Status of ISS Water Management and Recovery

Layne Carter[1] and Jennifer Pruitt[2]
NASA Marshall Space Flight Center, Huntsville, AL 35812

Christopher A. Brown[3]
Lockheed Martin Corporation, Houston, TX 77058

Jesse Bazley[4]
SGT, Inc. Houston, TX 77058

Daniel Gazda[5]
NASA Johnson Space Center, Houston TX 77058

Ryan Schaezler[6] and Lyndsey Bankers[7]
The Boeing Company, Houston, TX 77058

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 2016 and describes the technical challenges encountered and lessons learned over the past year.

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

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

[1] ISS Water Subsystem Manager, NASA MSFC ES62.
[2] ISS Urine Processor Design Lead, NASA MSFC ES62.
[3] ISS ETHOS, Lockheed Martin Corporation, Water Operations Lead for the Flight Operations Directorate.
[4] ISS ETHOS, SGT, Inc., Flight Operations Directorate
[5] Technical Monitor, Environmental Chemistry Laboratories
[6] ISS Water Recovery and Management Team Lead, The Boeing Company.
[7] ISS Waste & Hygiene Compartment Lead, The Boeing Company.

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.

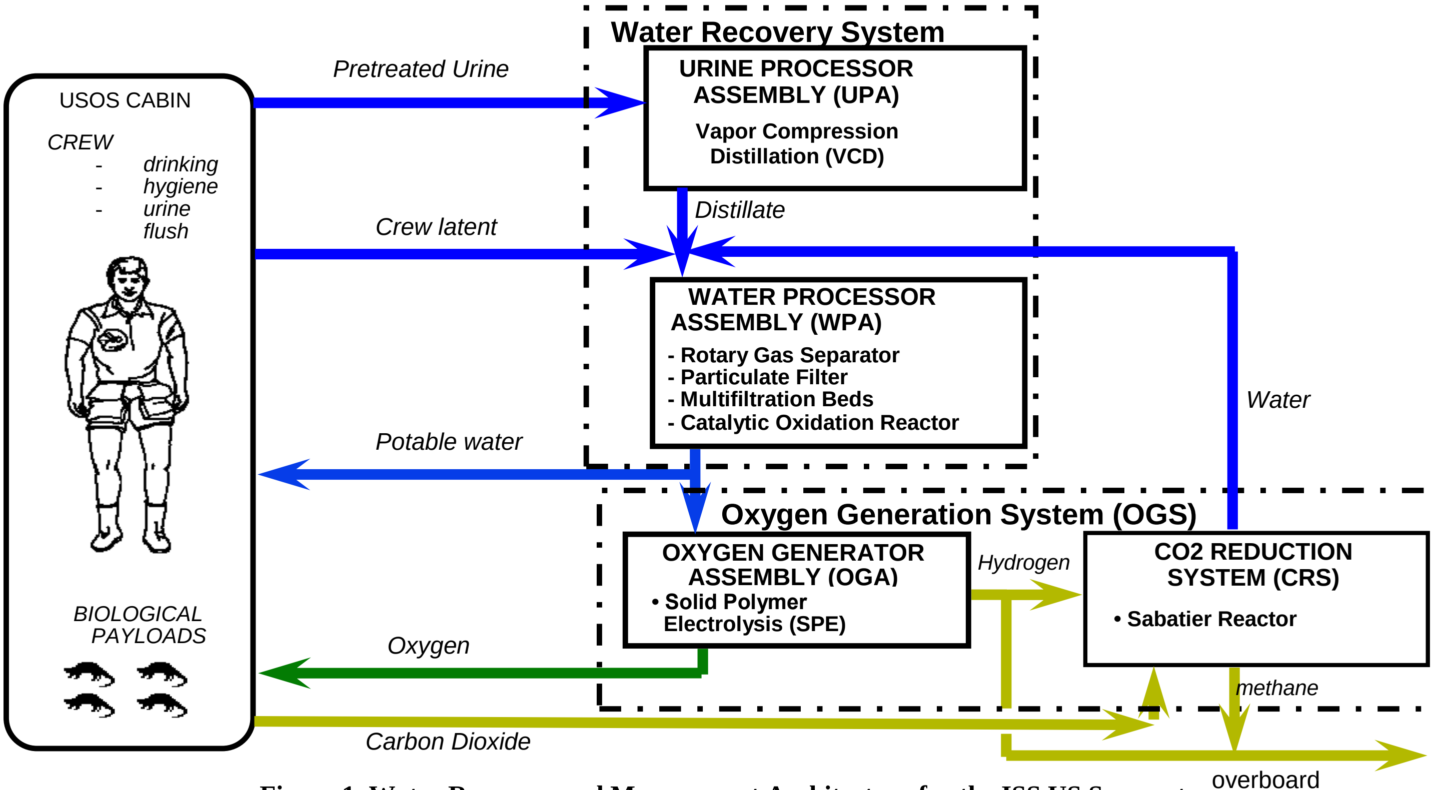

Figure 1. Water Recovery and Management Architecture for the ISS US Segment

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. In addition, pretreated urine is collected in Russian urine containers (called EDVs) 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 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.

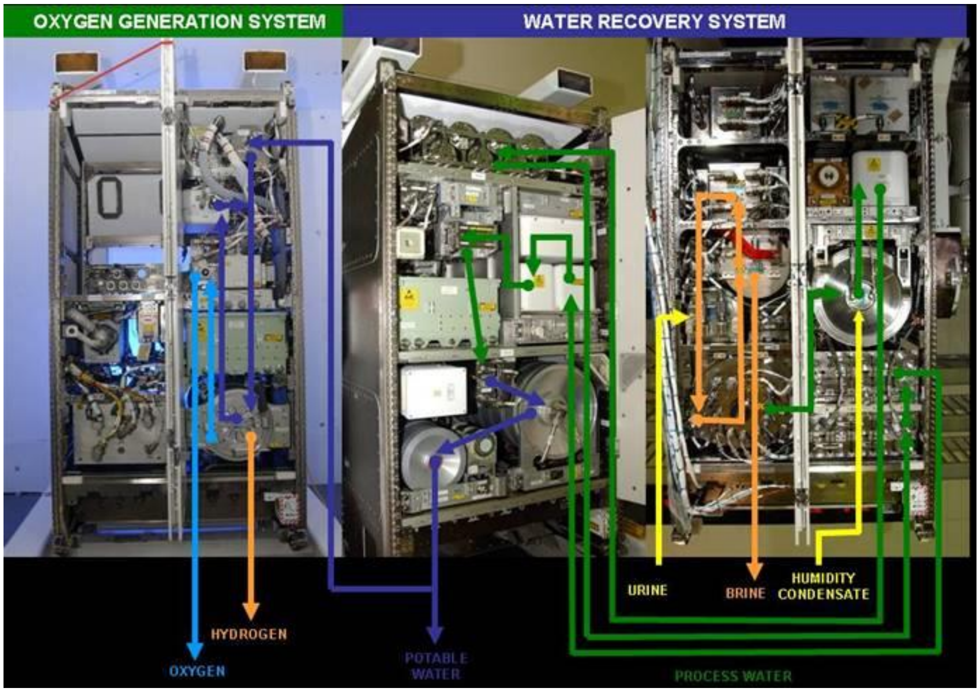

Figure 2. International Space Station Regenerative ECLSS Racks

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 (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 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.

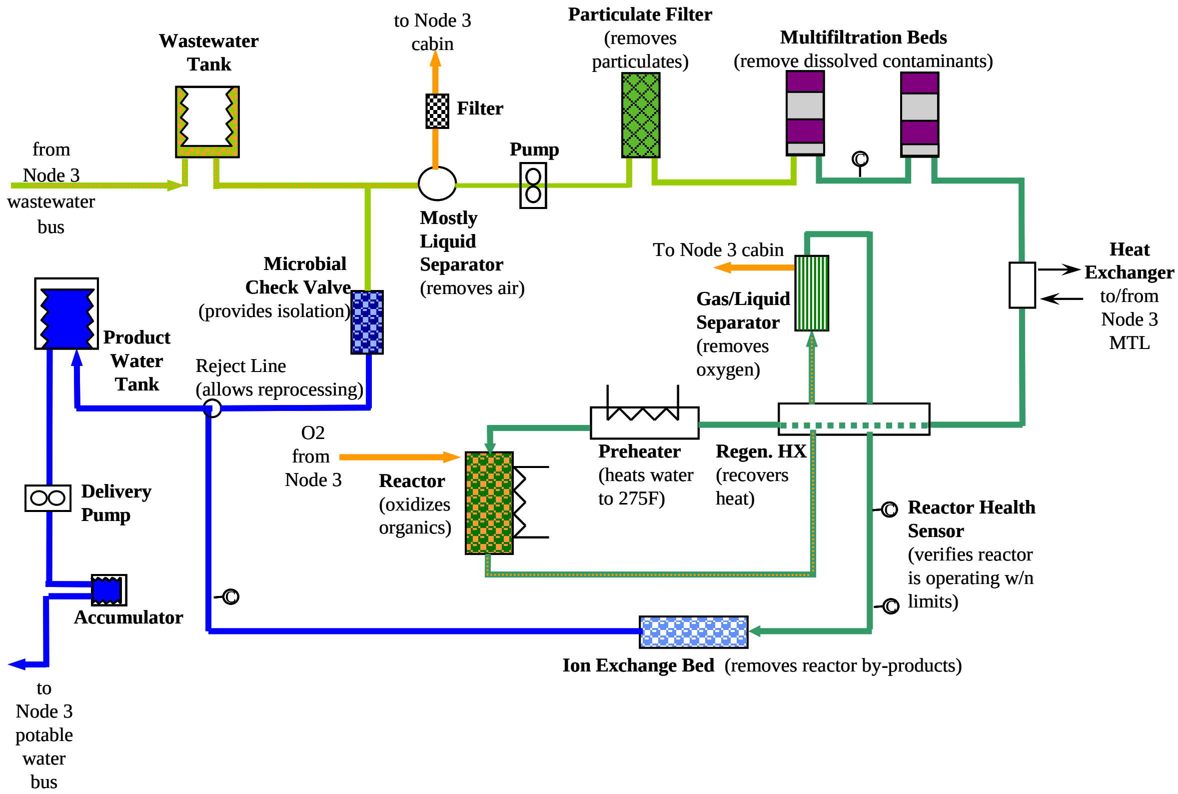

Figure 3. WPA Simplified Schematic

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) Waste and Hygiene Compartment (outfitted with a Russian urinal) or via manual transfer from the Russian EDV. In either case, the composition of the pretreated urine is the same; crew urine, flush water, and a pretreatment formula containing chromium trioxide and an inorganic 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 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 EDV or a Temporary Urine Brine Storage System (TUBSS). These containers are then emptied into the Russian Rodnik tank on the Progress vehicle for disposal. Upon the 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.

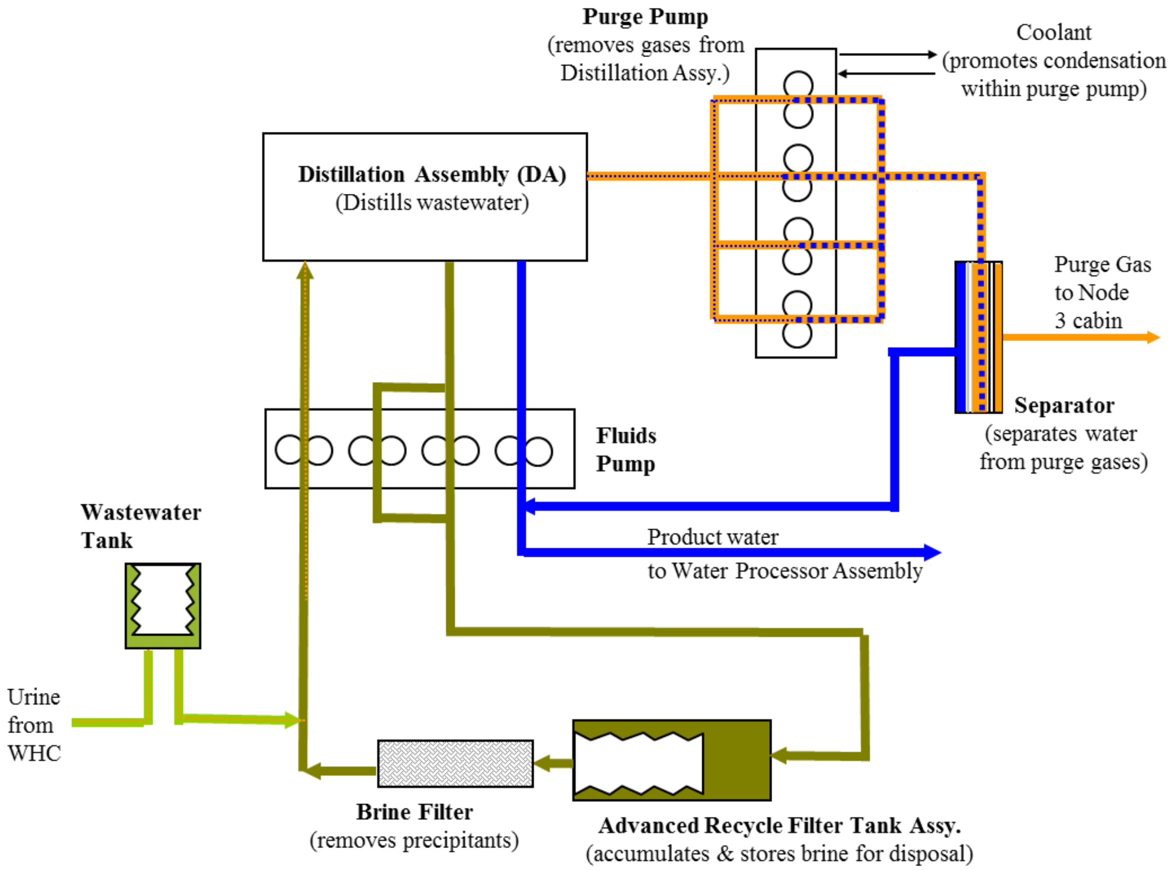

Figure 4. Urine Processor Assembly Schematic

The UPA was designed to process a nominal load of 9 kg/day (19.8 lb/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 year, 3734 L (8232 lbs) 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 of potable water on ISS for crew reserve while continuing to meet the various ISS needs for potable water. In late 2014, efforts were initiated 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. Any surplus waste / distillate was 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) were too full to continue normal operation.

As mentioned previously, the condensate tank is used as backup storage of condensate to the WPA waste tank. The need to use a back-up tank 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 to allow continued condensate collection. 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 removed from the tank. Previously, the tank was drained into a storage bag to be used at a later date. When needed, the stored water would 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 transfer operations, an alternate transfer option was used for the first time in 2016 to pump the water from the Lab Condensate tank directly to WPA Waste Water tank. The direct pumping reduced the overhead associated with storing the water and is now the preferred method to empty the back-up Lab Condensate tank. 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 for venting).

Management of the water mass balance on ISS is achieved through various means depending on the specific scenario that led to the imbalance and availability of crew time. There are many variables that affect the quantity of water in the various WRS tanks, requiring ground personnel to actively manage the water balance between the various tanks in response to periods of water deficit and surplus. To reduce the use of crew time to manage the systems, the ground teams can adjust several variables that can alter the amount of water collected by the WRS racks. Those variables include: Condensing Heat Exchanger (CHX) temperatures, the module where condensate is collected, Oxygen production, or the timing of scheduled activities that use water. Condensate collection rates are primarily adjusted by increasing or decreasing the coolant temperature of the CHX. This must be accomplished with consideration of which CHXs on ISS are collecting condensate. Typically only one CHX is operational at any given time, relying on intermodule ventilation to distribute the humidity throughout the US Segment. The location of the operational CHX is managed (again by coolant adjustments) to allow all CHXs to dry at least every 28 days to limit 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 and the temperature of the coolant going through the CHX, it is sometimes possible to manage condensate collection rates simply by controlling which CHX is operational at any given time. In addition, the schedule of activities that affect water use can be adjusted to occur at times when the system can support additional changes in water rates. For example, scheduled use of water can be moved to align with times when additional water is available. The goal of the ground teams is to ensure that minimal crew time is used to manage mass balance between tanks.

The US Segment and Russian Segment collect water at different rates. 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. If water transfer to the Russian segment is desired, the preferred method is to transfer US waste water (urine distillate and humidity 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.

Surplus water in the system is typically offloaded from the WRS Condensate and Waste Water tanks into a Contingency Water Container (CWC). A CWC is collapsible container similar to a large waterproof duffel bag. Excess water can also be offloaded from the WPA potable storage tank into an ICWC (Iodine Compatible Water Container), which is essentially a CWC compatible with the iodine biocide in the US potable water. Additionally, if the quality of the water in the WPA potable storage tank meets the stringent water quality required for Extravehicular Mobility Unit (EMU) suit use, a Payload Water Reservoir (PWR) or ICWC can be filled for future suit cooling loop maintenance and resupply. It is preferred to offload waste water into a CWC because it does not expire like the iodinated water in ICWC. 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 ICWC 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.

The US Segment currently has approximately 1,350 liters of stored potable water in ICWCs on ISS. In the event of a failure to the ISS water system, a minimum of 697 L must be maintained on ISS as reserve. Though this extra water is a positive benefit in terms of supporting various failure scenarios on ISS, it creates stowage problems in the crowded US Segment. Stowage space is limited on ISS and the ICWC have complex stowage requirements to protect them from incurring damage. Furthermore, ICWCs have a limited shelf-life which requires careful management of the order in which the bags are used to ensure that the water is used prior to expiration. After 74 months, if the water has not been removed from the ICWC, the bag is downgraded to waste water (condensate) grade. The previously described ground test to extend the life of water stored in ICWC was terminated in 2015 because the storage life has been extended well beyond the operational need to store water in reserves, and because alternate means for utilizing the water after expiration have been provided.

Hardware has been delivered to ISS that allows potable ICWCs to be emptied into the waste water bus without downgrading the ICWC. This is accomplished by pumping the potable water through a Microbial Check Valve (MCV), which is filled with ion exchange resin that releases iodine. The MCV is coupled with a mechanical check valve to prevent any back flow of contamination from the waste bus to the potable ICWC and transfer equipment. This hardware may be used to empty an ICWC that contains expired water and then allow the ICWC to be refilled with fresh iodinated water.

Several options currently exist to address a mass deficit. Potable ICWCs 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 paper[3]. ICWCs may also be pumped into the WPA's waste tank using the MCV as described above. This may be acceptable for times when the ISS reserve quantities are healthy and WPA is operating nominally. The ICWCs may be intentionally downgraded to condensate for ease and efficiency of water transfer. The ICWC is then disposed of when empty or saved for later condensate stowage if needed. In addition to the old and expiring ICWC, 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. Limiting use of potable water is not a practical method of managing a deficit. The two primary users (crew consumption and oxygen production) have continuous needs. Occasionally, ground teams may adjust oxygen production for short periods of time or re-schedule WHC flush tank fills, but these actions are only done as temporary measures until other methods can be used to restore balance.

Finally, NASA has approved development of a Water Storage System (WSS) that will add additional water storage and resupply capability to ISS. Increasing potable water capacity will be accomplished 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 75 L resupply tanks. The resupply tanks will be launched full, installed into the water 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 EDV 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 ISS Water recovery systems. For example, instead of spending ~1 hour to add ~20L of water, that same time can be used to pre-stage ~300 L of water. When the pre-staged resupply tanks are emptied, they can be changed out when new tanks arrive on ISS. The empty resupply tanks may provide additional disposal options for US generated brine. Work is ongoing to certify the resupply tanks to store UPA generated brine so that they may be used in place of EDV for disposal of brine. When the planned Russian urine processor arrives, the water surplus created by the US Segment's processing of Russian urine will cease to exist. The increased efficiency of the WSS will become an important factor for reducing crew time managing water transfers in the USOS.

V. Urine Processor Assembly Current Status

The UPA was initially activated on November 20, 2008. In the last year the UPA has produced 2270 L (5010 lb) of distillate at 70 to 75% recovery, cycling through 40 ARFTA cycles during that time. As of April 2, 2016, the total UPA production on ISS is at 11214 L (24,715 lb) of distillate. A graphical summary of UPA production rate and upmass required for ISS operations is provided in Figure 5. In the past year, 1 FCPAs, 1 SPA, 1 DA, and 3 brine filters have been replaced to maintain nominal UPA operations.

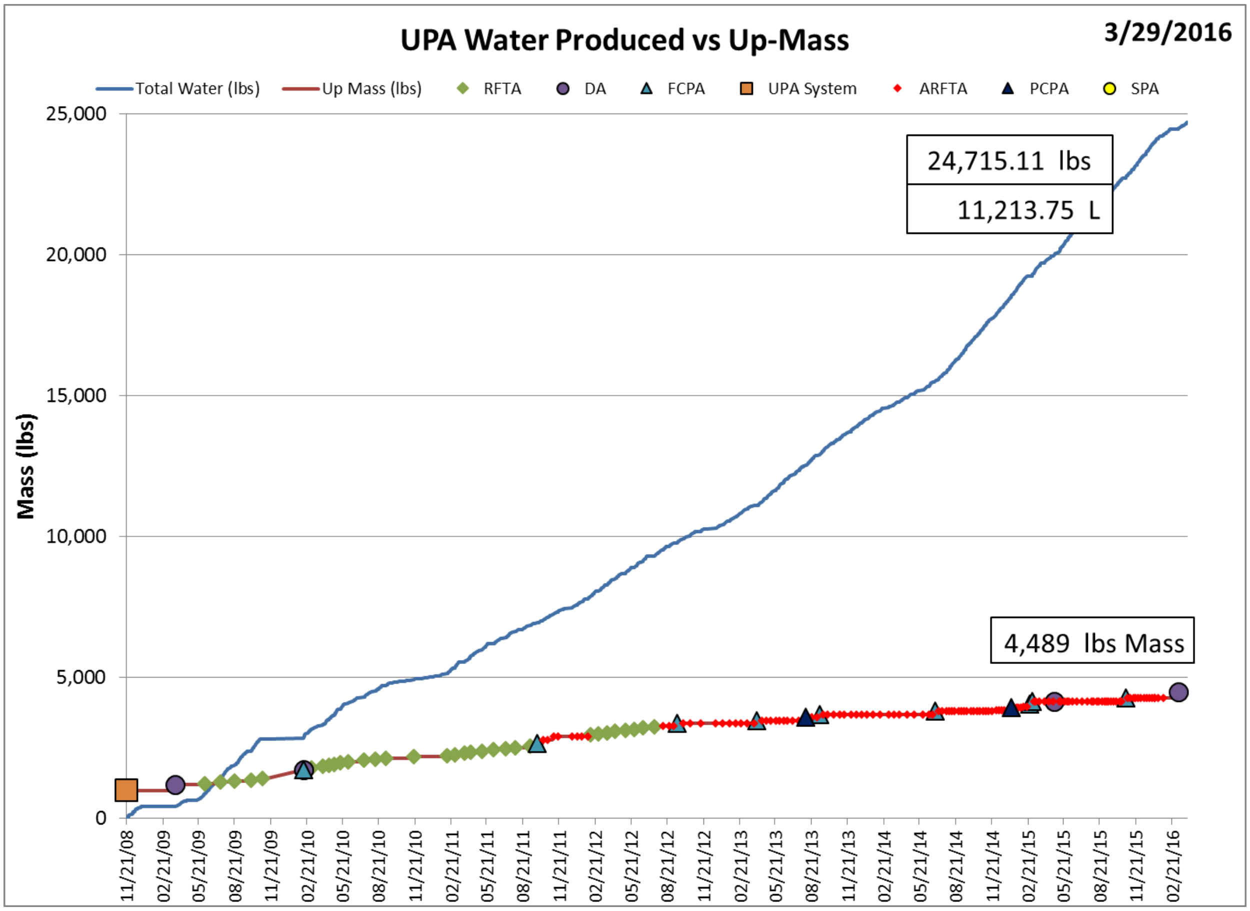

Figure 5. UPA Production and Upmass on ISS

The UPA has exhibited off-nominal performance since March 2015 due to excess gas in the system. This is primarily observed with elevated vacuum pressure in the DA, as shown with P16 (Figure 6). Trend analysis indicates this off-nominal performance began in March 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 fluid transferred from the EDV was actually free gas. This ingested gas impacts the UPA distillation process, resulting in elevated pressure in the DA. This unit 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 on April 28 2015, though system performance did not recover at this point. In August 2015, the UPA vacuum pressure between the DA and the PCPA indicated the rack resident hose connecting these ORUs was obstructed (presumably with distillate). This hose was replaced to reestablish a clear path, but again the overall system pressure did not recover.

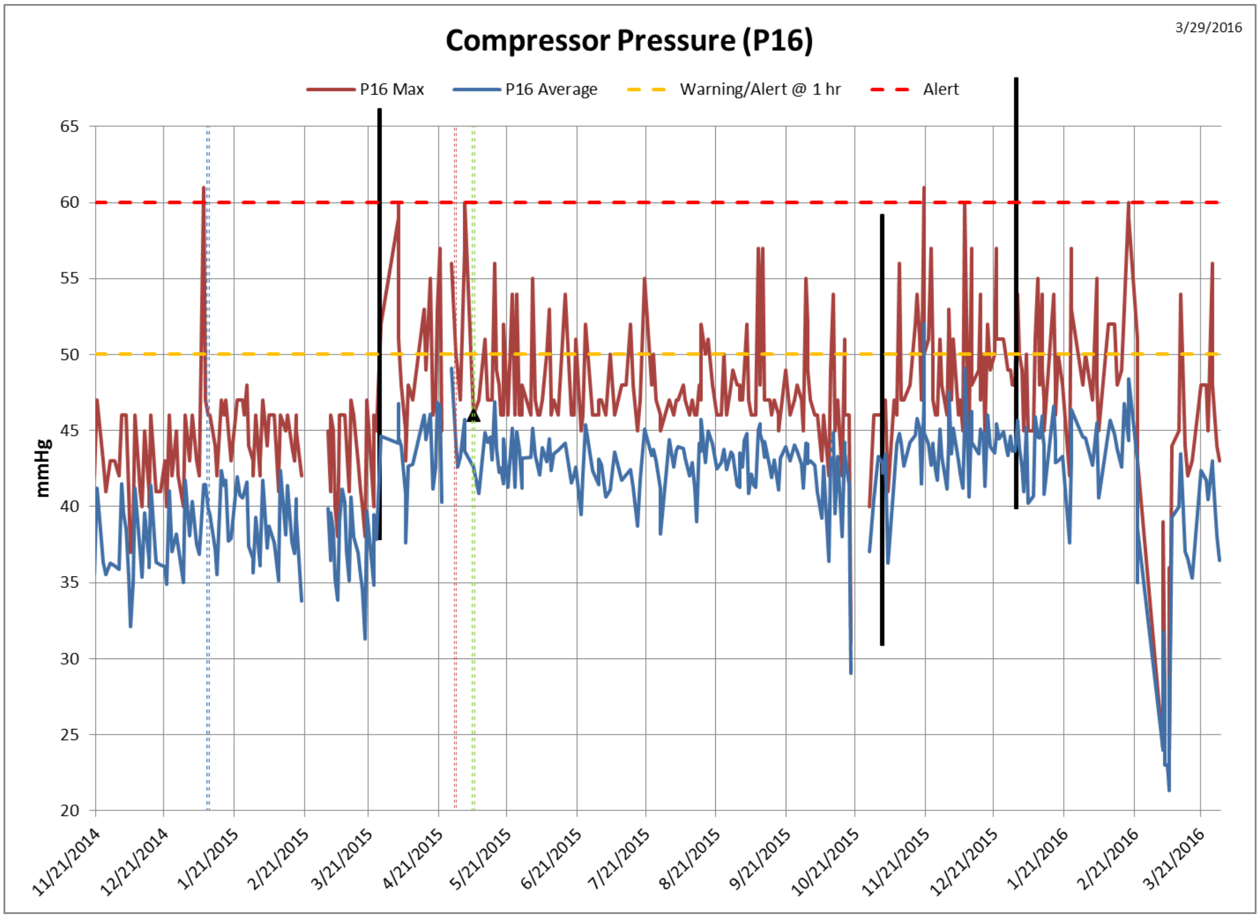

Figure 6. Distillation Assembly Compressor Pressure (P16)

In parallel with the UPA performance issues, two RS EDVs leaked while being offloaded to the UPA waste tank per the standard procedure. The first event was in November 2015, and the second occurred in January 2016. Due to concerns with the procedure for offloading the EDV, the Russian teams stopped transferring RS EDVs until a review of the process could be completed. As a result of this review, additional caution statements were made to the crew to reduce pressure applied to the EDV during the transfer. Also, the Russian compressor used in the US Segment was tested to verify its functionality. In summary, the US and Russian personnel agreed that the procedure and hardware was acceptable for further transfers. However, while this procedure was being reviewed, the UPA experienced a series of failures related to elevated P16 (DA vacuum pressure), including slippage of the belt that drives the DA centrifuge. A thorough review of the data determined that free gas from the SPA was being transferred to the DA during reprocess and dry-down modes (beginning and end of each process cycle), contributing to the elevated P16 (DA vacuum pressure). Elevated pressure in the DA will drive water vapor out of the centrifuge into the stationary bowl, resulting in the formation of condensate in the bowl. This is a known effect, and is managed with heaters surrounding the bowl to evaporate the condensate and drive the water vapor back into the condenser. It is likely this condensate was getting onto the centrifuge's drive belt, causing it to slip. The SPA was replaced on March 3, 2016, but repeated attempts to operation the DA were unsuccessful due to continued belt slippage. The DA was therefore also replaced on March 8, 2016, after which nominal UPA operations were established.

The UPA has experienced multiple failures of the FCPA in previous years due to various mechanical issues[1]. This spate of failures to a single ORU led NASA personnel to question the overall reliability of the FCPA pump for ISS and future manned missions. NASA MSFC developed an upgrade to the drive shaft design that replaced the harmonic drive with a planetary gear. Though the harmonic drive is considered appropriate for precision applications, tolerances in the DA 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 DA. This modification is expected to produce a marked increase in on-orbit reliability of the FCPA.

As reported previously[4,5], 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. As a result, calcium sulfate precipitated on ISS at 85% water recovery. This issue has been addressed since 2009 by reducing the water recovery to levels that prevent calcium sulfate from exceeding its solubility limit in the brine. This was initially at 70% recovery, but has been at 75% recovery since 2014 based on crew urine data showing reduced calcium concentration associated with increased water consumption. Subsequent data analysis has shown 75% water recovery actually exceeds the calcium sulfate solubility for the 95% confidence internal on the mean calcium concentration in crew urine. However, ISS program management have required this elevated % recovery to maximize water recovery and reduce crew time associated with changing out the brine tank at the completion of each concentration cycle. Analysis of UPA performance since 2012 indicates the calcium sulfate is primarily (if not completely) precipitating in the brine filter, which is the 10 micron filter located immediately downstream of the ARFTA brine tank. These filters typically load in approximately 3 months of operation on ISS, and ground analysis shows the loading is almost entirely due to calcium sulfate.

In parallel with this modification to on-orbit operations, NASA personnel have completed the effort to return UPA to 85% recovery. This was accomplished by replacing sulfuric acid in the urine pretreatment with phosphoric acid[6]. Testing has verified the modified pretreatment formula will support water recovery of 90% without exceeding the solubility limit for calcium sulfate in representative crew urine. Microbial tests have also been completed to verify the modified pretreatment provides the same level of microbial control as the baseline formulation. Materials compatibility tests have been tested in Russia 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 currently being implemented on ISS, including the launch of pretreat tanks filled with the modified pretreat and the delivery of a modified conductivity sensor for verifying each pretreatment dose is adequate. Since phosphoric acid has a lower ionic strength, the set point for the conductivity sensor had to be reduced for the alternate pretreatment. This hardware was delivered to ISS in December 2015and installed in the US Waste & Hygiene Compartment (WHC) in May 2016. In addition, to allow continued processing of pretreated urine collected from the Russian Segment (using the baseline pretreatment), ground tests were also performed to show that the phosphate-based pretreatment could be mixed with the sulfate-based pretreatment. This allows the UPA to continue to recover 70% of the RS pretreated urine, providing a significant cost savings for water resupply.

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 allows 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 remove/install the ARFTA following each concentration cycle. Therefore, this modification saves 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 WRS#2. This new hardware was installed in January 2016, and has performed nominally.

VI. Water Processor Assembly Current Status

The WPA was initially activated on November 22, 2008. As of March 27, 2016, the WPA has produced approximately 26,090 kg (57,519 lb) of product water, including 3,734 kg (8,232 lb) 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 DMSD through the WPA. The WPA Catalytic Reactor was replaced in February 2016 due to leaking seals, and two Multifiltration Beds were replaced in late 2015 due to DMSD breakthrough. The following discussion address these two issues and the ongoing efforts to mitigate their impact.

The impact of DMSD on the WPA treatment process has been discussed previously[8]. There have been 5 instances of increasing TOC in the WPA product water due to DMSD. Each TOC trend was initially detected by the TOC Analyzer (TOCA) on ISS, and a summary of the data is provided below in Figure 7.

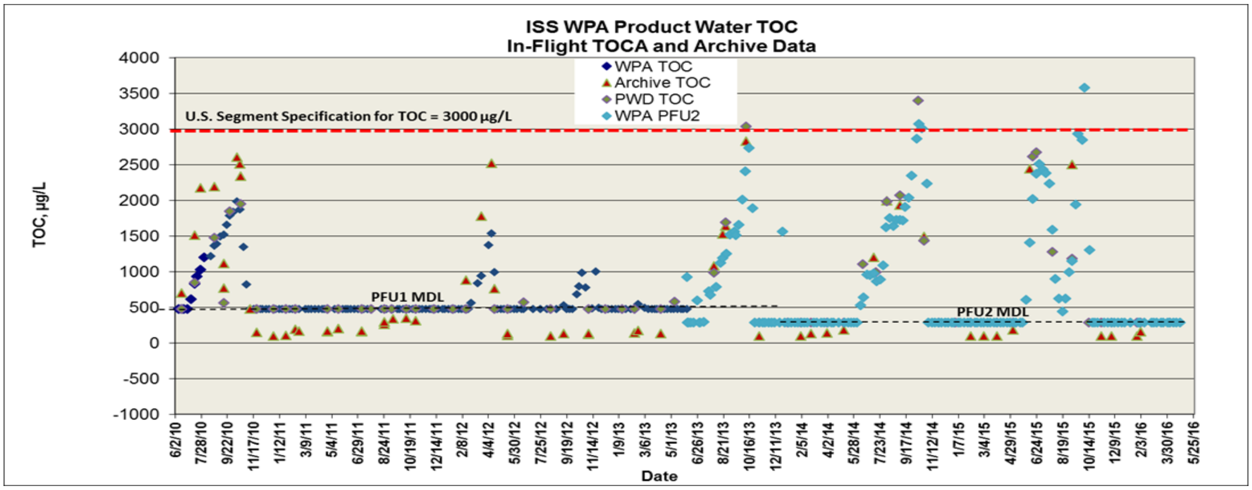

Figure 7. ISS WPA Product Water TOC[7]

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 ubiquitous on ISS, and analysis of condensate samples from ISS shows 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 8 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.

The normal approach to recover from a TOC increase involves replacing both MF beds. When the 5th TOC increase started in June 2015, no spare MF beds were available on ISS. This situation was exacerbated by the fact that the Reactor Health Sensor was showing elevated conductivity in the reactor effluent. It is believed that the elevated conductivity resulted from the combination of DMSD in the MF bed effluent and high ethanol in the condensate. The high ethanol levels in the condensate were caused by an increase in ethanol in the ISS atmosphere. More discussion on the ethanol trend can be found elsewhere[9]. WPA operations were modified during this time to increase the reprocess time at the end of each process cycle and the WPA feed was limited to urine distillate in an effort to slow the TOC increase. These efforts were initially successful, so much so that the TOC trend actually reversed for a short time. This recovery was short lived, however, as the increasing trend returned and the slope of the trend increased once condensate processing resumed. Interestingly, DMSD was not the primary compound responsible for the most recent TOC increase. Analysis of archive sample collected during the increase showed that either monomethylsilanetriol (MMST) or the sodium salt of MMST accounted for the majority of the TOC. MMST is structurally similar to DMSD and may be a partial oxidation product of DMSD that was produced during the extended reprocess cycles. The off-nominal trend of the RHS conductivity was recovered once new MF beds and a new IX bed were installed in the WPA.

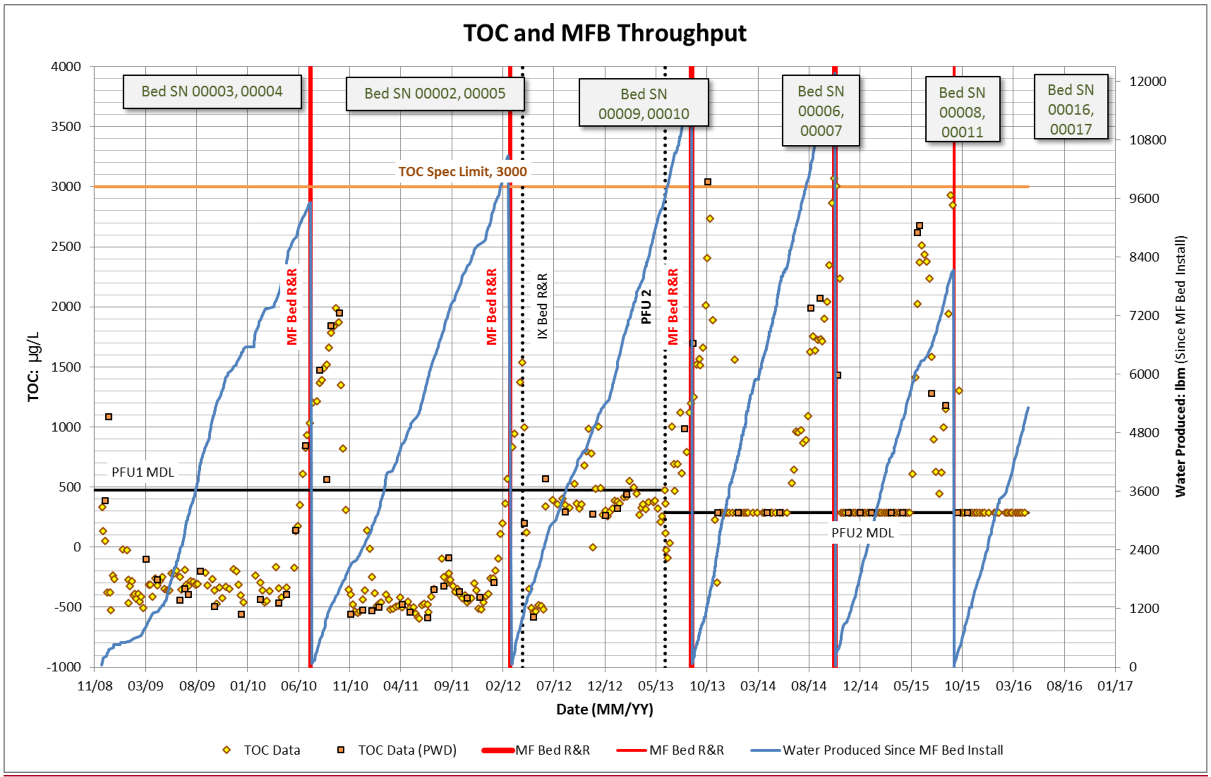

Figure 8. Correlation between Product Water TOC and MF Bed Throughput

To prevent DMSD from impacting potable water quality, engineering personnel have developed 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. 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 were effective at reducing the overall siloxanes in the atmosphere, but samples of condensate showed that the DMSD levels remained at nominal levels. A detailed description of the effort to remove the atmospheric siloxanes can be found elsewhere[10].

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 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. 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. In October 2015, this MCV was replaced. Unfortunately, the new MCV ORU failed on startup due to no flow. This failure is now under investigation. The previous ORU was reinstalled in the WPA. Surprisingly, at this time, the mechanical check valve in this ORU is actually functioning as intended. However, the pressure drop across the MCV has increased significantly. Though the upstream pressure has increased, there is still margin for WPA to continue to operate until a spare MCV is delivered later in 2016.

As noted previously[3], the Catalytic Reactor was redesigned in 2010-2011to 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. Attempts to modify the seal design and material have been unsuccessful in extending the life of this ORU. A design analysis to replace the non-metallic o-rings with metal seals was completed, but the cost to perform this redesign was considered too excessive given the expected additional life that would be achieved.

Previous inspection of ORUs returned to the ground showed the seals that were typically maintained at a reduced temperature during Standby were in better physical condition that those maintained at the elevated temperature continuously. Figure 9 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). However, this catalytic reactor began exhibiting signs of leaking in October 2015 and was replaced in February 2016 after almost two years in service. The failure signature manifested itself differently than previous events. The reactor exhibited erratic temperatures initially during a process cycle and would occasionally see a sudden drop in temperature. This signature continued to degrade over several months. In contrast, the previous reactor failures were sudden and the reactor could not recover after the initial fault. In this case, the WPA faulted due to the reactor leak for the first time in late November, but was able to operate until early February. The signature may be the result of the lower Standby temperature and how the leak manifests. Though the reduced Standby temperature did not appear to extend the life of this ORU, there were two instances in which the WPA was maintained in Reprocess mode (in which the reactor is maintained at 267 F) for an extended period of time that might have measurably reduced seal life. In addition, this Catalytic Reactor was in place when the MCV failed after installation in October 2015. The MCV failure cause a temperature spike in the Catalytic Reactor which may have impacted seal life. It was shortly after this event that the leak in the reactor was initially observed. Therefore, the reactor temperature will continue to be maintained at 205 F during standby in anticipation of extending the life of the reactor seals. Furthermore, this reactor will be evaluated after it is returned to the ground to fully understand the source and extent of the leak and how this may impact ongoing WPA operations.

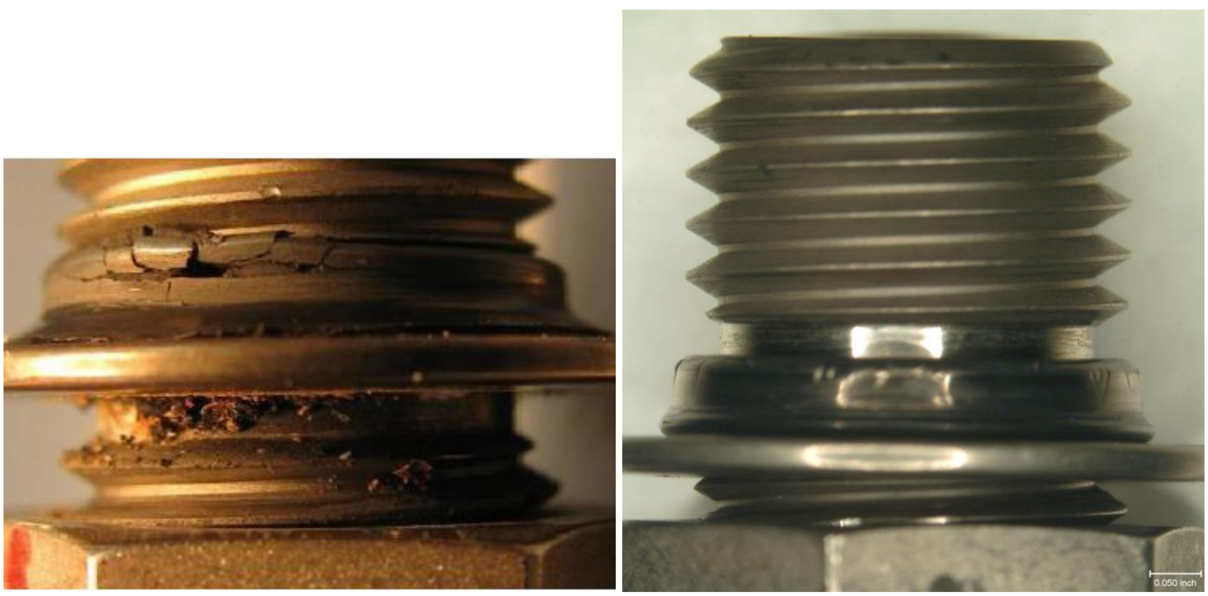

Figure 9. Catalytic Reactor Seals

The Gas Separator performance continued to degrade throughout the last year. The Gas Separator's ability to maintain temperatures during initial flow started to degrade in early 2014, though the hardware continued to separate the gas from the 2-phase mixture. No indications of free gas were ever detected downstream of the gas separator due to its degraded performance. However, to take advantage of the time when the crew was already in WRS#1 for replacement of the Catalytic Reactor, the separator was replaced in February 2016 after over 7 years of service.

As noted in 2015[1], the Reactor Health Sensor conductivity experienced an off-nominal trend in early 2015 that appeared to be related to an increase in ethanol in the ISS atmosphere, though it may have also been exacerbated by the competitive effects with DMSD and ethanol in the reactor as DMSD works its way through the WPA. More discussion on the ethanol trend can be found elsewhere[10]. This off-nominal trend of the RHS conductivity was recovered in May 2015 and has not recurred at the same level, though increases have been observed that do appear to correlate to excursion in the atmospheric ethanol concentration. Figure 10 provides the RHS trend for the previous year.

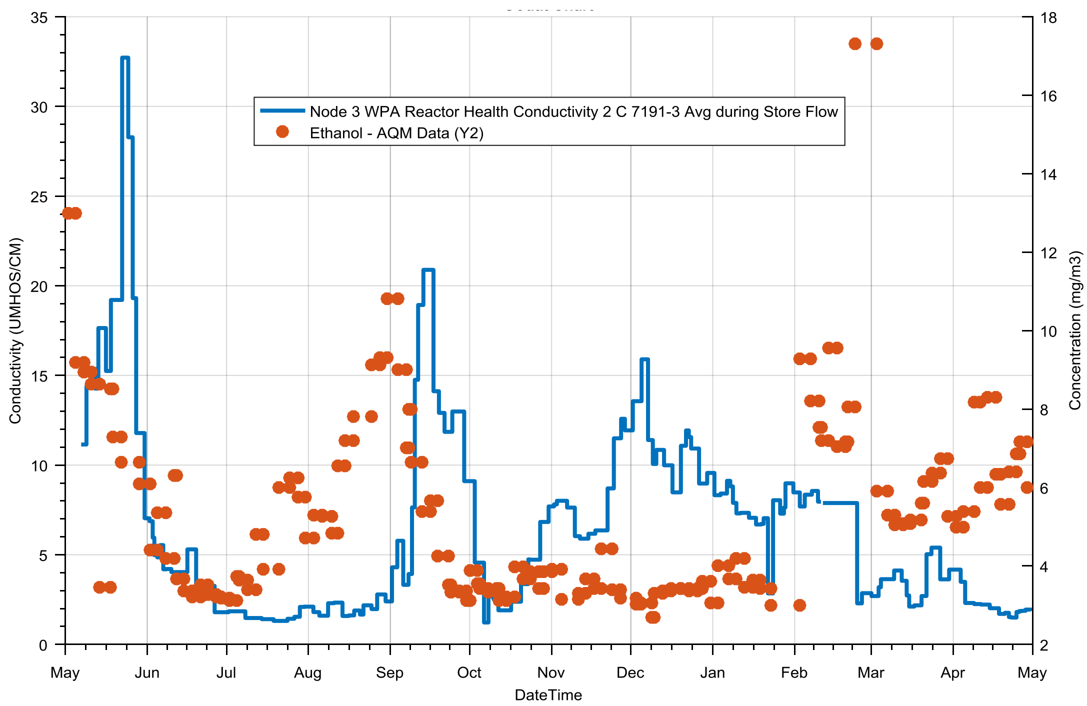

Figure 10. RHS Conductivity Data for May 2015 to May 2016

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. In the past year, the WPA has experienced a recurrence of the Catalytic Reactor seal leak and required replacement of two MF Beds in response to the ongoing issue with DMSD. Efforts are ongoing to deliver a filter to ISS for preventing DMSD from impacting the nominal MF Bed replacement schedule.

The UPA has experienced off-nominal performance due to elevated gas levels in the system, but the replacement of the SPA (gas separator) and the Distillation Assembly appear to have returned the system to nominal performance. Implementation of a phosphate-based urine pretreatment will allow the UPA to increase water recovery of urine from 75% to >85%, providing a significant decrease in water resupply and crew time required for maintenance. In addition, the incorporation of the ARFTA Fill/Drain valve has provided a significant crew time savings by allowing the crew to perform this task without removing the ARFTA tank from WRS#2. Finally, the implementation of a planetary gear drive in the FCPA has shown no performance issues since installation of the FCPA in October 2015. Currently this pump is at 551 operational hours, exceeding the nominal operational life of the previous pumps using the harmonic drive.

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