

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, and provides a status of the performance and issues related to the operation of the Water Processor Assembly (WPA) and Urine Processor Assembly (UPA). This paper summarizes the on-orbit status as of May 2015 and describes the technical challenges encountered and lessons learned over the past two years.

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 transferred to their permanent home in the Node 3 module.

II. Description of the ISS Water Recovery and Management System

The ISS WRM provides the capability to receive the waste water on ISS (crew urine, humidity condensate, and Sabatier product water), process the waste water to potable standards via the WRS, and distribute potable water to users on the potable bus. 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. In addition, waste water is also received 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). 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.

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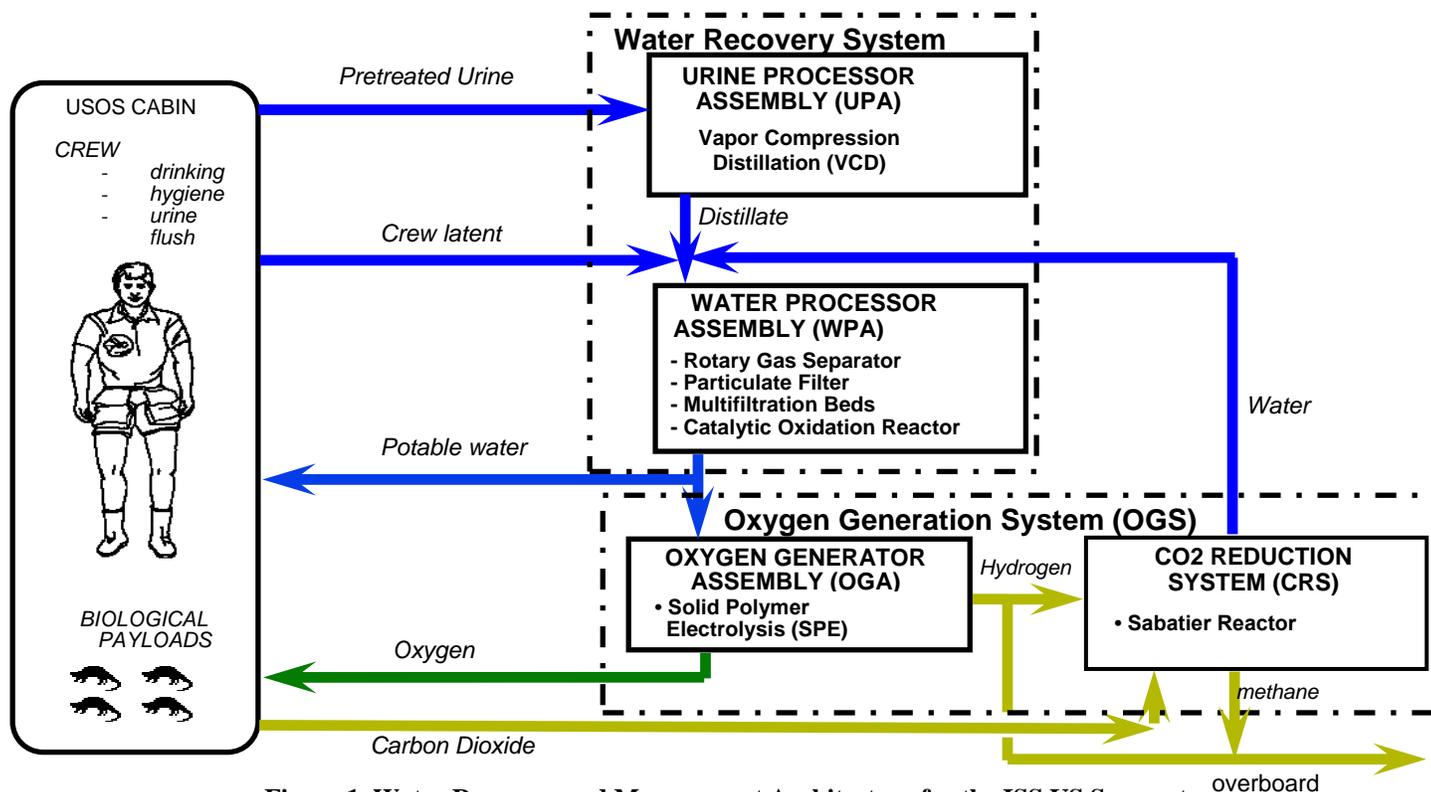


Figure 1. Water Recovery and Management Architecture for the ISS US Segment

Crew urine is collected in the Waste & Hygiene Compartment (WHC), which consists of a Russian Urinal system (referred to as the ACY) that has been installed in the US Segment. To maintain chemical and microbial control of the urine and hardware, the urine is treated with chemicals and flush water. The pretreated urine is then delivered to the Urine Processor Assembly (UPA) 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 from the various users. Users of potable water on 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 of potable water is maintained on ISS in Iodinated Contingency Water Containers (CWC-Is) 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. 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.

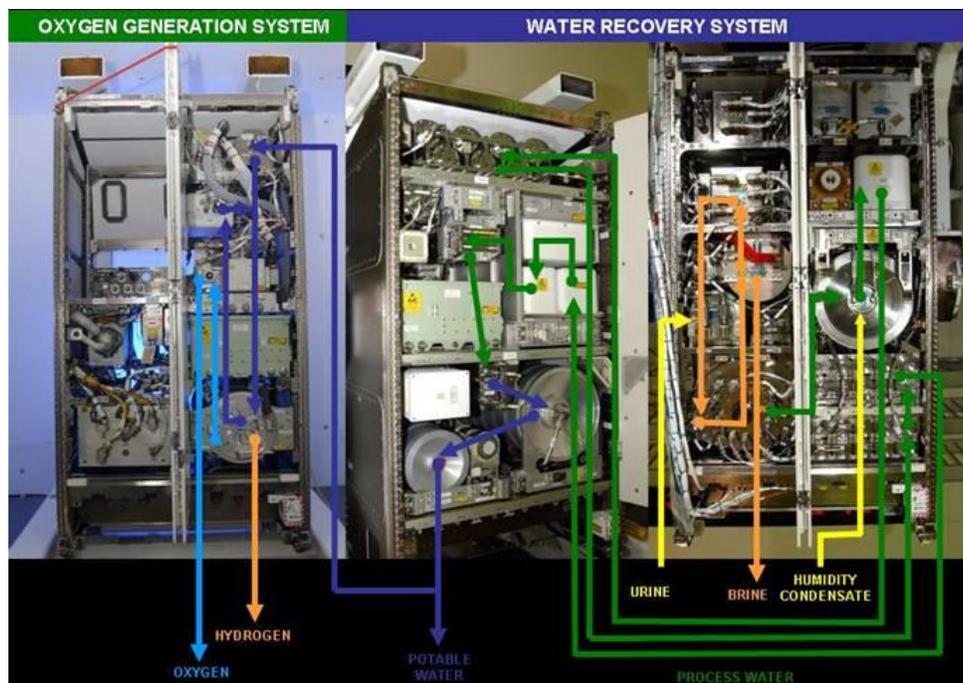


Figure 2. International Space Station Regenerative ECLSS Racks

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.

A. Water Processor Assembly Overview

A simplified schematic of the WPA is provided in Figure 3. The WPA is packaged into 16 Orbital Replacement Units (ORU), 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. 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. Once breakthrough of the first bed is detected, the second bed is relocated into the first bed position, and a new second bed is installed. The Sensor ORU located between the two MF beds determines when the first bed is saturated based on conductivity. 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. A regenerative heat exchanger recovers heat from the catalytic reactor effluent water 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 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 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.

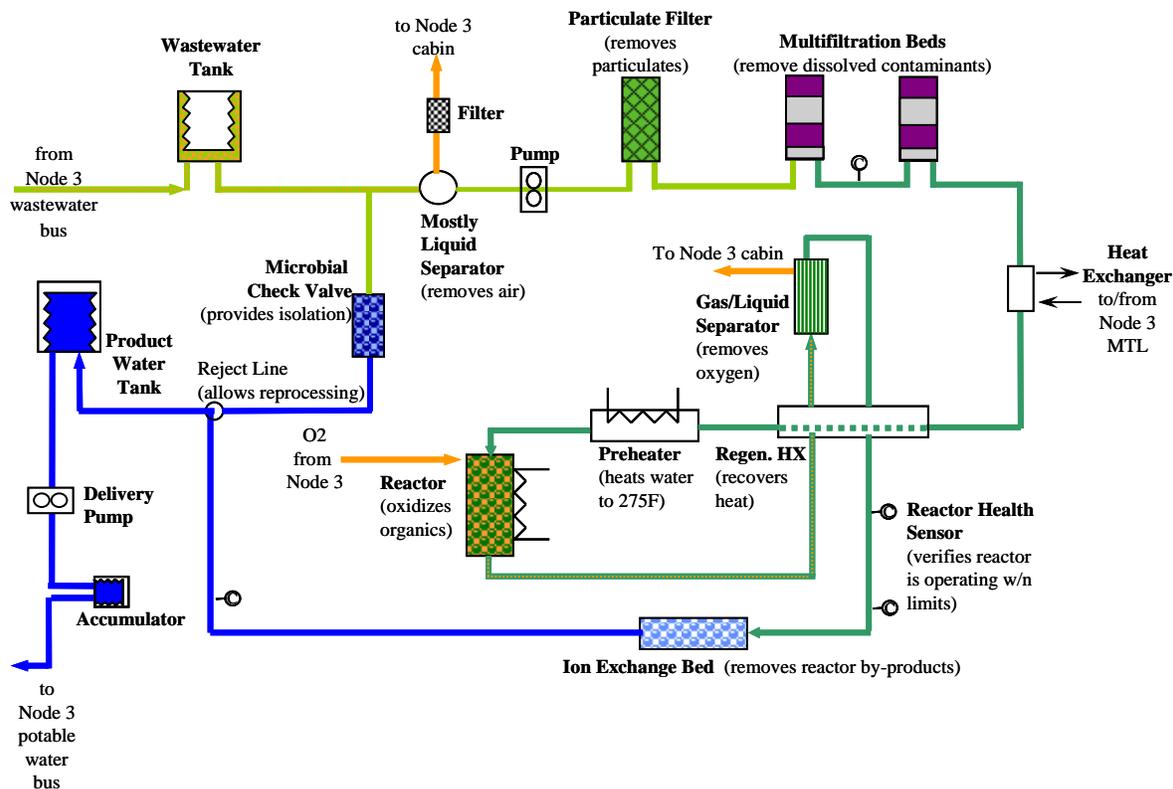


Figure 3. WPA Simplified Schematic

B. Urine Processor Assembly Overview

A simplified schematic of the UPA is shown in Figure 4. The UPA is packaged into 7 ORUs, which take up slightly more than half of the WRS Rack #2. Pretreated urine is delivered to the UPA either from the USOS Waste and Hygiene Compartment (outfitted with a Russian urinal) or via manual transfer from the Russian urine container (called an EDV). In either case, the composition of the pretreated urine is the same, including urine, flush water, and a pretreatment formula containing chromium trioxide and sulfuric acid to control microbial growth and the reaction of urea to ammonia. 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 is the heart of the UPA, and consists of a rotating centrifuge where the waste urine stream is evaporated at low pressure. The vapor is compressed and subsequently 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. The ARFTA has less capacity (approximately 22 L) than the RFTA (41 L), but the capability to fill and drain the ARFTA on ISS avoids the costly resupply penalty associated with launching each RFTA. When the brine is concentrated to the required limit, the ARFTA is emptied into an EDV, a Temporary Urine Brine Storage System (TUBSS), a Russian Rodnik tank on the Progress vehicle, or into the water tanks on the ATV vehicle. Upon next installation, it is refilled with pretreated urine, which allows the process to repeat. 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 water stream. A Firmware Controller Assembly (FCA) provides the command control, excitation, monitoring, and data downlink for UPA sensors and effectors.

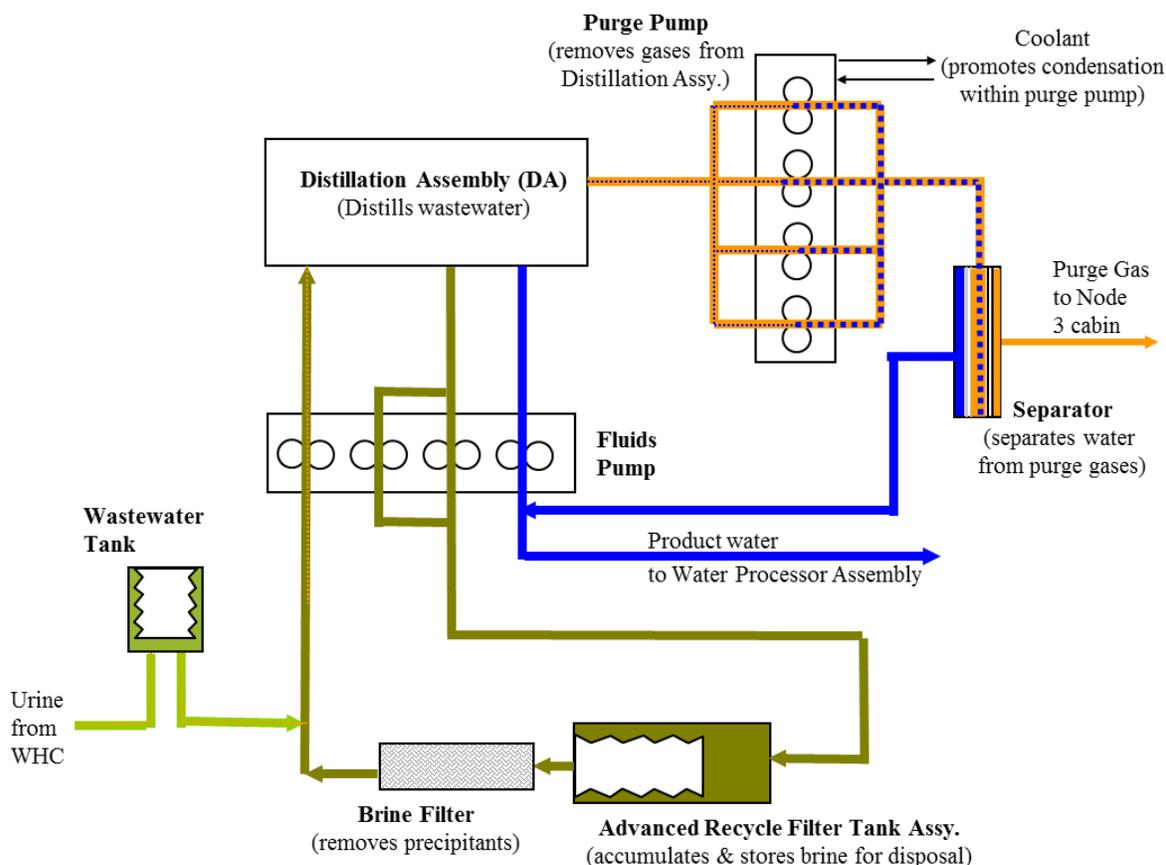


Figure 4. Urine Processor Assembly Schematic

The UPA was designed to process a nominal load of 9 kg/day (19.8 lbs/day) of wastewater consisting of urine and flush water. This is the expected quantity for a 6-crew load on ISS. Product water from the UPA has been evaluated on the ground to verify it meets the requirements for conductivity, pH, ammonia, particles, and total organic carbon. The UPA was designed to recover 85% of the water content from the pretreated urine, though issues with urine quality encountered in 2009 have required the recovery to be dropped to 75% for the US Segment and 70% for urine collected in the Russian Segment. These issues and the effort to return to 85% recovery are addressed in the discussion on UPA Status.

IV. Water Recovery and Management Status

In the last two years, 5833 L of potable water have been supplied to the US Segment potable bus. Management of the water mass balance has continued to be a challenge due to the need to maintain 697 L (updated from the previous requirement of 1002 L) of potable water on ISS for crew reserve while continuing to meet the various ISS needs for potable water. This effort is further complicated because of the importance of preventing the introduction of free gas into the potable bus, which limits the options for maintaining the mass balance.

As mentioned previously, the condensate tank is used as backup storage of condensate to the WPA waste tank. This can happen periodically when the WPA is off-line for maintenance or for contingency scenarios (such as power loss). If reconfiguration to the Lab Condensate Tank is required, the crew must manually connect the Condensate Tank to the waste water bus. Once the WPA Waste Tank is online again, the crew will disconnect the Condensate Tank from the waste water bus. Condensate collected in the Lab Condensate Tank must be subsequently offloaded into an empty container and stored. When needed, the stored water can then be pumped into the WPA waste tank or transferred to the Russian Segment for processing by the Russian Condensate Processor (referred to as the SRV-K). In an effort to minimize crew time associated with water management, an alternate transfer option was developed to pump the water from the Lab Condensate tank directly to WPA Waste Water tank. The direct pumping reduces the

overhead associated with storing the water. Finally, if there is no other option to process, store, or dispose of the waste water, the ISS has a water vent system that can expel the water to space (though venting is highly discouraged due to the loss of water consumables and use of propellant required to maneuver the ISS into an acceptable attitude).

Management of the water mass balance on ISS is achieved through various means depending on the specific scenario and availability of crew time. There are many variables that affect the quantity of water in the various WRS tanks, which requires ground personnel to actively manage the water balance in response to periods of water deficit and surplus. To minimize crew time associated with transferring water into or out of the WRS, the mass balance is managed to the extent possible with adjusting the segment in which condensate is collected. Condensate collection rates are primarily adjusted by increasing or decreasing the coolant temperature of the Condensing Heat Exchanger (CHX). This must be accomplished with consideration of which CHXs on ISS are collecting condensate. Typically only one CHX is operational at once, relying on intermodule ventilation to distribute the humidity throughout the US Segment. This operational approach is required to allow all CHXs to dry at least every 28 days to prevent biological growth on the wetted surfaces of each heat exchanger. Since each CHX collects condensate at different rates due to the humidity load in that area, the condensate collection rate can actually be managed by which CHX is operational at any given time.

To maintain an equal distribution of water on ISS between the US and Russian segments, water may be periodically transferred to the Russian Segment to compensate for excess condensate collected in the US Segment. Several options exist to compensate for unbalanced condensate collection. Each segment has limitations regarding the rate of condensate collection. If water transfer is desired, the preferred method is to transfer US condensate for processing by the Russian water system. Various other methods are available to help mitigate the effects of over collection on one segment or another. For example, if the US Segment is collecting excess condensate, the US Oxygen Generator can increase oxygen production. The extra oxygen production in the USOS could allow the Russian Segment to reduce its oxygen production rate, thus reducing the need for water in the Russian segment. The coordination and balance of condensate collection between the US and Russian systems is critical for managing common atmospheric constituents like water vapor and oxygen.

The mass balance has also been affected over the last year by the agreement between the US and Russian teams to process all urine generated on ISS, including Russian Segment (RS) urine. This decision was made to reduce the quantity of water that must be resupplied from the ground. This benefit outweighs the crew time impact associated with the transfer of RS urine to the US segment and the subsequent offload to the UPA waste tank. As a result the US segment is on average in a surplus mode.

Excess water in the system is typically offloaded from the WRS tanks into a Contingency Water Container (CWC). A CWC is very much like a large waterproof duffel bag. Excess water can also be offloaded from the WPA potable storage tank into a CWC-I, which is essentially a CWC compatible with the iodine that is used as a biocide in the US potable water. It is preferred to offload waste water into a CWC because it does not expire like the iodinated water in CWC-I. The disadvantage of storing waste water in CWCs is that the WPA must be available to process the water when the water is needed, whereas water from CWC-I may be used without additional processing. If problems occur with WPA's ability to process water, then clean iodinated water will need to be used from storage.

Though it is better to have a surplus, this excess water in the US Segment mass balance has created an issue. The US Segment currently has approximately 965 liters of stored potable water in CWC-Is on ISS. In the event of a failure to the ISS water system, 697 L must be maintained on ISS as reserve. Though this is a positive benefit in terms of supporting various failure scenarios on ISS, it creates stowage problems in the crowded US Segment. Furthermore, CWC-Is are currently only certified to contain potable water for 68 months. After 68 months, if the water has not been removed from the CWC-I, the bag is downgraded to waste water (condensate) grade. To extend the life of these CWC-Is, a shelf life test is being performed on the ground in parallel with ISS operations. During this test, samples are taken every 6 months to certify the CWC-I for a longer storage life. This has been an operational challenge over the last year as shelf life testing to extend the CWC-I certification was ongoing. Numerous CWC-Is would expire under their current certified life, only to be recertified as the shelf life testing results on the ground showed acceptable water quality. These bags became known as "zombie" bags as they would regularly expire, and then return to life based on the shelf life test results. The operations team had a challenge to use these zombie bags during the short window when they were recertified prior to reaching the next expiration date (which would then be extended yet again as testing continued).

Various solutions are currently being developed to address these issues. Two CWC-Is have been returned from ISS, and are being sampled periodically to extend the certified life of the CWC-Is on ISS. This process has extended the certified life to 68 months. The data from the 68 month shelf life test indicates that the CWC-I's may not pass the next test (74 months), at which point the shelf life testing will be complete. Also, hardware is currently being delivered that would allow potable CWC-Is to be emptied into the waste water bus without downgrading the CWC-Is. This is

accomplished by pumping the potable water through a Microbial Check Valve, which is filled with MCV resin and prevents any back flow of contamination from the waste bus to the potable CWC-I. Finally, engineering personnel are also evaluating the viability of adding additional water storage on ISS. This would be accomplished by launching a rack filled with multiple tanks that can be connected to the potable bus. Water could be automatically transferred to and from this water storage facility as needed for the water balance, thereby reducing crew time impacts for handling CWC-Is. In addition to assisting with management of the water reserve, the new rack will incorporate interchangeable launch tanks. The launch tanks will be launched full, installed into the water rack, and allow supplementing the water recovery system via commanding from the ground. The water recovery system reduces the amount of water resupply that is necessary, but the recovery system does not reclaim 100% of the water. CWC-Is are currently used to launch water, but transfer of water from the CWC-Is is crew time intensive. The new water rack will streamline the process of adding water to system and reduce overall crew time that is required.

Several options exist to address a mass deficit. Potable CWC-Is can be added to the WPA Storage Tank using the Microbial Removal Filter (MRF) and the tee hose. A detailed review of this process has been provided in a previous paper². CWC-Is may also be pumped into the WPA's waste tank, but this option results in the CWC-I becoming condensate grade hardware. Condensate grade hardware may not interface with any potable grade hardware. This may be acceptable for times when the ISS reserve quantities are healthy and WPA is operating nominally. The CWC-I's is often intentionally downgraded to condensate for ease and efficiency of water transfer. The CWC-I is then disposed of when empty. In addition to the old and expiring CWC-I, the CWC's containing waste water offloaded in response to a water excess can be pumped into the WRS waste tank. Finally, pretreated urine stored in EDVs may be transferred to the UPA Waste Tank to address a water deficit.

V. Urine Processor Assembly Current Status

The UPA was initially activated on November 20, 2008. In the last two years, the UPA has produced 2108 L (4648 lb) of distillate at 70 to 75% recovery, cycling through 61 ARFTA cycles during that time. As of April 30, 2015, the total UPA production on ISS is at 9100 L (20,050 lb) of distillate. A graphical summary of UPA production rate and upmass required for ISS operations is provided in Figure 5. In the past two years, 2 PCPAs, 4 FCPAs, 1 SPA, 1 DA, 6 brine filters and 1 purge gas filter have been replaced to maintain nominal UPA operations.

The UPA experienced two anomalies in the last year due to excess gas in the system. The first event was in early 2014, when the urine collected in the WHC was not adequately pretreated. This occurred because operating procedures for WHC allowed the crew to temporarily continue use of the WHC while performing steps to recover from the alarm stating the pretreatment is insufficient. This procedure was based on the understanding that there was enough residual pretreatment in the system to maintain microbial and chemical control for a short time, but a sustained period of off-nominal WHC performance in early 2014 resulted in off-nominal UPA performance that was ultimately traced to inadequate pretreatment. Insufficient pretreatment allows the pH to rise in the urine while also providing insufficient oxidizer for microbial control. As a result, excess gas is released during UPA processing due to microbial activity. The WHC was recovered by flushing it with WPA product water that contained elevated levels of pretreatment to shock the system. The UPA was recovered by processing urine collected in the Russian Segment ACY that had been adequately pretreated and then transferred to the US Segment in EDVs. EDVs can be offloaded to the UPA Waste Tank by using the Russian compressor to push the fluid from the EDV into a T-valve located between WHC and UPA in Node 3. By processing good quality pretreated urine, the UPA eventually returned to nominal operations. After this point, based on the existing deficit in the ISS water balance, the UPA continued to nominally process urine collected in the Russian Segment.

The second anomaly with free gas was in April 2015, when an EDV filled in the WHC was emptied into the UPA Waste Tank. After the crew stopped the transfer by closing the T-valve and stopping the compressor, the UPA waste tank quantity continue to increase. Further investigation determined this EDV had been used previously in the WHC in early 2014 when the pretreatment dosing was inadequate. Though it had been drained, it is now believed there was residual microbial activity that impacted its subsequent use. Analysis of the transfer and subsequent UPA operation indicates approximately 25% of the volume transferred from the EDV was actually free gas. This ingested gas impacts the UPA distillation process, resulting in elevated pressure in the DA. This DA had been operational in the UPA for 5 years and was already showing signs of imminent failure due to gear wear (expected end of life failure condition). The DA was replaced in May 2015 when system performance continued to degrade. Though system performance did improve at this point, the vacuum hose between the DA and the purge pump also required replacement due to a restriction detected by the pressure sensors in this line. Since this plumbing has no active microbial control, it is believed that the restriction was likely due to the accumulation of biomass coupled with condensation that may have been caused by the excess free gas still being processed by the system.

The UPA experienced multiple failures of the FCPA in the last several years due to various mechanical issues. S/N 002 failed in September 2011 due to insufficient lubrication of the pump motor bearing at the vendor. This issue was resolved by adding an inspection step at the vendor to insure adequate lubrication. S/N 001R (reflight of S/N 001) failed one year later due to a misalignment of the motor adaptor to the motor shaft on the harmonic drive. This assembly issue was addressed by modifying the procedure and including inspection steps to insure the shaft was properly aligned. S/N 003 failed in March 2013 after six months of operation due to misalignment of the harmonic drive and a discrepant snap ring groove, which was also identified as a manufacturing issue for two other FCPAs and four PCPAs. The snap ring groove was improperly machined by the vendor due to a misinterpretation of the drawing, and has been resolved for future ORUs. Unfortunately, this error potentially impacted multiple ORUs before it was detected and resolved. FCPA S/N 004 and 005 both failed early in their operation (5 months for S/N 004 and 10 months for S/N 005), both of which could have been due to either harmonic drive misalignment or the discrepant snap ring groove. The failure investigation of each of these ORUs is currently underway. Next, S/N 006 failed after 7 months in February 2015 due to a leak of pretreated urine, most likely through a pressure switch in the brine recycle loop. This ORU has not been returned for evaluation yet, but the UPA engineering team has already decided to eliminate the pressure switch from the UPA design to eliminate this potential failure mode. Finally, S/N 001R (2nd reflight) seized after only 41 minutes of operation. This ORU has also not been returned for a failure investigation, but it is known that the ORU could have a faulty snap ring groove.

This spate of failures to a single ORU has led NASA personnel to question the overall reliability of the FCPA pump for ISS and future manned missions. NASA is currently developing an upgrade to the drive shaft design that would replace the harmonic drive with a planetary gear. Though the harmonic drive is considered very reliable once properly installed, there are multiple opportunities for failure during the assembly and installation process. In contrast, the planetary gear design supports a robust installation process and is expected to produce a marked increase in on-orbit reliability of the FCPA.

As reported previously^{3,4}, Distillation Assembly (DA) S/N 02 failed on October 24, 2009 due to accumulation of solids in the Distillation Assembly. The root cause of the anomaly was due to the precipitation of calcium sulfate in the urine brine at the target recovery of 85%. Calcium is present in the urine primarily due to bone loss from the crew, whereas sulfate is present primarily due to the use of sulfuric acid in the urine pretreatment. Calcium levels on ISS are elevated compared to ground urine due to the absence of gravity. During ground testing, the UPA was proven to have no issues with recovering 85% of the water from pretreated urine. However, at 85% recovery on ISS, the higher concentration of calcium resulted in calcium sulfate exceeding its solubility limit. The initial response to this failure was to reduce the recovery to 70%. In parallel, ISS crew members have been instructed to drink more water primarily to improve overall health, but also to reduce the calcium concentration in the raw urine. Based on approximately two years of data, analysis of crew urine has determined that the average calcium concentration has dropped to a level that will support 75% recovery by the UPA.

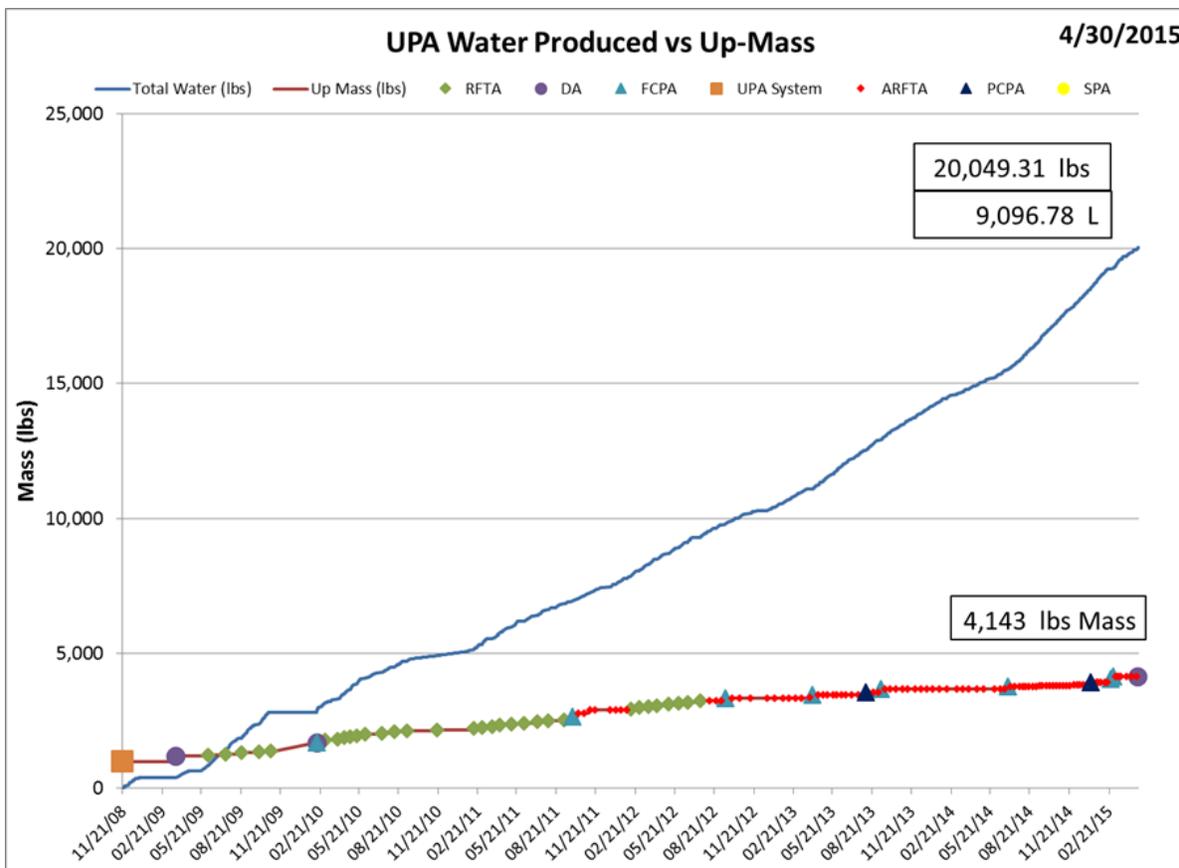


Figure 5. UPA Production and Upmass on ISS

In parallel with this modification to on-orbit operations, NASA personnel have continued with the effort to return UPA to 85% recovery. NASA personnel have completed development and testing on the modification to replace sulfuric acid in the urine pretreatment with phosphoric acid⁵. Testing has verified the modified pretreatment formula will support water recovery above 85%, with the exact % recovery to be defined by tests to be performed in the summer of 2015. Microbial tests have also been completed to verify the modified pretreatment provides the same level of microbial control as the baseline pretreatment. Materials compatibility tests have been tested in Russian for the ACY hardware and in the US for the UPA and ancillary equipment that supports WHC/UPA operations. The final step in this process is implementation on ISS, which requires launching pretreat tanks filled with the modified pretreat and delivering a modified conductivity sensor for verifying each pretreatment dose is adequate. The modified conductivity sensor is currently in assembly, and is scheduled to be delivered to ISS with the new pretreat tanks in time to support the transition to the modified pretreatment in late 2015. In addition, to support ISS water balance needs and increase water recovery from urine collected in the Russian Segment, NASA is currently negotiating with the Russian Space Agency to also implement the modified pretreatment in the RS ACY. This pretreated urine would continue to be processed through the UPA until installation of a new Urine Processor (delivered by NIICHIMMASH) in the Russian Segment.

A significant operational change for the UPA in 2012 was the integration of the Advanced RFTA (ARFTA). This hardware replaces the RFTA with a bellows assembly that can be drained and emptied on ISS^{2,3}. Though ARFTA operation requires more crew time to fill and drain each tank, it provides a significant savings in launch mass (avoiding approximately 200 kg annually for launching RFTAs). The UPA was configured for ARFTA in June 2012. There have been no operational issues with the ARFTA since that time. However, the crew time for ARFTA operation is significant. To address that issue, a final modification to the UPA/ARFTA concept has been built by Boeing. This modification will allow the crew to fill and drain the ARFTA without removing the tank from the rack. This modification is desirable because approximately 45 minutes of crew time is required to removal/install the ARFTA following each concentration cycle. Therefore, this modification would save approximately 12 hours of crew time each year, which is desirable due to the limited crew time available for maintenance tasks on ISS. This hardware primarily consists of a valve manifold that can be manually configured by the crew for nominal UPA operation, and

for draining and filling the ARFTA. Since this ARFTA valve includes a crew interface on the panel, NASA/Boeing took advantage of the opportunity to replace both WRS panels. The new panels implement features to reduce acoustic emissions, since the UPA is a major contributor to the Node 3 acoustics. The new panels also implement improved door latches that will make it easier for the crew to access WRS2. This new hardware is scheduled to be available on ISS in late 2015.

VI. Water Processor Assembly Current Status

The WPA was initially activated on November 22, 2008. As of April 21, 2015, the WPA has produced approximately 22,386 kg (49,353 lb) of product water, including 4,494 kg (9,907 lb) in 2014 and 1,327 kg (2,925 lb) so far in 2015.

Engineering personnel completed the investigation of the WPA process pump failure from October 2012. After 970 operational days on ISS, the process pump failed to operate when powered at the beginning of a process cycle. This pump is designed to operate for two years on ISS, but the failure on ISS is not consistent with the expected wear-out of the pump at end of life. The root cause for this failure was determined to be wear of the key that maintains the gear position on the idler shaft. Prior to this failure but subsequent to delivery of the pump that failed in 2012, the key material was switched from 316L stainless steel to stellite, which is a harder material. It is possible this material change will prevent subsequent failures, though a modification to the key design would ensure this anomaly did not recur.

The impact of DMSD on the WPA treatment process has been discussed previously¹⁻⁴. The TOC trend detected by the TOC Analyzer (TOCA) on ISS has occurred in 2010, 2012, 2013, and 2014 (see Figure 6). The WPA product water has exhibited nominal TOC levels in the past year, though another trend is expected later in 2015 based on the current understanding of how DMSD passes through the WPA. A detailed review of the fate of DMSD in the WPA is documented elsewhere⁷.

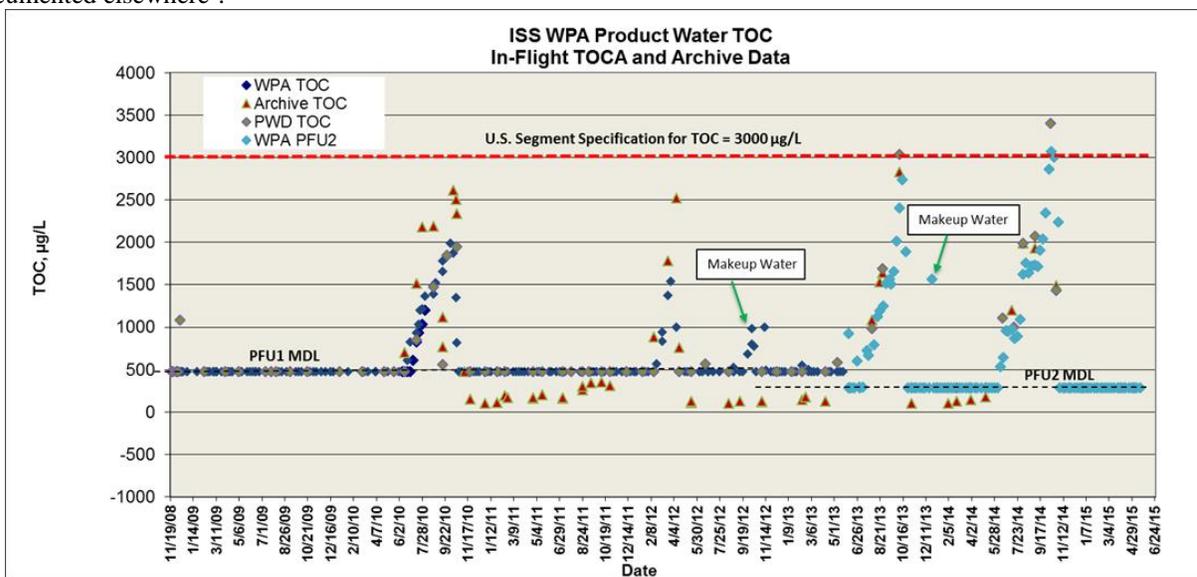


Figure 6. ISS WPA Product Water TOC⁶

DMSD is a common by-product of the degradation of polydimethylsiloxane (PDMS) compounds (also referred to as siloxanes), which are common compounds present in various products, including caulks, adhesives, lubricants, and hygiene products. Various PDMS compounds are prevalent on ISS, and analysis of condensate samples from ISS show that DMSD has been present in the WPA waste water since WPA operations began on ISS. In addition, approximately 40 mg/L of DMSD has been detected in samples of the MF Bed effluent taken immediately before the beds were replaced in 2010 and 2012. Following replacement of the MF Beds, samples of the effluent show DMSD is not present above the detection limit of 0.4 mg/L. These results indicate the MF Beds are initially removing the DMSD, but eventually the DMSD saturates the adsorbent and ion exchange resin in each bed. Figure 7 provides the correlation between MF Bed throughput and the product water TOC trend. The DMSD is then fed to the downstream reactor at a concentration of approximately 40 mg/L. Ground tests with a development reactor indicate the reactor will oxidize DMSD to a concentration of approximately 10 mg/L in the reactor effluent. If this ground test accurately represents reactor performance on ISS, the DMSD in the reactor effluent is being initially removed by the Ion Exchange Bed, given the fact that DMSD has a slight ionic charge. Eventually, the Ion Exchange Bed is saturated

with the DMSD, which results in a breakthrough curve consistent with the TOC trend observed from the ISS TOC Analyzer.

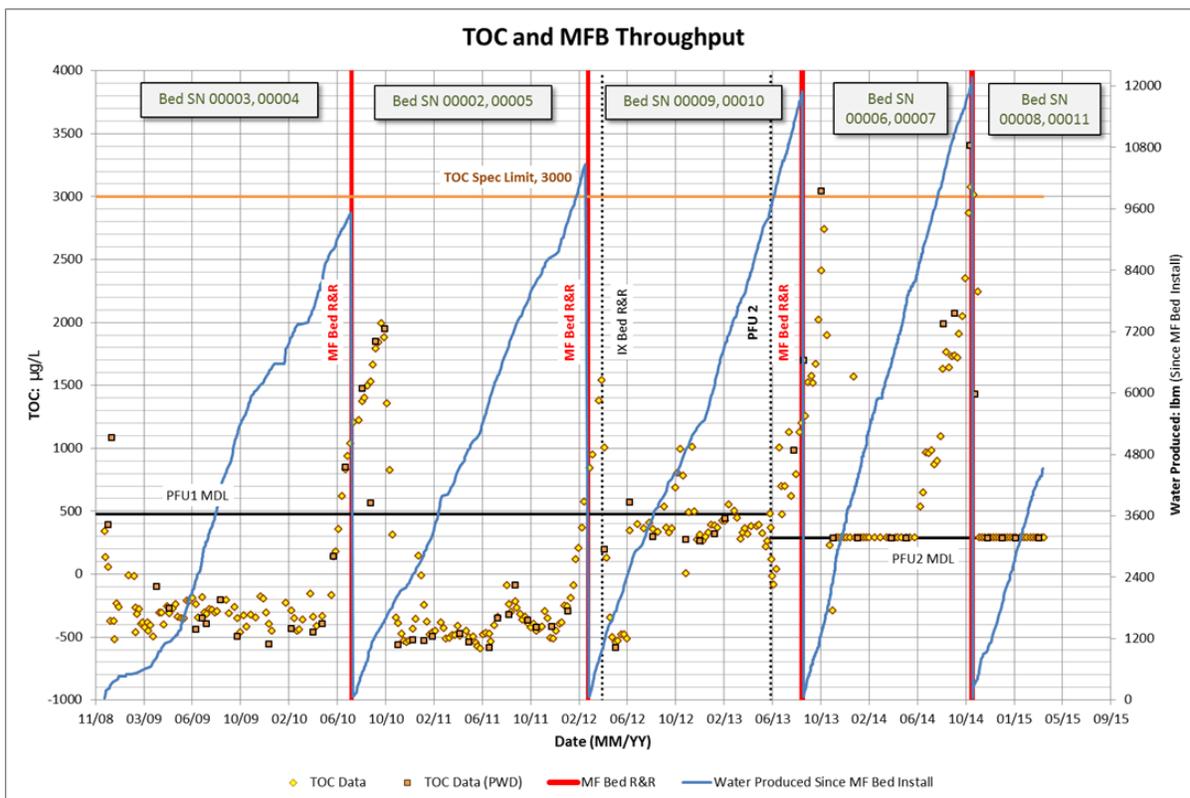


Figure 7. Correlation Between Product Water TOC and MF Bed Throughput

To prevent DMSD from impacting potable water quality, engineering personnel are developing a method to reduce DMSD concentrations to manageable concentrations in the condensate by removing the siloxanes in the atmosphere. This removal step would occur prior to each Condensing Heat Exchanger in the US Laboratory Module, Node 2, and Node 3. A detailed description of the effort to remove the atmospheric siloxanes can be found elsewhere⁸.

Previous papers²⁻⁴ have addressed the issue with increased pressure drop between the waste tank and the Mostly Liquid Separator (MLS). This anomaly occurred due to growth of biomass in the plumbing between the waste tank and the MLS, specifically in the two solenoid valves that have smaller clearances than the rest of the nominal plumbing. In 2010, a filter was installed upstream of the MLS's inlet solenoid valve to prevent the valve clearances from the biomass. In March 2011, the Waste Tank solenoid valve was replaced with a flow-through plug, and the waste water filter was replaced with a fresh filter. Since its installation, the waste water filter has been replaced a total of 3 times. WPA tank management has also been implemented since 2011 to insure the bellows is cycled over its nominal range each month. This prevents significant accumulation of biomass growth on the bellows. In addition to the tank management scheme, a software modification was implemented in April 2013 to flush the waste water filter and MLS inlet with iodinated water at the end of each process cycle. This action provides additional mitigation against biological growth by removing nutrients for biological growth and introducing a biocide to retard further growth.

The Microbial Check Valve ORU was replaced in November 2012 as scheduled maintenance. This 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, the installed ORU has not performed to expectations on ISS. Analysis of the data by engineering personnel determined that the mechanical check valve was 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. Operations personnel were able to periodically induce the check valve to function by cycling the valves to introduce a pressure drop across the MCV's check valve. However, after approximately 6 months of operation, this method was no longer successful. To insure waste water does not reach the potable lines, a WPA Reprocess mode is initiated every 24 hours to flush the reprocess

line with potable water. Future MCV ORUs may function as intended since the check valve design was slightly modified when a new vendor was used to delivery this component. However, the low pressure drop in this application may prevent a check valve from reliably functioning in this location.

The Gas Separator is showing indications of performance degradation after 5.5 years of use. The Gas Separator's ability to maintain temperatures during initial flow started to degrade in early 2014, but the hardware continues to separate the gas from the 2-phase mixture. The time limit for the temperatures to recover at the start of flow was increased and the Gas Separator has continued to operate with the degraded performance.

The Particulate Filter was replaced in July 2013 due to increased pressure drop between the process pump and the Multifiltration Beds. Subsequent data indicated that installation of a new Particulate Filter was only partially successful in reducing the pressure drop in this region. The other item downstream of the process pump was a check valve, which was installed prior to initial operation of the WPA in 2008 to prevent overpressurization of the Mostly Liquid Separator due to specific failure conditions that would remove power to the WPA. The software revision implemented in April 2013 addressed these failure conditions, allowing the check valve to be removed in January 2014. Subsequent operation of the WPA showed this activity reduced the pressure drop in this region of the WPA to less than 7 kPa (1 psig).

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. The o-ring material was replaced with a similar material that did not experience the same magnitude of swell when exposed to water at the elevated temperature and pressure. Unfortunately, the first Catalytic Reactor to undergo this redesign also developed a leak on ISS in March 2014 after less than two years of operation on ISS. The failed Catalytic Reactor was returned to the ground to evaluate the seal life and refurbishment. The seals that were maintained at the elevated temperature had no life remaining. These seals all had significant leaks at ambient temperature. One of the seals exposed to elevated temperatures only during process cycles (~20% of operating life) also leaked. During standby, this seal was in a region of the Catalytic Reactor that would cool down to approximately 93 C (200 F). However, the seals that were typically maintained at a reduced temperature during Standby were physically in better condition than those maintained at the elevated temperature continuously. Figure 8 provides a visual comparison of a continuously hot seal (seal on left) compared to a seal that was at the elevated temperature only 20% of the operating life. This failure investigation helped substantiate the assumed 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 93 C (200 F) instead of continuously maintaining it at the nominal temperature of 131 C (267 F). Starting in June of 2014, the Standby temperature for the reactor was incrementally reduced by 2.8 to 8.3 C (5 to 15 F) every few weeks (to allow analysis of the temperature change on thermal transients during mode transitions). By February of 2015, the Standby temperature had been reduced to 96 C (205 F). As of May 2015, the current Catalytic Reactor has been installed for 1 year and 2 months, and engineering personnel will continue to monitor its performance to determine if the reduction in Standby temperature will result in increased seal life.

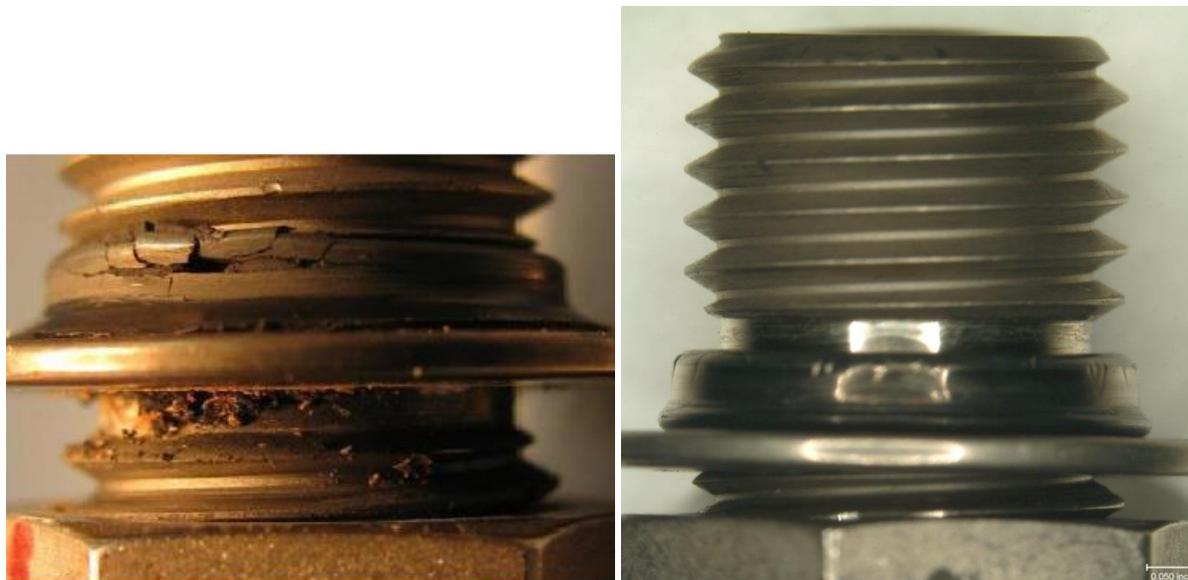


Figure 8. Catalytic Reactor Seals

In March 2015 the Reactor Health Sensor conductivity began an increasing trend that eventually exceeded the setpoint of 50 $\mu\text{mhos/cm}$, resulting in an extended reprocess cycle to recover the WPA ability to deliver potable water. Potential causes include an increase in the concentration of volatile organics in the humidity condensate, DMSD breakthrough of the MF Beds, degraded performance of the Catalytic Reactor, degradation of the Gas Separator, or possibly a combination of these factors. This issue was complicated by the fact that the conductivity continued to increase to approximately 100 $\mu\text{mhos/cm}$ during the extended reprocess cycle, during which the water was recycled through the system multiple times before the RHS conductivity finally began decreasing. It is unclear why this would occur, though possibly a volatile organic was introduced at a significant concentration or the reprocess cycle introduced a pH shift in the reactor effluent. After the RHS conductivity was recovered in reprocess, the system was first fed only urine distillate, followed by condensate collected before the conductivity excursion. In both cases, the RHS conductivity remained nominal ($<10 \mu\text{mhos/cm}$). Next, fresh condensate was fed to the WPA, after which the RHS conductivity rapidly increased. During this trend, the WPA flow rate was reduced from $\sim 5.7 \text{ kg/hr}$ (12.5 lb/hr) to $\sim 5 \text{ kg/hr}$ (11 lb/hr) to increase the residence time in the reactor for the oxidation process. The conductivity peaked shortly thereafter and gradually decreased to nominal levels, though it cannot be concluded this was due to the change in flow rate or some other unknown effect. Figure 9 shows the RHS trend since the extended reprocess cycle.

As stated previously, it is possible this trend is due to the increased concentration of volatile organics in the humidity condensate. The Air Quality Monitor (AQM) has indicated an increase in the ethanol concentration on ISS since March 2014 from less than 5 mg/m^3 to approximately 6 to 10 mg/m^3 . Figure 10 provide the AQM results for ethanol since January 2014. This increase is expected to be due to an unknown source of ethanol on ISS. Shortly after the RHS conductivity excursion in March 2015, the ethanol concentration reported by AQM increased to approximately 13 mg/m^3 , though this value is expected to be approximately 30% low because it is above the calibrated range of the AQM for ethanol. Also, several organics were observed at higher than normal levels in the November 2014 sample of the humidity condensate, primarily including ethanol but also methanol and 1-propanol. In early May, the ethanol concentration reported by AQM decreased back to approximately 8 to 10 mg/m^3 for reasons unknown to ground personnel. Though the ethanol increase observed in March 2015 occurred after the RHS conductivity increase, the ethanol decrease in early May occurred approximately at the same time as the RHS conductivity trended down. This correlation and the elevated ethanol levels will continue to be monitored by ground personnel and addressed as required to maintain WPA operation.

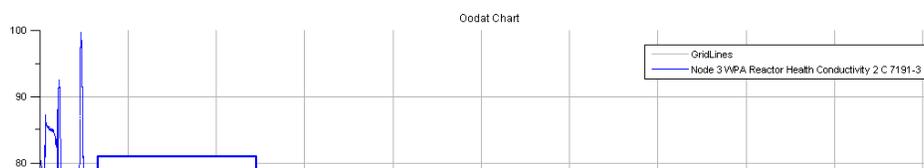


Figure 9. RHS Conductivity Trend

VII. Conclusion

In the past two years, 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. The UPA has operated at a reduced water recovery of 75% to prevent precipitation of calcium sulfate in the brine. Though progress has been made toward the goal of returning to 85% recovery, ongoing technology development will not be ready for implementation on ISS until late 2015. Furthermore, the current water balance on ISS does not require 85% recovery to meet current ISS needs, due to the continuing availability of the WRS, recovery of water from the RS urine, and the resupply capability of the Progress, HTV, and Commercial vehicles.

The UPA has experienced numerous FCPA failures in the last two years due to various reasons. The root cause for the drive shaft failures has been addressed with modifications to vendor inspection processes and the assembly process of the pump at MSFC. The leak in FCPA S/N 006 will likely be addressed by deleting this instrumentation in future ORUs. Though this ORU has presented significant logistics challenges toward maintaining UPA operation, the Distillation Assembly and SPA recently replaced operated well beyond their expected service life. Similarly, the Waste Tank and ARFTA (both bellows tanks) have operated without any performance issues, indicating this hardware is also viable for long term missions.

In the past two years, the WPA has experienced pressure drop issues leading to the replacement of the Particulate Filter and removal of the MLS check valve. A recurrence of the Catalytic Reactor seal leak has occurred, and ground personnel are currently monitoring anomalous Reactor Health Sensor conductivity and a degraded Gas Separator. Finally, efforts are ongoing to develop a design solution that will prevent DMSD from impacting the nominal MF Bed replacement schedule.

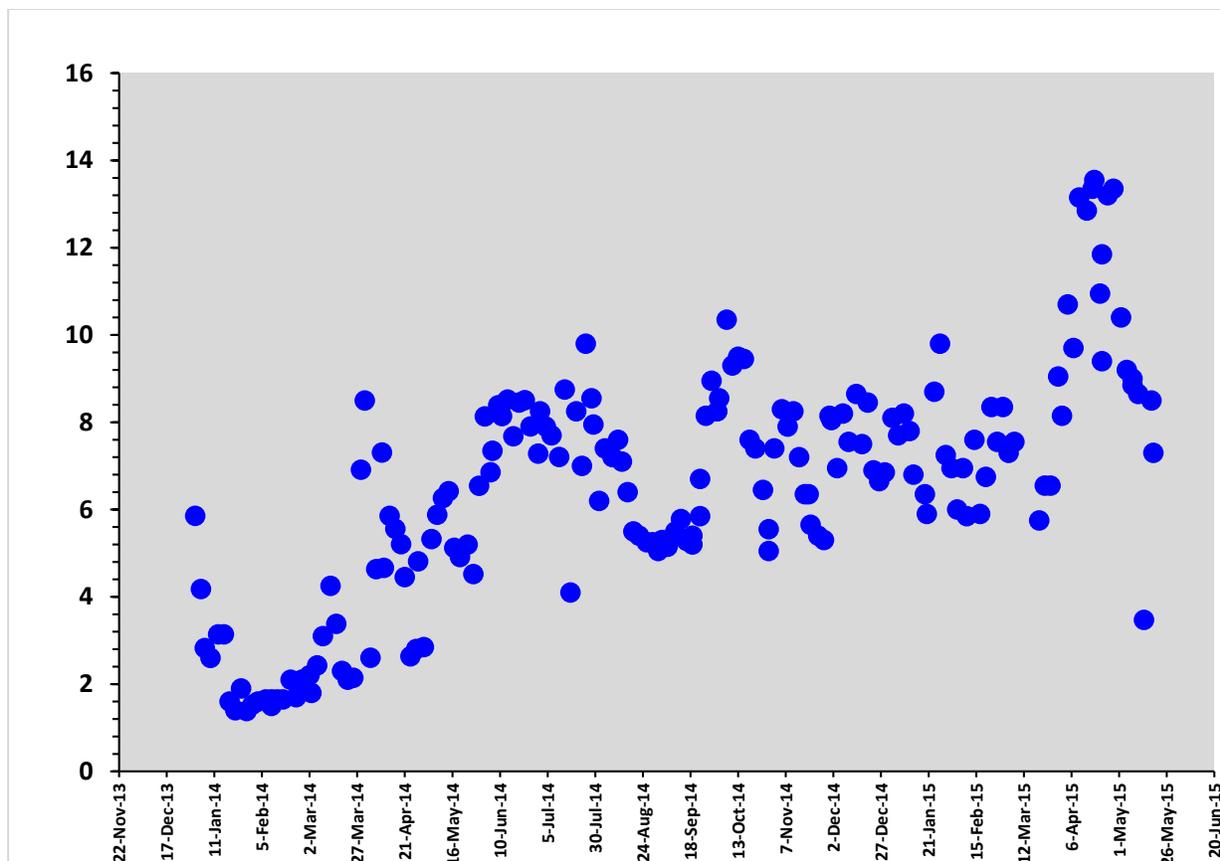


Figure 10. AQM Ethanol Trend⁹

Acknowledgments

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