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Upgrades to the International Space Station Water Recovery System

Matthew J. Kayatin[1], Jennifer M. Pruitt[2], Mononita Nur[1], Kevin C. Takada[1], and Layne Carter[3]
NASA George C. Marshall Space Flight Center, Huntsville, Alabama 35812, USA

The International Space Station (ISS) Water Recovery System (WRS) includes the Water Processor Assembly (WPA) and the Urine Processor Assembly (UPA). The WRS produces potable water from a combination of crew urine (first processed through the UPA), crew latent, and Sabatier product water. Though the WRS has performed well since operations began in November 2008, several modifications have been identified to improve the overall system performance. These modifications aim to reduce resupply and improve overall system reliability, which is beneficial for the ongoing ISS mission as well as for future NASA manned missions. The following paper details efforts to improve the WPA through the use of reverse osmosis membrane technology to reduce the resupply mass of the WPA Multifiltration Bed and improved catalyst for the WPA Catalytic Reactor to reduce the operational temperature and pressure. For the UPA, this paper discusses progress on various concepts for improving the reliability of the system, including the implementation of a more reliable drive belt, improved methods for managing condensate in the stationary bowl of the Distillation Assembly, and evaluating upgrades to the UPA vacuum pump.

Nomenclature

ARFTA	=	advanced recycle filter tank assembly	*psid*	=	pound force per square inch, delta
°F	=	degrees Fahrenheit	*psig*	=	pound force per square inch, gauge
cm	=	centimeter	*R&R*	=	remove and replace operation
DA	=	distillation assembly	*RO*	=	reverse osmosis
DMSD	=	dimethylsilanediol	*temp.*	=	temperature
°F	=	degrees Fahrenheit	*TOC*	=	total organic carbon
FCPA	=	fluids control and pump assembly	*UPA*	=	urine processor assembly
Ft	=	feet	*VOC*	=	volatile organic compounds
h	=	hour	*WPA*	=	water processor assembly
in	=	inch	*WRS*	=	water recovery system
ISS	=	international space station	η	=	single pass adsorption efficiency
L	=	liter	μ	=	micro
lb_m	=	pound, mass			
m	=	meter			
mg	=	milligram			
MF	=	multifiltration			
mhos	=	conductivity, siemens			
MSFC	=	marshall space flight center			
MTBF	=	mean time between failures			
OGS	=	oxygen generation system			
ORU	=	orbital replacement unit			
PCPA	=	pressure control and pump assembly			
ppm	=	parts per million, mass basis			
PTU	=	pretreated urine			

[1] Aerospace Engineer, ECLS Systems, Space Systems Dept., NASA Marshall Space Flight Center/ES62.
[2] ISS UPA Spares & Upgrades Project Manager, Human Exploration Dev. & Operations Office, MSFC/HP30.
[3] ISS Water Subsystem Manager, ECLS Systems, Space Systems Dept., NASA Marshall Space Flight Center/ES62.

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, and is 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 named WRS-1 and WRS-2 as shown by Figure 1. This hardware was delivered to ISS on STS-126 on November 14, 2008 and initially installed in the US Lab module. On February 18, 2010, the racks were transferred to their permanent home in the Node 3 module. The layout of the two WRS racks is as shown in Fig. 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 by Pruitt et al. (2015)[1] and by Carter et. al (2015)[2]. In addition to Ref. 1, Kayatin et. al (2016)[3] provides detailed information regarding recent ISS WRS upgrade efforts.

A notable change to WRS-2 was made in 2016 to improve accessibility and urine brine transfer operations to and from the Advanced Recycle Filter Tank Assembly (ARFTA). A new door was installed on WRS-2 that includes a three-way valve to fill, drain, or process the installed ARFTA tank without having to remove it from the rack.

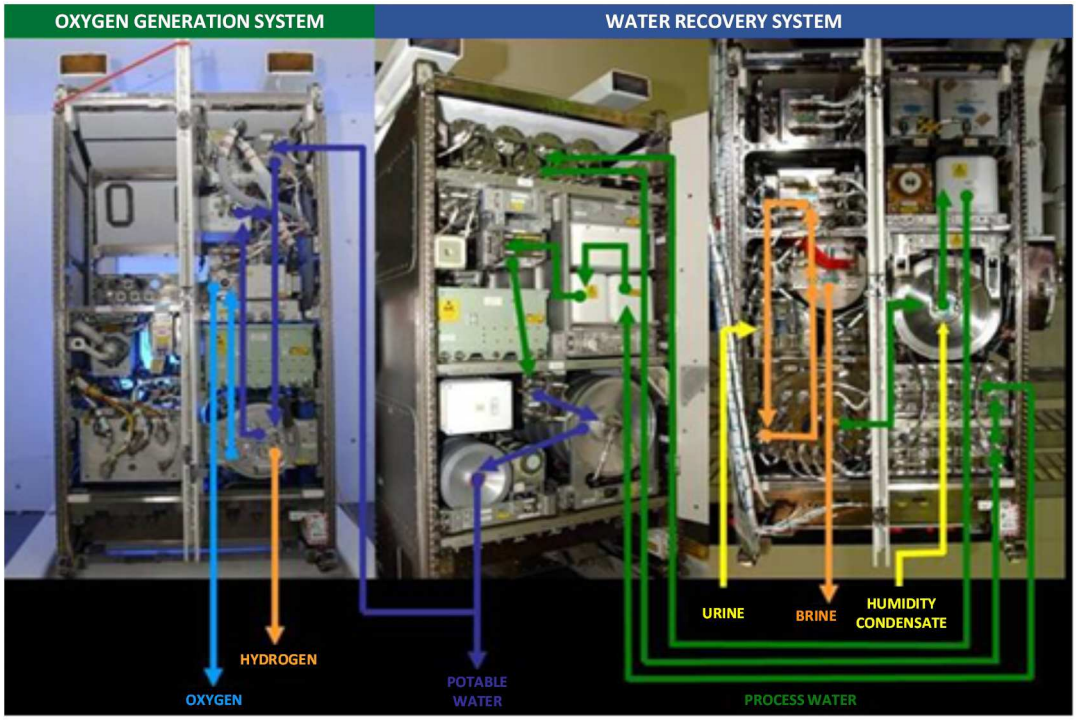

Figure 1. International Space Station Regenerative ECLSS Racks and process flows for the OGS and WRS.

II. Status of UPA Upgrades

As of April 2, 2017, the total UPA production on ISS was 11,214 L (24,715 lb_m) of distillate from crewmember urine since initial operation in 2008. Over that time, a total Orbital Replacement Unit (ORU) mass of 2,036 kg (4,489 lb_m) has operated in the UPA, including initial hardware installation, replacements of failed ORUs, and improved hardware like the ARFTA. Overall, the UPA hardware replacement rate is currently 0.18 lb_m of hardware per 1 lb_m of distillate that has produced.

In the pursuit to reduce replacement rates by improving robustness, durability, and extended life, several upgrades have been under evaluation. 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.

A. Distillation Assembly Design Upgrades

1. Seal Bearing Leak Path

During the recent high conductivity ISS fault tree investigation (2016 – present), a possible leak path close to the purge line was substantiated by the development unit. Disassembly of the test bed distillation assembly (DA) showed a pretreated urine (PTU) leak through the back bearing and screw into the condenser as shown by Figure 2. PTU carryover wasn't expected prior to disassembly. Previous DA teardowns (flight and ground) have shown that this back bearing gets washed out during operation, but this is the first time that an obvious leak like this was directly observed. A lip seal has been placed in the ground unit on wet side of the bearing to evaluate if rotation is affected. The lip seal is the same design that is used at another point along the shaft. One of the original design iterations of the DA had seals at three locations on the shaft, but were removed due to high drag during operation. Those seals were spring loaded, and in later iteration, a lip seal replaced one of those seals without causing high current. Current ground testing will determine if another lip seal can be added without additional load to the centrifuge.

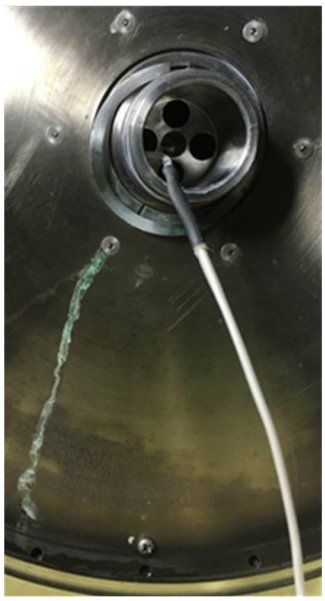

Figure 2. Pretreated urine leak though a bearing of the DA.

2. Drive Belt Redesign

Rotation of the DA is currently driven by an o-ring belt as shown in Figure 3. There is an ongoing risk, however, of belt slipping 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. Belt slippage at startup has been consistently observed in UPA operations on ISS. In February 2016, DA SN002 experienced a failure when the belt slipped during a process cycle, causing the centrifuge speed to fall. Attempts to recover the DA operation were unsuccessful at achieving more than 30 minutes of operation. As a result, the DA SN002 was replaced at only 30% of expected life. The failed unit was returned to MSFC in the summer of 2016 for hardware evaluation. Fortunately, this belt was already on the list of upgrades to the system. Before the belt slip failure, the UPA had shown indications of water in the stationary bowl, which is known to happen during nominal UPA operation. Heaters around the stationary bowl volume were added to the design to evaporate this water back into the condenser and prevent it from accumulating in the stationary bowl. However, as the condensate forms in the stationary bowl, droplets may form and reach the o-ring drive belt. Ground tests have shown that only a drop of water is required to cause the belt to slip.

Figure 3. The DA O-ring Drive Belt.

To improve the drive belt reliability in this environment, two design options are under consideration. A belt with teeth (such as a Gates belt design) would provide a more robust solution, but implementation would also require improved timing to insure the belt's teeth properly interface with both pulleys. This will be challenging since the pulleys have different diameters. Alternatively, another potential solution is a v-type belt design. This design change was also previously evaluated, resulting in the conclusion that a tensioner would be required to insure proper function. At the time, this approach was not considered viable due to the limited space available for the tensioner location. Incorporation of this technology would drive an enlargement of the DA, which was considered an unacceptable option. With the new information gleaned from the parametric testing regarding DA resizing, both of these design options are now under further consideration.

3. Liquid Level Sensor Tip Redesign

The liquid level sensor was added to the design in order to determine when the fluid layer in the evaporator is thicker than expected. This could indicate that there is an issue with the fluids control and pump assembly (FCPA) pumping, or a blockage that is flooding the evaporator. The sensor works well in ground testing, but was found to not work as expected in micro-gravity. The binary data shows erratic readings, suspected from splashing on the sensor which gives false positive readings for flooding. In order to remedy this issue the tip of the sensor will be redesigned with a shield to minimize the area splashing could effect.

4. Thermal Isolation of Front Plate

If water vapor leakage into the stationary bowl cannot be reduced, then mitigation will be relied on through related design upgrades. When in standby mode, the hardware lowers to room temperature a few hours after operation has completed. The coolant line around the motor is still active, reducing the temperature around the front plate and through to the stationary bowl. This can cause any water vapor in the stationary bowl to condense along that plate, right by the drive belt, and make the DA more prone to slippage. To reduce this condensation potential, a thermal isolation material will be added between the contact points of the coolant line and front plate. This will be tested within the ground unit with thermal analysis support. It is anticipated that there will be no operational change to the unit from this minor thermal design modification.

5. Insulation of Centrifuge

With the heater operation warming the stationary bowl, latent heat exchange between the condenser and evaporator volumes may be reduced from this additional heat input. This affects operation of the whole system as pressures can increase and make processing less efficient. The balancing of the centrifuge may be critical, but the engineering team will look to do ground testing with an insulation to reduce the heater effect on the centrifuge. The insulation will need to be a closed cell foam so water isn't absorbed to affect centrifuge balance and foster growth of microbial contaminants.

B. PCPA Design Upgrades

A persistent problem on ISS has been the short life spans of UPA pumps. The most prevalent failure has been harmonic drive failure for FCPA, but pressure control and pump assembly (PCPA) units have always failed from tube rupture. A down-select of possible purge pump technology upgrades will be done in 2018. Better strategies for thermal management and alternative pump architectures are under consideration for upgrades.

1. Cooled Tube Ring

During extended periods of PCPA operation, processing capability is reduced due to the heat entrained within the fluid. Water flashing can be seen as the PCPA struggles to maintain pressure after long periods of operation. To increase capability of the peristaltic tube and keep fluid cool, an additively manufactured tube ring was designed and printed with a channel to route the internal thermal control system fluid to the base of the tubing. This tube ring will replace the one in the ground unit to test function and increased fluid capacity.

2. Scroll Pump

A scroll pump may be a more efficient pump design than the peristaltic pump that is currently in the PCPA. During initial system design, scroll pumps were not found handle the two-phase fluid coming through the purge line well. With new technologies available, this alternate pump design is being evaluated within the ground test bed. A scroll pump was installed in place of the nominal PCPA for evaluation. Preliminary test data looks promising but evaluation of life duration and reliability is currently incomplete.

III. WPA Upgrades

The WPA encompasses a multistep process of adsorption, ion exchange, and catalytic wet oxidation working in series to produce potable water.[3] The Multifiltration (MF) Beds contain adsorption media and ion exchange resins to remove the majority of heavy to semivolatile organics and ionic species from the WPA wastewater stream. Low molecular weight, volatile organic compounds (VOC) not readily adsorbed are oxidized by the downstream catalytic reactor.

A. Multifiltration Bed Upgrades

Recent research efforts have focused on reducing the mass resupply penalty of the WPA MF Beds by evaluating a change in operational approach to reduce Remove and Replace operation (R&R) frequency.[3] The implementation of this approach on-orbit is still hindered by the presence of the environmental contaminant dimethylsilanediol (DMSD) in the ISS WPA wastewater stream.[4,5] In spite of launching and installing air scrubbers in Node 1 and evaluating the feasibility of capturing DMSD and/or precursors in the cabin air stream, the ultimate remediation solution remains elusive.[6,7] Insights into the breadth and pervasiveness of DMSD sources and generation routes were analyzed by Perry and Kayatin (2017) and reveal a more challenging problem than originally anticipated, potentially exacerbated by the local environment at ISS altitude.[8] As such, reverse osmosis (RO) implementation and catalyst activity upgrades may be relied on to a greater extent than previously imagined. These technologies will be discussed in subsequent sections.

Current studies at MSFC are addressing the obsolescence of the Barnebey-Cheney 580-26 activated charcoal layer used within flight MF Beds. Dow Chemical's Ambersorb® 4652 sorbent was selected as a candidate media to replace 580-26 and was recently evaluated within MF Bed life extension testing.[3] For further evaluation a certification test program was implemented at MSFC. To this end, three MF housings were provided by United Technologies Aerospace Systems as downgraded flight hardware. The candidate 4652 media was packed within each housing in accordance with flight procedures by Umpqua Research Company and returned to MSFC containing deionized water. One bed was treated with gamma irradiation by STERIS Corporation in accordance with the flight MF Bed sterilization procedure and returned to MSFC. The water entrained in the irradiated bed was collected and analyzed to identify any potential leachates by the NASA Toxicology and Environmental Chemistry Laboratory at Johnson Space Center. Test results were clean for volatiles, semivolatiles, leachates, and extractable compounds. The sorbent contained in the irradiated bed was removed and shared with NASA colleagues for analyses such as adsorption capacity and mechanical stability. The remaining two beds were evaluated in series for breakthrough capacity against a challenge wastewater Ersatz previously used within the MF Bed Life Extension testing.[3] Briefly, the Ersatz wastewater had a theoretical total organic carbon (TOC) target of approximately 57 ppm and a conductivity target of 170 µmhos/cm. All Ersatz water tanks were quality controlled by the MSFC ES62 Chemistry Laboratory to verify these parameters were ± 10% the target value. Note that this formulation included 22 mg/L of DMSD. The effluent of each bed was sampled daily for TOC and conductivity. Pressure drop across each bed was monitored to examine hydrodynamic effects from sorbent swell. The adsorption performance of the Ambersorb beds was tracked by the single pass adsorption efficiency (η) as described by Equation 1 wherein the TOC was measured at the bed inlet and outlet.

$$\eta = \frac{TOC_{in} - TOC_{out}}{TOC_{in}} \times 100\% \quad (1)$$

Figure 4 displays the measured performance of the 1st Ambersorb sorbent bed (ca. 2,675 mL resin), challenged at 13 lb_m/hr against the mean daily ersatz wastewater throughput of 125 lb_m. Note that the soluble organic load in the Ersatz formulation was boosted by a factor of 3 to bring the TOC target to 104.4 ppm. This change was made on test day 41 to try and increase bed loading but had no apparent effect on observed efficiency. The adsorption efficiency stabilized at approximately 50% at test start and has decreased linearly over time. Analysis indicates that breakthrough trends were initially due to light alcohol and acetone breakthrough followed by glycol roll-off by more strongly adsorbed compounds. A trend line is shown with a best fit correlation inset to Fig. 4. The displayed bed performance trend is consistent with previous observations.[3] Testing will continue until both beds are saturated with adsorbable organics and breakthrough of semivolatile compounds is detected. Comparisons to the breakthrough capacity of 580-26 charcoal will then be made. Testing of Bed #1 was interrupted by unexpected pressure drop rise which became untenable for implementation within the WPA near test day 60, spiking to 10 psid. Note that initial bed pressure drop was less than 1 psid and this trended upward slightly, starting at test day 30 forward, before a marked rise between test days 50 and 60. Prior to test day 72 the inlet and outlet lip seals were visually inspected for evidence of fouling and sampled for evidence of particle attrition. No apparent cause for the large pressure drop increase was observed by

this inspection. Furthermore, analysis of the predicted pressure drop at the test superficial velocity of 0.036 cm/s (1.2E-03 ft/s) was unable to match the observed pressure rise by changes in voidage and particle size distribution alone. In an attempt to salvage the test, 1 inch of Ambersorb (ca. 117 mL) was removed from the bed inlet. The bed retention spring located at the outlet shifted the bed packing as a solid plug towards the inlet upon reassembly. Remarkably, the observed pressure drop decreased from 25 psid to 5 psid after sorbent unloading. It was hypothesized that sorbent swell, combined with an oversized bed retention spring, was preventing stress build-up from being relieved along the bed length. To further test this hypothesis, the bed retention spring was completely removed prior to test day 71. Analysis indicated this was permissible since the minimum bed fluidization velocity was 0.142 cm/s (4.7E-03 ft/s) and therefore the lip seal alone should satisfactorily retain the bed in ground tests. A pressure drop of < 1.5 psid was observed with no spring installed, confirming that stress translation was previously inhibited. Measurements prior to test day 76 indicated that the bed had expanded 1.52 cm (0.6 in). These observations warranted an investigation into better quantifying sorbent swell.

The observed rise in bed pressure drop, relief upon spring removal, and linear bed expansion have motivated an in-depth study to both determine the source(s) and quantify the extent of particle swell. Experiments are underway at MSFC to determine the effect of sorbent hydration and organic adsorption on particle swell. The effect of various treatments will be quantified using optical microscopy and image analysis. Once the source and extent of swell is understood, a recommendation can be made to resize the MF bed retention spring to better accommodate anticipated swell.

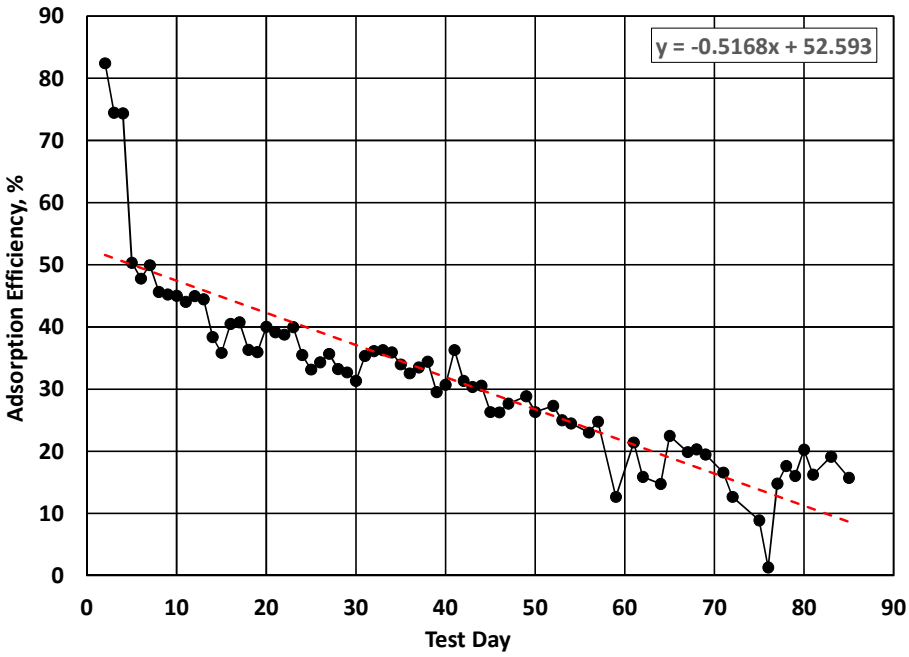

Figure 4. Ambersorb Bed #1 TOC adsorption efficiency. Approximately 125 lb_m of wastewater ersatz was processed each test day.

B. Reverse Osmosis Technology Evaluation

Historically, RO was evaluated for inclusion within the WPA in the 1980s but at that time the technology did not trade favorably due to membrane reliability concerns and a resupply upmass penalty from low membrane permeate recovery. Since that time, the state-of-the art in membrane science has advanced and recent ground[9] and flight[10] technology demonstrations have been carried out. Currently, state-of-the-art membranes of interest to NASA utilize a next generation biomimetic technology based upon naturally occurring aquaporin water channel proteins. The potential merits of this technology are excellent water permeability whilst maintaining adequate solute rejection. Furthermore, implementation of a membrane based purification technology is desirable to offset the large MF Bed resupply penalty of 50 kg (110 lb_m) each. It was hypothesized that infusion of this technology within the WPA would complement the MF Beds in such a manner that one bed may be eliminated and/or its lifetime greatly extended due to the decreased contaminant load being passed down from the RO process. Ground testing must first be completed, however, to support this architecture change. Current work at MSFC is evaluating the effect of surface area and system backpressure on the observed permeate recovery and solute rejection for hollow fiber modules. The wastewater Ersatz is identical to that used for the MF and Ambersorb testing as described herein. Note that the WPA system design limits the implementation of the RO technology since a desired backflow regeneration of the RO membrane due to microbial

fouling is not viable. Nonetheless, improvements in RO membrane technology have enhanced overall reliability, while water previously lost (i.e. during the 1980s trade) via the RO brine is now expected to be recovered due to recent development of technologies for water recovery from various brines. As a result, it is anticipated the resupply mass associated with a successful RO technology may ultimately be significantly less than that required for the sorbent based MF technology alone.

Although it was desired to maximize recovery by operation of the RO process in recirculating flow, this orientation would be challenging to implement within the current ISS WPA architecture. Instead, testing focused on a single pass flow path in which sufficient surface area and pressure drop are provided to achieve 95% water recovery. Therefore, initial testing was performed to determine the required process parameters to achieve this performance goal. Testing of the RO process began with 0.6 m^2 (6.46 ft^2) modules purchased from Danish Aerospace Company. A summary of test results and permeate quality is provided in Table 1 below. Test data showed that 4 of these modules operating in series was insufficient to provide the desired 95% recovery. However, the rejection of TOC (defined analogous to Eq. 1) and inorganic constituents was relatively good, specifically for DMSD. Since DMSD continues to be a problematic contaminant for the WRS, effective rejection of this contaminant from the WPA is highly desirable.

Table 1. RO performance summary with 0.6 m^2 modules.

	Area	Pressure	Recovery¥	TOC	Rejection	Cond.	Acetate	P. Glycol	DMSD
Test Day	**m^2**	**psid**	**% (mass)**	**ppm**	**% (TOC)**	**µmhos/cm**	**ppm**	**ppm**	**ppm**
Inlet Ersatz	---	---	---	56.6	---	170.0	16.4	17.6	22
1	1.8	40	55.7	20.7	55.7	23.7	1.3	-	-
2	1.8	40	53.9	21.8	53.9	30.3	2.3	1.7	1.8
3	1.8	40	56.1	23.0	56.1	30.8	1.9	-	-
4	1.8	55	75.9	21.7	75.9	28.8	1.9	-	-
5	1.8	55	72.3	16.3	72.3	26.2	1.1	1.1	< 1.0
6	1.8	55	74.5	15.8	74.5	-	0.8	-	-
7	1.8	40	57.9	16.6	57.9	23.5	0.6	-	-
8	2.4	40	65.1	15.7	65.1	-	1.3	-	-
9	2.4	40	74.1	17.7	74.1	27.5	1.1	2.0	1.3
10	2.4	40	76.3	17.2	76.3	-	1.4	-	-
11	2.4	48	85.6	18.8	85.6	-	2.8	-	-
12	2.4	54	90.0	19.4	90.0	57.0	4.6	5.1	4.4
13	2.4	53	87.4	19.3	87.4	-	5.0	-	-
14	2.4	40	67.9	17.1	67.9	54.8	3.8	-	-

¥Target recovery of 95 %.

To improve water recovery, additional modules of new housing design were evaluated, each providing 2.3 m^2 (24.75 ft^2) of surface area. Testing began with two modules but increased to three modules as was required to provide the necessary recovery at a reduced operational pressure drop. Test data is summarized in Table 2. By operating three modules against a pressure drop of 25 psid, approximately 97 % water recovery was achieved. The permeate quality was degraded, however, showing less than 30 % TOC rejection.

Complete results from the 2.3 m^2 RO module test runs are pending analysis (e.g. DMSD), so a limited dataset is currently accessible. Available data indicates no measurable removal of the various VOCs currently removed by the catalytic reactor. Similarly, acetate ($C_2H_3O_2^-$) rejection was poor, even though a relatively high percent TOC rejection was achieved with the smaller 0.6 m^2 RO modules. Furthermore, many inorganic constituents were not effectively removed, as shown by Table 2. Overall, the improved water recovery realized with the higher surface area modules has compromised permeate purity to a deleterious extent.

In summary, the data acquired to this point indicates some benefit may be achieved with RO technology implementation (mainly some sorbent life extension), but an improvement in permeate quality will be required to justify the effort to integrate this technology into the ISS WPA. It is possible that relaxation of the water recovery target and/or investigation into alternative RO membrane geometries may provide further benefit (e.g. flat membrane sheets to remove capillary action) and these options will be evaluated moving forward.

Table 2. RO performance summary with 2.3 m^2 modules.

Test Day	Area m^2	Pressure psid	Recovery[¥] % (mass)	TOC ppm	Rejection % (TOC)	Cond. µmhos/cm	$C_2H_3O_2^-$ ppm	Cl^- ppm	NH_4^+ ppm	SO_4^{2-} ppm	K^+ ppm
Inlet	---	---	---	56.6	---	170.0	16.4	24.1	6.8	3.1	26.6
29	4.6	28.0	98.7	40.0	27.9	143.0	9.4	9.5	5.0	0.9	15.8
30	4.6	30.0	98.3	40.8	29.4	-	13.2	10.9	5.0	0.8	17.4
31	4.6	30.4	94.3	36.7	39.3	-	10.0	8.8	3.6	0.8	12.6
32	4.6	30.4	91.5	37.4	34.9	74.0	10.1	8.9	3.6	0.8	12.3
33	4.6	31.0	87.9	38.0	32.1	-	7.3	9.2	3.6	< 0.6	13.5
34	4.6	31.3	86.6	36.4	36.1	62.1	5.8	7.4	2.8	0.7	9.4
35	4.6	31.4	86.8	34.5	43.5	-	7.2	6.5	2.9	0.7	8.7
36	4.6	31.5	85.4	33.7	44.6	55.1	7.0	6.4	2.8	0.7	7.6
37	4.6	31.6	85.2	36.7	40.0	83.0	10.1	10.1	3.7	1.4	10.6
38	6.9	31.2	99.3	47.6	19.2	-	17.9	16.3	6.4	1.2	23.3
39	6.9	28.4	99.1	47.9	17.9	123.1	14.5	14.4	6.0	0.8	20.5
40	6.9	28.6	99.1	48.6	20.2	-	15.7	16.5	7.2	0.8	22.8
41	6.9	28.0	99.3	48.5	13.2	150.7	20.3	18.3	6.7	3.9	24.1
42	6.9	30.0	99.2	47.1	18.2	-	17.6	15.7	6.7	3.1	23.5
43	6.9	30.3	99.2	46.3	17.0	-	18.5	15.5	6.2	3.2	22.4
44	6.9	24.4	97.9	43.8	21.0	106.0	11.4	10.7	5.2	< 3.0	17.6
45	6.9	24.5	98.2	41.3	25.5	-	11.9	10.8	4.9	3.4	16.9
46	6.9	24.6	98.1	40.7	23.4	101.0	10.7	9.8	4.9	3.6	17.1
47	6.9	24.6	98.2	39.8	26.4	-	11.7	10.0	5.0	3.3	16.3
48	6.9	24.5	98.2	43.7	19.1	-	13.5	12.0	4.9	3.3	18.5
49	6.9	20.4	95.1	41.4	22.9	-	13.1	10.0	5.4	3.3	18.4
50	6.9	20.7	91.9	40.2	30.9	90.2	10.8	9.0	4.8	3.0	15.7
51	6.9	20.6	91.6	41.1	28.0	-	12.2	10.3	5.0	3.3	15.9
52	6.9	24.8	97.3	42.2	24.0	107.5	14.8	4.9	5.7	3.1	18.2
53	6.9	24.7	96.7	44.7	18.8	-	12.5	< 3	5.7	4.8	17.8
54	6.9	24.8	96.8	41.2	28.1	106.7	12.1	11.2	5.5	3.4	17.9
55	6.9	24.6	97.3	43.5	21.5	-	15.0	18.5	5.8	3.6	18.7

[¥]Target recovery of 95 %.

C. WPA Thermal Oxidation Catalyst Upgrades

Two advanced candidate WPA catalyst formulations were recently evaluated at MSFC for operation at reduced temperature (temp.) and pressure. The candidate materials were produced by United Technology Aerospace Systems and Umpqua Research Company and the details of their development were described previously by Kayatin et. al (2016)[3] and Yu et al. (2016)[11]. Table 3 highlights the various process conditions studied under a constant wastewater process flow rate of 13 lb_m/hr with injection of 0.011 lb_m/hr of molecular oxygen. Each catalyst was tested against three Ersatz water formulations: 1) Standard [alcohols, aldehydes, acetone, glycols. TOC = 35.8 ppm]; 2) Challenge [elevated Standard Ersatz load plus formic acid and urea. TOC = 64.8 ppm]; and 3) DMSD [64.9 ppm TOC, Standard Ersatz load plus 40 ppm DMSD]. Test results indicated that both enhanced mass transfer properties from support pore/channel size selection and high catalyst surface areas were synergistically necessary to enhance catalytic activity at reduced reactor temperature and pressure setpoints. Furthermore, a candidate WPA catalyst upgrade was identified with single pass TOC and DMSD oxidation efficiency in excess of 97% and 92%, respectively, at 270°F/55 psig. The mechanical stability of the support was investigated by laser light scattering (Microtrac

Table 3. Process conditions for WPA catalyst evaluation. Test conditions were implemented from top down.

Ersatz	Temp. (°F)	Pressure (psig)
Standard	270	55
	230	45
	200	0
	200	30
	200	55
Challenge	270	55
	230	45
	200	0
DMSD	270	55
	230	45
	200	0

S3500, 780 nm) of the reactor effluent. Diffraction particle size measurements were made by Microtrac Particle Analysis Laboratory (York, PA), over a range of 0.02 µm – 2,800 µm. Particle attrition rates were below detection limits in the sample as collected. The long term performance of this material will be evaluated and supplemented with testing in an integrated RO/MF/Catalytic Reactor test configuration.

D. Integrated Functional Demonstration of an Advanced WRS

Test plans are underway for an integrated test demonstration of an advanced exploration WRS architecture comprised of RO membranes in an optimized configuration (total surface area; backpressure), a single half-scale MF Bed, and a catalytic reactor packed with a candidate advanced WPA catalyst. Successful implementation and operation of this WPA configuration will be the basis for a technology demonstration on ISS.

IV. Conclusion

Potential upgrades to the ISS WRS have been identified and evaluated herein. These modifications aim to reduce resupply, increase performance, and improve overall system reliability; all of which are beneficial for the ongoing ISS mission as well as for future manned, exploration-class missions. Concepts for improving the reliability of the UPA system, including the implementation of a more reliable drive belt, improved methods for managing condensate in the stationary bowl of the DA, and evaluating upgrades to the UPA vacuum pump were discussed. For the WPA, a promising candidate catalyst formulation was identified for inclusion within a reactor upgrade. At present time, efforts to reduce the resupply mass of the WPA MF Bed through implementation of RO membrane technology was limited due to poor permeate quality.

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