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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 May 2018 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

<i>ARFTA</i> = Advanced Recycle Filter Tank Assembly	<i>PCPA</i> = Pressure Control and Pump Assembly
<i>ACY</i> = Russian Urinal	<i>PWD</i> = Potable Water Dispenser
<i>ACTEX</i> = Activated Carbon and Ion Exchange Cartridge	<i>PWR</i> = Potable Water Reservoir
<i>BPA</i> = Brine Processor Assembly	<i>RHS</i> = Reactor Health Sensor
<i>CDRA</i> = Carbon Dioxide Removal Assembly	<i>SPA</i> = Separator Plumbing Assembly
<i>CWC</i> = Contingency Water Container	<i>TOC</i> = Total Organic Carbon
<i>CCAA</i> = Common Cabin Air Assembly	<i>TOCA</i> = Total Organic Carbon Analyzer
<i>DA</i> = Distillation Assembly	<i>UPA</i> = Urine Processor Assembly
<i>DMSD</i> = dimethylsilanediol	<i>UTAS</i> = United Technologies Aerospace
<i>EMU</i> = Extravehicular Mobility Unit	<i>UTS</i> = Urine Transfer System
<i>EIB</i> = Russian water container	<i>UWMS</i> = Universal Waste Management System
<i>FCA</i> = Firmware Controller Assembly	<i>WHC</i> = Waste & Hygiene Compartment
<i>FCPA</i> = Fluids Control and Pump Assembly	<i>WRM</i> = Water Recovery and Management
<i>ICWC</i> = Iodinated Contingency Water Container	<i>WPA</i> = Water Processor Assembly
<i>ISPR</i> = International Standard Payload Rack	<i>WRS</i> = Water Recovery System
<i>IX</i> = Ion Exchange	<i>WRT</i> = Water Resupply Tank
<i>MCV</i> = Microbial Check Valve	

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MLS = Mostly Liquid Separator
MF = Multifiltration
ORU = Orbital Replacement Unit

WSS = Water Storage System
WSTA = Wastewater Storage Tank Assembly

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 on STS-126 on November 14, 2008 and initially installed in the US Lab module. On February 18, 2010, the racks were relocated to their permanent home in the Node 3 module.

II. Description of the ISS Water Recovery and Management System

A conceptual schematic of the WRM is provided in Figure 1. The waste water bus receives humidity condensate from the Common Cabin Air Assemblies (CCAAs) on ISS, which condenses water vapor and other condensable contaminants and delivers the condensate to the bus via a water separator. Waste water is typically delivered to the WPA Waste Tank. 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. In addition, waste water may also be delivered from the Carbon Dioxide Reduction System. This hardware uses Sabatier technology to produce water from carbon dioxide (from the Carbon Dioxide Removal Assembly (CDRA)) and hydrogen (from the electrolysis process in the Oxygen Generation System). However, the performance of the Sabatier reactor degraded over the last several years and was removed from service in October 2017 and returned to ground for a failure investigation. The ISS Program Office is currently planning to build another Sabatier reactor for operation on ISS in 2020.

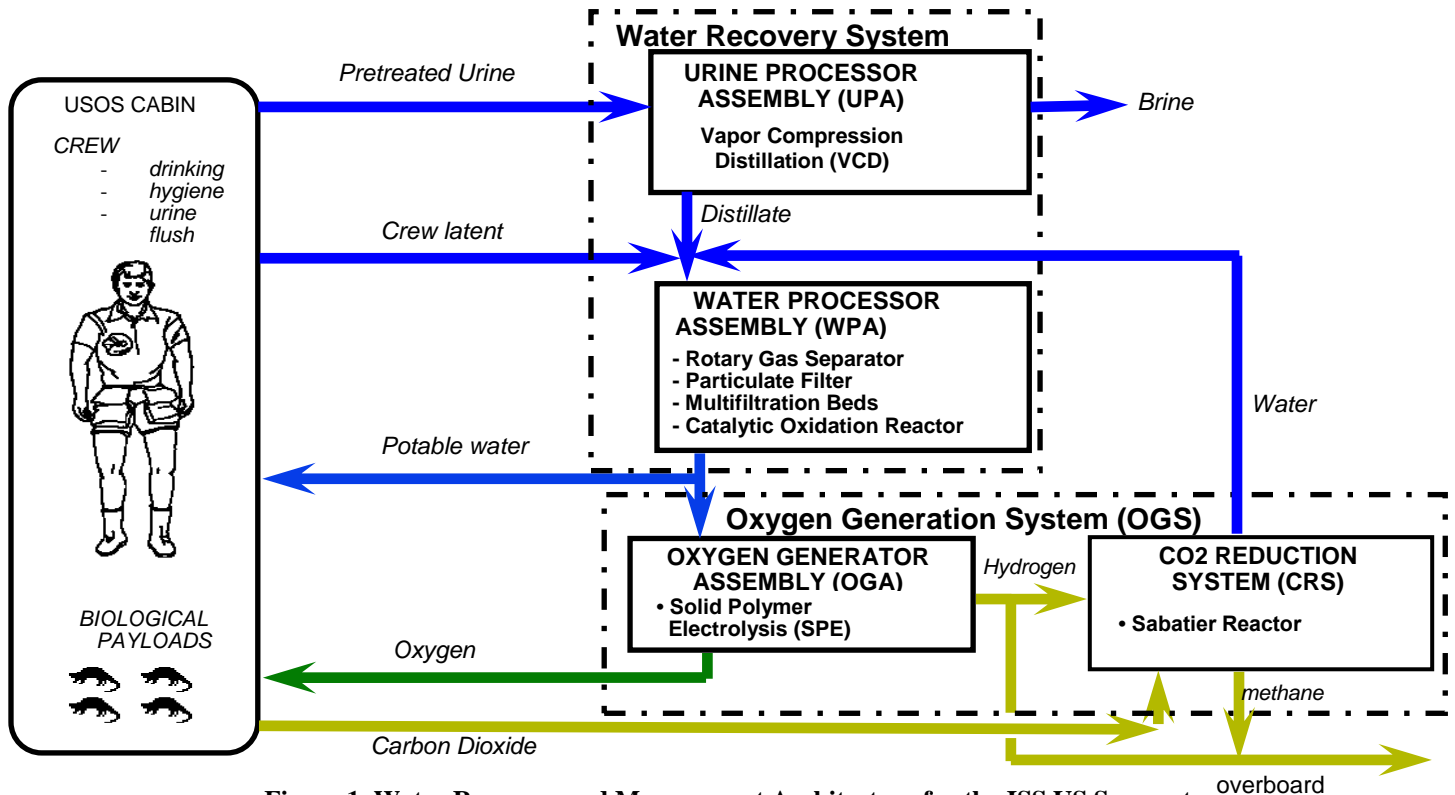


Figure 1. Water Recovery and Management Architecture for the ISS US Segment

Crew urine is collected in the Waste & Hygiene Compartment (WHC), which consists of a Russian Urinal system (referred to as the ACY) that is installed in the US Segment. 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 then delivered to the Urine Processor Assembly (UPA) for subsequent processing. In addition, pretreated urine is collected in Russian urine containers (called EDBs) in the Russian Segment, manually transported to the US Segment, and offloaded into the UPA Waste Tank for subsequent processing. The UPA produces urine distillate, which is pumped directly to the WPA Waste Water Tank, where it is combined with the humidity condensate from the cabin and Sabatier product water, and subsequently processed by the WPA. A detailed description of the UPA and WPA treatment process is provided in Section III.

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 System (OGS), 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 697 L (1537 lbs) of potable water is stored on ISS in Iodinated Contingency Water Containers (ICWCs) and Potable Water Reservoirs (PWRs) 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.

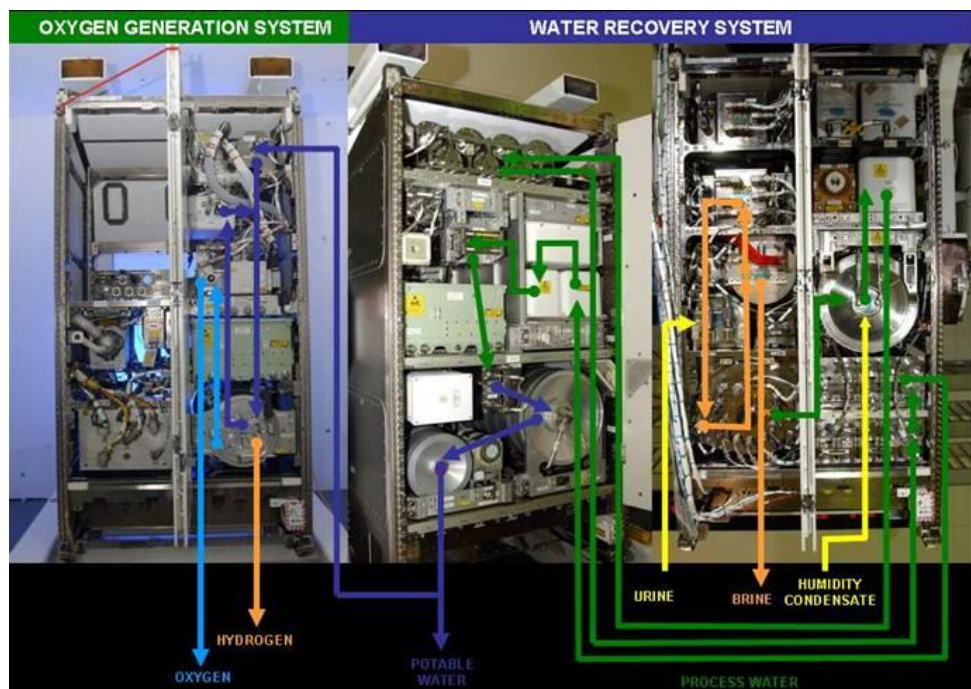


Figure 2. International Space Station Regenerative ECLSS Racks

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 1-5.

A. Water Processor Assembly Overview

A simplified schematic of the WPA is provided in Figure 3. The WPA consists of 16 Orbital Replacement Units (ORUs), and occupies WRS#1 and the right half of WRS#2. Wastewater delivered to the WPA includes condensate from the Temperature and Humidity Control System, distillate from the UPA, and Sabatier product water when

available. This wastewater is temporarily stored in the Waste Water Tank ORU. The Waste Water Tank includes a bellows that maintains a pressure of approximately 5.2 – 15.5 kPa (0.75 to 2.25 psig) over the tank cycle, which serves to push water and gas into the Mostly Liquid Separator (MLS). Gas is removed from the wastewater by the MLS (part of the Pump/Separator ORU), and passes through the Separator Filter ORU where odor-causing contaminants are removed from entrained air before returning the air to the cabin. Next, the water is pumped through the Particulate Filter ORU followed by two Multifiltration (MF) Beds where inorganic and non-volatile organic contaminants are removed. The Sensor ORU located between the two MF beds determines when the first bed is saturated based on conductivity, and additional conductivity sensors are located downstream of the second MF Bed to detect ionic breakthrough. Following the MF Beds, the process water stream enters the Catalytic Reactor ORU, where low molecular weight organics not removed by the adsorption process are oxidized in the presence of oxygen, elevated temperature, and a catalyst. In addition, any microorganisms present in the process water are killed in the Catalytic Reactor due to the elevated temperature. A regenerative heat exchanger recovers heat from the effluent of the catalytic reactor to make this process more efficient. The Gas Separator ORU removes excess oxygen and gaseous oxidation by-products from the process water and returns it to the cabin. The Reactor Health Sensor (RHS) ORU monitors the conductivity of the reactor effluent as an indication of whether the organic load coming into the reactor is within the reactor's oxidative capacity. Finally, the Ion Exchange (IX) Bed ORU removes dissolved products of oxidation and adds iodine for residual microbial control. The water is subsequently stored in the Water Storage Tank prior to delivery to the ISS potable water bus. The Water Delivery ORU contains a pump and small accumulator tank to deliver potable water on demand to users. The WPA is controlled by a firmware controller that provides the command control, excitation, monitoring, and data downlink for WPA sensors and effectors.

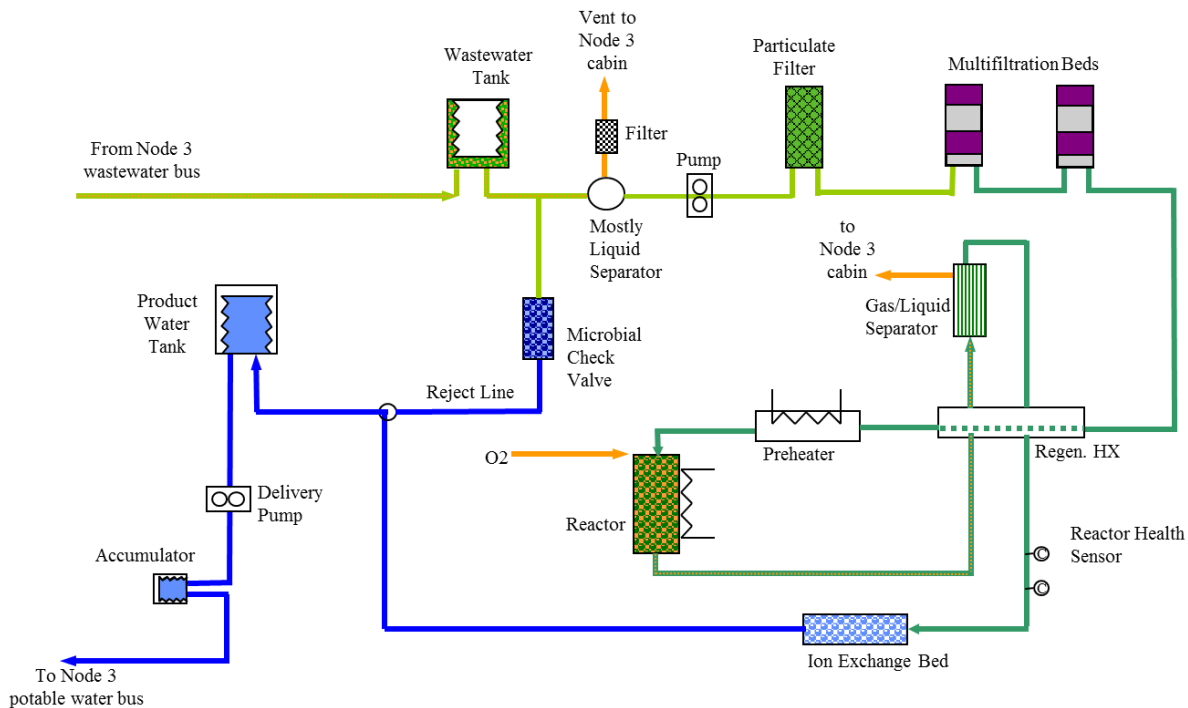


Figure 3. WPA Simplified Schematic

B. Urine Processor Assembly Overview

A simplified schematic of the UPA is shown in Figure 4. The UPA consists of 7 ORUs, which take up slightly more than half of the WRS Rack #2. Pretreated urine is delivered to the UPA either from the US On-orbit Segment (USOS) WHC (outfitted with a Russian urinal) or via manual transfer from the Russian E/D/B. 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 urine is temporarily stored in the Wastewater Storage

Tank Assembly (WSTA). When a sufficient quantity of feed has been collected in the WSTA, a process cycle is automatically initiated. The Fluids Control and Pump Assembly (FCPA) is a four-tube peristaltic pump that moves urine from the WSTA into the Distillation Assembly (DA), recycles the concentrated waste from the DA into the Advanced Recycle Filter Tank Assembly (ARFTA) and back to the DA, and pumps product distillate from the DA to the wastewater interface with the WPA. 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 EDB. The EDB 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 another four-tube peristaltic 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.

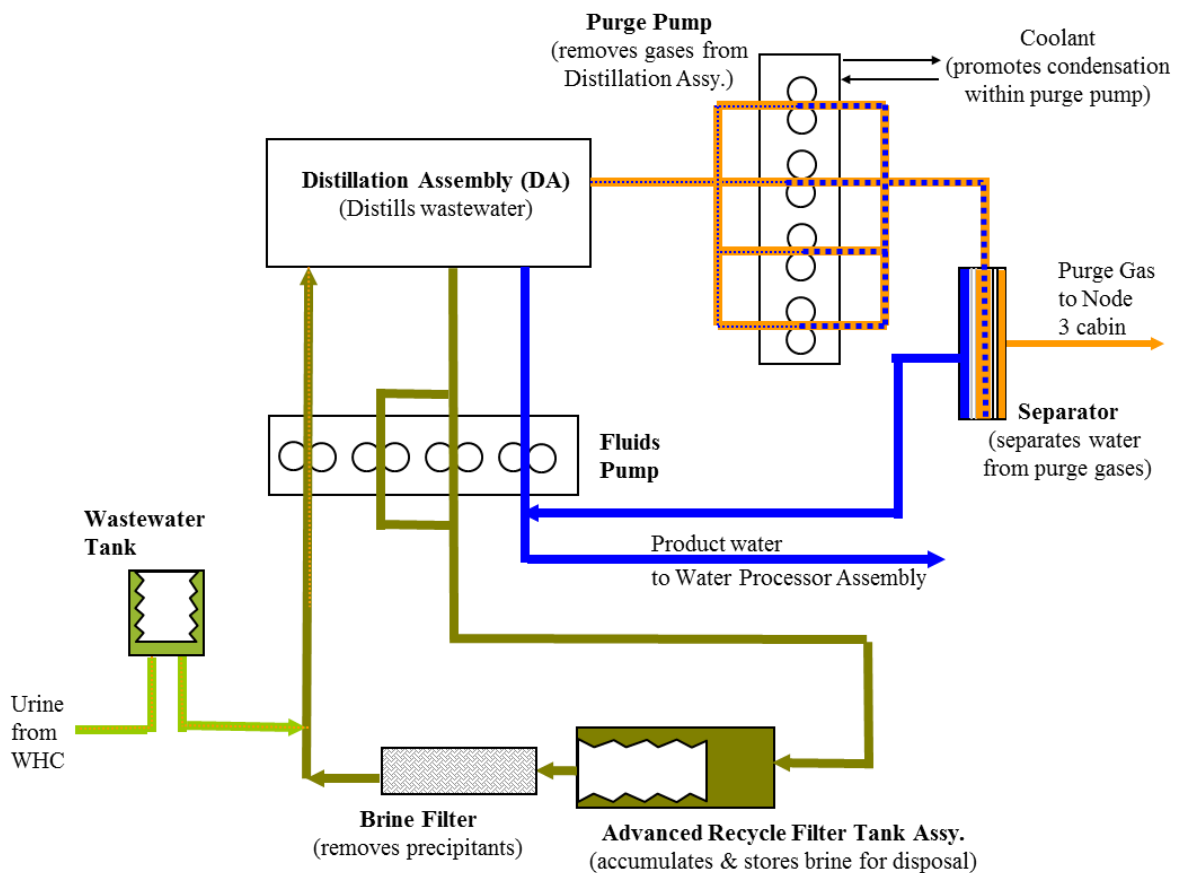


Figure 4. Urine Processor Assembly Schematic

The UPA was designed to process a nominal load of 9 kg/day (19.8 lb/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 in early 2016 allowed the UPA to return to 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.

IV. Water Recovery and Management Status

In the last year, 4320 L (9520 lbs) of potable water have been supplied to the US Segment potable bus by the WPA. In addition, 1920 L (4233 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 continued to be a challenge due to the need to maintain 697 L (1537 lbs) of potable water on ISS for crew reserve while continuing to meet the various ISS needs for potable water. This task has been impacted by the decision in late 2014 to process all available urine from the Russian Segment. Processing of urine from the Russian segment generates distillate quantities in excess of the losses experienced by the rest of the ISS regenerative water systems. This excess has reduced the need to supplement the USOS water systems with stored water and generated a surplus of water in the USOS. Surplus water is stored for later use by draining the WPA Waste Water Tank or WPA Water Storage tank when the WRS rack tanks (UPA wastewater, WPA Waste, and WPA potable tanks) are too full to continue normal operation. This surplus of water in the US Segment is expected to shift in 2018 with the delivery of a Russian Segment Urine Processor on Progress 70P. Installation of this hardware has been completed by the RS crew arriving on Soyuz 54S. This crew is now performing the initial checkout of the system with urine collected in the Russian Segment, after which Russian personnel anticipate no more urine transfer to the US Segment. Distillate from the Russian Urine Processor is 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.

Following the loss of the 65 Progress mission in late 2016, NASA provided deiodinated water to the Russian Segment from the USOS stockpile. The Russian systems are incompatible with the iodine biocide used in USOS stockpile water. A new operation was developed and performed to remove the iodine. The Russian container was simply placed down stream of an ACTEX (Activated Carbon and Ion Exchange) filter and water was pumped through the filter using a contingency pump. This operation occurred in the crew cabin using USOS water storage containers (ICWC) and Russian EDB containers, therefore generating this water did not interfere with the operation of the USOS water recovery systems. Approximately 505 L were transferred in 2017, and an additional 95 L is still available for transfer based on the agreement between NASA and the Russian Space Agency.

When the WRS Racks were initially delivered to ISS, NASA also delivered a Microbial Shock Kit (MSK) that included a Microbial Check Valve (MCV) designed to produce a solution containing 40 mg/L of iodine by flowing water through the iodinated resin within the MCV. This hardware was delivered to provide a means to disinfect and recover function of the potable distribution bus following a microbial upset by shocking the bus with the solution containing elevated iodine concentration. Fortunately, this hardware has never been required on ISS during the 9.5 years of WRS operation. In late 2017, the ISS crew relocated the Microbial Shock MCV (stored in a plastic shipping bag) and observed solid black particles in the packaging. Since this residue could only be due to an issue with the MCV, the hardware was returned to ground for evaluation. As a result, there is currently no capability on ISS to recover the potable bus from a microbial upset. In addition, NASA and Boeing personnel acknowledged that limited data is available on the actual health of the potable bus since there are no regular samples directly from the bus. Samples of drinking water (from the PWD) are returned approximately every quarter as part of routine environmental monitoring. However, these samples do not necessarily reflect the health of the potable bus because the PWD includes a bed with media to remove iodine from the WPA product water as well as a 0.2 micron microbial filter. Due to the sorbent media and the microbial filter, the PWD water samples provided limited insight into the actual conditions on the potable bus. To accurately assess the health of the potable bus, NASA and Boeing personnel agreed to begin taking annual samples of the potable bus for ground analysis. The first sample collected from the bus showed no microbial growth in the WPA product water, which was expected given the rigorous controls present in the WPA to sterilize the water in the catalytic reactor, remove organic carbon to low levels to minimize nutrients for microbial growth, and add iodine as a biocide. The effectiveness of these controls support the argument to no longer maintain a method for recovery from microbial upset. Instead, NAS should maintain the capability to launch a shock solution if sample results or on-orbit data indicate microbial contamination. NASA and Boeing are also evaluating the possibility of providing a disinfectant solution that may be used in conjunction with a separate action to reposition the spare PWD on ISS. The results of this investigation will be reported in the next year.

Several significant modifications to the ISS water system are currently in development, including a Water Storage System (WSS), a Universal Waste Management System (UWMS), a Urine Transfer System (UTS), and a Brine Processor Assembly (BPA). The WSS addresses the water management issues associated with water resupply and potable water storage. Potable water storage capacity will be increased by launching four tanks recovered from Space

Shuttles Endeavor and Atlantis. The former space shuttle tanks will be connected to the potable bus with inlet valves that will be controlled by ground personnel. Water will be automatically transferred to and from this WSS as needed for the water balance. The additional capacity will greatly increase 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 new rack will incorporate interchangeable 73 L (161 lbs) resupply tanks. These tanks are commercially available, and have been tested to insure compliance with the ISS requirements (including launch vibration and materials compatibility). The resupply tanks will be launched full, installed into the WSS rack, and emptied into the WPA waste tank via commanding from the ground. The water from the resupply tanks will be transferred to the WPA waste tank via the waste water bus using the same compressor currently utilized for ARFTA and EDBs transfers. 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 to add to the existing WPA waste water tank and Lab condensate tank. WSS will add a commandable valve in front of the Lab condensate tank. The valve will allow the condensate tank to remain connected and isolated instead of manually connecting and disconnecting it when the WPA waste water tank is not available. When the pre-staged resupply tanks are emptied, they can be changed out with new tanks as they arrive on ISS. The empty resupply tanks may then provide additional disposal options for brine generated by the UPA, which will reduce procurement of costly EDBs. Assuming the Russian Urine Processor is operational in late 2018, the water surplus created by the US Segment's processing of Russian urine will cease. The increased efficiency of the WSS will become an important factor for reducing crew time currently used to manage water transfers in the USOS. The WSS rack, Shuttle tanks, and resupply tanks are scheduled to be delivered to support initial operation in early 2019. A view of the WSS rack and how the tanks are installed is shown in Figure 5.

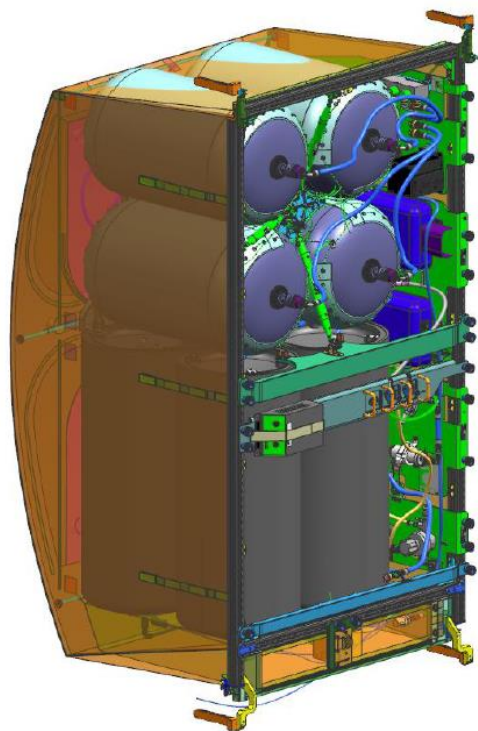


Figure 5. WSS Rack without Covers

The UWMS is a new toilet in development by United Technologies Aerospace Systems (UTAS). This hardware is planned for use in the Orion vehicle and will be initially demonstrated on ISS beginning in mid-2019. To support ISS operations, the urinal uses the phosphate-based pretreatment so that urine can be processed by the ISS UPA. Assuming a successful demonstration, the UWMS may be maintained on ISS to support the increased US crew expected beyond 2018. To support the operation of two urinals on ISS (UWMS and WHC), a Urine Transfer System

(UTS) is being built by Boeing. This hardware will automatically manage input from each urinal, insuring that parallel operation does not impact the delivery of urine from either separator to the UPA. This is accomplished by diverting flow from the WHC to a backup EDB any time pressure sensors indicate the UWMS is also delivering urine to the UPA. This EDB can subsequently be drained to the UPA when neither urinal is in use. As part of the UTS delivery, Boeing has also identified a commercially available compressor that can be used for the same applications as the Russian compressor. This hardware will be used nominally by UTS to transfer pretreated urine from EDBs to the UPA WSTA and for offloading the UPA brine tank (ARFTA) into the BPA.

The BPA will be operated on ISS as a technology demonstration for NASA Exploration missions. This hardware will process the brine generated by the UPA (see Figure 1) to remove water and thereby achieve near-complete water recovery. This hardware is being delivered to NASA by Paragon Space Development and is scheduled for delivery in mid-2019. 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. More detail on this technology can be found elsewhere^{6,7}. If successful, NASA may continue to use the technology on ISS to reduce the water resupply requirement from earth.

In addition to these items, the European Space Agency (ESA) is flying the Advanced Close Loop System (ACLS) technology demonstration in 2019. ESA is using ACLS to evaluate oxygen generation via water electrolysis, carbon dioxide (CO₂) removal, and CO₂ reduction for future manned missions. ACLS will use steam desorption for CO₂ removal, resulting in approximately doubling the quantity of water vapor that must be removed by the ISS Condensing Heat Exchangers. ACLS will be initially located in the US Laboratory module, where it will interface with both the potable bus and the waste water bus. ACLS has a unique requirement to remove and deliver water to the condensate bus. To prevent impacts to the WPA waste tank, NASA and Boeing have decided to separate the waste water bus in the US Laboratory. In this configuration, condensate collected in the US Lab, Node 2, and Columbus modules (along with the condensate tank) will interface with the ACLS while condensate collected in Node 3 and Airlock will feed the WPA waste tank. The additional humidity generation coupled with the split waste water bus is expected to complicate the mass balance on ISS, periodically requiring the bus to be reconnected to transfer condensate from the Condensate Tank to the WPA waste tank.

V. Urine Processor Assembly Current Status

The UPA has produced 2789 L (6147 lb) of distillate at 70% (Russian urine treated with baseline pretreatment) to 85% recovery (US urine treated with alternate pretreatment) in the last year, cycling through 31 ARFTA cycles during that time. As of May 10, 2018, the total UPA production on ISS is at 16,179 L (35,659 lb) of distillate. A graphical summary of UPA production rate and upmass required for ISS operations is provided in Figure 6. In the past year, one PCPA (harmonic gear drive), one SPA (end of life condition), and 4 brine filters (expected loading) have been replaced to maintain nominal UPA operations.

The UPA has experienced multiple failures of the FCPA in previous years due to various mechanical issues^{4,5}. These failures led to the development of an improved drive shaft design, replacing the harmonic drive with a planetary gear. Though the harmonic drive is considered appropriate for precision applications, tolerances in the FCPA assembly and installation processes provide multiple opportunities for failure. In contrast, the planetary gear design supports a robust installation process and is also more advantageous for the power transfer application in the FCPA. This modification was expected to produce a marked increase in on-orbit reliability of the FCPA. As of May 10, 2018, FCPA S/N 04 has operated for 4045 hours, significantly exceeding the life of any previous FCPA with the harmonic drive. However, the PCPA failed in March 2018 most likely due to a harmonic drive failure. As previously seen with this failure in the FCPA, motor current gradually increased for several months until ORU replacement was required. The US crew installed PCPA S/N 4 on March 29 2018. This PCPA includes the planetary gear drive though there is also one remaining spare PCPA on ISS that has a harmonic drive.

As noted previously¹, the UPA experienced elevated conductivity in the urine distillate from April 2016 to April 2017. Based on on-orbit data, NASA engineering determined pretreated urine/brine was leaking into the distillate internal to the DA. After replacing the DA, the distillate conductivity returned to normal as shown in Figure 7. The DA was returned to ground and a failure investigation was performed to determine the most likely root cause was a leak through the centrifuge rear bearing, though it is also possible that carryover through the demister also contributed to the elevated conductivity. This leak path through the rear bearing has been observed in previous DAs, but never to the extent seen with DA S/N 3. The rear bearing is located in the centrifuge shaft, so a leak path in microgravity is not obvious. Engineering personnel believe it is likely either splashing in microgravity or fluid wicking up the brine pitot tube to the center shaft. No mechanical deficiencies were identified during the failure investigation to explain why

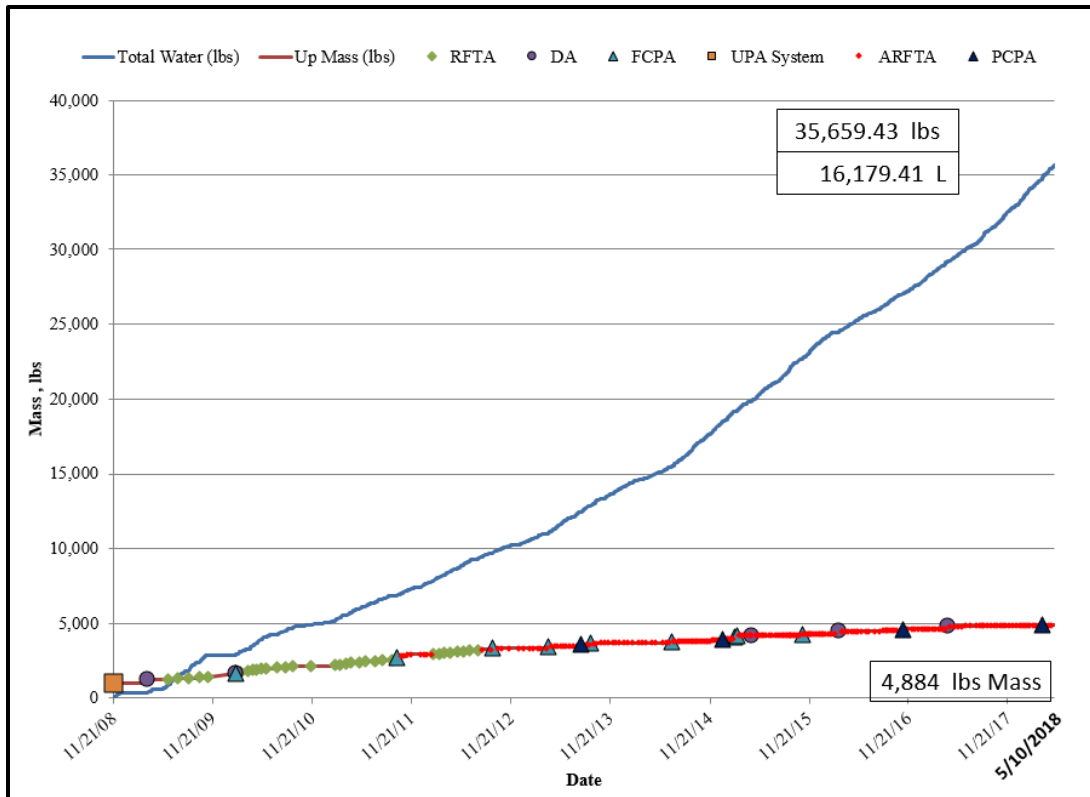


Figure 6. UPA Production and Upmass on ISS

this particular DA allowed a larger leak of pretreated urine/brine through the rear bearing. NASA engineering believes the primary difference with DA S/N 3 was that more pretreated urine/brine was reaching the rear bearing, but no obvious differences in the actual hardware could be identified that would explain why this would happen. To prevent recurrence, NASA is planning to implement a lip seal to prevent fluid from reaching the rear bearing. A lip seal was originally employed in the design to protect against this leak path, but this lip seal was removed to eliminate the drag placed on the centrifuge shaft. As part of the effort to implement upgrades to the UPA, this lip seal will be added back to the design. However, the drag introduced by the lip seal is still a concern because it may cause the centrifuge drive belt to slip (resulting in a separate DA failure). The UPA design team is currently implementing an improved drive belt (likely a V-belt instead of the current o-ring drive belt) to provide a design less susceptible to belt slippage. Once the design for this drive belt is complete, the lip seal on the rear bearing will also be implemented.

Since the leak path through the rear bearing is a known design issue, NASA engineering expected this event to recur with the current DA though the magnitude of the effect was not known. NASA engineering observed the initial indication of this issue after approximately six months of operation. Figure 8 shows a conductivity spike during startup, indicating a leak of pretreated urine/brine into the condenser during Standby that is then flushed out once the DA begins processing. This duration is consistent with other DAs but measurably longer than DA S/N 3, which showed initial indications of a fluid leak through the rear bearing after only six weeks of operation. This data indicated the leak path in the current DA would be more consistent with the previous DAs, not DA S/N 3. After 12 months in operation for the current DA, NASA engineering has seen no indication of the conductivity spikes during process mode that plagued DA S/N 3.

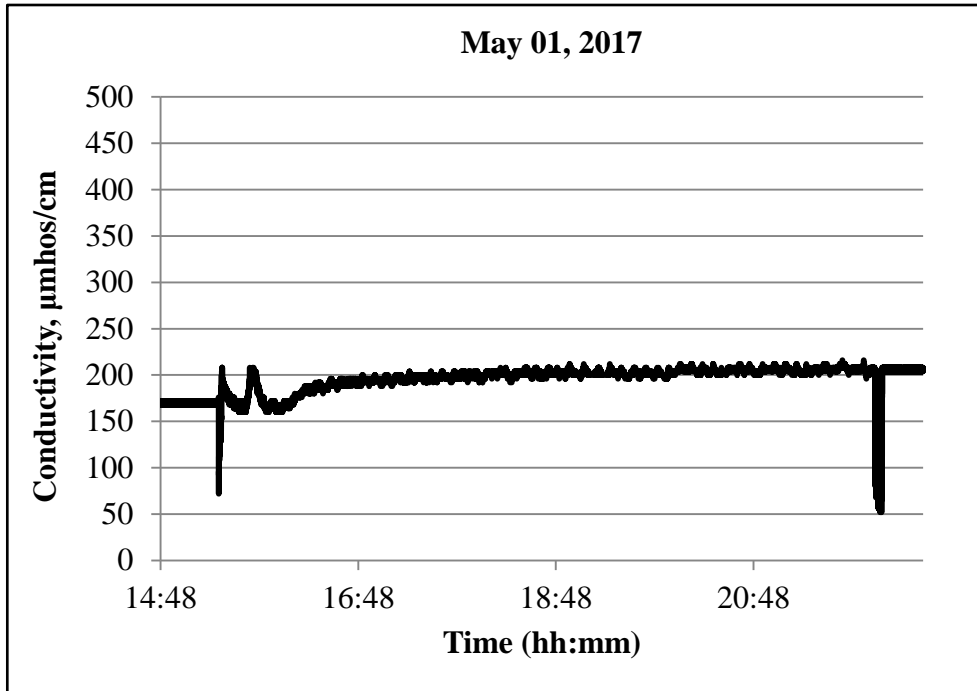


Figure 7. Nominal distillate conductivity observed after replacing the distillation

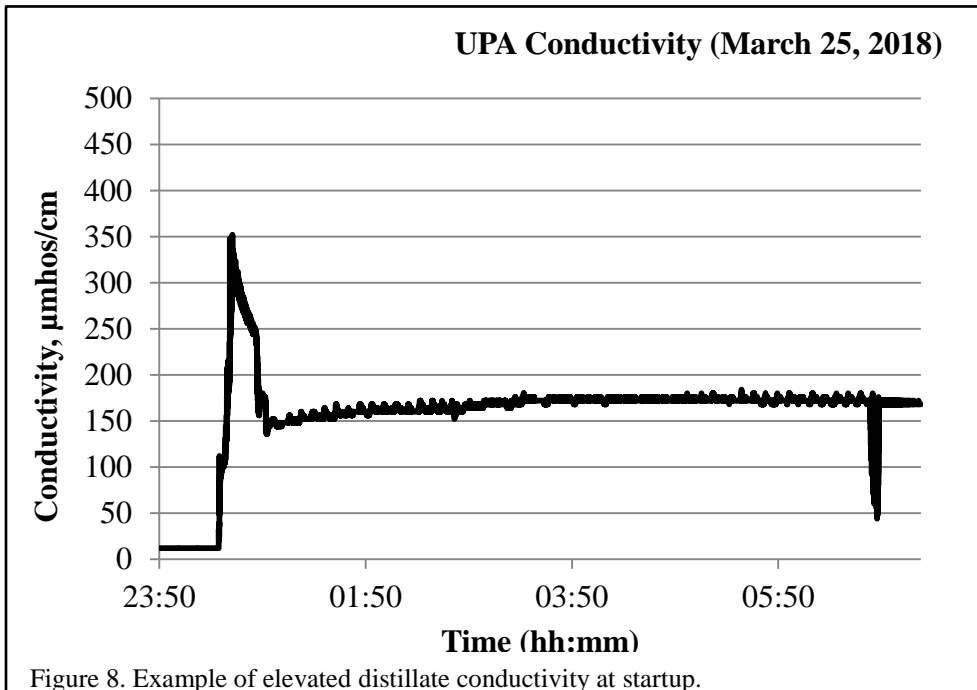


Figure 8. Example of elevated distillate conductivity at startup.

Beginning in late December 2017, the UPA product water line showed indications of free gas. The conductivity sensor located downstream of the SPA displayed sharp decreases in signal during processing of the UPA, as shown in Figure 9. These downward spikes are indicative of free gas, which has no significant conductivity and therefore provides this unique signature. Corroborating data of free gas in this line was evident in the distillate pressure sensors, showing decreased pressure swings. Due to peristaltic action of the FCPA, nominal distillate pressure profiles during operation show relatively large pressure swings as the peristaltic pump pumps against the liquid-solid lines. Free gas

in these lines provides gas compliance and thus these large pressure swings are minimized. Several sources of free gas in the product water lines were identified; however, data trending strongly suggested a SPA failure to separate and remove gas from the purge distillate line. Installation of a new SPA was completed January 24th, 2018. Shortly thereafter, indications of free gas ceased, as shown in Figure 8. The removed SPA will be returned on SpX-15 for a failure analysis.

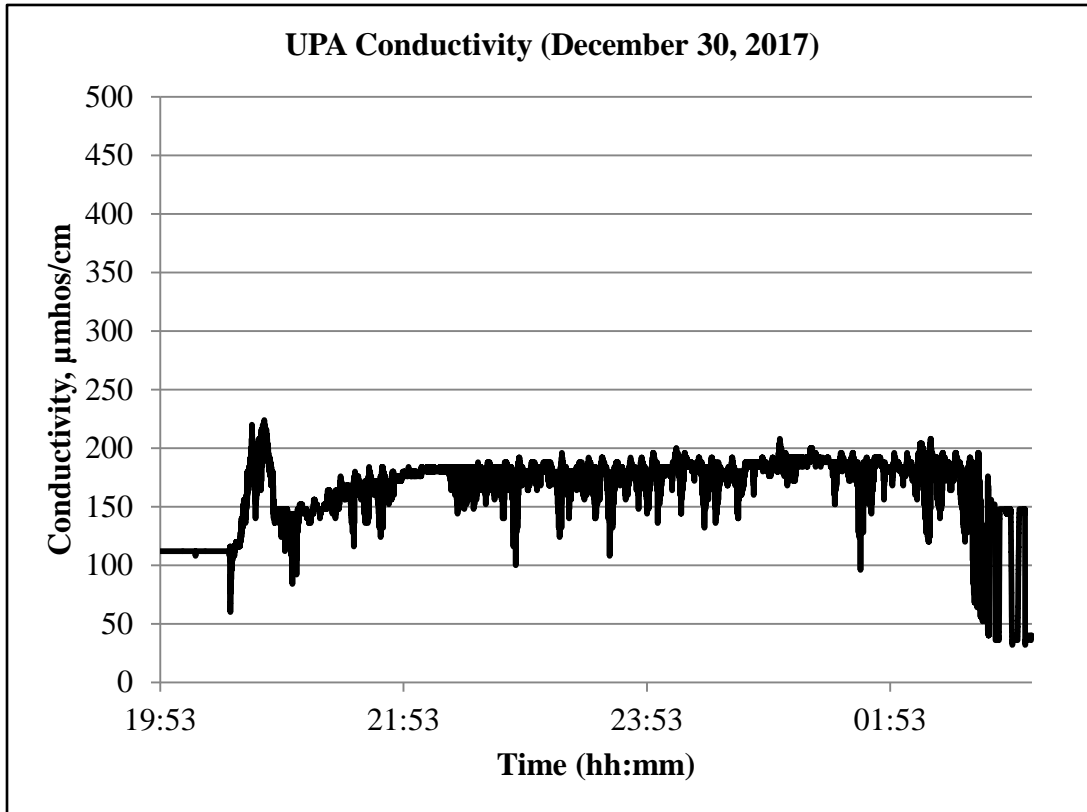


Figure 9. Indication of Free Gas in Purge Distillate

VI. Water Processor Assembly Current Status

As of May 6, 2018, the WPA has produced approximately 34,680 L (76,450 lbs) of product water, including 4320 L (9520 lbs) in the previous year. The two primary issues that impact WPA operations on ISS continue to be the Catalytic Reactor seals and the passage of dimethylsilanediol (DMSD) through the WPA, though neither have required replacement in over two years. The WPA Catalytic Reactor was last replaced in February 2016 due to leaking seals, and two Multifiltration Beds were replaced in late 2015 due to DMSD breakthrough. The following discussion addresses these two issues and the ongoing efforts to mitigate their impact.

Multifiltration Bed life has been dictated by the passage of DMSD through the WPA. The source of DMSD and its impact on the WPA treatment process has been discussed previously^{9, 10}. An extensive investigation in the past year into the formation of DMSD on ISS is also available elsewhere¹¹, along with an assessment of DMSD sources on ISS¹². There have been 6 instances of increasing Total Organic Carbon (TOC) in the WPA product water due to DMSD, including the current trend. Each TOC trend was initially detected by the TOC Analyzer (TOCA) on ISS, and a summary of the data is provided below in Figure 10. However, the current trend has deviated from previous trends. In the past, once TOC has been detected by the TOCA, it has consistently increased until exceeding the potable specification of 3000 µg/L, necessitating the replacement of both MF Beds. In the current trend, the TOC peaked at approximately 1800 µg/L and has reached a steady state condition around 1000 µg/L for the last year. A product water sample returned to the ground for analysis has confirmed the source of the TOC is DMSD as expected. Engineering personnel believe a lower concentration of DMSD in the reactor effluent is the reason for the atypical trend, but it is not obvious why DMSD would be at a lower concentration. Possible explanations include a more efficient reactor,

lower DMSD concentration in the humidity condensate, or impacts to the mass transfer zone of DMSD in the MF Beds associated with reprocessing or processing clean water to address elevated RHS trends.

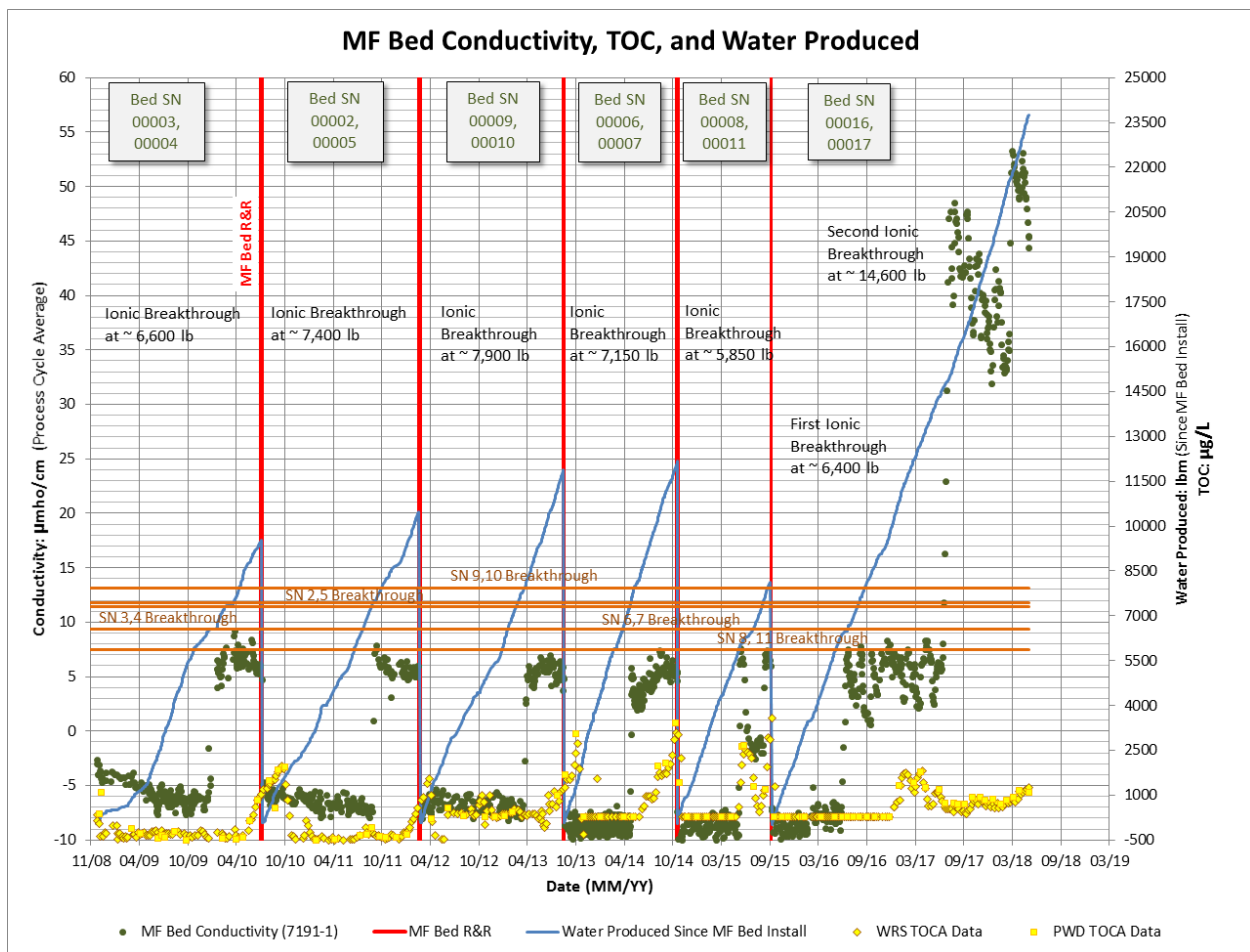


Figure 10. Correlation between Product Water TOC and MF Bed Throughput

The extended DMSD trend provided the first opportunity to extend the life of the MF Beds, since all previous beds were replaced after approximately one year in operation. The initial ionic breakthrough of MF Bed #1 had occurred before DMSD appeared in the product water, after approximately 2800 kgs of throughput. Subsequently, ionic breakthrough of MF Bed #2 occurred after 5900 kgs of throughput. Typically this ionic breakthrough would have resulted in the replacement of both MF Beds. However, previous testing at the NASA Marshall Space Flight Center had shown that the initial breakthrough contaminants could be processed by the Catalytic Reactor¹³. Using an ersatz based on the ISS waste water and a half-scale pair of MF Beds, discrete breakthrough trends were detected via conductivity for bicarbonate, acetate and ammonium, in that order. In addition, a flight-like Catalytic Reactor was challenged with each contaminant to show that the reactor could process all contaminants along with the nominal organic load. Since bicarbonate and acetate are oxidation products of ethanol (the primary organic processed by the reactor), it was expected that the reactor could accommodate their additional load. Though the reactor was also able to process ammonium, it is not expected to allow this on ISS since the MF Bed ersatz test showed that trace concentrations of several potential catalyst poisons were also present when ammonium breakthrough occurred.

Based on the data from these ground tests, NASA and Boeing engineering agreed to continue operating the MF Beds on ISS after the initial ionic breakthrough of MF Bed #2. This decision has been justified by the product water TOC, which appears to be unaffected by the additional load. To provide more insight into this trend, samples from the effluent of each MF bed were taken by the crew and returned to ground for analysis. These samples determined that acetate had saturated both MF Beds, not bicarbonate as expected based on ground tests. The reason for the change in order is not presently understood, though it is not critical since the reactor can accommodate the load from both

contaminants if necessary. Since ionic breakthrough of MF Bed #2 occurred, two additional breakthrough trends have occurred in MF Bed #1. Based on ground testing, these contaminants are expected to be bicarbonate and ammonium. Additional samples have been taken to identify these contaminants, though results are not yet available. Figure 11 provides the conductivity trend for the MF Bed #1 effluent, including the contaminants anticipated to have caused each breakthrough. Figure 12 provides the same data for MF Bed #2, identifying acetate as the initial contaminant to pass through both beds and be processed by the Catalytic Reactor along with the nominal load of volatile organics. Assuming sample results are as expected and WPA performance continues to be acceptable, NASA and Boeing personnel intend to operate the MF Beds until the third breakthrough of MF Bed #2 occurs. This would be a significant increase in MF Bed life and likely establish the expected procedure for loading MF Beds for the remainder of ISS.

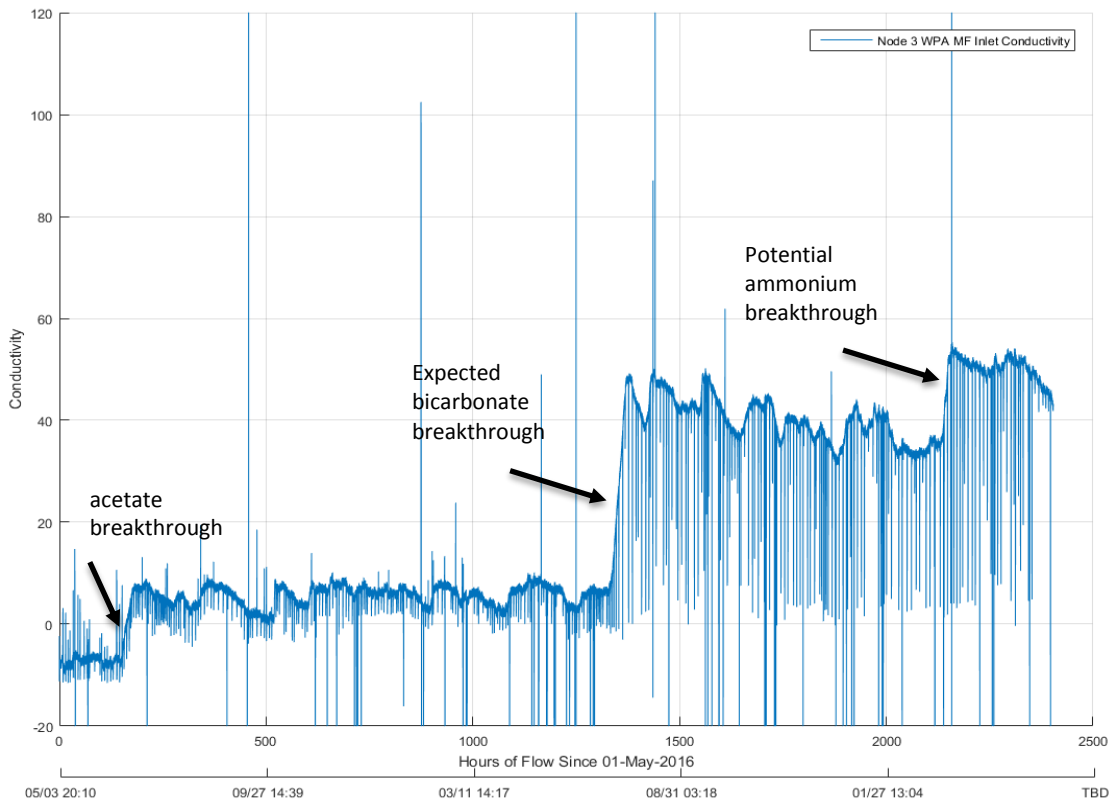


Figure 11. Ionic Breakthrough of WPA MF Bed #1

Since repeating the current DMSD trend cannot be guaranteed, NASA and Boeing have continued to develop and implement a mitigation strategy for DMSD. There are two paths to reduce the concentration of DMSD in the humidity condensate by ~50%, which would establish a concentration that the Catalytic Reactor could reliably remove to acceptable potable levels. First, research into the sources of the siloxanes on ISS has been ongoing¹². Though there are many sources of siloxanes, various crew items are the primary contributors. Crew items with significant contribution to the ISS siloxane load have been identified, including anti-perspirants, body lotions, wet wipes, and hair conditioner. Siloxane-free alternatives have also been identified and evaluated by the crew, resulting in the selection of viable alternatives for the crew to choose from. These siloxane-free products are expected to be used by the crew beginning in 2019. In parallel, Boeing is delivering Charcoal/HEPA filters to be installed on ISS in late 2018. These filters will remove atmospheric siloxanes before they can decompose to DMSD. This removal step would occur prior to each Condensing Heat Exchanger in the US Laboratory Module, Node 2, and Node 3. In April 2015, charcoal filters were installed in front of the Cabin Fan in Node 1 as an intermediate step to the filters in front of the Condensing Heat Exchangers. Node 1 was chosen due to it not having a heat exchanger which requires HEPA filtration. The charcoal filters have been effective at reducing the overall siloxanes in the atmosphere, but samples of condensate showed that the DMSD concentration remained at nominal levels. The addition of siloxane filters throughout ISS is expected to have a more significant impact on the DMSD concentration in the condensate. In addition to efforts to

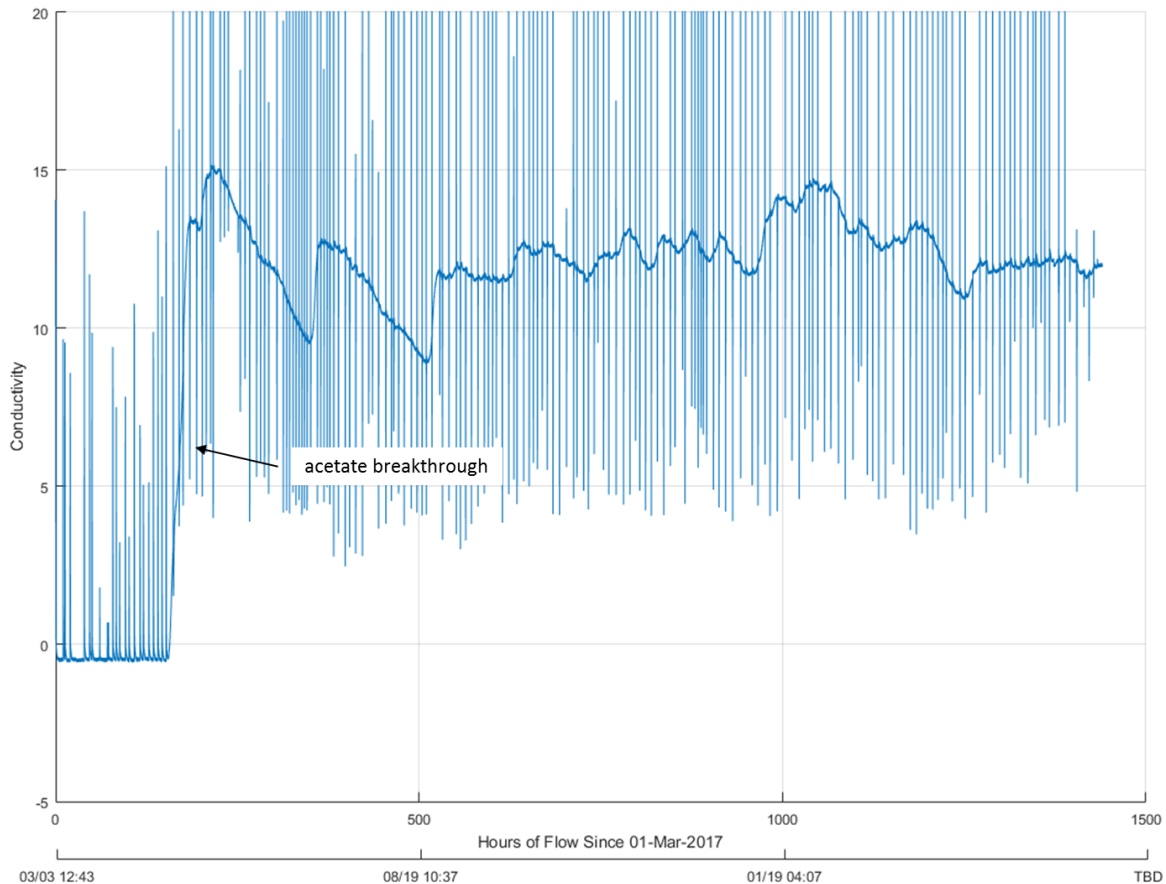


Figure 12. Ionic Breakthrough of WPA MF Bed #2

reduce DMSD in the condensate, NASA has worked with various vendors to develop an improved catalyst for the WPA Catalytic Reactor¹³. This effort identified a catalyst (developed by United Technologies Aerospace Systems, UTAS) that showed an increase in DMSD removal efficiency from 75 to 92%. Boeing and UTAS are now funded to deliver a reactor implementing this new catalyst to improve WPA capacity for DMSD.

As noted previously³, the Catalytic Reactor was redesigned in 2010-2011 to address the degradation of o-rings after prolonged exposure to the reactor's operating temperature. This investigation showed that the o-ring material developed a compression set that allowed the seal to leak after approximately two years in service. Previous inspection of ORUs returned to the ground showed the seals that were typically maintained at a reduced temperature during Standby (depending on their location in the reactor) were in better physical condition than those continuously maintained at the elevated temperature. This failure investigation substantiated the root cause, which is that the seal material is not compatible with the elevated process temperatures of the Catalytic Reactor for the planned 5 year life. To improve seal life, engineering personnel decided to reduce the Catalytic Reactor temperature in Standby to 96 C (205 F) instead of continuously maintaining it at the nominal temperature of 131 C (267 F). This operational scenario was ultimately implemented on the previous Catalytic Reactor, and has been used with the current Catalytic Reactor since it was initially installed. While the previous reactor did not show any actual improvement in operational life, the reduced standby temperature was not fully implemented until after one year of service. Furthermore, the leakage signature for this reactor was slower than previously seen, indicating the reduced temperature may have had an effect. A disassembly and inspection of this reactor after it was returned to ground showed that the lower standby temperature did improve the overall appearance of the seals. The current reactor has been operating at the reduced standby temperature since it was installed in the WPA. After approximately 26 months in operation, there has been no indication of a leak.

Though reducing the temperature in standby may provide some benefit, it is not considered to be viable for future missions because it is not expected to extend o-ring life beyond three years. To address this issue, NASA has funded Boeing and United Technologies Aerospace System (UTAS) to develop a Catalytic Reactor with metal seals. As noted previously, this reactor will also implement the improved catalyst developed by UTAS and tested by NASA. This hardware is expected to be operated on ISS in 2021 to provide engineering confidence for future manned missions.

The current Microbial Check Valve ORU was replaced in July 2016 after less than 4 years in operation in response to elevated pressure drop and to address the anomaly with the leaking internal mechanical check valve^{1,2}. The MCV ORU includes an iodinated resin to prevent microorganisms from growing into the potable section of the WPA, and a mechanical check valve to prevent water from the waste tank from flowing into the potable section (which is at a lower pressure than the waste tank). However, previous MCV ORUs have not performed to expectations on ISS due to the mechanical check valve working intermittently after installation. Because the Waste Tank is at a slightly higher pressure than the product lines upstream of the 3-way valve in the reprocess line, waste water can flow upstream when this valve is not checking. The check valve can sometimes be coaxed into checking by cycling the upstream 3-way valve, which provides a momentary boost in pressure drop (by referencing the upstream pressure to the sub-ambient Storage Tank). When the new MCV was installed in July 2016, it typically did not check on its own but did check after ground commanding cycled the upstream 3-way valve. In the past year, ground personnel have allowed more time (typically approximately one hour) for the check valve to check on its own. With the additional time, the check valve has consistently checked on its own without assistance. However, improving the reliability of this check valve design is currently being evaluated.

The Pump Separator ORU has been exhibiting a new trend in the Mostly Liquid Separator (MLS) motor temperature. The Pump Separator ORU contains the MLS and also the process pump for the WPA. The MLS is a rotary separator that removes any gas entrained in the incoming waste water. The MLS motor is cooled with a bypass flow of the WPA waste water. The motor temperature is monitored by two surface-mounted temperature sensors (see Figure 13). The sensor data shows the increasing trend for the last year of the MLS Temp and the MLS Temp Switch. The cause of the temperature increase is unknown, but it is believed that the bypass flow path around the motor may be partially obstructed. This theory is supported by the previous biofouling in this section of the WPA that required replacement of the ORU in 2010 and resulted in the waste tank management scheme discussed in previous papers¹⁻⁵. The current Pump Separator ORU has been installed since 2012 and both the MLS and pump continue to function as expected. If the MLS Temperature Switch exceeds 245 F, the ORU will have to be replaced. A spare Pump Separator ORU with a new MLS is available on-orbit and an additional spare will be available on the ground later in 2018.

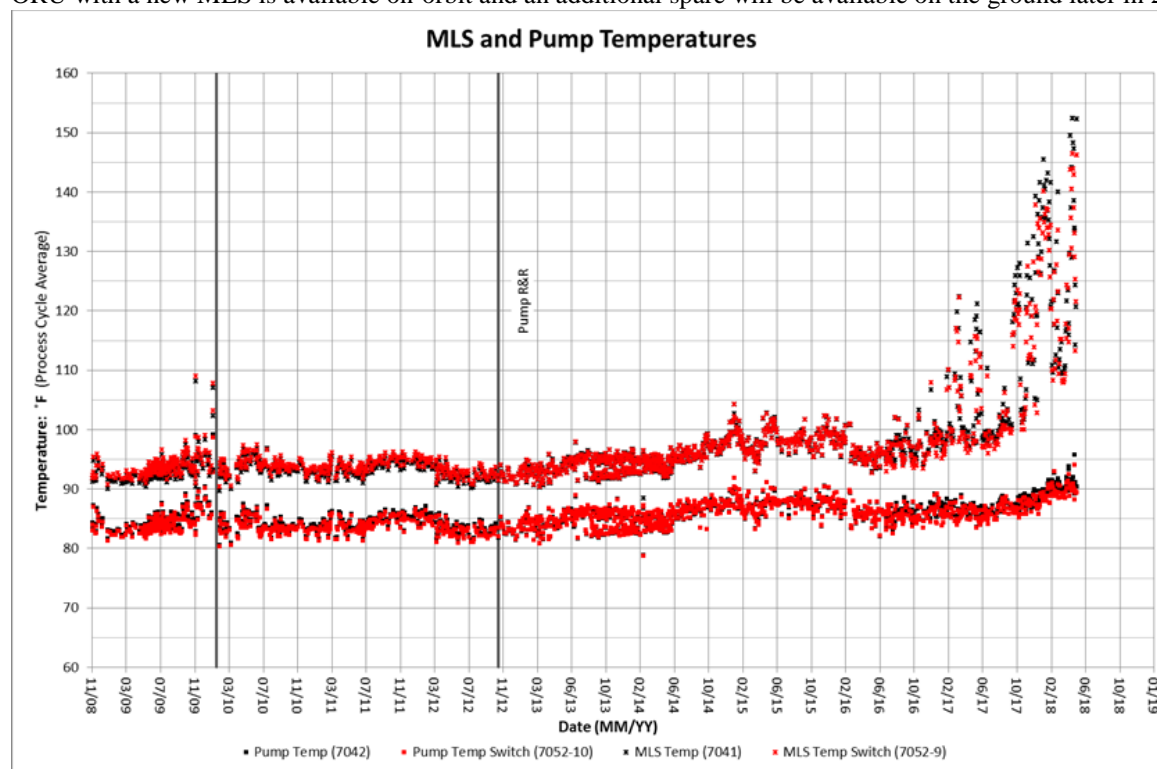


Figure 13. Increasing Temperature Trend of the MLS Motor

VII. Conclusion

In the past year, 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 no significant failures. The MF Beds have now been installed for 31 months due to the extended DMSD trend, and the Catalytic Reactor is operational after 26 months in service.

The UPA has experienced off-nominal performance due to condensate in the stationary bowl, resulting in elevated vacuum pressure and periodic shutdown events. However, there has been no increase in belt slippage during this time that would indicate condensate in the bowl might ultimately require replacement of the DA. Since this new DA has been installed, the UPA has continued to produce distillate with nominal conductivity levels. This observation indicates this DA will not be plagued with the elevated conductivity experienced by the previous DA due to a leak of pretreated urine through the rear bearing. Finally, implementation of a phosphate-based urine pretreatment in early 2016 has allowed UPA to return to 85% water recovery, during which time NASA engineering has observed no performance issues with the use of the phosphate-based pretreatment.

The initial Water Resupply Tank (WRT) was launched on Orbital OA-8 with plans to offload into the WPA waste tank in 2018. In the next year the WSS rack and associated tanks will be delivered and launched as soon as space is available. Design and delivery of other critical hardware (BPA, UWMS, UTS) will continue but this hardware will not be operational on ISS until 2019.

Acknowledgments

The authors wish to acknowledge the effort of the many engineers at NASA MSFC/JSC, Boeing, UTAS, Umpqua Research Company, and the on-board ISS astronauts and cosmonauts that have performed excellent work in the last year toward the operation, troubleshooting, and recovery of the Water Management System hardware on ISS.

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