Payload Rack
IX	=	Ion Exchange
MCV	=	Microbial Check Valve
MLS	=	Mostly Liquid Separator
MF	=	Multifiltration
ORU	=	Orbital Replacement Unit
ORU	=	Orbital Replacement Unit
PCPA	=	Pressure Control and Pump Assembly
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
WWT	=	Waste Water Tank

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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. This 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 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). 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 containers (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 recovered[2].

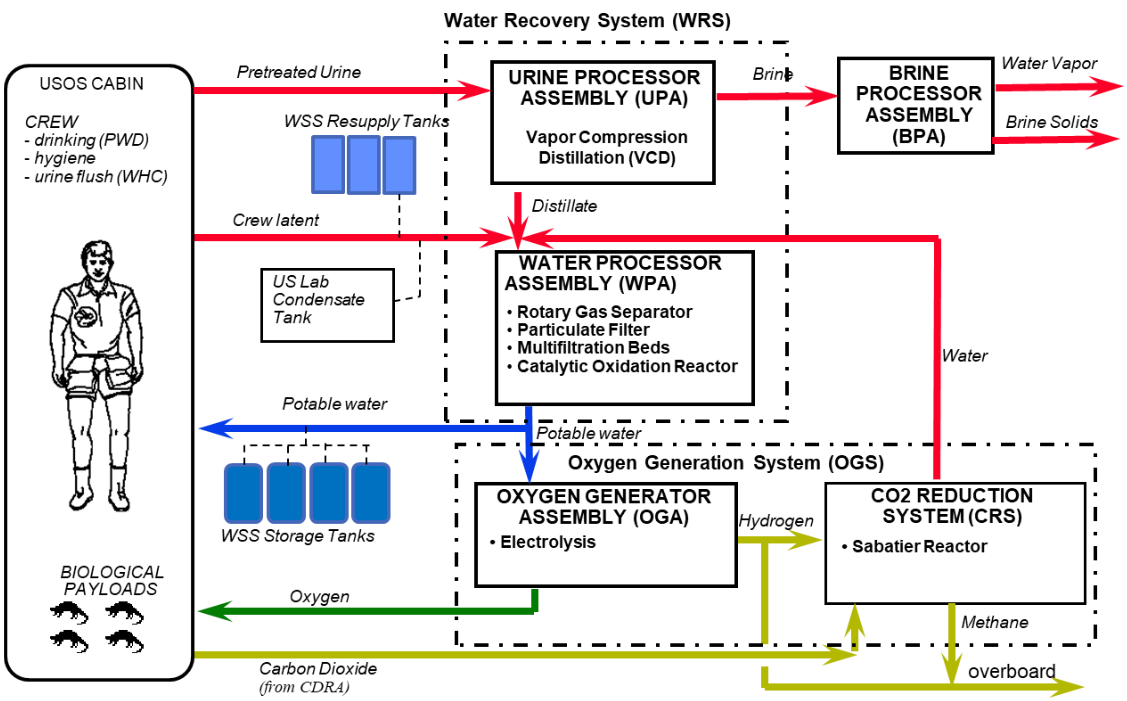

Figure 1. Water Recovery and Management Architecture for the ISS US Segment

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 280 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.

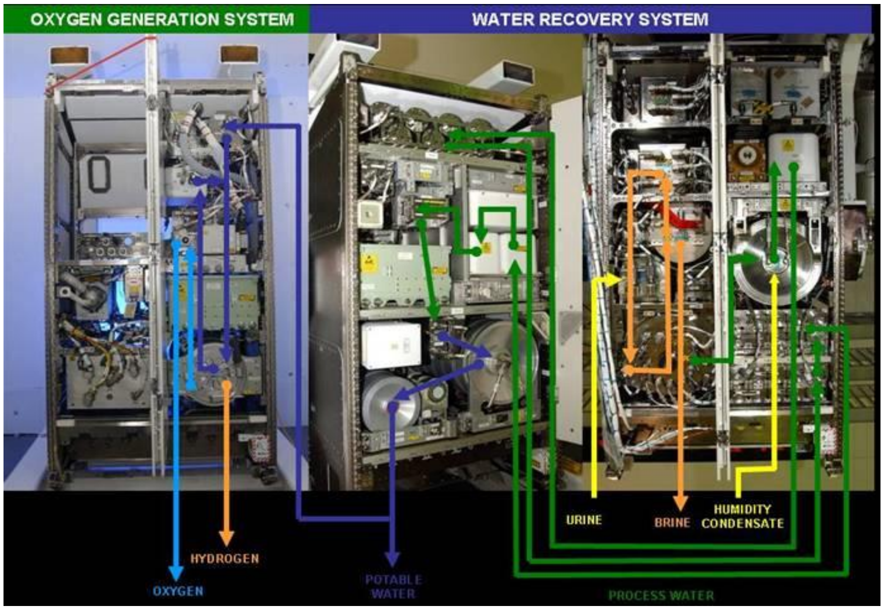

Figure 2. International Space Station Regenerative ECLSS Racks

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 1,4-6.

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 four-tube peristaltic purge pump which provides for the 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.

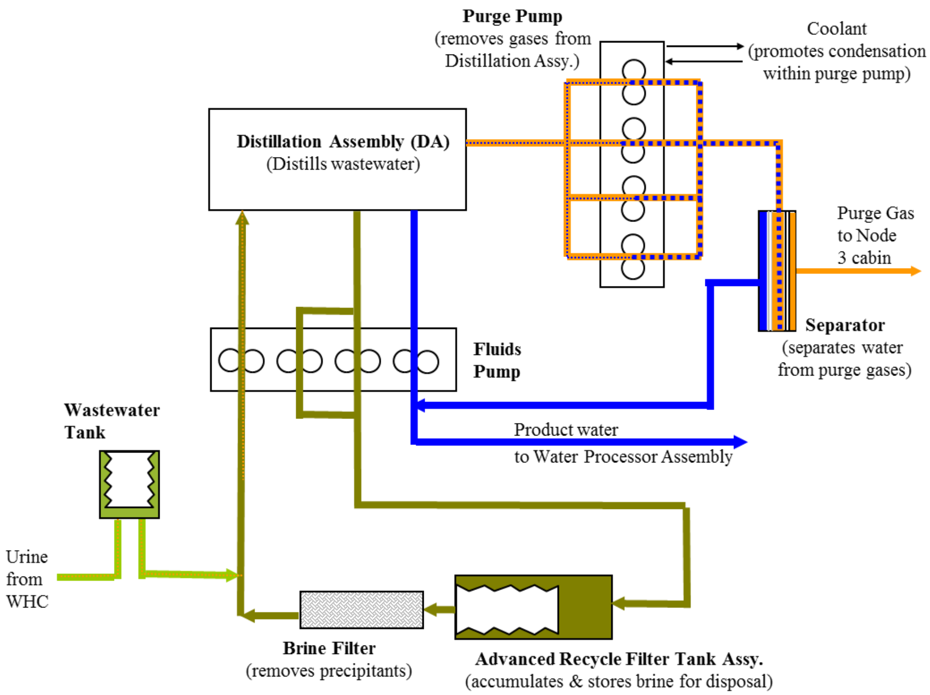

Figure 3. Urine Processor Assembly Schematic

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 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.

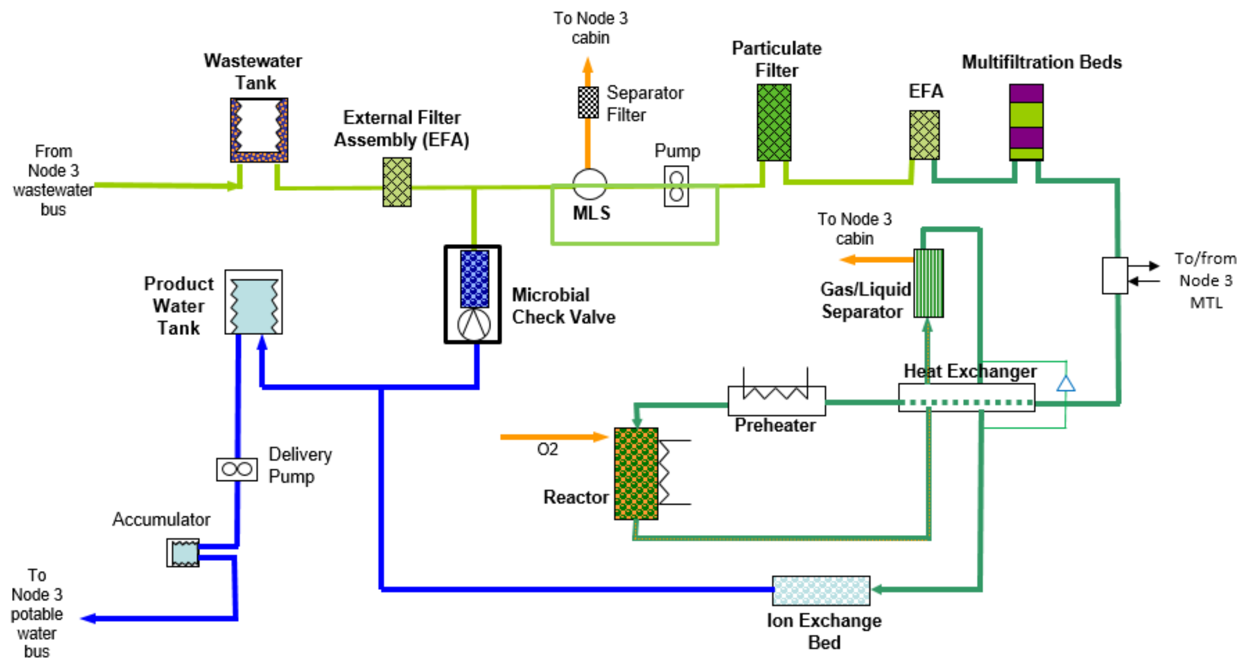

Figure 4. WPA Simplified Schematic

IV. Water Recovery and Management Status

Between February of 2022 and February 2023, WPA has produced approximately 7,399 L (16,314 lbs) of product water. In addition, 1,603 L (3,535 lbs) of potable water is currently stored on ISS for resupply water and in reserve to protect 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 system 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. *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.

Urine Transfer System

There were anticipated challenges with increased crew sizes as well as the introduction 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 input from all inputs (WHC, UWMS, ЕДВ), ensuring 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 for offloading the UPA brine tank (ARFTA) into the BPA or to brine ЕДВs. Moreover, the use of this hardware will reduce the burden on the crew to manually transfer urine and will overall save crew time spent on ISS for system maintenance and operation[19].

For the past three (3) years, the system has managed to perform nominally with limited, transient anomalies. Current designs of the UTS utilized an SD card that has seen occasional file corruption requiring replacement. The corruption seen is within family with other systems using SD cards, and is expected within operations that require reflashing of the SD. There are multiple indicators for the corruption of the UTS SD card. The first is a loss of telemetry. If UTS is not recoverable from power cycling, system behavior prior to loss of telemetry is reviewed. In the case of an SD card corruption, UTS will start drawing less current and maintain new lower baseline current. This is the primary indicator that the SD card is corrupted and should be replaced. In order to remove and replace the SD card, Crew must remove 11 fasteners to get the UTS cover off to reach the SD card location. To reduce crew time, a plan is in work to implement a SD card extension cord to be routed from the inside of the UTS cover to the outside of the rack to more easily access the SD card. UTS SD cards are easily procured and manifested as both blank cards and preloaded with software. The UTS and WSS systems use the same SD card, imaged with the correct software for the specific hardware. Blank SD cards require crew time and ground teams to image the SD card on orbit for UTS or WSS operation. One other notable anomaly focuses on the compressor operations. There have been several 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. In both instances, the system would recover and return to nominal operations. A new UTS compressor will be ready as an on-orbit spare in early 2024.

UWMS, "Toilet"

The ISS saw its first US designed toilet arrive and installed in December 2020. As with most new technology installations, there were notable issues seen with the UWMS "Toilet" installation and activation[8]. Since February 2022, Toilet has seen several more restart attempts and limited check-outs to further realize technology demonstrations and Artemis perspective test objectives.The lack of direct monitoring pretreat dose quality and reported fluid release internal to the Toilet operations have been notable, thus, limiting crew use. Further details are provided in a concurrent publication[21]. At this time, Toilet is in a stand-down configuration until hardware replacement can be supplied.

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 convection. The final 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 20 dewatering cycles since first activation. Early dewatering cycles of BPA unfortunately has imparted significant odor impacts to crew. Since the first dewatering cycle, odor mitigation efforts have incorporated a dedicated exhaust filter strategically design to target 'urine-themed' odors to reduce cabin atmosphere loading of odor generating constituents. With that said, since February 2022, BPA has completed 14 dewatering cycles, approximately 305 liters of urine brine. Of that, it is estimated ~260 liters of water has been returned back to humidity condensate, a significant water return. Moreover, the BPA has provided a significant reduction in trash management and logistics by reducing the total volume of brine for disposal (trashing off the ISS vehicle). . Further details on BPA operations, and accomplishments can be found in separate conference papers[2,22]. Successful demonstration of this technology is considered 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 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 3,872 L (8,535 lbs) of distillate at 70% (Russian urine treated with baseline pretreatment) to 87% recovery (US urine treated with alternate pretreatment) from February 2022 to February 2023, completing 44 ARFTA cycles during that time. A graphical summary of UPA production rate and upmass required for ISS operations is provided in Figure 5. In the past year, 8 brine filters (expected loading) have been replaced to maintain nominal UPA operations. Over the last year, UPA has accomplished several significant milestones for ORU operational life. In May of this year, the four (4) major UPA ORUs (DA, FCPA, PCPA, and SPA) have all crossed the 100% mark for predicted life run time for the units currently installed. Although UPA has had prior singular ORUs reaching over the 100% predicted installed life, this is the first time where all sets have surpassed this milestone together. A few months later in October, the currently installed upgraded DA SN002 became its fleet leader for a DA on-orbit operational life surpassing our first fleet leader, DA SN001 at 5,377 hours. DA SN002, as of February 2023, has logged over 6,280 hours, approximately 143% of its predicted life. This significant increase in runtime is achieved thanks to the many years and purposeful upgrades and redesigns to address known failure modes and degraded performance factors.

In the coming year, we plan to install the Purge Pump and Separator Assembly (PPSA) to replace the PCPA, SPA, and 20 micron Purge Filter baselined designs. PPSA will demonstrate the use of a new scroll pump design, replacing the peristaltic pump design within PCPA. The new pump provides an overall smaller footprint so that the Separator and Filter subassembly can all be within the original baseplate design of the PCPA. Another new feature is the ability for the pump and filter subassemblies to all be removed and replaced individually. These are considered planned maintenance at a more component level rather than historical ISS approaches for whole ORU replacement philosophy. These new designs and features will demonstrate Exploration objectives for reducing volume and mass and increasing maintainability of limited life assemblies.

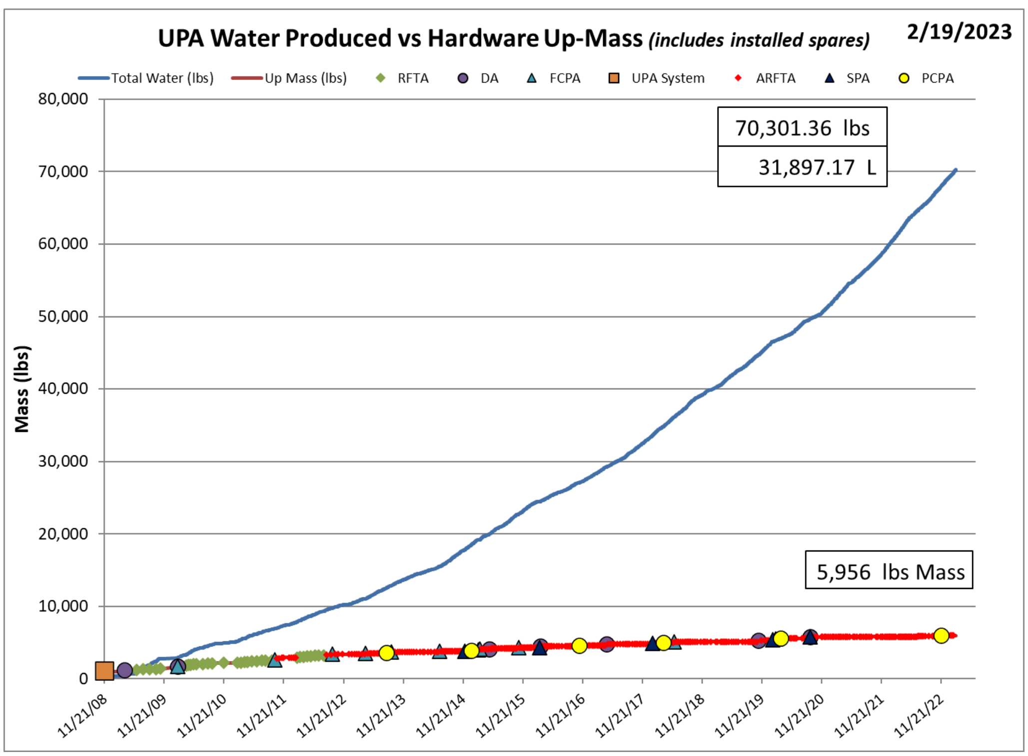

Figure 5. UPA Production and Upmass on ISS

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 SN002 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 percent recovery can continue to be incrementally increased.

Since last reporting, UPA has experienced one major ORU failure requiring full ORU replacement one limited degraded performance anomaly. In November 2022, the PCPA SN005 failed due to a peristaltic tube rupture. The last PCPA SN004 (install ahead of SN005) failed due to mechanic failure within the planetary gears around 2300 hours of operation. It was expected to see similar failure modes and runtime hours in SN005 as it had the same planetary gear drive design. However, the primary PCPA failures have been attributed to peristaltic tube rupture, with the last tube rupture failure in 2016, after 2185 hours of operation. Thus, seeing this recurrence on SN005 was not unexpected.. Despite the failure of the PCPA SN005, it had surpassed its full predicted life with over 3500 operating hours at the time of the failure (approximately 140% of predicted life), making it also the fleet leader for known failure modes for the UPA purge pump

In terms of failure detection modes for a PCPA peristaltic tube rupture, this one is quite evident. During this failure, UPA was actively processing urine when the pump housing vacuum pressures (housing volume for the peristaltic tubing is kept under vacuum to prevent tube collapse) began climbing faster and higher than expected operations. Along with this, the DA condensing vacuum pressure climbed and sustained above expected operating conditions causing a preemptive conclusion of the process run. While transitioning to a standby state, the relevant vacuum pressures upstream of the purge pump continued to climb, causing the system to fault into a shutdown, safed mode. Secondary insights downstream of the pump, in this case the purge outlet pressure sensor, began to decrease in pressure, supporting evidence of a tear in the peristaltic tubing allowing equilibration of inlet and outlet pressures of the pump to occur. All this data combined points to a rupture of the peristaltic tubing. After UPA reached the safed, shutdown state, the vacuum pressures stopped climbing. The vacuum pressure stabilizing out was most likely caused by the final location of the pump's roller cam head pinching off the teared location. With the anticipation of the PPSA install later this year, the choice PCPA replacement after this failure was the legacy, harmonic drive PCPA. This allows a pristine planetary PCPA spare to be maintained as the viable spare should the PPSA require replacement.

In February 2022, during a nominal planned UPA recycle brine tank, "ARFTA", drain and fill activity, ground teams noticed off-nominal recycle pressures signatures during the brine offload. The UTS compressor used during these activities cycled on and off more frequently than seen on past drains. This signature was noticed on a UPA recycle pressure senor. The nominal signature is described as a sawtooth pattern with peaks and valleys as the compressor cycles on and off. The UTS compressor operations utilizes pressure switches to maintain appropriate pressure operations, commanding the compressor on and off within set limits. This increased cycling indicates a faster loss of pressure as seen by the pressure switches. This does not allow for nominal compressor operations and caused a longer activity to achieve the same result. While this off-nominal behavior caused a longer drain timeframe, the ARFTA drain and fill were still successfully completed.

Isolating the root cause of this signature was necessary to minimize compressor cycling. Troubleshooting began with crew visually inspecting air hoses to confirm no kinks and properly mated connections with nothing reported off-nominal. Continued isolation activities with alternate air compressor hoses and vent adaptors were also completed. It was concluded the air leak was isolated to a vent adaptor used on an ARFTA. This is an easily replaceable component. Once this vent adaptor was replaced with an alternate serial number, nominal operations was achieved. The root cause of the vent adaptor air leak has yet to be isolated to what causes this system response; however, there are plans to launch a new pristine spare vent adapter to ensure adequate coverage.

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 increase of crew size and continued processing of Russian urine. UPA has seen significantly more operational run time (>30% increase) in a given year since 2020. A comparison of UPA operations from 2020 through 2022 is presented in Table 1. Despite this increase duty cycle on UPA, there has been limited issues to report a 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 Pounds Processed (lbs)	Total Pounds Brine Generated (lbs)
2020	5 (max: 6)	245	25	1657	5355	1197
2021	8 (max: 11)	326	34	2544	8296	1627
2022	8 (max: 11)	345	44	2786	9278	2105

VI. Water Processor Assembly Current Status

WPA has processed increasing amounts of wastewater as average crew sizes continue to increase on the ISS. Despite the increased throughput, the WPA continues to operate well with only a few notable issues in 2022/2023. Since February 2022, WPA has replaced one MF bed, one EFA filter, and one catalytic reactor.

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 6.

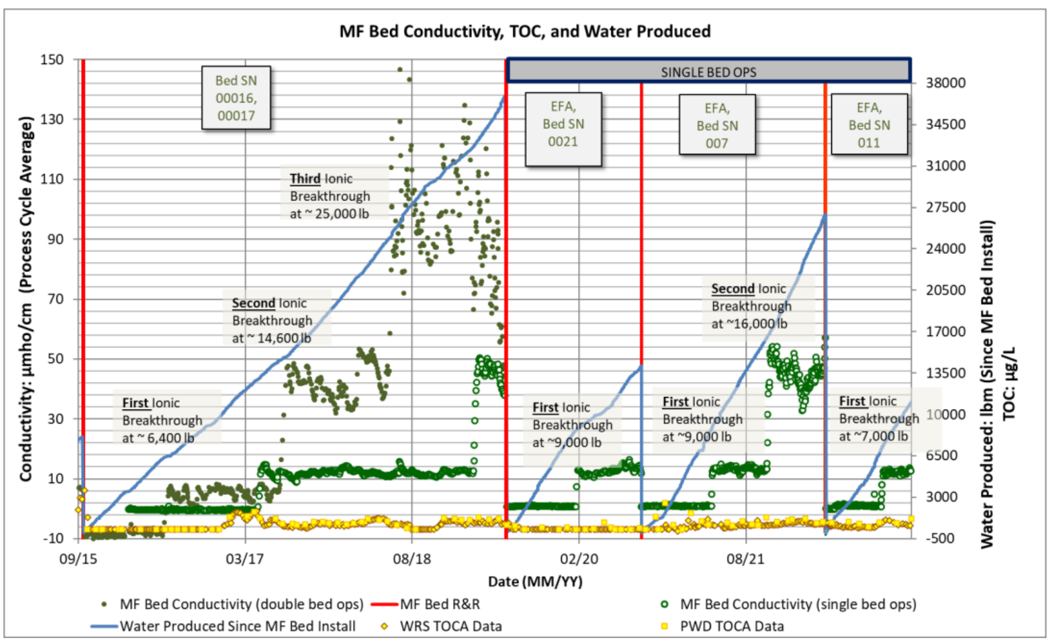

Figure 6. Correlation between Product Water TOC and MF bed Throughput

A previous publication[20] has elaborated on the DMSD influence on WPA generated water quality and how single bed operations, paired with CHIP filter efficiencies, has mitigated significant disruption in WPA operations. 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. Since mid-2020, WPA has also started and continue to use the upgraded MF bed design with the new sorbent media (Ambersorb). Detailed discussion on the upgraded MF bed media can be found in prior WPA upgrades publications[16-17]. The MF bed SN007 was installed in September 2020 and was R&R'd late April 2022 after reaching the third ionic breakthrough. It is expected the third ionic breakthrough will release ammonium and other similar ionics that could degrade or foul the reactor catalyst. Thus, removing the MF bed as soon as this third breakthrough is reported is crucial. With that said, this MF bed (single bed ops) was able to process over 26,800 lbs of wastewater. This bed was replaced with SN11 (upgraded). The current MF bed has since experienced its first of three ionic break-through after about 7,000 lbs of wastewater processing, compared to SN with its first ionic breakthrough around 8,700 lbs. Figure 7 highlights the MF bed total processed water overlayed with TOC as found in the WPA and DMSD concentration as found at the PWD. This compares the current and prior two MF bed installations. During the current MF bed installation, there was an increase in overall TOC around the time of the first ionic breakthrough. This trends well with expected performance of lower affinity species releasing at the time of the first bicarbonate breakthrough. The magnitude of the TOC at this time was closely monitored to understand the severity of this TOC wave release. As discussed in previous papers[20], the benefit of this single bed ops was theorized to minimize this severity despite the likely cause due to DMSD release.

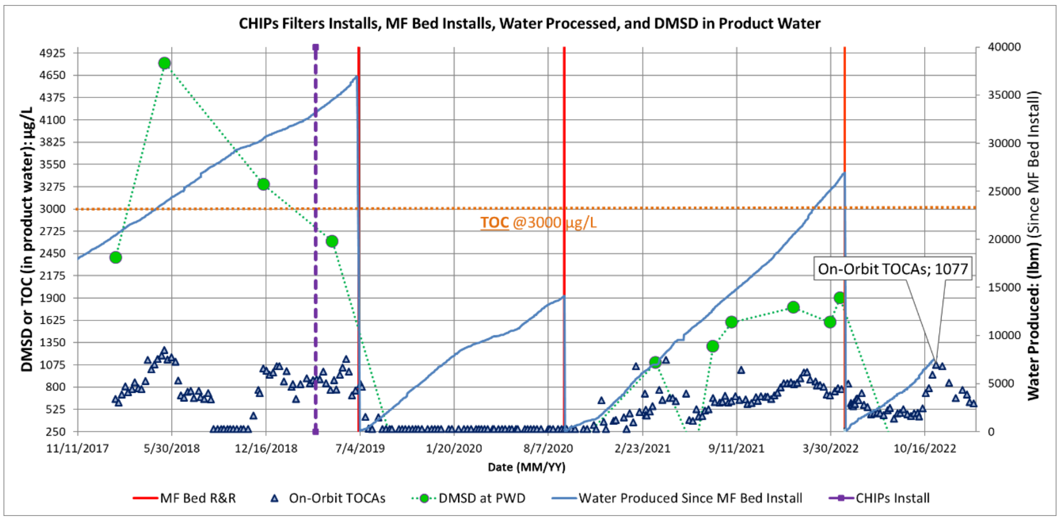

Figure 7. DMSD responses in product water before and after CHIPs and MF bed Installs. Only reportable DMSD levels are displayed on chart. Note: DMSD reporting limits are 1000 µg/L.

Moreover, there is still reportable DMSD in the product water, contributing to the TOC loading. Returned samples have yet to publish what the most recent potable water levels are for DMSD around the time of that TOC wave to confirm what the majority contribution was. 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.

2. Catalytic Reactor

The typical failure mode for Catalytic Reactors is leaking of the Hot Item Assembly elastomeric seals, which are subject to wear from oxidation and thermal cycling during WPA processing. This was one of the primary drivers, along with a better catalyst with better efficacies towards DMSD oxidation, for the upgraded Demonstration Catalytic Reactor (DTO). Reactor high pressure sensors are used to monitor the start and progression of a potential seal leak. In nominal operations, a single repressurization follows a process cycle due to thermal cooldown following the previous process cycle, as seen in Figure 8, first plot. A second repressurization is possible with extended time in standby due to nominal Reactor seal leakage, or due to either an internal (through a pressure regulator or check valve) or a small external leak. Three or more repressurizations are not common in nominal processing operations and indicative of degraded elastomeric seals in the Cat Reactor no longer holding pressure. Not pictured but complementary insights to this indication of a leak is a drop in the Wastewater Tank quantity confirming mass transfer rebalancing into the Cat Reactor ORU volume during the active repressurization event.

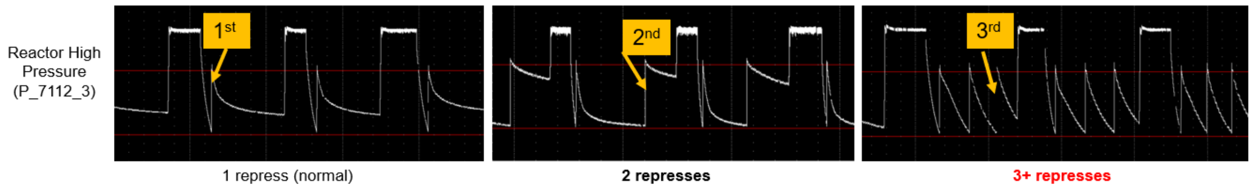

Figure 8. Comparison of increasing repressurizations between WPA process runs

Catalytic Reactor SN 5 demonstrated signs of significant leakage (three or more repressurizations) and was R&R'd in June 2022, after an expected number of cycles based on historical averages of prior Reactors operating at the same temperature and pressure. Typically, in the current operating configuration, the second repressurization starts at approximately 300-400 process cycles. SN 5, however, first started showing this second repressurization sooner than expected, at around 150 cycles. Because this second repressurization was seen sooner than average but the Reactor still reached average life before gross leak occurred, it is suspected that there was a premature internal leak in either the inlet check valve, inlet isolation valve, or pressure regulator. SN 5 returned on SpX-26 and will be investigated to assess valve performance and identify root cause of failure.

3. 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 that had experienced a short installation time on the ISS in March 2021. Notable upgrades address known elastomer seal failures and allow for variable oxygen flow control 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. The Demo Catalytic Reactor is currently undergoing rework to correct the seal glands to proper size to accommodate the selected metal seals. A new testing procedure has also been developed and is being implemented to incorporate improved flight-like heat cycling and increased leak testing during and post-processing to ensure a leak-tight ORU and avoid recurrence of infancy failure. Assembly and testing is anticipated to complete by April 2023 and is targeting SpaceX-28 for launch.

4. Microbial Check Valve

The mechanical check valve in the Water Processor Assembly (WPA) Microbial Check Valve (MCV ORU) has not exhibited the desired reliability on-orbit, due to a limited amount of system pressure available to close the check valve. The MCV ORU is the physical and microbial barrier between the wastewater stream to the potable bus. The function of the MCV is to allow WPA water to recirculate back through the system for either nominal operations or when necessary conditions during processing requires WPA to enter a 'reprocessing' mode. The MCV prevents backflow via a check valve and use of a iodinated resin to impart iodine to the wastewater for microbial control. Figure 4 shows this physical location in the WPA Schematic. Historically, the mechanical check valve has not performed at a high level of reliability with recurrences of the check valve failing opening. The current check valve has gone through two iterations of design to help improve this issue. The first original design often did not function as intended and allowed back flow that would create hazardous conditions for WPA product water contamination if not for daily ground team intervention. The second design exhibited desired functionality upon initial installation. However, after some time the valve showed delayed response and occasionally needed ground team intervention (utilizing valve commanding to induce delta pressure), and ultimately the check valve stopped checking completely. The pressure sensor within the Water Storage ORU (downstream of the MCV) shows if and when the check valve is actuating, as shown by the screenshot of telemetry below.

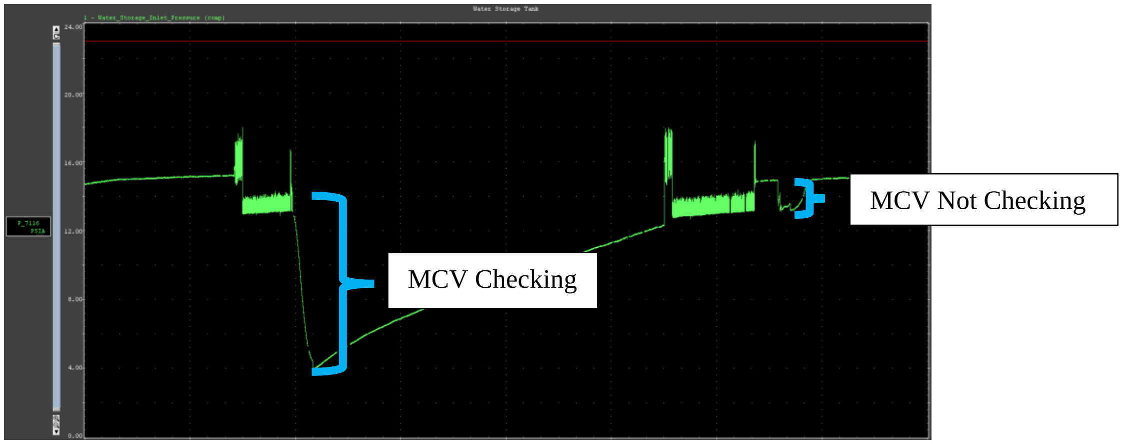

Figure 9. Water Storage Inlet Pressure for when the MCV is checking vs not checking

The pressure drop in Figure 9 is an indication of the check valve closing. The 3-way valve will switch to the recirculation loop where the MCV ORU is located during standby. The MCV will check, isolating the line downstream of the check valve, thereby alleviating the differential pressure across the MCV as shown by the pressure drop in the graph above.

An upgraded MCV is in work to ensure a reliable checking function within WPA. The new design implements a stronger spring to increase the spring force to close the poppet, resulting in an increasing of a delta pressure from 1 psid max to 1-2 psid max. To increase the reliability of the check valve closing, a redesign of the poppet included reducing the truncation diameter of the poppet to improve the ability of the poppet to seat correctly. These modifications are expected to complete in May 2023 and should improve the MCV check valve performance.

VII. Conclusion

Since 2022, the WRS has continued to provide the ISS crew with potable water for drinking, 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 expected end-of-life operations (MF bed ionic breakthrough) and external water leaks (catalytic reactor seal leak); 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. Most notable is the significant milestone for UPA operating all of its major ORUs past their predicted operational life in the same ORU configurations.

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 exception performances. The rebuilt Demo Catalytic Reactor and Toilet hardware deliveries will get their return for exploration demonstration, likely within the year.

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