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History, Current Operations and Management of Water Systems on the International Space Station

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Abstract

In November 2000, the Expedition 1 crew to the International Space Station (ISS) arrived onboard, thus beginning a 19+ year need to provide potable water to the crew, as well as water to key life support systems. For the first 8 years of ISS operations, the water systems' operations were relatively simple. It consisted of manifesting water via cargo ships or generated via the Space Shuttle fuel cells and stored on ISS to supplement the water processing systems on the Russian segment of the ISS. In 2008, the Water Processor Assembly (WPA), Urine Processor Assembly (UPA), along with a U.S. provided toilet arrived onboard, supplementing the Oxygen Generator Assembly (OGA). This new equipment, known as Regen ECLSS (Regenerative Environmental Control and Life Support Systems), provided a significant capability in recycling fluid within the ISS and minimized manifestation needs. Early in the operations of the Regen ECLSS system, it became clear that the tank capacities were under sized. This led to excessive use of costly crew time to perform water operations. In 2012, a group of ISS flight controllers and engineers proposed and developed a new system that would provide integrated water tanks that could be fully operated from Mission Control on the ground to move water around within the systems. This system has very recently been installed on the ISS and commissioning operations have occurred. This paper will provide a general history of water operations on the ISS, as new systems arrived, and new operations were required. Challenges with water balance, to both avoid overfilling the system as well as avoid running out of water, will be discussed, along with touching on the convoluted steps the Flight Control team had to perform daily to predict future water needs. Finally, the new water storage system will be discussed and the benefits it brings to ISS water operations.

Keywords: Water Management, Water Storage, Regeneration, Closed Loop Life Support, ECLSS, Logistics

Acronyms/Abbreviations

CFU: Condensate Feed Unit
CWC: Contingency Water Container
CWC-I: Contingency Water Container-Iodine
ECLSS: Environmental Control and Life Support Systems
EDV: 22 Liter Water Tanks
EDV-U: Urine water EDV
EDV-ZV: Potable water EDV
ISS: International Space Station
OGA: Oxygen Generator Assembly
SRV-K: Russian Water Processor
UPA: Urine Processor Assembly
WHC: Waste & Hygiene Compartment (toilet)
WPA: Water Processor Assembly
WSS: Water Storage System

1. Introduction:

Water storage and management on the International Space Station (ISS) has evolved over the two decades the station has been inhabited. From the early days of delivering tank by tank to the ISS, to today where water is recovered from humidity, urine, and CO2 reduction. From the early days of intensive crew operations to transfer water to various systems for use, to today when Mission Control Environmental Control and Life Support Systems (ECLSS) flight controllers can command the water systems to manage water storage operations, thus significantly minimizing the crew time required to manipulate water operations, saving weeks of crew time and associated costs ever year.

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Approximately 3.8 liters per crew per day is consumed. This volume is required to provide water for drinking, hygiene, flush water for the toilet, and water to electrolyze into O2. Without recycling water on ISS, approximately 8,300 kg of water would need to be launched to ISS. Even as the costs for launch are reduced, this level of resupply is unsustainable without recycling water. The more recycling that can be done, the more savings can be achieved. From the early days of only recycling humidity, a savings of 1.5 liters/crew/day, to the recent ability to process urine as well and even produce water from CO2 and H2, ISS water operations have gone through a significant changes over the last two decades. This paper explores some of the most significant changes and challenges to efficiently use and recycle water on ISS.

2. Russian Water Systems

2.1 Storage Tanks

The Russian segment Service Module contains two Rodnik Tanks. Rodnik tanks are 210 liter[1] water tanks that are the primary means by which water is stored on the Russian segment. These tanks consist of a bladder in a shell that can be pressurized on the backside of the bladder to expel water or vented to ambient pressure to allow them to be refilled.

The Russian segment utilizes smaller water tanks as well, called EDVs, that hold up to 22 liters[1]. These EDVs have several different uses. The EDV-ZV contains potable water from which crew can drink directly, and the EDV-U holds urine from the toilet. These EDVs consist of a bladder held within an outer metal shell. Like the Rodnik tanks, by either pressurizing the volume between the bladder and outer metal shell, or by equalizing that volume to ambient pressure, fluid can be transferred in or out.

2.2 Water Processing

The Russian segment water processor (the SRV-K) is a key part of the Russian water system architecture. Water collected by air conditioning systems feed into the SRV-K where it is processed and delivered to the Russian galley. In addition to the air conditioning units being a source of water, the Condensate Feed Unit (CFU) pump can transfer condensate fluid from a U.S. water bag into the SRV-K for processing.

2.3 Water Delivery

Since the beginning of ISS operations, Russian Progress vehicle delivery of water has been a fundamental and consistent means by which water is delivered and stored on the ISS. Progress vehicles contain two Rodnik tanks. While the Progress is docked to the ISS, crew pulls water out of the Rodnik tanks as need be. The water from the Progress Rodnik tanks can either be transferred directly from the Progress vehicle or can first be transferred to the Service Module Rodnik tanks for future use. Which path is taken depends on several variables, including the state of the current water inventory quantity, available containers, the current and near-term crew compliments (i.e. expected changes in consumption rates).

Along with launching water in the Rodnik water tanks, EDVs can be launched full as well, if the extra water consumables are needed at that time.

This was the prime method by which water was delivered to the ISS in the early days of station operations, as well as the only method available to deliver water during the post-Columbia accident timeframe when Shuttle flights were grounded. Like many challenges during those non-Shuttle flight years, water storage and management was an important one. In fact, in December of 2004, the ISS was approximately 1-2 weeks from running out of water due to the logistics challenge of relying on a single transport vehicle to manifest the crews' water needs.

3 U.S. Water Storage

3.1 Contingency Water Containers (CWCs)

In the early days of ISS, the Russian segment was prime for water processing and storage. However, the U.S. augmented the supply and collection of water. The U.S. would provide water storage inventory via portable water containers filled in the shuttle middeck. The CWCs were used by the Shuttle program for contingency storage reasons. The Space Shuttle was powered via fuel cells that utilized hydrogen and cryogenic oxygen to generate power. As a by-product of this power generation, water was produced. In fact, more water was produced than the Shuttle's crew required, leading the Shuttle to vent water periodically. When Shuttle mission's destination was to the ISS, the crew would offload the excess water into CWCs and then transfer them to the ISS during the docked mission phase. Overtime this built up enough reserves to both supplement the

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Russian provisions as well as provide contingency water if a Progress vehicle failed to arrive with its planned stores.

The water generated by the Shuttle's fuel cells was pure water, containing no minerals or biocides. Minerals were added to the CWCs during the offload process to improve taste. In addition, silver-based biocide was added in order to mitigate microbial growth while the water was stored on ISS.

As the U.S. and Russian systems were developed independently, the Russian and U.S. equipment used different variations of silver biocides that were incompatible. If U.S. and Russian water were to mix, the biocides would react with each other and precipitate out of solution, thus leaving the water with no protection against bacterial growth. Therefore, when the U.S. provided water to the Russian segment, the Russian teams would process the CWC water through the SRV-K (similar to how condensate was processed) to prevent the biocides from mixing.

3.2 Lab Condensate Tank

In February 2001, the STS-98 Shuttle mission delivered the U.S. Destiny Laboratory (Lab). The Lab contains a bellow style condensate tank that can hold approximately 73 liters of water. However, to maximize the lifetime of the bellows tank, the usable tank volume is restricted to approximately 45 liters. The tank stores condensate collected from the ISS atmosphere. Numerous air conditioner systems throughout the US, European, and Japanese modules condense humidity from the air and transfer the liquid condensate through common ISS plumbing to the Lab's Condensate Tank.

Until the U.S.'s water processing systems arrived 7 ½ years later, the Lab condensate tank would be regularly drained into CWCs for storage. These CWCs would then be stored and later processed by the Russian CFU and SRV-K, which is not plumbed directly to the U.S. segment. Offloading the Lab condensate tank into a CWC is a manual process, so in order to save crew time spent on this operation, the U.S. and Russian air conditioner systems were managed to maximize condensate collection on the Russian segment and minimize collection on the US segment.

On occasion, albeit rare, all the available ISS condensate storage capacity would be completely filled. Issues with the operations of the air conditioning systems, the manifestation of water when stores were already relatively high, a failure of the CFU system limiting the ability to transfer condensate to the Russian segment, are all examples of how the storage capacity could reach its full mark. In these rare occasions, the Lab condensate (and sometimes condensate filled CWCs) were vented overboard. This was highly undesirable as venting water is a waste of a valuable consumable, both water and propellant up-mass. ISS venting of water has occurred less than five times in the twenty years of operations. In addition, the water vent system is in the process of being converted to an additional waste gas vent for new technology development.

4. Shared Water Storage Issues

In August 2007, shuttle flight STS-118 flew to ISS and delivered eight CWCs. When a few the water samples taken were analyzed on the ground, several them were found to be contaminated with the Wautersia bacteria. Wautersia is only harmful to someone with a compromised immune system, but this was a big shock to the ISS water management system. Precautions are taken at every step of the water system's procedures to ensure an outbreak of bacteria does not occur. An investigation into this outbreak was performed, but the source was never determined. Wautersia is resistant to silver biocides, which also allowed it to propagate across ISS systems.

After these samples showed the presence of Wautersia, additional control and constraints were put into place regulating the use of water and water related hardware. Any stowage bags, hoses, connectors, etc. that may have come into contact with Wautersia was relegated to only be used in non-potable water systems, namely, the toilet flush water and the oxygen generator system. Any system that would come in contact with the potable water system was kept under tight control. These actions have prevented Wautersia from manifesting itself in the potable water system, thereby helping to maintain crew health.

5. Regenerative ECLSS

The largest advancement in water management onboard ISS came when the Regenerative ECLSS arrived on STS-126 in November of 2008. The Water Processor Assembly (WPA), Urine Processor Assembly (UPA), and Waste & Hygiene Compartment (WHC) were launched and installed in the U.S. Lab module to join the Oxygen Generator Assembly (OGA), which had been onboard for a couple of years. These systems together

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significantly helped to move towards a more closed-loop system, thereby significantly reducing the need and cost for manifesting water.

5.1 UPA

Crew's urine is routed from the WHC to the UPA waste tank. When the tank is full enough to warrant a process cycle, the UPA processes the urine and separates it into distillate and highly concentrated brine. This separation is performed via a low-pressure evaporation centrifuge. The urine water vapor that evaporated at low pressures is collected, condensed, and transferred to the WPA waste tank. The remaining fluid, concentrated brine, is collected in a brine tank with a filter, which is emptied after every couple dozen liters of throughput.

When the UPA was first installed, this brine tank & filter combination was removed and returned to the ground for refurbishing, to then be returned to ISS and reinstalled. With the onset of Shuttle retirement, this process that relied on round-trip refurbishment was not sustainable. Therefore, a new filter system was developed that allowed the crew onboard to remove and replace the filter separately. The new system's brine tank can be emptied into either the Progress vehicle's Rodnik tanks or old EDVs intended for disposal. This significantly reduced the amount of launch mass required to maintain UPA operations. The only loss in the regenerative system comes from the loss of the brine when it is emptied out of the filter tank. This results in an approximate loss of 15% of crews' urine output, about 0.2 liters/crew/day, just ~10% of what was lost before the Regenerative ECLSS systems became operational.

5.2 WPA

The UPA distillate along with the crews' latent humidity removed from the atmosphere is collected together in the WPA waste tank. When the waste tank reaches a level warranting a process cycle, the waste water is transferred through a series of filters, ion exchange beds, gas separators, and a high-temperature catalytic oxidizer in order to process the fluid into safe potable water for crew consumption. The WPA has gas and conductivity sensors throughout its processing stream such that any errant reading, indicating a possible breakthrough of a contaminant, will drive the WPA to cycle that fluid back to the waste water tank and reprocess. Upon the water successfully being cleaned, iodine is added as a biocide and the water is then stored in a product water tank which feeds the ISS potable water bus. This potable water bus leads to the crew galley for drinking and hygiene needs as well as to the OGA for oxygen generation.

5.3 OGA

The OGA uses water from the potable waterbus to generate oxygen via electrolysis. As the water is required to be extremely pure, the OGA strips the iodine biocide from the source water before electrolysis. As hydrogen is a byproduct of this electrolysis, the OGA has numerous gas sensors to ensure that no bubbles, that contain oxygen, can be mixed inside the system with hydrogen to create a potential combustion source.

5.4 Sabatier

To help close the water loop even further, a Sabatier system was flown on ISS for a number of years. The Sabatier system would gather the hydrogen from the OGA's electrolysis process and combine it with carbon dioxide collected from the ISS carbon dioxide scrubbing systems. The Sabatier would combine the oxygen and carbon dioxide to create water and methane. The water was transferred back to the WPA for processing and the methane was vented overboard. The Sabatier in many ways was a technical demonstration system and after many years of operation was removed from service and returned to the ground. A new updated Sabatier unit is expected to return to ISS in the next few years.

6. Introduction to Water Balance Operations Utilizing Regenerative ECLSS

The Regenerative ECLSS systems were essential to enable six-person crew occupation of ISS. The amount of up-mass in the form of water would have been impractical to sustain without the ability to reclaim the mass of water. As of 2020, the Regen systems have saved over 39,000 kilograms[3] of water. Recycling water is and will be required for any long-term space flight mission and was one of the biggest advancements that enabled the ISS to increase the crew capacity from three to six crew. Maintaining a vehicle as complicated as ISS requires a certain amount of hands on maintenance. Filters clog, walls get dirty, and crew must control the entropy of their home. An increase in the number of crew onboard means a lower percentage of the total crew time is spent simply keeping things running. More crew time availability allowed the ISS program to focus more on science, research, and ISS utilization, than on maintenance. However, this benefit did not come without a

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substantial amount of oversight and management required from both the crew and ground. [2] The Regenerative ECLSS systems were very well designed but, over time, unforeseen operational and system performance issues began to arise. The teams of ground flight controllers and engineers managing these systems faced repeated challenges related to biofilms, system failures, logistics, variations in input vs output, and the drive to minimize crew time spent managing the Regen systems.

7. Early Issues with Regenerative ECLSS Water Balance

During early operations of the Regenerative ECLSS systems there were occasional start-up transient failures as the teams learned how the systems operated in microgravity. The systems were adjusted and recovered from each of these transient faults, but depending on how long it took to recover the system and how much water was in the potable tank at the time of failure, it was possible for the crew to run out of potable water. The process for manually adding potable water from ISS reserves to the potable water tank was time consuming and often introduced air bubbles that had the effect of clogging potable water filters, as microbial filters do not allow air bubbles to pass through the filter at potable water system pressures. The clogged filters would drive the need for additional crew time to replace. To increase the time available to recover from unknown future failures, the team maintained the potable water tank full as possible, in order to maximize the available drinking water. This led to processing waste water as often as possible. This mode of shorter, more frequent process cycles caused the waste water tank's bellow to move over a relatively small range. It was suspected that biofilm grew between the pleats of the tank's bellows as the tank travelled over a relatively small volume [4]. When a large amount of condensate collection occurred between process cycles, the waste water tank would fill, which compressed the bellows pleats and likely extruded large quantities of biofilm from the bellows into the waste water (see Fig. 1). During the subsequent process cycles, the released biofilm would clog downstream components. The recovery was costly in crew time and spare parts, so operational workarounds were developed to mitigate biofilm growth and release in the waste tank.

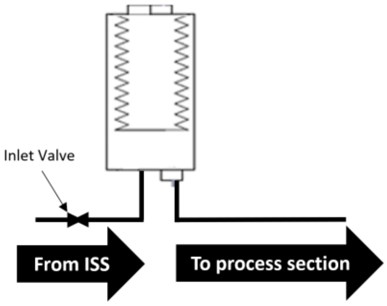

Figure 1: Waste Water Tank

7.1 Biofilm Controls

The first of these was to cycle regularly the waste tank such that the bellows regularly moved through the full range of extension and contraction. The hope was that large amounts of biofilm would not be released all at once, and that this could limit the growth with regular cycling. Follow-on water sampling did show an improvement in the mass of biofilm.

The second control was to minimize flow reversal across components with small clearances, such as system valves and connectors. Maintaining one-way-flow into the tank's inlet helped keep biofilm from being released, but increased the complexity of managing the ISS water systems. Some of the challenges related to the inability to backflow from this tank will be discussed in section 8.

In addition to the two operational controls, additional filtration was added on the outlet of the waste tank to capture biofilms before it reached the processing components of the WPA.

Lastly, clean water is occasionally added to the waste water tank to supplement the water consumption on ISS. Most of this supplement water is relatively clean and sometimes contains low levels of biocide. It is preferred to add water to the waste tank and process it into potable grade water rather than to manually fill the potable water tank. Potable water transfer exposes the potable water connections to potential contamination and ingestion of air during the transfer operation.

8. Potable Water Reserve Logistics

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As the Space Shuttle Program neared retirement, every effort was made to preposition as much water as possible on ISS. At the end of the STS-135 mission, approximately 2700 liters of water had been stored on ISS mostly in the form or iodinated water. The silver water was stored in 45 liter CWCs and the iodinated water in a smaller 22 liter iodine compatible version of the CWCs, known as Contingency Water Container-Iodine (CWC-I). Both containers use bladders to contain water inside of a protective outer cover. There was a minimum quantity of iodinated water that was needed to maintain on orbit to cover contingencies such as a missed resupply. At first, nearly all the prepositioned water was potable grade (silver and iodinated).

The storage of iodinated water in CWC-Is created some logistics difficulties due the water's limited shelf-life and the bladder's gas permeability. A 1-year shelf life for the stored iodinated water was driven by an interaction between the iodine and the container materials. It was known that the iodine could be absorbed by the bladder material and that would result in reduced biocide effectiveness over long periods of time. There was no long-term data on iodinated water stored in these containers, so a test was started to collect data on how the water quality was affected over time. The test involved analyzing samples from a CWC-I on the ground until there was not enough water to continue the test. The test showed that storing iodinated water in this configuration was acceptable for 3 years. On ISS, if the iodinated water expired, its contents would be pumped to the WPA waste tank. In doing so, the container would be downgraded and discarded. Refilling a downgraded container with potable water risked contaminating potable water equipment, so the container would have to be discarded.

To maintain the potable water stockpile, the crew would need to transfer the about-to-expire water to the potable tank (see Fig. 2). The use of the water in the potable water tank was closely monitored and when all of the old water had been consumed from the tank, the crew would then fill the same CWC-I with freshly iodinated water. The goal was to maximize the quantity of unexpired water on ISS and downgrading the limited quantity of potable CWC-Is to condensate grade was considered unacceptable.

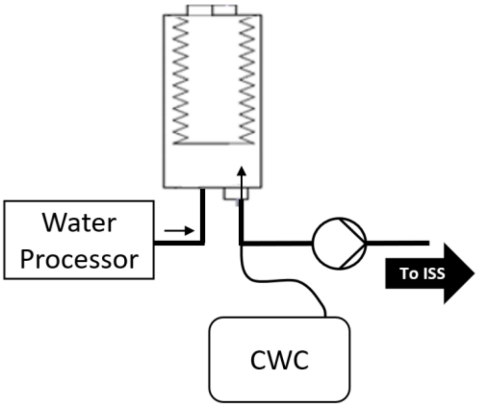

Figure 2: Water Transfer to Potable Water Tank

The potable water tank refill process was extremely inefficient and consumed a large amount of crew time that will be described in section 9. If the shelf life of the CWC-I water could be extended, the "dump and fill" operation needed to maintain the stockpile of clean potable grade CWC-Is could be minimized, thus saving a substantial amount of crew time. Unfortunately, the only available water old enough to continue the ground test was in low earth orbit. Therefore, three of the older CWC-Is were returned to earth to re-start the lifetime test.

The test water and much of ISS water were essential the same age, so this set up a fleet leader situation. The test on the ground would be sampled and analyzed periodically. A balance between the frequency of collecting samples and the ability to run a long-term test had to be made. Frequent sampling would allow for more CWC-Is to remain within shelf-life but would also shorten the test's ultimate duration.

This scenario would play out as follows. A sample would be taken on the ground and large batches of water would have their shelf life extended. Many months later, another sample would be taken to extend the shelf life. Between the sample collections, large quantities[1] of CWC-Is would expire and then unexpired when the next round of samples were analyzed. The CWC-Is that were experiencing the expiration / unexpired cycles were affectionately called "Zombie bags". From the time that the newly unexpired CWC-Is were cleared until they

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[1] Large quantity of CWC-Is expired in very narrow windows according to the date by which they were filled on previous shuttle missions.

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expired was a window to use the container. This process led the teams to prioritize adding large quantities of water to the potable system while the water was unexpired.

9. Challenges of Potable Water Transfer

As mentioned in section 8, it was preferred to manage water quantities by adding and removing water at the waste tank as it was more efficient. There were many reasons for this, but the most important were:

- Easy crew access to waste water connections
- Waste water does not expire
- Could avoid exposing potable water connections to contamination
- Water processor could handle large air bubbles, so no need to degas the CWC beforehand
- Cross-contamination less of a concern
- Operation to remove waste water used less crew time and did not interrupt potable water supply

The transfer of potable water directly to the potable water systems presented an additional set of challenges. The potable water system cannot accept air bubbles because they would clog the microbial filters at the potable water dispenser in the crew galley. Thus, adding air bubbles to the potable water system would result in an inability for crew to access drinking water and resulted in hours of unscheduled crewtime replacing filters.

9.1 Managing Air Bubbles in Microgravity

Without the buoyancy provided by gravity, air bubbles in water can be difficult to remove. Condensate collected by air conditioners have centrifugal separators to remove air bubbles. Unfortunately, there was no acceptable separator available to remove gas from the potable water reserve CWC-Is. The CWC-Is that were used to contain the potable water reserve used a bladder that was gas permeable. This would cause bubbles to form and grow over time to the point where the amount of bubbles would become unacceptable. The crew had to manually remove the air bubbles to prevent them from entering the potable water system. This is not an easy task in micro-gravity. To remove air bubbles, an operation was developed whereby the crew would wrap the container in elastic cords, then the crew would spin themselves while holding the bags and orienting the containers' drain outlet towards the center of rotation. Watching the air bubbles through the transparent bladder, as the bubbles migrated towards the drain port the crew would open a valve and vent the bubble.

9.1.1 Degassing Cost

This was not a desirable situation. The degassing process was very time consuming, messy, and tedious. Crew was required to remove all visible bubbles because even small bubbles would coalesce at the filters and eventually clog them. The crew reported that they could remove the large air bubbles easily but quickly ran into diminishing returns as they tried to get all the smaller bubbles. Every one of the about-to-expire bags had to be degassed and refreshed.

9.1.2 Solution to Microgravity 2-Phase Fluids

Alternate means were investigated to degas the containers, including centrifugal separators, membrane separators, and hollow fiber separators, but each of the available technology had drawbacks. The concerns were mostly related to microbial control at the gas liquid interface and/or cost of developing a new custom technology.

Potential for cross contamination is always a concern with onboard water systems, so operational controls and hardware controls were developed to mitigate that risk. One of the hardware items developed was a point of use microbial filter for exchange of water between the US and RS systems. The filter was intended to prevent cross-contamination (in either direction) when water was exchanged to assist the other partner with nominal and contingency operations. The filter included a 0.2 micron element to prevent microbial transfer and thus it suffered the same issues of the potable water bus filters, it would clog with air. One difference the new filter had from the other microbial filters in the potable water systems was that the point of use filter included an easy to access vent port. The filter was not intended to be used with potable water systems, but the ground teams saw the value in something that could potentially save a significant amount of crew time spent removing the small bubbles in the CWC. After consulting with microbiologists and water quality experts to make sure that the proposed degassing use would not affect the rest of the potable water systems, program approval to repurpose a subset of these filters to test as gas traps was obtained quickly.

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9.1.3 Implementation of Gas Separation within Stored Potable Water

The gas removal sequence was updated to connect the filter between the CWC-I container and the potable water tank. The tank is sub-ambient, so it would suck water through the filter until the filter was loaded with air. Mission control teams could monitor the transfer rates on the ground and when flow stopped, could ask the crew to vent the filter when they had a free minute between their activities.

This proved to be a very effective method to degas the water, saved significant amounts of crew time, and provided an additional layer of microbial protection that did not exist before. Over time, it was determined that a combination of a quick spin to remove large bubbles followed by letting the filter capture small bubbles was the most effective use of crew time. No potable water systems have been air clogged since implementing this methodology.

10. Challenges of Managing an Underdamped System

The Regenerative ECLSS internal tanks were sized for average use rates. Spaceflight has shown that individual crews can produce and consume a wide range of water volume. Therefore, average rates were the only good method of determining costs and manifests, but when it came to the Regenerative ECLSS tanks, sizing them based on an average crew use rate led to the system being underdamped.

Many variables contribute to the water in – water out rate balance. Many different variables must be considered when trying to predict water needs in and out of the ISS water systems. Some (but not all) of the variables include, crew individual differences, plant growth, atmospheric mixing, temperature of the condensing heat exchangers, international partner operations, changes in crew compliments, sudden changes in cabin temperature, water system failures, recovery systems efficiency, oxygen production, spacewalks, changes in cabin volume (visiting vehicles, etc.) must all be carefully considered when trying to predict the next time crew would need to add or remove water. Sometimes the changes were predictable as in the operations described in section 8 for refreshing the potable water reserve, others were very difficult to predict such as system failures. The problem was that a small change in any of these variables drove a change in rate. That variability combined with the systems limited storage capacity resulted in an underdamped system.

With the system being underdamped, water had to often be removed at times and then added back just a short time later. This constant juggling of where (and when) to hold water led to a new type of operations the ECLSS flight control team had to develop, that of Water Balance. Water Balance is nothing more than a term referring to the interplay between input, output, and capacity of the individual tanks within the water recovery system. In all, the ECLSS team initially had approximately 24 variables to consider in order to predict when process cycles would be required for UPA or WPA, and thus where water would be located, across the waste and product tanks. The flight control team quickly adapted to this new need, however, given the variables were constantly changing, the ability to predict was limited to the near term. In general, the ECLSS flight control team could accurately predict water balance operations one day into the future, make a close prediction three days out, and a vague conceptual idea a week away. Due to the variability in this, it was determined that multiple hours twice a week would be kept open for crew to perform water balance operations if required. This was an unfortunate use of crew time as it could lead to cancelling a two-hour block of time at the last minute without providing sufficient time to have crew perform other work, thereby losing hours of crew productivity.

10.1 WPA Failures

The WPA has three independent sections: collection, processing, and delivery. A failure in the water processor’s process section forced crew to drain the waste water collection tank and manually fill the potable delivery tank every few days.

A loss of the WPA’s waste water collection function required a quick response from the crew to reconfigure the condensate collection capability to the backup Lab Condensate tank. The two tanks could not be connected at the same time due to the interplay between the two tanks’ bellows backpressure. The WPA waste water tank bellows had a higher spring force and thus waste water would backflow out of the tank and fill the condensate tank. Recall in section 7.1, that back flow is highly undesirable due to the risk of biofilm clogging the inlet valve as well as the restriction on the upper limit of the Lab condensate tank, mentioned in section 3.2, would severely limit the operational use of the WPA waste tank if they were combined. After the WPA was recovered, crew would once again reconfigure the waste water systems. The water collected in the condensate would be drained to a CWC, stored, and then at some point in the future be pumped into the WPA.

A failure of the WPA's delivery function would force the crew to consume potable water from the Russian systems, as there was no backup capability to the WPA for potable water delivery. The US and Russian life support teams have agreements in place to support each other in the event of temporary system failures.

10.2 Maximizing Urine Processing

Soon after the US regenerative ECLSS system was commissioned, agreements were reached between Roscosmos and NASA for the US to begin processing Russian urine from the Russian toilet. This was mutually beneficial to both segment with respect to saving up-mass and for creating a means for disposing the Urine processor's brine. The Russian teams would dispose of urine in the emptied Rodnik water tanks. The US processing of Russian urine reduced the volume of fluid that needed to be disposed on Progress and reduced the up-mass required to supplement the non-closed-loop nature of ISS systems. The ECLSS team began coordinating with the Russian Life Support Flight Control teams (SOZh) to begin processing Russian urine. The operation was quite simple. The cosmonauts would transfer a EDV of urine to the US segment, and a few days later the US segment would return the empty container. Periodically, the US Urine processor's brine would be transferred to an EDV and when the Progress Rodnik water tanks were empty, all of the stored brine EDVs would be transferred to the Progress Rodnik tanks. The Russian development teams were also refining their urine processor (an improved version from what was used on MIR) and this arrangement where the US UPA processed Russian urine helped cover the period of time until the Russian urine processor system was commissioned. While this arrangement aided both sides, it did put increased throughput on an already underdamped system that often exacerbated the water balance issues outlined above.

10.3 Crew Time Associated with Water Re-Supply

With the current ISS system configuration, approximately 1000 liters a year is required to be manifested until further improvements could be made to further "close the loop". Resupplying the ISS water needs consumes a significant amount of crew time. On average, it takes approximately 40 minutes to manually add 20 L of water, which translates to about 30 hours per year. Adding more than about 20 L at a time was undesirable due to the overall system capacity and adding less was not efficient with respect to crew time.

11 Addressing Water Management Challenges

As mentioned at the beginning of section 10, soon after commissioning the Regenerative ECLSS system, flight controllers recognize the need for supplemental capacity. As ISS evolved from the era of assembly and into the era of utilization, there was increased pressure to minimize crew time spent maintaining systems. Flight controllers began looking for a way to add capacity and facilitate ground control of when and where water is stored. ECLSS flight controllers brought a proposal to the ISS Program office to add water system capacity for the purposes of saving crew time. Several proposals were considered between flight controllers, engineering and the ISS program office.

11.1 Efficient Water Resupply

The teams settled on a design that would add several large disposable water containers and several tanks capable of storing potable water. The disposable containers were commercially available and would be plumbed into the ISS waste water bus as Resupply Tanks. The flight control team would have the ability to transfer the water contents on demand, as the Regenerative ECLSS systems needed additional fluid. Additionally, the design would allow the Lab Condensate tanks to be plumbed directly to the waste water bus with the addition of a ground-controlled valve. That meant if the WPA waste collection failed during crew sleep, flight controllers could redirect condensate to any of the backup tanks with a few commands from the ground (see Fig. 3).

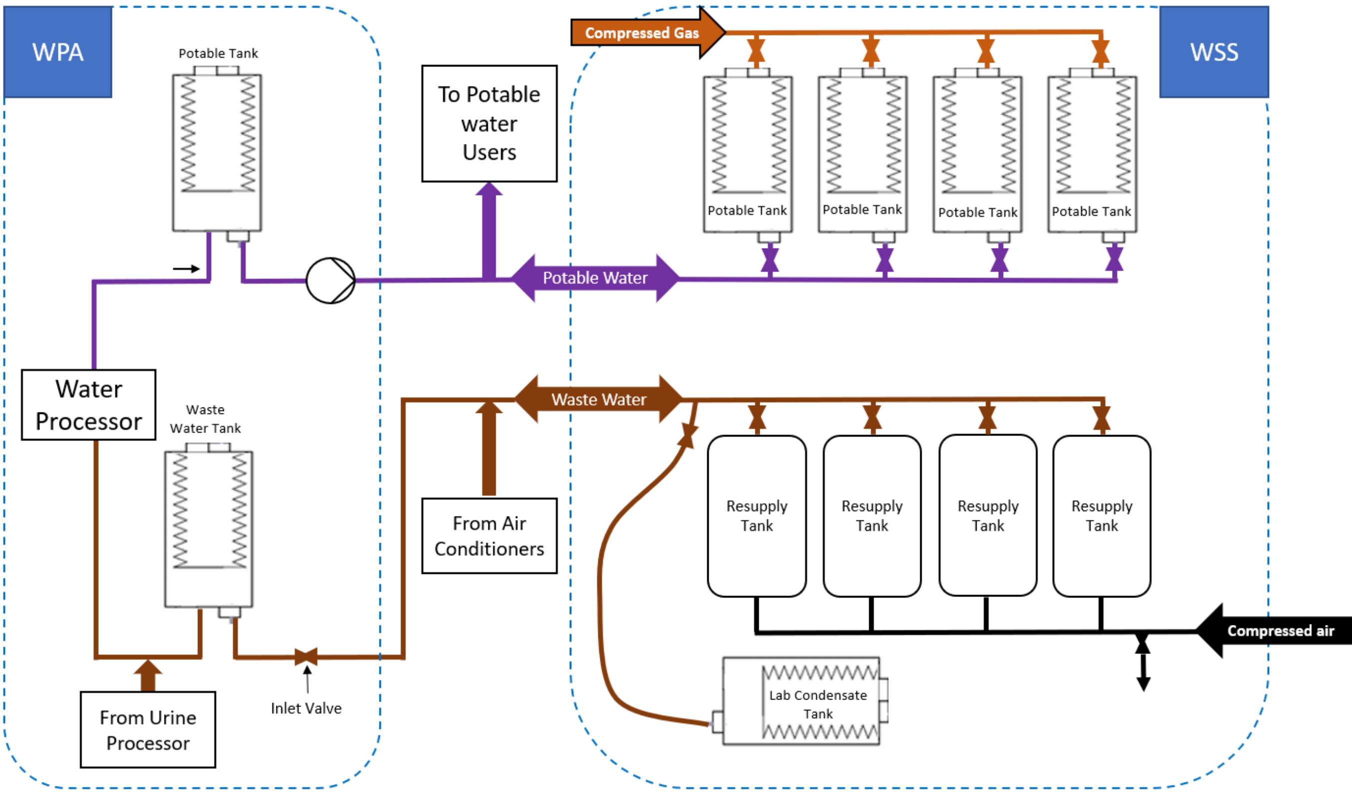

Figure 3: WPA and Water Storage System

11.2 Back-up Potable Water Capability

The potable tanks would provide a backup potable water delivery capability if WPA failed. There were not as many options for potable water tanks that would meet the potable water requirements, have enough capacity, able to be pressurized to expel water, survive launch vibration, etc. Fortunately, the recently retired shuttle fleet had several tanks that met these needs. Arrangements were made to source several of the Shuttle's fuel cell tanks and fly them to ISS as part of a new Water Storage System (WSS). The addition of potable tanks provided a new back-up capability to the WPA's potable tanks and would allow up to a month of water supply. This time would provide crew and ground teams time to identify the cause of the WPA failure and schedule a crew repair. Before this capability, the ISS crew and ground teams would have to respond immediately, troubleshoot, and schedule repair to prevent paying high costs in terms of crew time and lost utilization.

During the development of the WSS, resupply plans were changing within NASA. The resupply of water after the Russian Urine processor was activated would need to be planned months in advance. The commercial tanks for the WSS had a capacity of approximately 75 liters. Four of these tanks could be changed out in one 30-minute crew activity. In theory, 300 liters of volume could be changed out in the time it used to take to pump in a single 20 liter CWC-I. This economy of scale was a great advantage of switching to the large disposable tanks for resupplying ISS. The disadvantage is that they tanks were not collapsible as were the CWC-I and thus took up more physical space.

11.3 Back-up Brine Disposal Capability

The tanks rigid shell was not a complete liability. Flight Controllers recognized that the tanks could provide a benefit that the CWC-I could not. The tanks could be used to dispose of the concentrated brine generated by processing urine. Without processing Russian urine, the demands for finding storage for brine were reduced, but there was only one option and that depended on the availability of the empty Progress Rodnik tanks.

Using commercially available water tanks to hold water was not that difficult to figure out, however, using them to hold brine with concentrated pretreated urine presented a bit more of a challenge, due to the acidic pretreat. The tanks were thoroughly tested to ensure materials compatibility and ultimately were approved to hold brine as an alternate means of disposal with operational controls that limited the duration of exposure.

The WSS parts were flown across several resupply mission and were assembled on ISS in mid-2019. After the WSS was assembled, flight controllers performed a series of leak checks and functional checkouts.

Soon after the system was tested, a critical component within the WPA began to show signs of imminent failure. The water processor heats up for each process run to sterilize water and facilitate catalytic reaction. The

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failing component was degrading after each thermal cycle. Using the WSS, flight controllers were able to extend the amount of water processed for each thermal cycle. A WPA process cycle was started, when the WPA waste tank would get close to empty, flight controllers would refill water from one of the four WSS Resupply tanks. When the WPA potable water tank would get nearly full, water would be transferred to the WSS potable water tanks. Using these techniques around the clock, hundreds of liters of water could be processed in a single thermal cycle. Eventually, the processing function of the WPA failed. Flight controllers then reconfigured potable water delivery and waste water collection to WSS. All these actions were performed without any crew interaction.

12. Summary

As we look back over the 20 continuous years of crew living on the International Space Station, the ISS life support system has evolved significantly since the first element launch and will continue to evolve, and along with it, water storage and management. Operational techniques and workarounds have allowed these systems to continue to support life on the ISS and these techniques will continue to adapt to solve unknown future challenges. The ISS is the best place in the universe to improve this hardware so that future missions can take humans deeper into space and return them safely to Earth. In fact, there are many efforts currently on ISS that will advance the state of the art of life support systems. Many more systems are planned to be tested in the upcoming years. This is truly a very interesting time to be involved with life support systems.

Acknowledgments:

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