Status of ISS Water Management and Recovery

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Water management on ISS is responsible for the provision of water to the crew for drinking water, food preparation, and hygiene, to the Oxygen Generation System (OGS) for oxygen production via electrolysis, to the Waste & Hygiene Compartment (WHC) for flush water, and for experiments on ISS. This paper summarizes water management activities on the ISS US Segment as of May 2019 and provides a status of the performance and issues related to the operation of the Water Processor Assembly (WPA) and Urine Processor Assembly (UPA).

Nomenclature

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

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MLS	=	Mostly Liquid Separator
MF	=	Multifiltration
ORU	=	Orbital Replacement Unit
WSS	=	Water Storage System
WSTA	=	Wastewater Storage Tank Assembly

I. Introduction

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

II. Description of the ISS Water Recovery and Management System

A conceptual schematic of the WRM is provided in Figure 1. The waste water bus receives humidity condensate from the Common Cabin Air Assemblies (CCAAs) on ISS, which condenses water vapor and other condensable contaminants and delivers the condensate to the bus via a water separator. Waste water is typically delivered to the WPA Waste Tank. A separate Condensate Tank located in the US Laboratory Module is available as a back-up in the event the WPA Waste Tank is unavailable for waste water collection. In addition, waste water may also be delivered from the Carbon Dioxide Reduction System. This hardware uses Sabatier technology to produce water from carbon dioxide (from the Carbon Dioxide Removal Assembly (CDRA)) and hydrogen (from the electrolysis process in the Oxygen Generation System). However, the Sabatier reactor was removed from service in October 2017 and returned to ground for a failure investigation, which determined that various contaminants (sulfur, fluoride, silicon) poisoned the reactor[1]. The ISS Program Office is currently planning to build another Sabatier reactor for operation on ISS in 2021, while also implementing measures to reduce the source of the catalyst poisons.

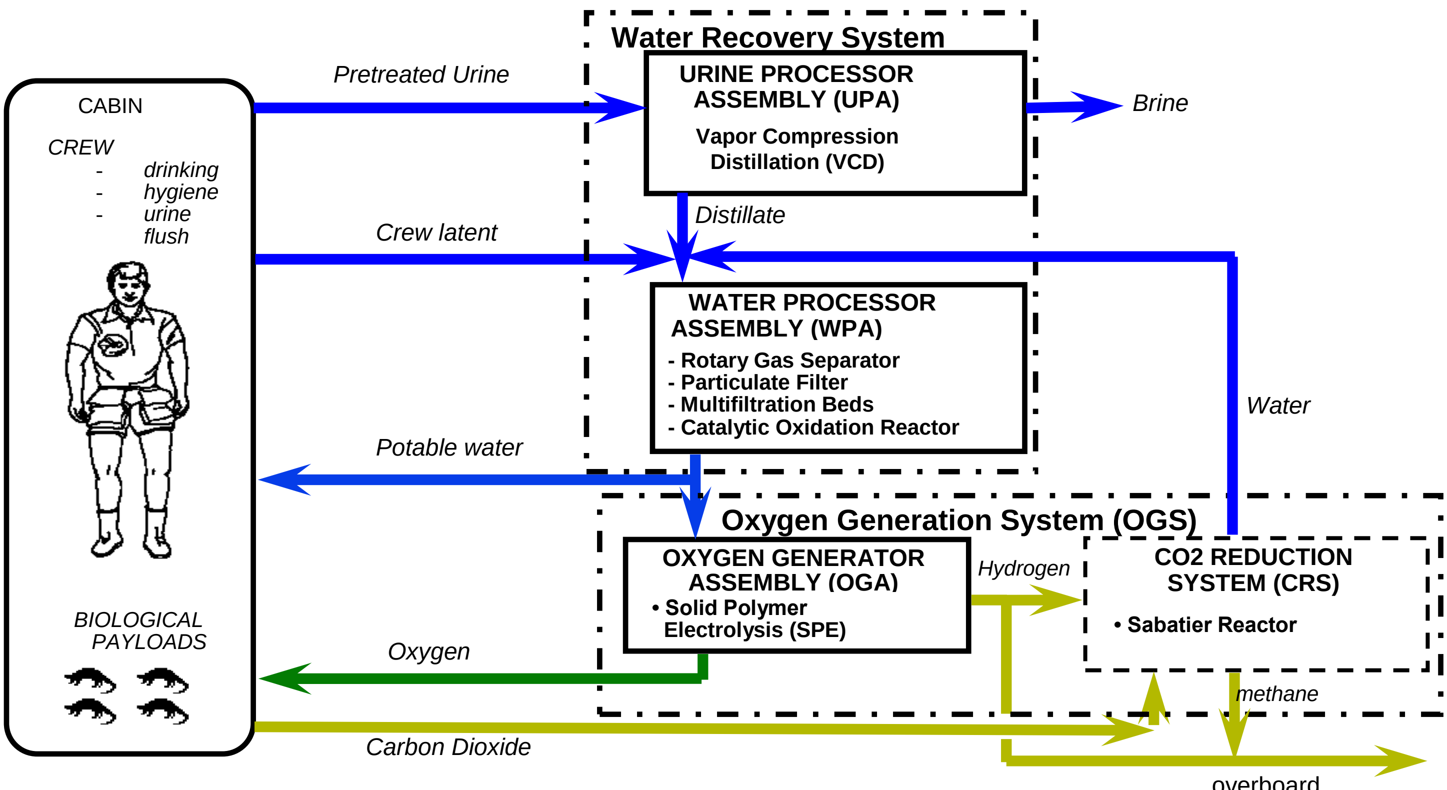

Figure 1. Water Recovery and Management Architecture for the ISS US Segment

Crew urine is collected in the Waste & Hygiene Compartment (WHC), which consists of a Russian Urinal system (referred to as the АСУ) that is installed in the US Segment. To maintain chemical and microbial control of the urine and hardware, the urine is treated with an oxidizer and an inorganic acid. The pretreated urine is then delivered to the Urine Processor Assembly (UPA) for subsequent processing. In addition, pretreated urine is collected in Russian urine containers (called ЕДВs) 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 (when available), 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 818 L (1803 lbs) of potable water is stored on ISS in Iodinated Contingency Water Containers (ICWCs) and Water Resupply Tanks (RSTs) to maintain ISS operations in response to contingency scenarios.

III. Description of the ISS Water Recovery System

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

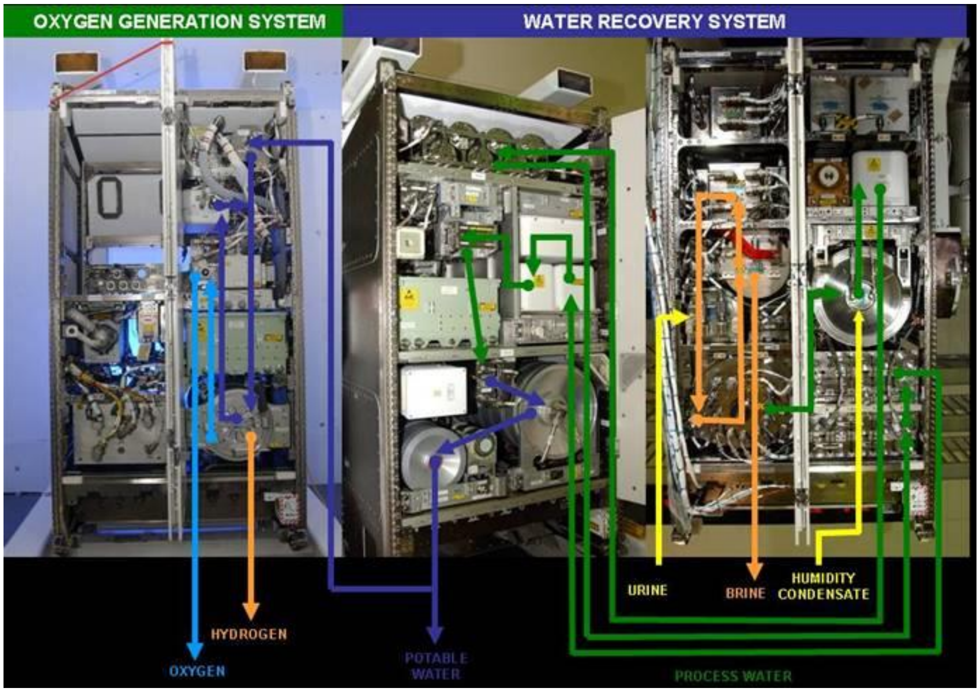

Figure 2. International Space Station Regenerative ECLSS Racks

The following section provides a description of the WRS, current operational status, and describes issues and lessons learned during the past year. For the prior years' status, see references 2-6.

A. Water Processor Assembly Overview

A simplified schematic of the WPA is provided in Figure 3. The WPA consists of 16 Orbital Replacement Units (ORUs), and occupies WRS#1 and the right half of WRS#2. Wastewater delivered to the WPA includes condensate from the Temperature and Humidity Control System, distillate from the UPA, and Sabatier product water when available. This wastewater is temporarily stored in the Waste Water Tank ORU. The Waste Water Tank includes a bellows that maintains a pressure of approximately 5.2 – 15.5 kPa (0.75 to 2.25 psig) over the tank cycle, which serves to push water and gas into the Mostly Liquid Separator (MLS). Gas is removed from the wastewater by the MLS (part of the Pump/Separator ORU), and passes through the Separator Filter ORU where odor-causing contaminants are removed from entrained air before returning the air to the cabin. Next, the water is pumped through the Particulate Filter ORU followed by two Multifiltration (MF) Beds where inorganic and non-volatile organic contaminants are removed. The Sensor ORU located between the two MF beds determines when the first bed is saturated based on conductivity, and additional conductivity sensors are located downstream of the second MF Bed to detect ionic breakthrough. Following the MF Beds, the process water stream enters the Catalytic Reactor ORU, where low molecular weight organics not removed by the adsorption process are oxidized in the presence of oxygen, elevated temperature, and a catalyst. In addition, any microorganisms present in the process water are killed in the Catalytic Reactor due to the elevated temperature. A regenerative heat exchanger recovers heat from the effluent of the catalytic reactor to make this process more efficient. The Gas Separator ORU removes excess oxygen and gaseous oxidation by-products from the process water and returns it to the cabin. The Reactor Health Sensor (RHS) ORU monitors the conductivity of the reactor effluent as an indication of whether the organic load coming into the reactor is within the reactor's oxidative capacity. Finally, the Ion Exchange (IX) Bed ORU removes dissolved products of oxidation and adds iodine for residual microbial control. The water is subsequently stored in the Water Storage Tank prior to delivery to the ISS potable water bus. The Water Delivery ORU contains a pump and small accumulator tank to deliver potable water on demand to users. The WPA is controlled by a firmware controller that provides the command control, excitation, monitoring, and data downlink for WPA sensors and effectors.

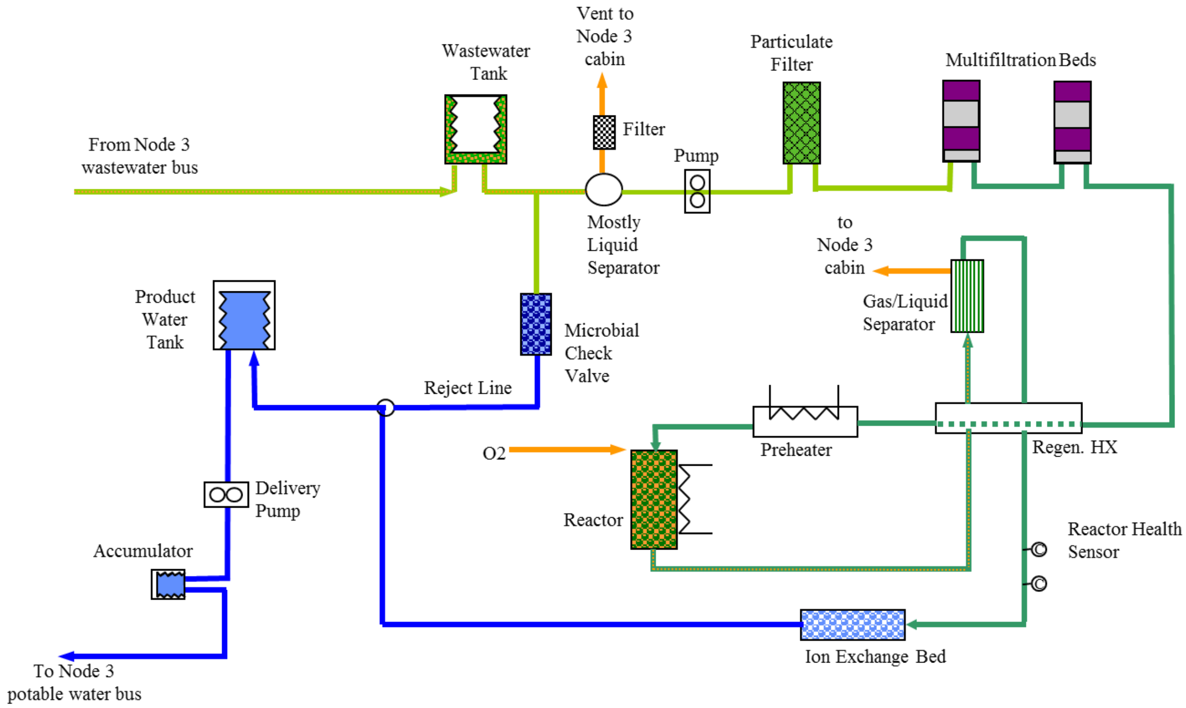

Figure 3. WPA Simplified Schematic

B. Urine Processor Assembly Overview

A simplified schematic of the UPA is shown in Figure 4. The UPA consists of 7 ORUs, which take up slightly more than half of the WRS Rack #2. Pretreated urine is delivered to the UPA either from the US Segment WHC (outfitted with a Russian urinal) or via manual transfer from the Russian ЕДВ. In either case, the composition of the pretreated urine is crew urine, flush water, and a pretreatment formula containing chromium trioxide and an inorganic acid to inhibit microbial growth and the conversion of urea to ammonia. In the Russian segment, the inorganic acid is sulfuric acid. In the US Segment, the inorganic acid has been switched to phosphoric acid to address precipitation issues with calcium sulfate. The 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 fluids pump that moves urine from the WSTA into the Distillation Assembly (DA), recycles the concentrated waste from the DA into the Advanced Recycle Filter Tank Assembly (ARFTA) and back to the DA, and pumps product distillate from the DA to the wastewater interface with the WPA. The DA consists of a rotating centrifuge where the waste urine stream is evaporated at low pressure. The vapor is compressed and condensed on the opposite side of the evaporator surface to conserve latent energy. A rotary lobe compressor provides the driving force for the evaporation and compression of water vapor. Waste brine resulting from the distillation process is stored in the ARFTA, which is a bellows tank that can be filled and drained on ISS. When the brine is concentrated to the required limit, the ARFTA is emptied into an ЕДВ. The ЕДВ containers are emptied into the Russian Rodnik tank on the Progress vehicle for disposal. The ARFTA is refilled with pretreated urine to initiate a new concentration cycle. The Pressure Control and Pump Assembly (PCPA) is four-tube peristaltic purge pump which provides for the removal of non-condensable gases and water vapor from the DA. Liquid cooling of the pump housing promotes condensation, thus reducing the required volumetric capacity of the peristaltic pump. Gases and condensed water are pumped to the Separator Plumbing Assembly (SPA), which recovers and returns water from the purge gases to the product distillate stream. A Firmware Controller Assembly (FCA) provides the command control, excitation, monitoring, and data downlink for UPA sensors and effectors.

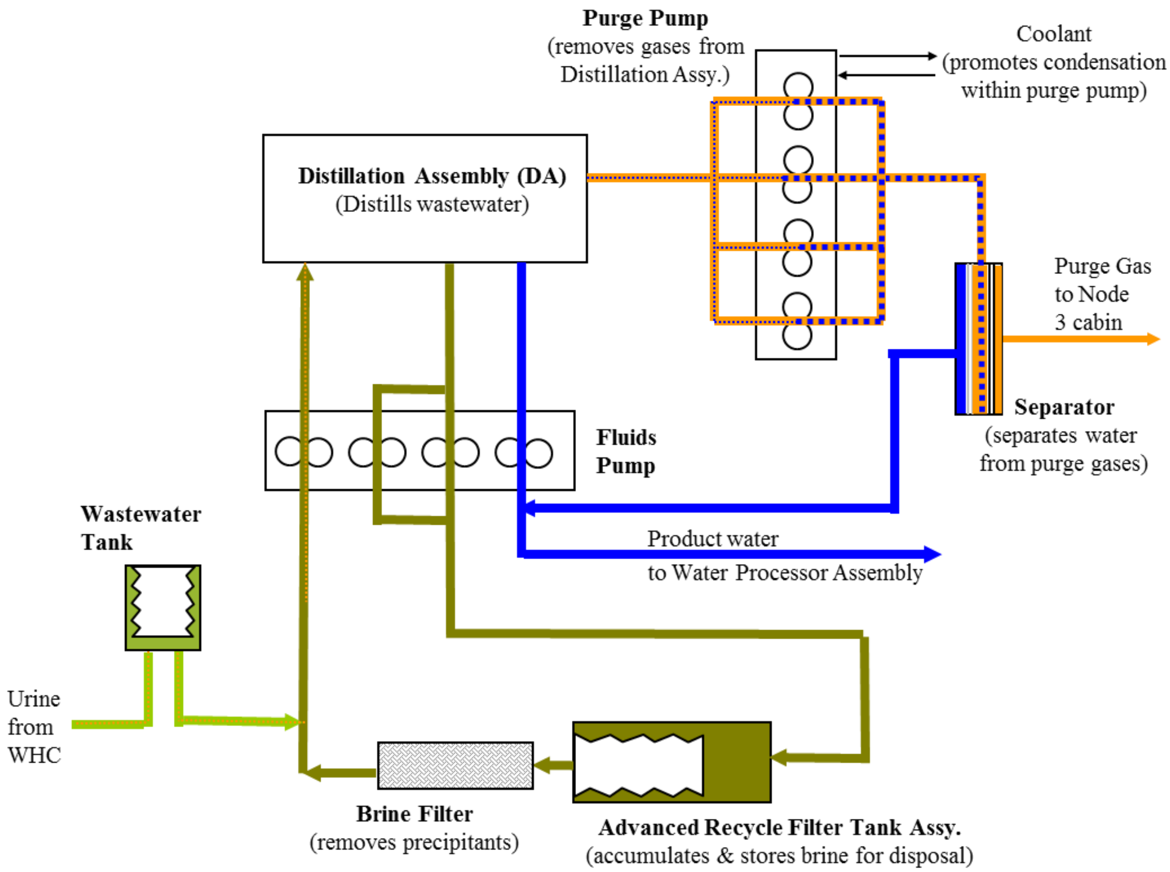

Figure 4. Urine Processor Assembly Schematic

The UPA was designed to process a nominal load of 9 kg/day (19.8 lb/day) of wastewater consisting of urine and flush water. This is the expected quantity for a 6-crew load on ISS. The UPA was designed to recover 85% of the water content from the pretreated urine, though issues with urine quality encountered in 2009 required the recovery to be dropped to 75% for the US Segment and 70% for urine collected in the Russian Segment. Implementation of a phosphate-based urine pretreatment[8] in early 2016 allowed the UPA to return to a minimum of 85% Recovery of urine collected in the US Segment, though urine recovery from urine collected in the Russian Segment remains at 70% because no changes have been made to the pretreatment in the Russian Segment.

IV. Water Recovery and Management Status

In the last year, 4474 L (9863 lbs) of potable water have been supplied to the US Segment potable bus by the WPA. In addition, 1920 L (4233 lbs) of potable water is currently stored on ISS for resupply water and in reserve to protect for contingencies. Management of the water mass balance has continued to be a challenge due to the management of approximately 2000 L of potable water in the US Segment (exceeding the requirement of 818 L for crew reserve). This task has been further impacted by the ongoing directive to process available urine from the Russian Segment. Processing urine from the Russian segment generates distillate quantities in excess of the losses experienced by the rest of the ISS regenerative water systems. This approach has reduced the need to supplement the US Segment water systems with stored water and generated a surplus of water. Surplus water is stored for later use by draining the WPA Waste Water Tank or WPA Water Storage tank when the WRS rack tanks (UPA wastewater, WPA Waste, and WPA potable tanks) are too full to continue normal operation.

This surplus of water in the US Segment is expected to shift in 2019 with the delivery of a distiller for the Russian Segment Urine Processor. Installation of the Urine Processor was completed in 2018, but the distiller failed during initial checkout. Russian engineering personnel have added filtration to the pretreated urine collected in the Russian segment and updated the system controls to the Urine Processor to address issues believed to have resulted in the failure of the previous distiller. Distillate from the Russian Urine Processor is planned to be used for flush water, feed water to the Russian Elektron, and feed water to their condensate processor pending successful results from analysis of distillate samples returned to the ground.

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

Several significant modifications to the ISS water system are nearing completion and delivery to ISS, including a Water Storage System (WSS), a Universal Waste Management System (UWMS), a Urine Transfer System (UTS), and a Brine Processor Assembly (BPA). The WSS addresses the water management issues associated with water resupply and potable water storage. Potable water storage capacity will be increased by launching four tanks recovered from Space Shuttles Endeavor and Atlantis. The former space shuttle tanks will be connected to the potable bus with inlet valves that will be controlled by ground personnel. Water will be transferred (via ground commands) to and from this WSS as needed for the water balance. The additional capacity will greatly increase the WRS's ability to absorb disturbances to the mass balance by adding system capacity and increase the time that ISS crew has to respond to mass balance upsets. The increased time for response will allow ground teams to mitigate mass balance upsets and potentially prevent crew involvement. In addition to assisting with management of the water reserve, the new rack will incorporate interchangeable 73 L (161 lbs) resupply tanks. These tanks are commercially available and have been tested to ensure compliance with the ISS requirements (including launch vibration and materials compatibility). The resupply tanks will be launched full, installed into the WSS rack, and emptied into the WPA waste tank via commanding from the ground. The water from the resupply tanks will be transferred to the WPA waste tank via the waste water bus using the same compressor currently utilized for ARFTA and ЕДВ transfers. The increased size of the resupply tanks and the ability for multiple tanks to be installed into the WSS greatly decreases the frequency and total crew time required to add water to the WRS. The resupply tanks will also provide back-up condensate collection volume in addition to the existing WPA waste water tank and Lab condensate tank. WSS will add a commandable valve in front of the Lab condensate tank. Currently the condensate tank must be isolated from the WPA waste tank because the two bellows tanks have overlapping backpressure. If both tanks are connected to the waste water bus at the same time, the WPA Waste Water tank will push waste water into the Lab Condensate tank. Besides the operational impacts associated with filling the condensate tank, this reverse flow would expose the WPA Waste Water Inlet valve to the biomass present in the waste tank, thereby increasing the risk of internal blockage. This constraint requires the crew to manually disconnect or reconnect the condensate tank to the bus as needed based on the availability of the WPA waste tank. The new WSS valve will allow ground commanding to isolate or connect the condensate tank to the waste bus without crew involvement.

When the pre-staged RSTs are emptied, they can be changed out with new tanks as they arrive on ISS. The empty resupply tanks may then provide additional disposal options for brine generated by the UPA, which will reduce procurement of costly ЕДВs. Assuming the Russian Urine Processor is operational in 2019, the water surplus created by the US Segment's processing of Russian urine will cease. The increased efficiency of the WSS will become an important factor for reducing crew time currently used to manage water transfers in the US Segment. As of May 2019, three resupply tanks have been delivered to ISS and one has been successfully offloaded to the WPA. In November 2018, four Shuttle water tanks were delivered to ISS on Cygnus NG-10 and assembled into the WSS rack in February 2019. The remainder of the WSS components were delivered to ISS in May 2019 on SpX-17 and will be installed in the rack to achieve full functionality. A view of the WSS rack is shown in Figure 5 and a photograph of the installation of the Shuttle tanks in the rack is provided in Figure 6.

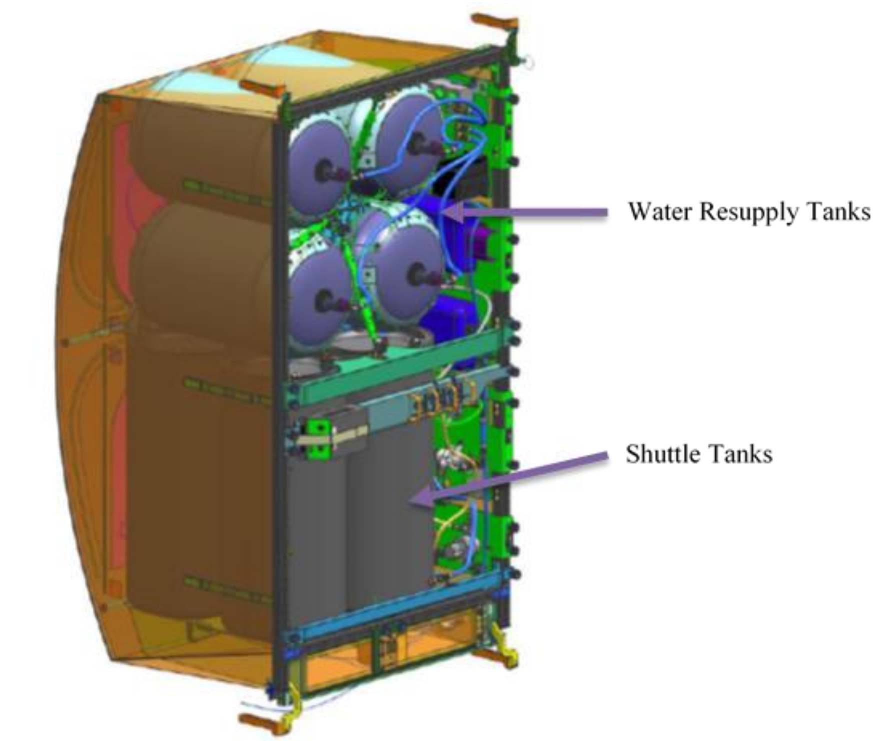

Figure 5. WSS Rack without Covers

Figure 6. Installation of the Shuttle Tanks into the WSS Rack on ISS

The UWMS is a new toilet in development by Collins Aerospace (formally United Technologies Aerospace Systems, UTAS). This hardware is planned for use in the Orion vehicle and will be initially demonstrated on ISS. To support ISS operations, the urinal uses the phosphate-based pretreatment so that urine can be processed by the ISS UPA. Assuming a successful demonstration, the UWMS will be maintained on ISS to support the increased US crew expected in 2020 associated with the commercial crew activity. To support the operation of two urinals on ISS (UWMS and WHC), a Urine Transfer System (UTS) is being delivered by Boeing. This hardware will automatically manage input from each urinal, insuring that parallel operation does not impact the delivery of urine from either separator to the UPA. This is accomplished by diverting flow from the WHC to a backup ЕДВ any time pressure sensors indicate the UWMS is also delivering urine to the UPA. This ЕДВ can subsequently be drained to the UPA when neither urinal is in use. As part of the UTS delivery, Boeing has also identified a commercially available compressor that can be used for the same applications as the Russian compressor. This compressor will be used with UTS to transfer pretreated urine from ЕДВs (filled in the Russian Segment) to the UPA WSTA and for offloading the UPA brine tank (ARFTA) into the BPA. UTS hardware will be delivered to ISS and installed in 2019, and the UWMS is now scheduled for delivery in early 2020.

The BPA will be operated on ISS as a technology demonstration for NASA Exploration missions. This hardware will process the brine generated by the UPA (see Figure 1) to remove water and thereby achieve ~98% water recovery. This hardware is being delivered to NASA by Paragon Space Development and is scheduled for delivery in late 2019. Successful demonstration of this technology is considered a critical step prior to future manned missions beyond ISS (i.e., a mission to Mars) because of the necessity to recover as much water as reasonably possible due to the launch costs for water and the absence of resupply capability. More detail on this technology can be found elsewhere[7]. If successful, NASA may continue to use the technology on ISS to reduce the water resupply requirement from earth.

In late 2018, the European Space Agency (ESA) delivered the Life Support Rack (LSR), previously referred to as the Advanced Closed Life Support (ACLS), to ISS for a technology demonstration in 2019. ESA is using LSR to evaluate oxygen generation via water electrolysis, carbon dioxide (CO_2) removal, and CO2 reduction for future manned missions. LSR will use steam desorption for CO_2 removal, resulting in approximately twice the quantity of water vapor that must be removed by the ISS Condensing Heat Exchangers. LSR will be initially located in the US Laboratory module, where it will interface with both the potable bus and the waste water bus. LSR has a unique requirement to remove and deliver water to the waste water bus. To prevent impacts to the WPA waste tank, NASA and Boeing have decided to separate the waste water bus in the US Laboratory during LSR operations. In this configuration, condensate collected in the US Lab, Node 2, and Columbus modules (along with the condensate tank) will interface with the LSR while condensate collected in Node 3 and Airlock will feed the WPA waste tank. The additional humidity generation coupled with the split waste water bus is expected to complicate the mass balance on ISS, periodically requiring the bus to be reconnected to transfer condensate from the condensate tank to the WPA waste tank. Installation of the WSS will add an isolation valve in front of the condensate tank, which will negate the need to split the waste water bus for LSR operations.

LSR operation was initiated in November 2018. Overall system performance will be addressed in the future by ESA, though two separate failures occurred that required support from the NASA and Boeing team to recover LSR functionality. First, LSR was unable to achieve initial flow of water into its process tank, presumably due to a check valve that had failed closed. This issue was resolved by deadheading the CCAA water separators providing condensate to the LSR. This action generated higher pressure at the check valve, which was successful in opening the check valve and allowing flow into LSR. No subsequent recurrence of this anomaly has recurred. The second failure occurred due to a loaded 10 μ filter screen at the inlet to the LSR. This filter provided insufficient depth for the particulate load present in the condensate. As a result, it is suspected the filter quickly loaded and no longer allowed condensate flow. Filters available on ISS were identified to replace this filter screen until a modified filter (with greater capacity) can be delivered by ESA to ISS. The new filters were installed in March 2019 and LSR functionality is expected to be recovered after resolution of a power anomaly. The LSR filter screen will be returned to the ground for further analysis to identify the source of the particulates that loaded the filter.

V. Urine Processor Assembly Current Status

The UPA has produced 2789 L (6147 lb) of distillate at 70% (Russian urine treated with baseline pretreatment) to 85% recovery (US urine treated with alternate pretreatment) in the last year, completing 31 ARFTA cycles during that time. As of May 10, 2019, the total UPA production on ISS is 16,179 L (35,659 lb) of distillate. A graphical summary of UPA production rate and upmass required for ISS operations is provided in Figure 7. In the past year, one FCPA (planetary gear drive) and 4 brine filters (expected loading) have been replaced to maintain nominal UPA operations.

In the past year, NASA initiated the effort to increase the UPA % Recovery beyond 85%. Increasing the % Recovery is desirable to recover additional water, but primarily to extend the duration of the UPA concentration cycle and thereby reduce crew time required for ARFTA drain and fills. The rationale for increasing the % Recovery is based on previous ground testing that showed the change to the alternate pretreatment would support increased water recovery beyond 85%, potentially up to 90%. This is because the alternate pretreatment eliminated addition of sulfuric acid from the pretreatment, which was contributing to the calcium sulfate precipitation that caused the failure of DA S/N 2 in 2010. To further evaluate the viability of increasing water recovery on ISS, brine returned from ISS (in loaded Brine Filters) was analyzed to determine its additional capacity for concentrating calcium sulfate. Based on these analyses coupled with the ground test results (see summary of data in Figure 8), the UPA % Recovery was increased from 85% to 86% in October 2018. Additional analysis will be performed every 6 months to determine if the % Recovery can continue to be incrementally increased.

The UPA has experienced multiple failures of the FCPA in previous years due to various mechanical issues[4,5]. These failures led to the development of an improved drive shaft design, replacing the harmonic drive with a planetary gear. Though the harmonic drive is considered appropriate for precision applications, tolerances in the FCPA assembly and installation processes provide multiple opportunities for failure. In contrast, the planetary gear design supports a robust installation process and is also more advantageous for the power transfer application in the FCPA. This modification was expected to produce a marked increase in on-orbit reliability of the FCPA. The first FCPA with the planetary gear drive failed in May 2018 after 4181 hours of operation. This lifetime significantly exceeding the life of any previous FCPA with the harmonic drive. However, NASA engineering personnel anticipated the planetary gear drive would allow the FCPA to operate until failure of the peristaltic tubing, which was not the case. The subsequent failure analysis determined the planetary gear drive had failed due to wear. The vendor confirmed this was the expected end of life condition for these sintered gears, but the gear life could be measurably extended with machined instead of sintered gears. This capability was not available at the time the previous planetary gear drive was delivered by the vendor, but subsequent FCPA ORUs will now incorporate the machined gears for extended life.

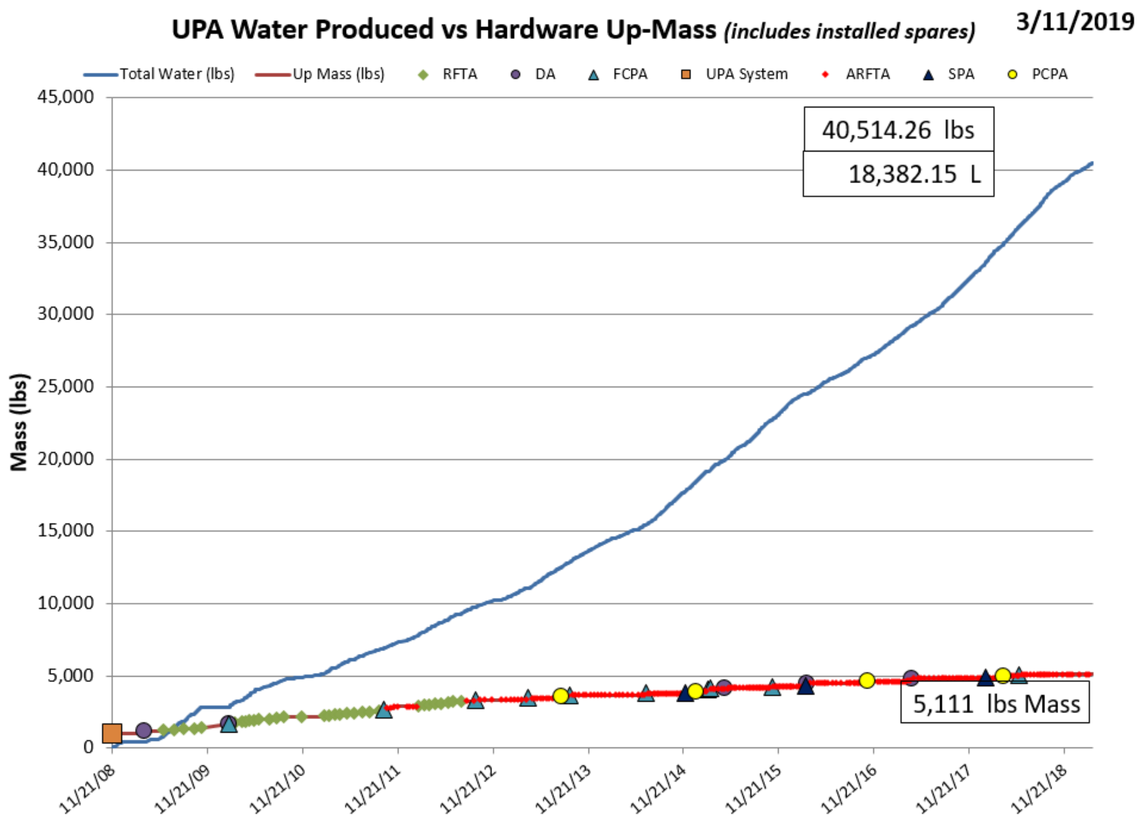

Figure 7. UPA Production and Upmass on ISS

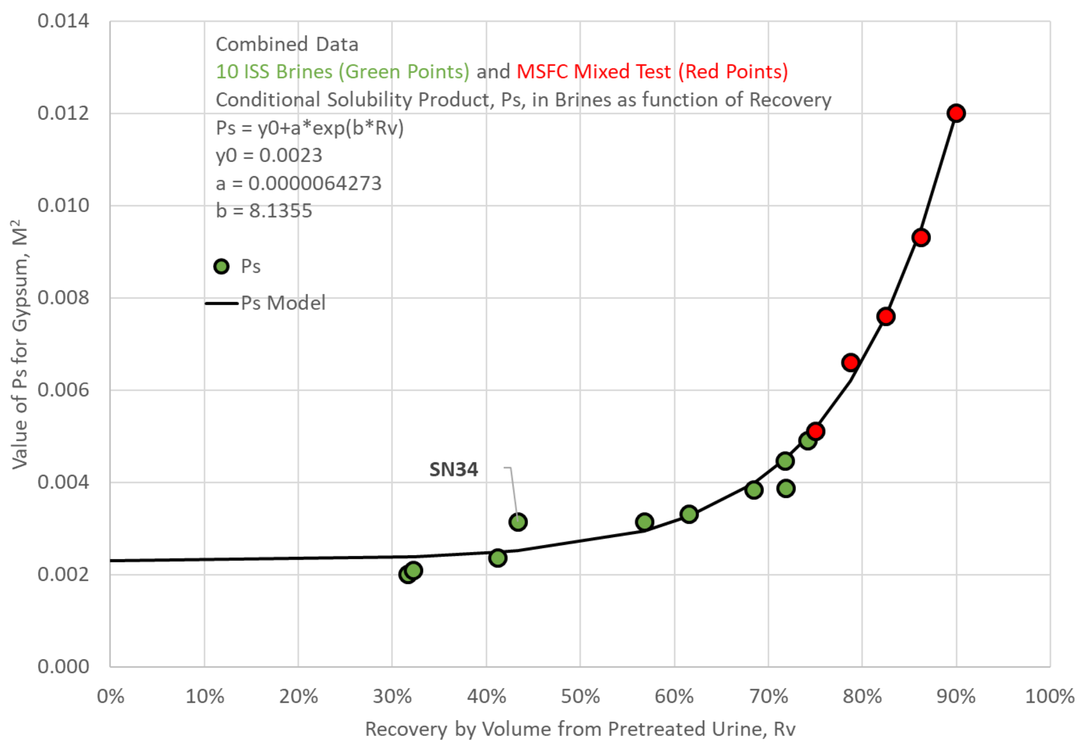

Figure 8. Conditional Solubility Product of Calcium Sulfate in Brine

The current PCPA was installed in March 2018, replacing a PCPA that likely failed due to harmonic drive failure (investigation not yet complete). This PCPA includes the planetary gear drive and currently has over 1200 hours of operational life. Recent increases in motor current indicate the planetary gear drive is near end of life, which would be consistent with the expected life of the PCPA based on the observations of the planetary gears in the FCPA.

As noted previously[2,3], the UPA Distillation Assembly (DA) has experienced various anomalies in the past related to the drive belt slipping on startup, elevated conductivity in the urine distillate, and elevated pressure in the evaporator. The current DA (installed 4/13/2017) has experienced all of these anomalies to a minor extent, but none significant enough to require replacement. Belt slips were observed intermittently after initial installation but have been relatively infrequent during the life of this DA. Typically, a belt slip during the centrifuge ramp-up lasts just a few minutes, enough time for the condensation that causes slippage to evaporate and the belt to regain traction. An example of belt slippage and recovery is provided in Figure 9. UPA engineering have observed that belt slips occur more frequently with reduced crew, likely because the additional time in Standby mode results in additional condensation on the drive belt. Since January 2019, there have been two separate instances of belt slips causing UPA shutdowns; however, at each shutdown event, UPA was able to recover and continue to operate nominally.

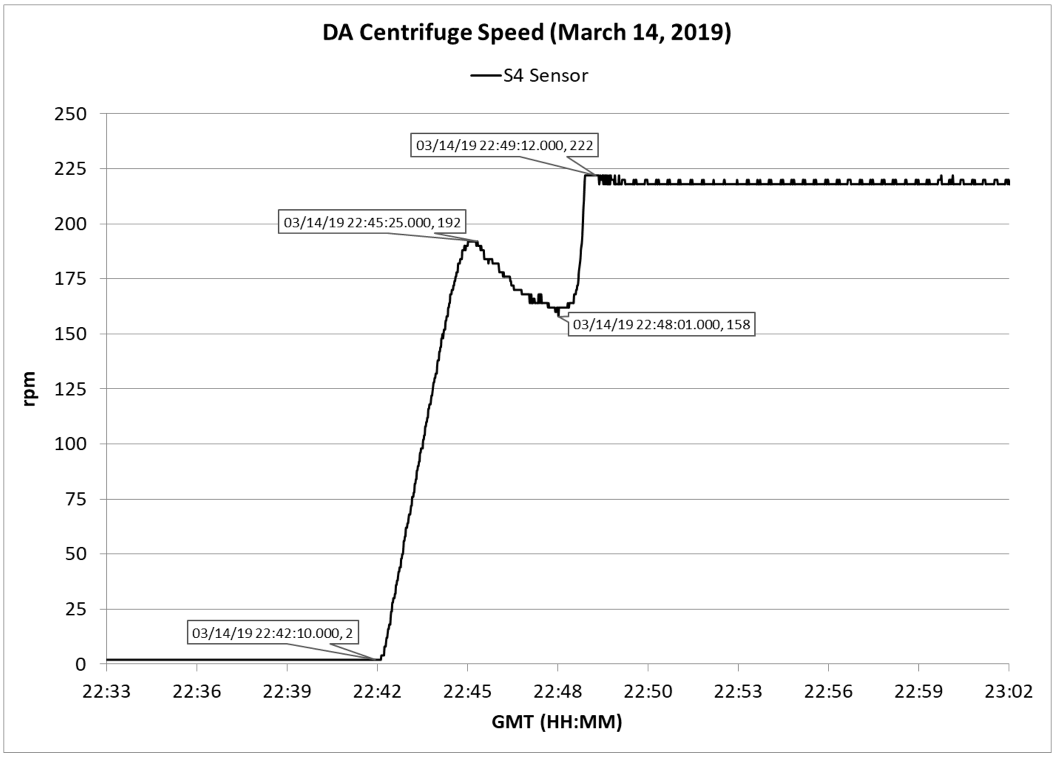

Figure 9: Centrifuge Belt Slip

With regard to elevated distillation conductivity, there have been no instances of the conductivity spikes observed with DA SN003 that were ultimately attributed to pretreated urine in the purge distillate. However, this DA has exhibited the conductivity spike at the beginning of each process cycle consistent with previous DAs (see Figure 10) and attributed to pretreated urine washing out the lubricant in the centrifuge's rear bearing and leaking into the condenser during Standby mode. This data continues to support the theory that pretreated urine will consistently wash out this rear bearing, but the significance of the leak will vary for each DA. Most recent distillation conductivity has seen minimal start-up spike occurrences. This may be attributed to the reduced processing, allowing more time for crystallization of the pretreated urine to occur at the leak path. As process frequency increases with full crew, this crystallization may re-dissolve and allow for pretreated urine to cross into the distillate stream again. NASA MSFC is currently implementing a lip seal for this rear bearing to mitigate this design issue.

Finally, the elevated pressure observed in the DA has not been a significant concern. This pressure is typically driven by elevated gas (dissolved and free) in the pretreated urine that ultimately drives more condensation in the stationary bowl. As a result, the heaters in the stationary bowl must operate more frequently to evaporate this condensate, which then drives up the pressure in the centrifuge. An example of this effect can be seen in Figure 11.

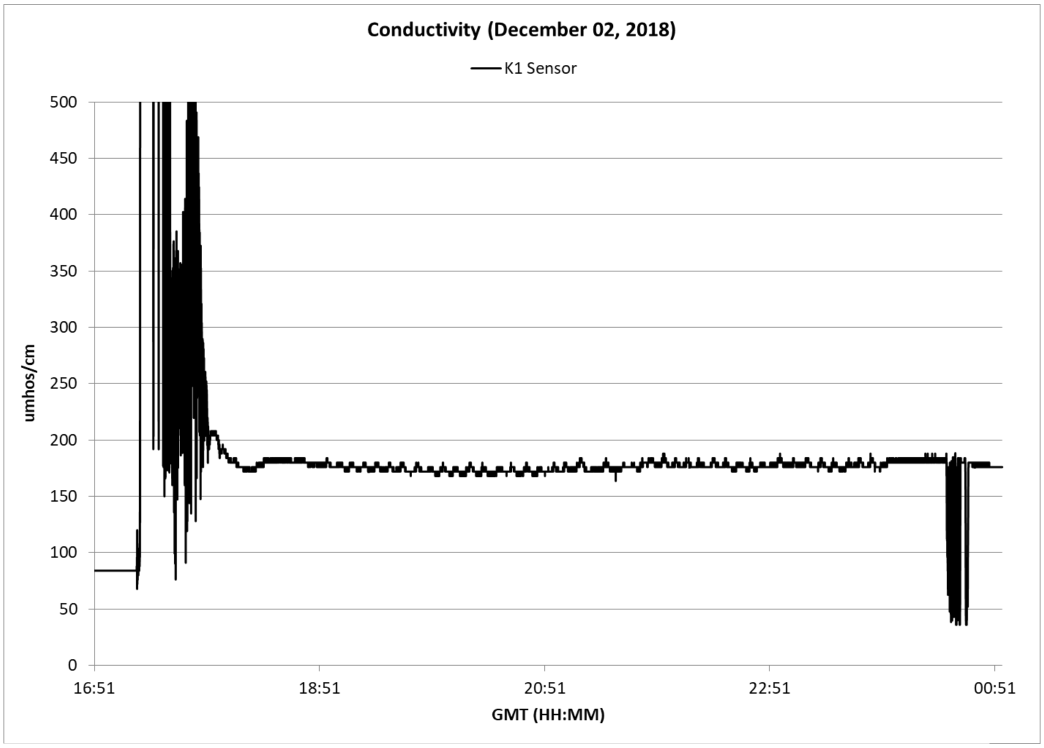

Figure 10: Elevated conductivity spikes at beginning of process runs

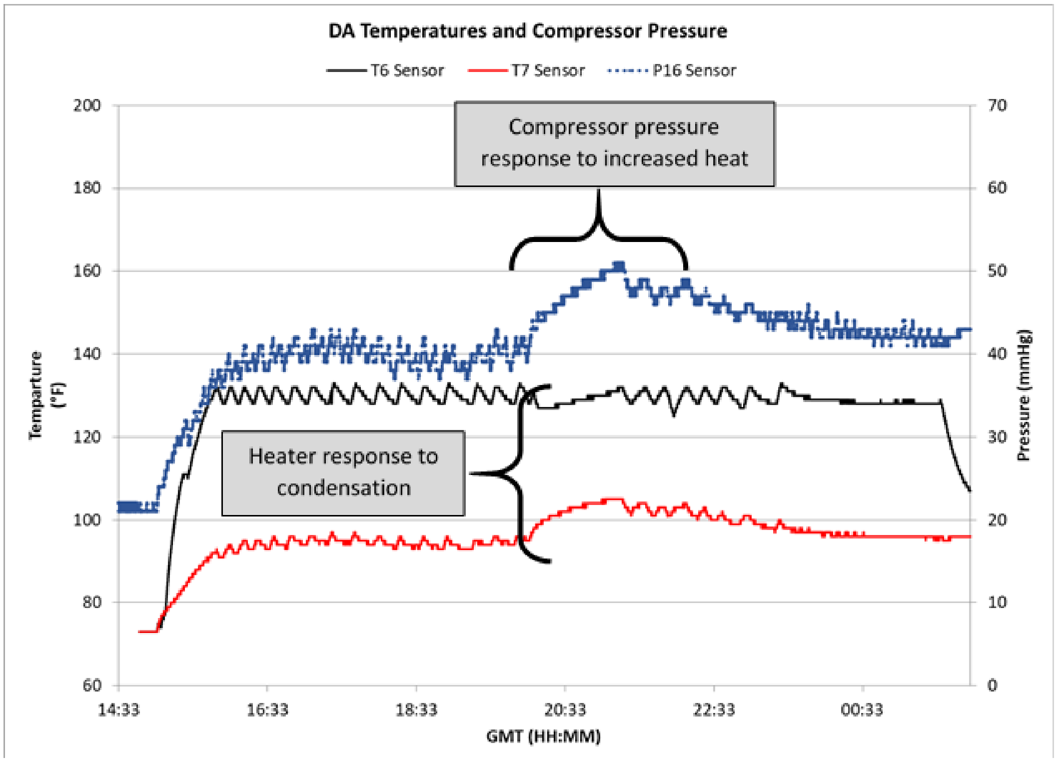

Figure 11: Temperature and pressure responses to condensation in stationary bowl

VI. Water Processor Assembly Current Status

As of May 9, 2019, the WPA has produced approximately 39,154 L (86313 lbs) of product water, including 4474 L (9863 lbs) in the previous year. The primary issue associated with WPA operations on ISS continues to be the passage of dimethylsilanediol (DMSD) through the WPA and the associated ionic breakthrough of the two Multifiltration (MF) Beds. MF Bed life has typically been dictated by the passage of DMSD through the WPA. The source of DMSD and its impact on the WPA treatment process has been discussed previously[9]. An extensive investigation into the formation of DMSD on ISS is also available elsewhere[10], along with an assessment of DMSD sources on ISS[11]. There have been 6 instances of increasing Total Organic Carbon (TOC) in the WPA product water due to DMSD, including the current trend. Each TOC trend was initially detected by the TOC Analyzer (TOCA) on ISS, and a summary of the data is provided below in Figure 12. However, the current trend has deviated from previous trends. In the past, once TOC has been detected by the TOCA, it has consistently increased until exceeding the potable specification of 3000 μg/L, necessitating the replacement of both MF Beds. After installation of the current set of MF Beds in late 2015, the DMSD reached the product water in late 2016. The resulting TOC peaked at approximately 1800 μg/L and has reached a steady state condition around 1000 μg/L for the last year. Engineering personnel believe a lower concentration of DMSD in the reactor effluent is the reason for the atypical trend, but it is not obvious why DMSD would be at a lower concentration. Possible explanations include a more efficient reactor, lower DMSD concentration in the humidity condensate, or impacts to the mass transfer zone of DMSD in the MF Beds associated with reprocessing or processing clean water to address elevated RHS trends.

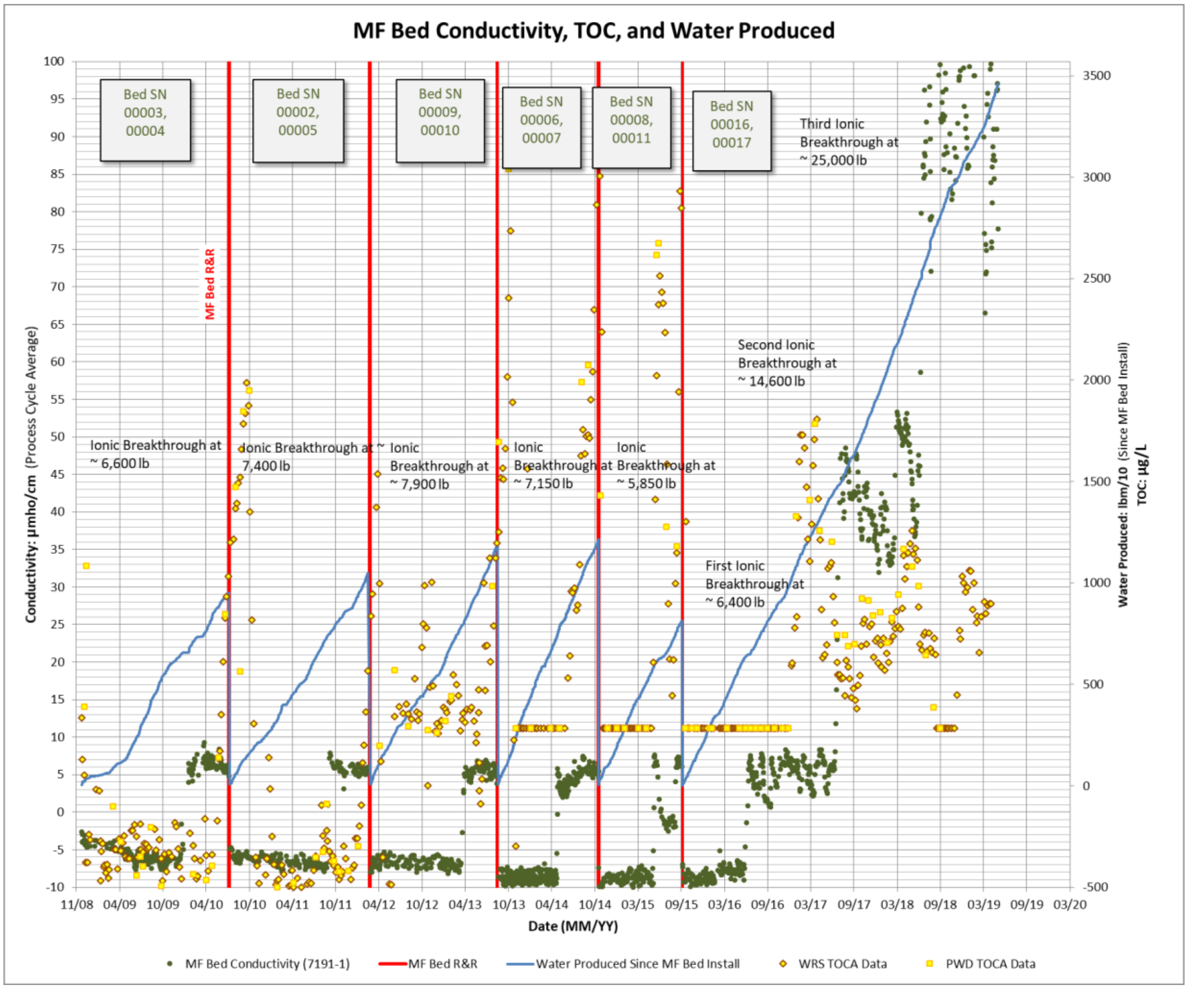

Figure 12. Correlation between Product Water TOC and MF Bed Throughput

The extended DMSD trend provided the first opportunity to extend the life of the MF Beds since all previous beds were replaced after approximately one year in operation. The initial ionic breakthrough of MF Bed #1 had occurred before DMSD appeared in the product water, after approximately 2800 kgs (6200 lb) of throughput. Subsequently, ionic breakthrough of MF Bed #2 occurred after 5900 kgs (13000 lb) of throughput. Typically this ionic breakthrough would have resulted in the replacement of both MF Beds. However, previous testing at the NASA Marshall Space Flight Center had shown that the initial breakthrough contaminants could be processed by the Catalytic Reactor[13]. Using an ersatz based on the ISS waste water and a half-scale pair of MF Beds, discrete breakthrough trends were detected via conductivity for bicarbonate, acetate, and ammonium, in that order. In addition, a flight-like Catalytic Reactor was challenged with each contaminant to show that the reactor could process all contaminants along with the nominal organic load. Since bicarbonate and acetate are oxidation products of ethanol (the primary organic processed by the reactor), it was expected that the reactor could accommodate their additional load. Though the reactor was also able to process ammonium, it is not expected to allow this on ISS since the MF Bed ersatz test showed that trace concentrations of several potential catalyst poisons were also present when ammonium breakthrough occurred.

Based on the data from these ground tests, NASA and Boeing engineering agreed to continue operating the MF Beds on ISS after the initial ionic breakthrough of MF Bed #2. This decision has been justified by the product water TOC, which appears to be unaffected by the additional load on the reactor. To provide more insight into this trend, samples from the effluent of each MF bed were taken by the crew and returned to ground for analysis. These samples determined that acetate had saturated both MF Beds and that the second breakthrough contaminant is bicarbonate. The reason for acetate breakthrough before bicarbonate is not consistent with ground test, though it is not critical since ground test showed the reactor can accommodate the load from both contaminants. Since ionic breakthrough of MF Bed #2 occurred, complete ionic breakthrough of MF Bed #1 has occurred, as well as the second breakthrough trend for MF Bed #2. Ammonium is the primary contributor to the third breakthrough, though it is accompanied by other cations at trace levels. Figure 13 provides the conductivity trend for the MF Bed #1 effluent, including the contaminants anticipated to have caused each breakthrough. Figure 14 provides the same data for MF Bed #2, identifying acetate as the initial contaminant to pass through both beds and be processed by the Catalytic Reactor along with the nominal load of volatile organics. Assuming WPA performance continues to be acceptable, NASA and Boeing personnel intend to operate the MF Beds until the third breakthrough of MF Bed #2 occurs. This would be a significant increase in MF Bed life and likely establish the expected procedure for loading MF Beds for the remainder of ISS.

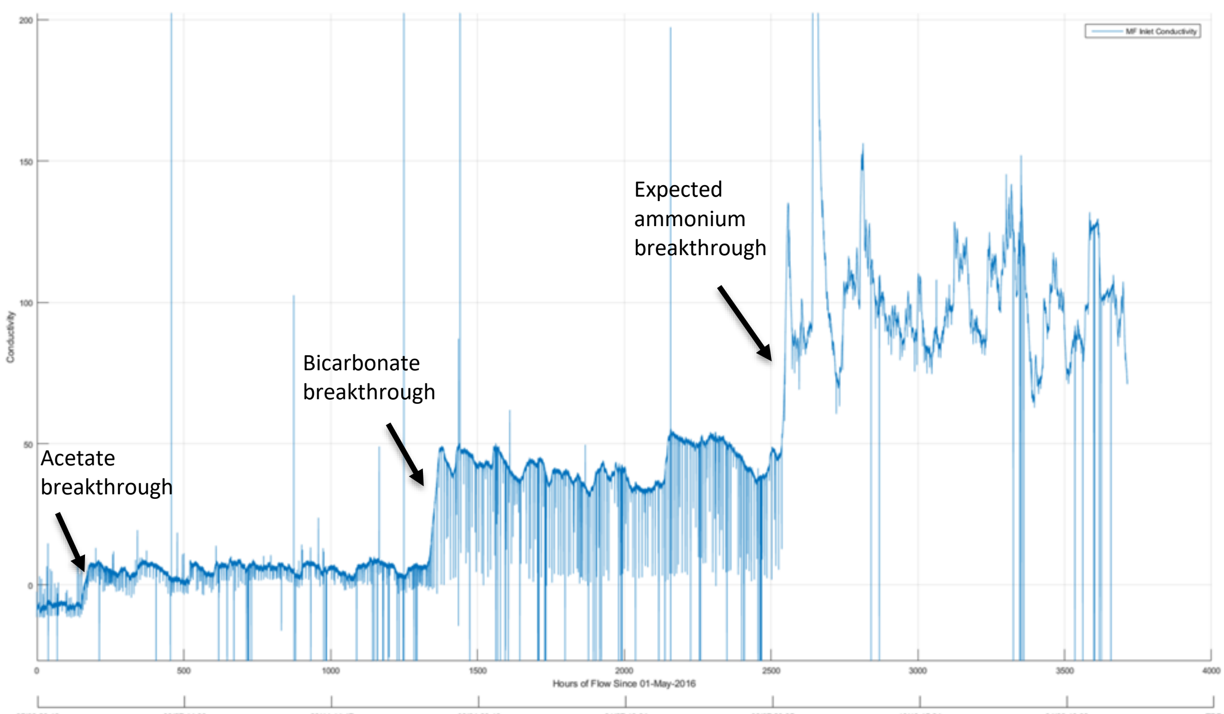

Figure 13. Ionic Breakthrough of WPA MF Bed #1

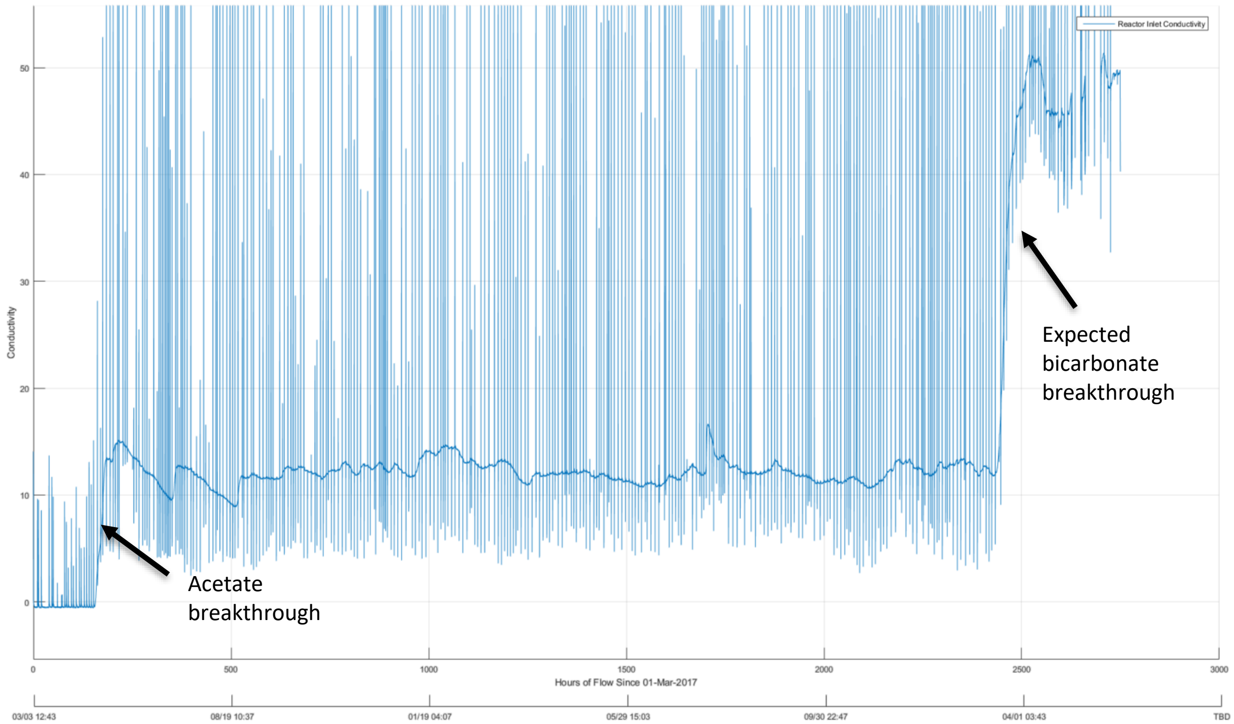

Figure 14. Ionic Breakthrough of WPA MF Bed #2

Since repeating the current DMSD trend cannot be guaranteed, NASA and Boeing have continued to develop and implement a mitigation strategy for DMSD. There are two paths to reduce the concentration of DMSD in the humidity condensate by ~50%, which would establish a concentration that the Catalytic Reactor could reliably remove to acceptable potable levels. First, research into the sources of the siloxanes on ISS has been ongoing[11]. Though there are many sources of siloxanes, various crew items are the primary contributors. Crew items with significant contribution to the ISS siloxane load have been identified, including antiperspirants, body lotions, wet wipes, and hair conditioner. Siloxane-free alternatives have also been identified and evaluated by the crew, resulting in the selection of viable alternatives for the crew to choose from. These siloxane-free products have been delivered to ISS in early 2019 for use by the crew, though the crew has discretion to use products with siloxanes as necessary for crew comfort. In parallel, Boeing is delivering Charcoal/HEPA filters to be installed on ISS in 2019. These filters will remove atmospheric siloxanes before they can decompose to DMSD[12]. This removal step would occur prior to each Condensing Heat Exchanger in the US Laboratory Module, Node 2, and Node 3, providing the heat exchanger coating with additional protection against contaminants that degrade the coating's hydrophilicity. In addition to efforts to reduce DMSD in the condensate, NASA has worked with various vendors to develop an improved catalyst for the WPA Catalytic Reactor[13]. This effort identified a catalyst (developed by Collins Aerospace) that showed an increase in DMSD removal efficiency from 75 to 92%. Boeing and Collins are now funded to deliver a reactor to ISS in 2021 that implements this new catalyst to improve WPA capacity for DMSD.

As noted previously[1-5], the Catalytic Reactor has been limited to approximately a two year life due to leaking o-rings. Though initial ground testing was favorable, subsequent failure analysis has concluded the o-ring material is not compatible with the elevated process temperatures of the Catalytic Reactor for the planned 5 year life. To improve seal life, engineering personnel decided to reduce the Catalytic Reactor temperature in Standby to 96 C (205 F) instead of continuously maintaining it at the nominal temperature of 131 C (267 F). This operational scenario has been used with the current Catalytic Reactor since it was initially installed in the WPA in February 2016. After approximately 38 months in operation, engineering personnel have observed initial indications of a leak, including more frequent pressurization cycles of the reactor and temperature instability due to liquid external to the preheater. WPA Fault Detection limits have been expanded to allow continued operation pending crew time availability for a replacement with the on-orbit spare.

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

The Pump Separator ORU began exhibiting a new trend in the Mostly Liquid Separator (MLS) motor temperature in late 2016. The Pump Separator ORU contains the MLS and also the process pump for the WPA. The MLS is a rotary separator that removes any gas entrained in the incoming waste water. The MLS motor is cooled with a bypass flow of the WPA waste water. The motor temperature is monitored by two surface-mounted temperature sensors. The sensor data in Figure 15 shows the increasing trend of the MLS Temp and the MLS Temp Switch. The cause of the temperature increase is unknown, but it is believed that the bypass flow path around the motor may be partially obstructed by free gas or biomass. This theory is supported by the previous biofouling identified in this section of the WPA that required replacement of the ORU in 2010 and resulted in the waste tank management scheme discussed in previous papers[1-5]. As seen in Figure 15, the temperature increase has stabilized in the last year, though the temperatures are still elevated. The current Pump Separator ORU has been installed since 2012 and both the MLS and pump continue to function as expected. If the MLS Temperature Switch exceeds 245 F, the ORU will have to be replaced. Two spare Pump Separator ORUs with a new MLS are available on-orbit.

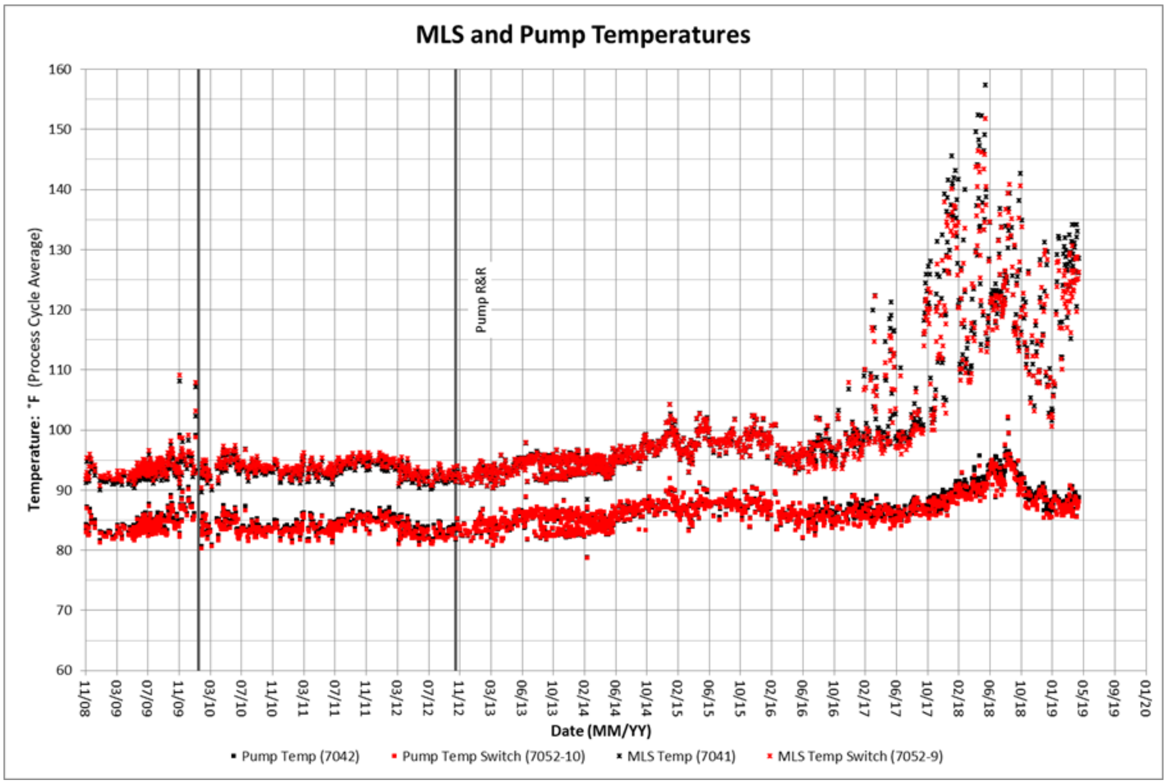

Figure 15. Increasing Temperature Trend of the MLS Motor

VII. Conclusion

In the past year, the WRS has continued to provide the ISS crew with potable water for drinking, electrolysis via the Oxygen Generation System, flush water for the Waste & Hygiene Compartment, hygiene water, and payloads. During this time, the WPA has experienced no significant failures. The MF Beds have now been installed for 42 months due to the extended DMSD trend and ionic breakthrough of both MF Beds. The Catalytic Reactor has exhibited indication of a slow leak after 38 months in service and is expected to be replaced in June 2019. This reactor has operated 14 months longer than previous ORUs with the increased seal life due to operating the reactor at reduced temperature during Standby.

The UPA experienced a failure of the FCPA in the last year, due to a degraded planetary drive gear. Though this was an expected condition according to the vendor, a design change to a machined gear is expected to extend the functional life of the planetary mechanism. Since the new DA has been installed, the UPA has produced distillate with nominal conductivity levels without unexpected incidents of belt slippage or elevated centrifuge pressure. This observation indicates this DA will not be plagued with the elevated conductivity experienced by the previous DA due to a leak of pretreated urine through the rear bearing. Finally, implementation of a phosphate-based urine pretreatment in early 2016 has allowed UPA to increase water recovery to 86%, during which time NASA engineering has observed no performance issues with the use of the phosphate-based pretreatment.

The initial Water Resupply Tank (RST) was launched on Orbital OA-8 and successfully offloaded into the WPA waste tank in 2018. Two additional tanks were launched on NG-10 in 2018 but have not been offloaded into the WPA as of May 2019. An additional 8 RSTs are planned to be launched on HTV-8. The repurposed Shuttle water tanks have been delivered and installed in the WSS Rack on ISS, while the remainder of the rack components were delivered in May 2019 to initiate operation of this critical function. Design and delivery of other critical hardware (BPA, UWMS, UTS) will continue but this hardware will not be operational on ISS until 2020.

Acknowledgments

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

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