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Upgrades to the International Space Station Urine Processor Assembly

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The ISS Urine Processor Assembly (UPA) began operations in November 2008. Though the UPA has successfully generated distillate from crew urine, several modifications and upgrades have been implemented to improve overall system performance throughout the years. Current and future upgrades to the UPA will continue to focus on improved system performance and reliability, focusing next on a flight demonstration experiment of a vacuum pump utilizing scroll pump technologies. The upgraded Distillation Assembly, described in further detail in previous publications, will also be available for on-orbit integration within the year. The following paper discusses progress on the Purge Pump and Separator Assembly (PPSA), and concept considerations for future UPA upgrades.

Nomenclature

cm = centimeter
DA = distillation assembly
FCPA = fluids control and pump assembly
ISS = international space station
MSFC = marshall space flight center
OGS = oxygen generation system
ORU = orbital replacement unit
PCPA = pressure control and pump assembly
PPSA = purge pump separator assembly
psig = pound force per square inch, gauge
SPA = separator plumbing assembly
TT&E = tear-down testing and evaluation
UPA = urine processor assembly
WPA = water processor assembly
WRS = water recovery system

I. Introduction

The International Space Station (ISS) Water Recovery and Management System provides potable water for crew drinking and hygiene activities, oxygen generation, urinal flush water, and various payloads. To this end, wastewater is collected in the form of crew urine, humidity condensate, and Sabatier product water and subsequently processed by the Water Recovery System (WRS) to potable water quality standards. This product water is provided to the potable bus for the various users. The WRS is comprised of the Urine Processor Assembly (UPA) and Water Processor Assembly (WPA), which are located in two International Standard Payload Racks named WRS-1 and WRS-2 as shown by Figure 1. The layout of the two WRS racks is as shown in Figure 1, along with the Oxygen Generation System (OGS). The WPA is packaged in WRS Rack 1 and partially in WRS Rack 2, linked by process water lines running between the two racks. The remaining portion of WRS Rack 2 houses the UPA. Detailed process descriptions and schematics of the entire WRS are provided elsewhere[1,2].

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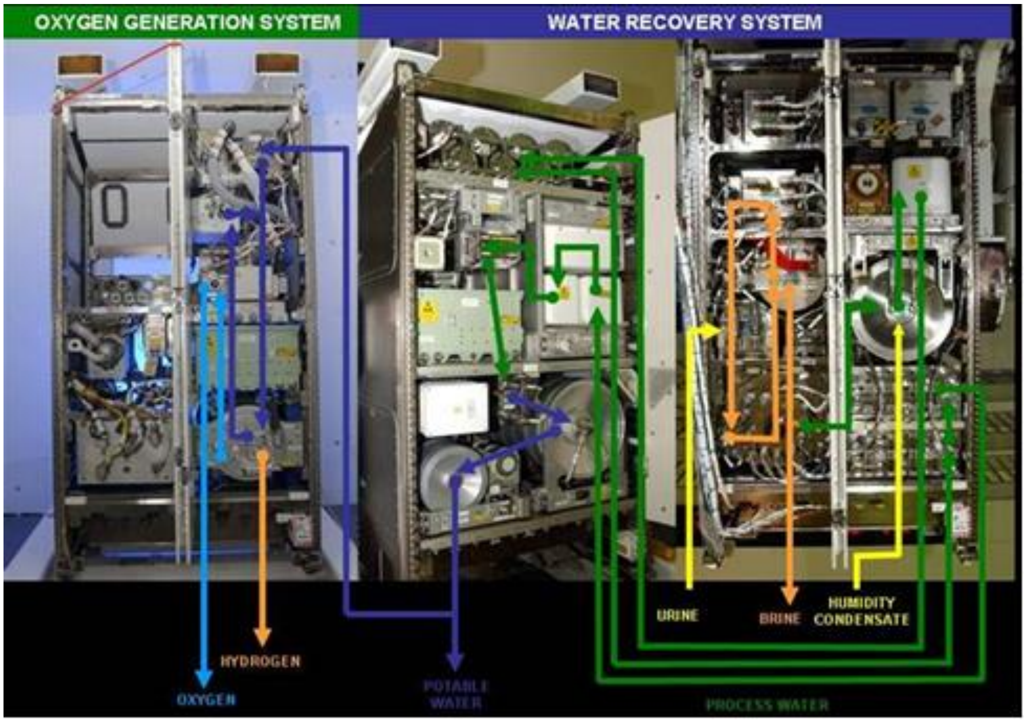

Figure 1. International Space Station Regenerative ECLSS Racks and process flows for the OGS and WRS.

II. Status of UPA Upgrades

NASA MSFC Engineering completed an extensive evaluation of the UPA hardware in 2017 to identify all areas in which improved reliability would better position UPA as a viable technology for future missions. These areas were prioritized and an agreement was reached with the ISS Program Office to fund those that provided the highest return on the investment. Once developed, these upgrades will be incorporated into ISS UPA ORUs to collect extended performance demonstration in an operational flight environment. Successful demonstrations will provide tangible life cycle cost benefits to the ISS over its remaining operational life and increase confidence that the UPA design can meet demanding exploration mission needs. More recent failures and subsequent investigations have identified further areas of redesign to extend reliability.

A. PCPA Design Upgrades

A persistent problem on ISS has been the short life span of UPA pumps. The most prevalent failure has been harmonic drive failure for FCPA, but pressure control and pump assembly (PCPA) units have typically failed from tube rupture without achieving the desired lifetime. Only one PCPA failure was induced by the frequently observed harmonic drive failure like that of the FCPA. Most recently the first planetary drive PCPA failed due to high motor current. A failure investigation is still pending. As a result, better strategies for alternative pump architectures have been pursued.

1. Purge Pump Separator Assembly (PPSA)

The peristaltic pump technology was previously selected for the vacuum pump because it could pump two-phase flow and the peristaltic tubing was compatible with the fluid composition (water, water vapor, and non-condensable constituents from the pretreated urine). However, the peristaltic pump is relatively large and is challenged to maintain the vacuum required for the DA operation, especially when excess gas (either dissolved or free) is fed to the UPA or when the stationary bowl heaters are powered to remove condensate in the stationary bowl. With respect to scroll pumps, previous designs did not effectively deal with the two-phase fluid coming through the purge line. However, NASA personnel have identified a scroll pump that provides improved efficiency compared to the peristaltic pump that is currently in the PCPA. The unique design of the pump head allows it to process liquid and gas simultaneously while starting up against the vacuum maintained by the DA and pumping against the backpressure (~4 psig) required to push the purge distillate through the Separator Plumbing Assembly (SPA) and into the distillate delivered to the WPA. This pump provides more capacity than the current peristaltic pump while requiring about 1/3 of the power for operation.

Sufficient ground tests have been completed to merit a technology demonstration of this hardware on ISS. Though the materials used in the scroll pump head were acceptable for ground tests, they will have to be upgraded for a flight unit to ensure compatibility with potentially corrosive liquid this pump may be exposed to during operation. In addition, NASA MSFC is selecting a new motor for the pump to meet performance and life requirements for this application. The new motor/pump assembly will be significantly smaller than the current peristaltic pump, providing sufficient volume for integrating the current SPA ORU with the new scroll pump. This integration is desirable because currently the SPA ORU has to be replaced in its entirety when the SPA membrane reaches end of life. This is a significant mass penalty given the SPA membrane itself weighs less than 1 kg. By integrating the new scroll pump with the components in the SPA ORU (including the SPA membrane, a regulator, the purge filter, and a manifold), approximately 27 kg (60 lbs) of mass will be saved. Moreover, additive manufacturing efforts are being pursued which will further reduce the overall mass. The PPSA in its entirety will have 5 major subassemblies that will be fully integrated into the same footprint as the PCPA: Purge Pump, Manifold (additively manufactured), Controller, Separator Regulator and the Separator and Filter Subassemblies.

The scroll purge pump subassembly and manifold designs have been used during urine brine production and other test series during the past years at MSFC on the UPA development unit. Current ground testing has logged well over 1200 hours on the scroll pump, maintaining adequate vacuum in the UPA system with no significant performance degradation reported. Necessary scroll pump cooling considerations have also been addressed by designing an efficient coolant mount.

This new combined ORU assemblies with maintainability as a forefront in design will provide the means to remove and replace the scroll pump, the SPA membrane and the purge filter without replacing any of the ORU’s structural frame. To support this effort, the limited life items will have quick disconnects, captive fasteners and ease in accessibility. Particularly, the SPA and filter are the most accessible components as they are more planned maintenance. This hardware is currently anticipated for delivery to ISS in 2021 for a functional demonstration.

2. Scroll Pump Subassembly Prototype I

A prototype scroll pump was constructed, integrating the vender supplied custom scroll pump head with the motor and cooling mount. This prototype was used to prove the design, fabrication, and added requirements to address new sealing and material selection concerns from the commercial-off-the-shelf model. Although this prototype would not have a full flight-like construction (with the exact quick disconnects and final material fabrications), successful testing of the new custom scroll pump head could still be assessed. Figure 2 shows the scroll pump integrated with the motor and coolant mount. The prototype was fully integrated into the MSFC UPA development test unit for a suite of testing including but not limited to pumping efficiencies and thermal effects. This series of testing would be used to identify any necessary redesigns.

Prototype I testing continued to exhibit improved pumping capacity when compared to the PCPA. On-orbit considerations for pumping capacity plays a significant role when new ORUs are installed. Particular ORUs are flown under vacuum; however, during natural vacuum decays, these ORU can lose some of their vacuum the longer they sit in stowage. A study was conducted that captured the efficiency of the scroll pump reflected in the elapsed time from a fully evacuated DA (largest volume ORU) from ambient pressure. The scroll pump was able to bring the pressure down to near operating vacuum condition in just over 35 minutes. This far exceeds the PCPA pump efficiencies where several hours of 100% duty cycle were required to achieve operating vacuum conditions.

During the Prototype I testing, it was also identified that corrosion was still a concern for selected internal components still integrated in the Prototype I. Rusting of non-corrosion resistant components exposed to water accumulation within the scroll pump were observed. Despite the corrosion events, the pump performance was not influenced in any measureable manner, a testament to the technology’s robustness. However, a second generation Prototype II is currently being pursued to modify internal components with corrosion resistant components and complementary redesign of the scroll head to reduce residual water accumulation within the scroll pump. Once this updated prototype unit is available, further testing can be pursued.

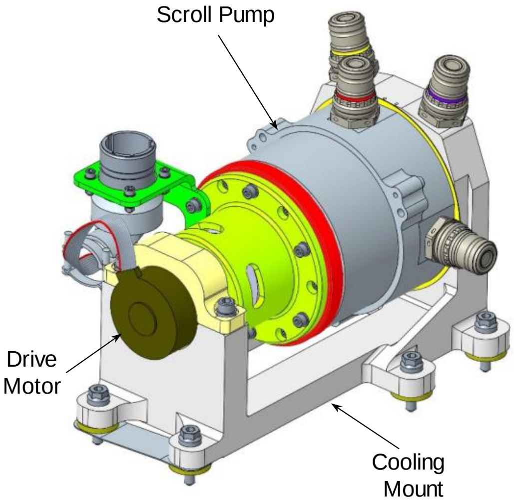

Figure 2. Scroll pump for UPA Technology Demonstration.

3. Purge Pump Separator Assembly (PPSA) Astronaut Trainer

The PPSA technology demonstration marks a shift in NASA MSFC ECLSS hardware design philosophy towards intermediate level maintenance, as future long duration missions will necessitate crew maintainable hardware. One aspect of building crew maintainable hardware is providing an astronaut trainer prior to delivery of the hardware. To that end, the PPSA technology demonstration package includes an astronaut trainer. The main goals of the astronaut trainer are providing a low cost and high-fidelity prototype of the PPSA for astronauts to train on.

To achieve these goals, a relatively novel approach to building the astronaut trainer was implemented. This approach combined additively manufactured components with flight-like parts in several subassemblies. While some components are strictly flight-like and others are strictly additively manufactured, most subassemblies combined both approaches. This combination of additively manufactured components and flight-like components has been implemented to allow astronauts to train on every mechanical/electrical/fluid interface that could potentially need maintenance in flight.

Examples of additively manufactured components include the quick disconnects on the front of the astronaut trainer enclosure, as shown in Figure 3. Procuring flight-like quick disconnects was not feasible due to the high cost and long lead times, along with a lack of cost effective alternatives. MSFC engineering personnel determined the best approach was to these components in a CAD software so they could be additively manufacture. Using this approach, components of acceptable dimensional accuracy were produced that are capable of interfacing with certified quick disconnect components for training purposes.

A combination of flight-like and additively manufactured components has been utilized throughout the subassemblies within the PPSA unit. These include the manifold, purge pump, regulator, and controller box. The PPSA manifold, for example, utilizes additively manufactured pressure sensors that can be successfully mated to flight-like electrical connectors. A wiring harness has also been made with flight-like parts which can be connected to and disconnected from the pressure sensors. Figure 4 showcases the additively manufactured pressure sensors with flight-like electrical connections. This combination of components provides a low cost, dimensionally accurate subassembly that can be used to simulate potential maintenance activities for the subassemblies in the PPSA.

Figure 3. Additivity manufactured quick disconnect compared to flight quick disconnect.

Figure 4. Additivity manufactured pressure sensors with flight-like electrical connections on manifold.

There are many ways to approach building an astronaut trainer, and methodologies will change based on different design drivers. The PPSA project is NASA MSFC ECLSS first attempt at building an astronaut trainer. The project aimed to strike a balance between different components and technologies that fit its budget and design drivers. This led to a relatively novel approach of merging flight-like parts with additively manufactured components to create most of the subassemblies at a fraction of the cost of buying actual flight parts or traditionally manufacturing prototypes of them. Because of this, it is expected that this approach will be strongly considered and utilized where possible on future astronaut trainer projects.

B. Distillation Assembly Design Upgrades

In early 2020, the upgraded DA SN002 Rebuild arrived on the ISS. This unit contains the next exploration upgrade designs which will further enhance performance, functionality, and reliability of the Distillation Assembly. Provided below are the five major upgrades fully integrated in this upgraded unit: Toothed (synchronous) belt drive, centrifuge bearing seals, liquid level sensor, Teflon spacer seal, and motor mount thermal isolator. The newly upgraded DA SN002 will be installed after the current DA SN004 is removed. There is much anticipation to install this new unit to begin runtime in fully on-orbit configurations to confirm technology functions.

1. Drive Belt Redesign

Rotation of the DA is currently driven by an O-ring belt (Figure 5). However, this belt frequently slips during operation due to the steam environment in the DA. The risk is greatest at the beginning of a process run, since the steam has time to condense as the DA cools between processing cycles. Belt slippage at startup has been consistently observed in UPA operations on ISS. In February 2016, DA SN002 (earlier build) experienced a failure when the belt was unable to maintain sufficient centrifuge speed. This occurred after several months of off-nominal UPA performance in which the DA was consistently challenged with excess condensate in the stationary bowl[2,3]. The previous DA SN005 and currently install DA SN004 have both experienced belt slip during startup; however, centrifuge speeds have continued to recover upon restart.

Figure 5. The DA O-ring drive belt.

The toothed belt is a synchronous drive belt where no friction is require to transmit power, unlike that of the O-ring. Not only would the toothed belt provide near 100% efficiency in transmitting power, but is expected to handle increased loads on the drive system due to other DA seals upgrades. Integrating this toothed belt into the design required a redesign of the compound pulley and an added tensioner. Figure 6 shows the toothed belts along with a 3D printed pulley and tensioner, used during fit checking. Ground testing has logged well over 600 hours of the new synchronous drive belt system with expected performances of 100% power transmission. Additional testing with dynamic sealing described later, where increased loads were expected, the toothed belt design effectively managed the higher torque demand and power transmission. Going forward, the implementation of the toothed belt design, not the V-belt approach, will be used in the next generation DA.

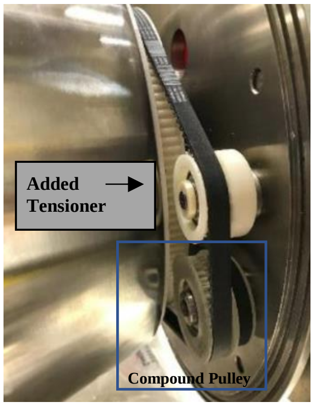

Figure 6. Toothed synchronous drive belt.

2. Seal Bearing Leak Path

NASA personnel identified a leak path through the rear bearing in 2016/2017 that resulted in elevated conductivity in the distillate delivered to the Water Processor Assembly (WPA). This contaminated distillate presented significant operational impacts to both the UPA and WPA. Previous inspections of DAs returned from ISS have shown the grease in this rear bearing is washed out by pretreated urine during operation, but this is the first time that a leak of this magnitude impacted UPA operations. The subsequent investigation of the returned DA at MSFC could not identify any mechanical variances with this DA that would explain why pretreated urine leaked through the rear bearing at a measurably greater rate compared to previous DAs operated on ISS. Despite the inconsistency, NASA personnel agreed that it is imperative to address this leak path by the addition of a lip seal to protect the rear bearing from exposure to pretreated urine. In the initial design of the DA at MSFC, three lip seals were located on the centrifuge shaft (rear bearing at the centrifuge hub, the motor bearing and the demister) to protect various bearings from exposure to pretreated urine. However, these lip seals introduced drag on the centrifuge that increased the risk of belt slippage, and as a result, the lip seals at the rear bearing and motor bearing were removed before the UPA was initially installed on ISS. In response to the anomalous operation on ISS, MSFC engineering has measured the drag introduced by the lip seal and determined it will contribute to additional belt slippage with the current O-ring drive belt. Incorporating this lip seal design into the next on-orbit DAs depends on the success of the drive belt redesign described earlier. In fact, the introduction of the new toothed synchronous drive belt during ground testing has shown sufficient performance margin to accommodate the drag associated with the installation of the lip seals. Based on this finding, the additional lip seal on the rear bearing will be implemented in the upgraded DA.

3. *Liquid Level Sensor Tip Redesign*

The liquid level sensor was included in the original design to determine when the fluid layer in the evaporator is thicker than expected. This could indicate an issue with the fluids control and pump assembly (FCPA) or an obstruction that is flooding the evaporator. The sensor works as intended in ground testing, but does not work as expected in microgravity. Sensor data shows erratic readings, likely due to droplets of pretreated urine splashing on the sensor during operational transitions (starting up or shutting down). The tip of the sensor has been redesigned with a non-metallic shield to minimize the possibility of droplets reaching the sensor. Figure 7 highlights, in green, the redesigned liquid level sensor shield.

Figure 7. Shield design for protecting liquid sensor from droplets.

4. *Implement Seal to Stationary Bowl*

Condensate in the stationary bowl has been a consistent issue for the DA. As the water vapor is generated in the evaporator, it is pumped to the condenser by the DA's compressor. The condenser rotates within the DA's stationary bowl, but there is a radial gap of 0.16 cm between the condenser and the compressor. This gas then allows water vapor to leak into the stationary bowl. Over time, the bowl will become saturated with water vapor, at which time it will condense on the cooler surfaces. This condensation is detected by temperature sensors, which subsequently turn on the stationary bowl heaters to drive the water back to the vapor phase before it can introduce a drag to the centrifuge. These heaters consume approximately half of the UPA power, which is highly undesirable for future missions. Furthermore, this heat increases the operating temperature and pressure of the DA, which reduces the DA efficiency and can result in a shutdown if the vacuum pump cannot get the pressure below the required setpoint. In addition, the O-ring drive belt is located in the stationary bowl. MSFC engineering believe the primary reason the drive belt tends to slip on startup is because of condensation occurring during standby. For these reasons, MSFC engineering has pursued multiple options to reduce the quantity of water vapor that can leak into the stationary bowl.

The latest approach to mitigate this issue is the addition of a spacer seal to reduce the radial gap from 0.16 cm to near 0.05 cm; therefore, significantly reduce the amount of the water vapor that leaks into the stationary bowl. An earlier approached discussed in detail in a early paper[4], considered the VariSeal concept. This approach had reduced the gap to 0.0 cm, which provided full contact of the seal to the rotating centrifuge. This did reduce the water in the stationary bowl; however, excessive shedding of the material was observed.

Further efforts beyond the VariSeal approach to decreases this leak path incorporated a Teflon seal instead of the at the same location. Acting as a spacer, a thin Teflon ring design is a compromise to reduction of water vapor into the stationary bowl while avoiding the potential for material shedding. Similar Teflon seal design is already incorporated on the hub end of the DA, which proves a viable sealing option within this dynamic environment. These Teflon seal designs reduce in gap size at the interface, which should reduce the amount of water vapor. Because there is no material touching the moving surfaces, there is no concern for shedding or increased drag onto the system.

Ground testing installed a Teflon seal achieving a 75% reduction in gap, which has shown similar reductions of fluid found during the VariSeal testing.

5. *Thermal Isolation of Front Plate*

Though the stationary bowl seal will reduce the amount of water vapor that leaks into the stationary bowl, for now, it is not expected to eliminate it. One of the areas of primary concern for condensation is on the DA's front plate, which is typically colder than the rest of the stationary bowl because of its proximity to the coolant line used for the DA motor. The front plate is located directly in front of the drive belt, such that condensation in this area puts the belt at increased risk for slippage. To reduce the potential impact of condensed water on the drive belt, MSFC engineering is installing a Torlon thermal isolator between the front plate and the coolant line. This new material thermally isolates the conductive path from the motor to the compressor. Initial ground testing has shown increased temperatures, by up to 20 degrees Fahrenheit on the compressor endplate, confirming effective thermal isolation.

C. Planetary Gear Drive Redesign

In the Summer 2018, a Fluids Control and Pump Assembly (FCPA) utilizing the first generation planetary gear drive designed failed due to high motor current after about 4000 hours runtime. This was at least 5 times longer than any other FCPA installed, on average – a significant improvement in observed performance. All prior FCPA ORUs used a harmonic drive design that historically shown limited operating life on-orbit due to failure within the harmonic drive itself. The subsequent ground Tear-down Testing and Evaluation (TT&E) of this first generation planetary gear drive concluded the root cause of failure was due to catastrophic wear on the final stage sintered metal sun gear of the planetary drive. The final stage exhibits the highest torque and thus wear on these gears was expected. Moreover, the sun gear was manufactured using powder metallurgy, which typically achieve 80 to 90% of the life of an equivalent machined gear. In March 2020, the first PCPA that utilized the same first generation planetary gear drive system failed due to high motor current after about 2300 hours runtime. This pump uses the same gear drive system as the FCPA, only the PCPA has a lower gear ratio and spins faster. Future ground TT&E will be necessary to confirm root cause failure. However, theoretical expected life on the PCPA due to similar sun gear failure by correlating total revolutions suggested this unit was near 100% of its predicted life.

Improvements to the planetary gear drive system to enhance the reliability, thus extended runtime, are actively being pursued for the next pump builds. Replacing the sintered sun gears for machined sun gears is the primary upgrade for both PCPA and FCPA. A second upgrade pursued increases the planetary gears size to improve wear by increasing surface area, thus reducing pressure on the gear teeth. Added redesigns to maximize life will incorporate needle bearings, caged stages to improve stiffness, and utilizing press-fit rather than welding to control tolerances and fitment. Unfortunately, these further redesign can only be pursued on FCPA units due to a necessary axial growth of the gearbox to accommodate these redesigns. Current on-orbit configurations and clearances above the PCPA cannot support these added improvements. Table 1 below summarizes the upgrades for either PCPA or FCPA.

Table 1. PCPA and FCPA Planetary Gear Drive Upgrades.

PCPA (purge pump)	FCPA (fluids pump)
Sintered metal gears are replaced with machined metal	Sintered metal gears are replaced with machined metal
Larger gears on the final output stage	Larger gears on the final output stage
	Use of caged needle bearings to improve wear and more tolerant of any misalignments.
	Use of press-fit instead of welding to better control tolerances and fitment which serves to reduce wear and premature failure.

D. Future Concept Considerations

Engineering continues to look for ways to further enhance UPA reliability, function, and capabilities. The team is considering options that compliment a more maintainable and serviceable environment. Furthermore, troubleshooting during on-orbit operations have been limited given the heritage designs that led to full ORU replacement rather than component isolation and recovery. Future upgrades are considering expanding system level insights potentially via added telemetry, sensors, assembly modification, to name a few.

1. Single Channel Peristaltic Pump

Near term pursuits are considering the use of single-channel peristaltic fluids pumps, rather than current four-channel fluids pump design. The current FCPA has one channel dedicated to moving urine from the WSTA into the Distillation Assembly (DA), two channels dedicated to recycling the concentrated waste from the DA into the Advanced Recycle Filter Tank Assembly (ARFTA) and back to the DA, and the last channel pumps product distillate from the DA to the wastewater interface with the WPA. All four channels use the same, single roller to provide the positive displacement.

There are several advantages separating of each fluids channel to individual pumps with respect to troubleshooting, variable operations, isolation of faults, and maximizing component level maintenance. Specifically, a single channel approach can better isolate failure modes to a single localized unit or leg of the UPA system. One of the current failure modes is tube rupture of the peristaltic tubing. This was a reoccurring failure for the PCPA units, which is also a four-channel peristaltic pump. Although this particular failure mode is easily detectible in the PCPA, the current UPA telemetry insights for a tube rupture in a FCPA is lacking which makes it difficult to detect quickly. It is hopeful that this concept could improve detection of a tube rupture. There is also a significant opportunity to incorporate component level maintenance for each pump – replacing tubing, motors, sensors, etc, reducing the mass penalties of entire ORU replacement.

Preliminary testing on a concept single channel peristaltic fluids pump has been ongoing at MSFC. A smaller footprint design of each individual pumps, while maintaining the required volumetric displacement has been achieved. Initial concept work suggests a viable integration within the current FCPA housing making rack integration feasible. In tandem are studies for better pump tubing material in hopes of longer expected lifetime. As testing of the new tube material continues, mechanical and design engineers can improve the current single channel designs.

2. Troubleshooting Study

A recent on-orbit UPA anomaly occurred in the early 2020 reconfirmed that UPA current configurations can lack insights to isolation root causes for failures or degraded performances. There is a desire to identify more ways to either improve detection of UPA faults by either adding more telemetry insights with added sensors or by identifying more ways to improve the major UPA assemblies. The single channel pump concept is an example to better isolate faults within each channel of the FCPA, but consideration for added pressures sensors, flow meters, or other in-line flow dynamic sensors could more simply address this area of need. Therefore, market research, reassessment of system level failure mode and effects analysis, and ground testing will be used to better identify the future upgrade work for UPA. This not only supports ongoing efforts to maintain the ISS water recovery system, but to better prepare technology for future manned exploration missions.

III. Conclusion

The ISS Urine Processor Assembly (UPA) is the preferred NASA technology for future manned missions beyond ISS. However, based on the over 10 years of operation on ISS, the reliability of this hardware needs improvement in several areas. The PPSA technology demonstration, proving to enhance pumping efficiencies beyond the current state-of-the-art, utilizes a scroll pump technology. This unit will be delivered to ISS in Summer 2021. To support the PPSA demonstration, an astronaut trainer has been built using both flight-like and additive manufacture components to save of cost but maintain fit and functionality. Current UPA peristaltic pumps utilizing the first generation planetary gear drive have already provided a marked improvement from the earlier harmonic drives life on ISS. Recently, a life limiting design of the planetary sun gear is now being addressed through manufactured gears instead of sintered gear fabrication. Additional DA upgrades as outlined in this paper are currently integrated in newly arrived DA SN002 Rebuild, waiting to be installed to begin runtime to prove technology functionality. Future upgrades to UPA will always continue and look for ways to improve performance. The added desire to look for maintainability at a component level as well as added insights to better isolate potential system faults quickly will also be pursued. Near term concepts will look towards single-channel pumps for the fluids pump application.

Acknowledgments

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References

[1] Pruitt, J.M., Carter, D.L., Bagdigian, R.M., and Kayatin, M.J., "Upgrades to the ISS Water Recovery System," ICES 2015-133, *45th International Conference on Environmental Systems,* Bellevue, Washington, 2015.

[2] Carter, D.L., Williamson, J., Brown, C., Bazley, J., Gazda D., Schaezler, R., Thomas, F., "Status of ISS Water Management and Recovery", Paper # 2018-088, *48th International Conference on Environmental Systems*, Albuquerque, New Mexico, July, 2018

[3] Carter, D.L. J.M. Pruitt, C. Brown, J. Bazley, D. Gazda, R. Schaezler, L. Bankers, "Status of ISS Water Management and Recovery", Paper # 2016-017, *46th International Conference on Environmental Systems*, Vienna, Austria, July, 2016

[4] Williamson, J., Carter, D.L. Hill, J., Jones, D, Morris, D., Graves, R., "Upgrades to the International Space Station Urine Processor Assembly", Paper # 2019-43, *49th International Conference on Environmental Systems*, Boston, Massachusetts, July, 2019