

# Upgrades to the International Space Station Water Processor Assembly

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**The International Space Station Water Processor Assembly provides contaminant control and deionization to the Water Recovery System. The Water Processor Assembly presently utilizes sorbent-based Multifiltration Beds and a downstream Catalytic Reactor for these operations. Upgrades and process improvements are desired to improve performance, increase reliability, and decrease consumable resupply. To this end, reverse osmosis membrane separation technologies were evaluated to reduce influent contaminant loads, candidate additives to inhibit wastewater biofilm formation were studied, and life stability testing was completed for a recently developed high-activity catalyst. Evaluation of an adsorption media integration concept was also completed. The performance and applicability of these new technologies within the Water Processor Assembly, as well as their suitability for exploration missions, are discussed herein.**

## Nomenclature

$^{\circ}F$	=	degrees Fahrenheit
%REC	=	percent recovery
cm	=	centimeter
$d$	=	mean particle diameter
DMSD	=	dimethylsilanediol
hr	=	hour
in	=	inch
ISS	=	International Space Station
L	=	liter
lb	=	pound, mass
m	=	meter
$\mu$	=	micro
MIC	=	minimum inhibitory concentration
MF	=	multifiltration
MSFC	=	Marshall Space Flight Center
OGS	=	Oxygen Generation System
psid	=	pound force per square inch, delta
RO	=	reverse osmosis
s	=	seconds
TIC	=	total inorganic carbon
TOC	=	total organic carbon
UTAS	=	United Technologies Aerospace Systems
UPA	=	Urine Processor Assembly
WRS	=	Water Recovery System
WPA	=	Water Processor Assembly

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## 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. 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 in Node 3 named WRS-1 and WRS-2. 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 by Pruitt et al. (2015)<sup>1</sup> and by Carter et. al (2015)<sup>2</sup>. In addition to Ref. 1, Kayatin et. al (2016)<sup>3</sup> and Kayatin et. al (2017)<sup>4</sup> provide detailed information regarding recent ISS WRS upgrade efforts.

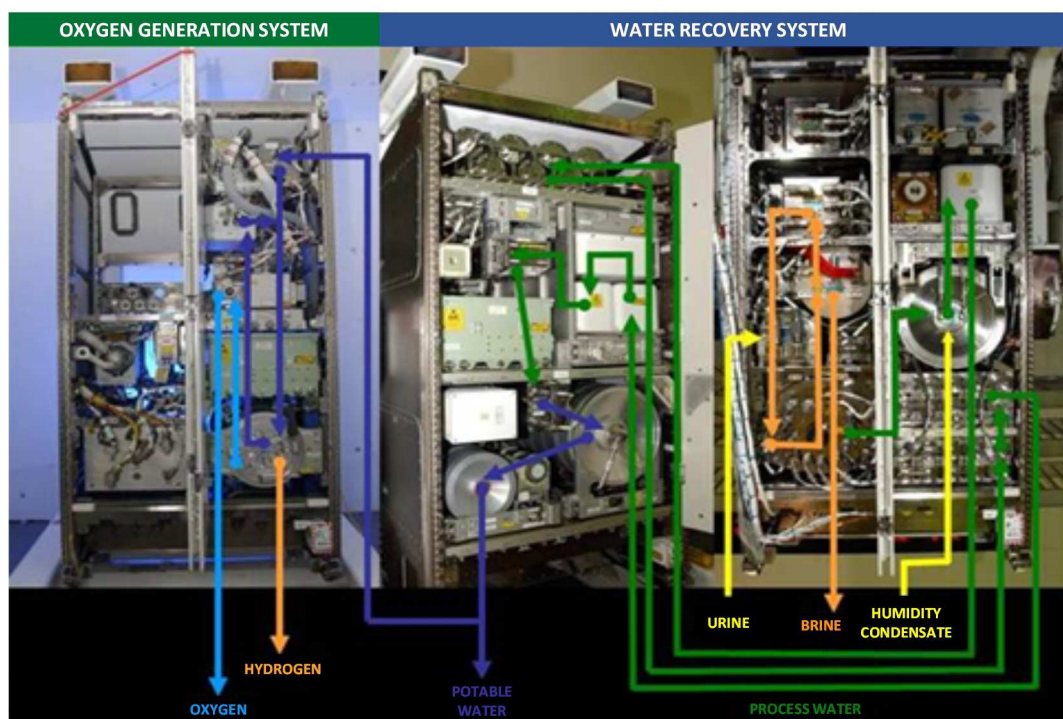


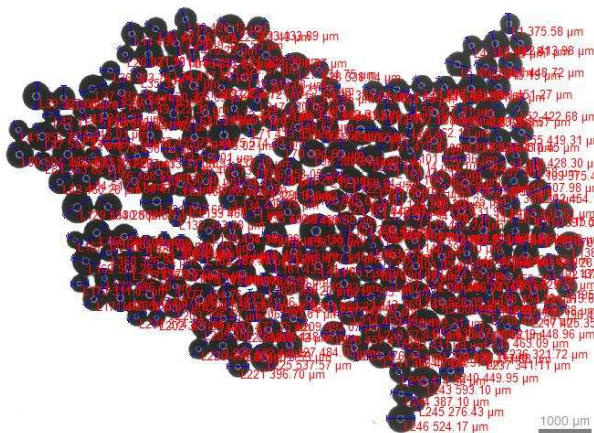
Figure 1. International Space Station Regenerative ECLSS Racks and process flows for the OGS and WRS.

### A. Ambersorb Sorbent Certification for Multifiltration Bed Implementation

Studies have been underway at MSFC since 2016 to address the obsolescence of the Barnebey-Cheney 580-26 activated charcoal layer used within flight Multifiltration (MF) Beds by certifying Dow Chemical's Ambersorb® 4652 as a drop-in replacement. A 2017 MSFC test program was successful in characterizing the contaminant breakthrough profile of an ersatz wastewater challenge through a MF Bed housing packed with 4652 media.<sup>4</sup> This test program was interrupted by an unexpected pressure drop rise across the bed which was eventually lessened by removing 1 inch of inlet sorbent media and fully mitigated by removal of the bed media retention spring located at the tube outlet. Measured pressure drop fell from near 25 psid to < 1.5 psid after spring removal. Figure 2 (black circles) displays the untenable pressure drop rise across a single MF Bed tube observed in 2017 breakthrough testing. This behavior is detrimental to WPA operability since three sorbent tubes are implemented in series within each of the two ISS MF Beds. The upstream WPA pump simply cannot overcome such losses whilst maintaining appropriate downstream

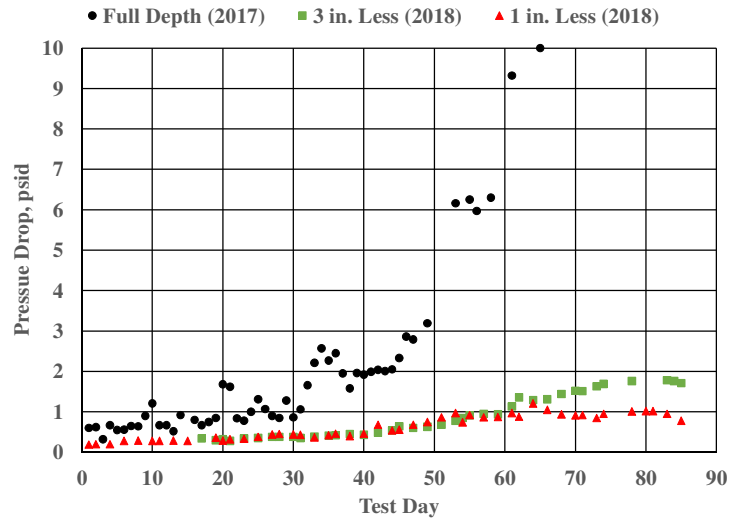
Catalytic Reactor pressure setpoint. The observed recovery of pressure drop to the initial magnitude at test start hinted towards a potential root-cause of media swell. Bed packed length measurements indicated a 1.52 cm (0.59 in) expansion and we estimate this may have been as large as 1.57 cm (0.62 in) had no sorbent been removed from the bed inlet. NASA and Boeing personnel hypothesized two credible causes for media swell resulting from media hydration and adsorption which warranted further investigation.

MSFC performed small-scale experiments using optical microscopy measurements to elucidate the magnitude of sorbent swelling associated with media hydration and/or adsorption. Precisely 250 individual particles of fresh Ambersorb media were collected and imaged. Image analysis was done manually to measure particle diameters under reflected light. Images were recorded on an Olympus SZX12 stereo microscope using a 0.5x objective with 10x magnification in front of the camera. Imaged lengths were calibrated using measurements of a stage micrometer. Due to the perfectly spherical shape of the media and the symmetric illumination provided by a LED ring located around the microscope objective, a symmetrical ring reflection was visible on each particle and guided reproducible bisection of the particle diameter with software measurement vectors. Figure 3 displays a typical image analysis used for all particle measurement steps. Measurements are reported as mean diameter ( $d$ )  $\pm$  standard deviation ( $\sigma$ ) in microns. The measured geometric mean diameter of the dry starting material was found to be  $452.7 \pm 81.4 \mu\text{m}$ . These 250 particles were subsequently carried through a series of various treatments followed by imaging and measurements to determine the observed stepwise effect on particle diameter. Treatments included soaking in boiling water daily for 5 days to test hydration swell, soaking in the ersatz wastewater organic concentrate formula, and soaking in the “less-soluble organic” chemical cocktail also used in preparation of ersatz wastewater. The effect of each treatment was analyzed using the F-test statistic which compares sample means for statistically significant differences. Table 1 summarizes



**Figure 3. Optical microscopy of neat Ambersorb. Scale bar = 1,000  $\mu\text{m}$ .**

the treatment type, particle size measurements, and statistical p-value of the F-test between treatments. Boiling sorbent in water for 5 days did not result in a significant change ( $p = 0.486$ ) in observed mean particle diameter. This result indicated that hydration swell was not a viable root-cause and thus pretreating sorbent with boiling water would not prevent swell. Note that as highlighted in the table, the effect of subsequent treatments was compared to the mean particle diameter post-boil of  $448.1 \pm 75.6 \mu\text{m}$ . Remarkably, although a measured diameter increase of  $8.1 \mu\text{m}$  was observed between the boiled step and organic concentrate soak step, and a second increase of  $9.1 \mu\text{m}$  was observed between organic concentrate soak and less-soluble organic soak, neither step change individually was statistically significant. Conversely, in comparing the boiled starting size against the final less-soluble step size, the combined effect of these two treatments can be seen as statistically significant ( $p = 0.012$ ) with an observed  $17.3 \mu\text{m}$



**Figure 2. Ambersorb pressure drop rise comparison for various packed MF tube configurations. Mean throughput of 125.5 lb/day.**

size increase. These results indicate that the cause of sorbent swell may be a non-specific organic adsorption and uptake of contaminants. The 17.3  $\mu\text{m}$  diameter increase is equivalent to a 4% particle swell. As a rough order of magnitude calculation, the effect of a 4% particle swell on the initial packed bed length of 22.9 in. was estimated in a worst-case scenario of end-to-end mean particle diameter swelling along the packed bed length. Approximately 1,300 particles would span the 22.9 in. bed and applying a 4% swell would increase packed bed length by 0.92 inches. Recall that a 0.62 in. bed length increase was measured/estimated experimentally and thus we conclude that adsorption induced particle swell is a plausible source of the pressure drop rise observed in the testing.

Although the large pressure drop across the MF Bed was relieved by removing the MF Bed retention spring, bed fluidization was a concern. At a nominal flowrate of 13 lb/hr the superficial velocity was estimated to be 0.0356 cm/s. The method of Wen and Yu (1966) was used to predict a minimum bed fluidization velocity of 0.1423 cm/s (51.9 lb/hr) indicating that operation with no spring was viable in ground tests at the current flowrate.<sup>5</sup> In microgravity, bed fluidization would be unavoidable with no retention spring. Two options were considered moving forward: 1) resizing of the MF Bed spring and 2) reducing the nominal packed bed length requirement. Due to cost and schedule limitations, the second approach was chosen and two MF tubes were repacked with

**Table 1. Effect of treatments on Ambersorb particle swell.**

Treatment	D $\pm$ $\sigma$	Effect Between Treatments			
	d [ $\mu\text{m}$ ]	diameter change [ $\mu\text{m}$ ]; (p-value)			
Dry	452.7 $\pm$ 81.4	-4.6; (0.486)	8.1; (0.254)	9.1; (0.176)	17.3; (0.012)
Boiling Water	448.1 $\pm$ 75.6				
Organic Conc.	456.2 $\pm$ 76.8				
Less-soluble	465.4 $\pm$ 77.1				

Ambersorb media by Umpqua Research Company in accordance with modified flight procedures. One MF tube was packed with 1 in. less media and the second tube was packed with 3 in. less media with respect to nominal flight bed packed length specifications. Based on spring force measurements at MSFC, we estimate an initial face-pressure reduction of 2.4 psi and 7.6 psi, respectively. In order to evaluate the viability of each approach, breakthrough testing was initiated in the same manner previously used to challenge the MF tubes.<sup>4</sup> Each bed was independently challenged with quality controlled ersatz wastewater and pressure drop was continuously monitored across each bed with calibrated online sensors. Effluent water quality analyses were also made to gather additional bed breakthrough datasets needed to assess the impact of packed bed length on sorbent lifetime and included Total Organic Carbon (TOC), Total Inorganic Carbon (TIC), alcohols, acetate ion, glycols (inlet and outlet), semi-volatiles, and dimethylsilanediol (DMSD).

Figure 2 overlays the observed bed pressure drop for each modified media packing configuration against the test data for the full-length Ambersorb bed tested previously in 2017. While both packing configurations with 1 in. and 3 in. media removed appear to be trending upwards in similar fashion, neither showed a pressure drop increase of magnitude similar to that seen in the full-length bed tested in 2017. Physical bed length measurements were taken approximately every 20 test days in an attempt to correlate measured particle swell with observed pressure drop. This is possible due to spring deflection against a floating spring plate near the bed exit. No changes in measured bed lengths have been observed thus far which is in agreement with the hypothesis of swell causing pressure drop rise. While there was also substantially more sensor noise in the 2017 test configuration, we note that the pressure drop sensor was validated by a 2<sup>nd</sup> mechanical differential pressure sensor apparatus. Test results indicate that a modified bed packing depth is sufficient to mitigate a detrimental pressure drop condition over bed lifetime. We hypothesize that increased particle mobility during bed saturation helps mitigate particle locking into a high pressure drop configuration. Note that the Ersatz wastewater was switched to a high TOC formulation (104.4 mg/L) on test day 82, matching that used in the 2<sup>nd</sup> half of 2017 Ambersorb testing.<sup>4</sup> This change was made to try and encourage media swell and further challenge the implemented modified media packing solution.

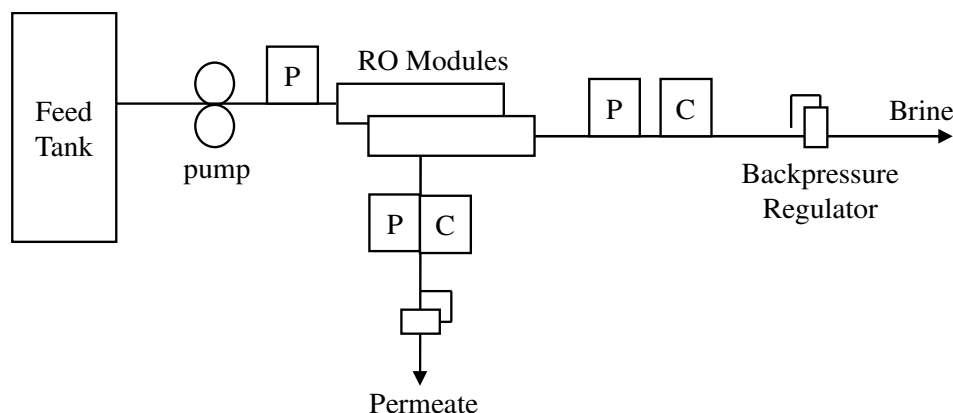
## B. Reverse Osmosis Technology Evaluation

Reverse osmosis (RO) technology was initially traded against MF Bed technology for ISS application in the 1980s. At that time, RO was considered undesirable due to reliability concerns and the resupply mass associated with the limited water recovery available from RO technology. However, advancements in RO membrane technology have

improved overall reliability while ongoing research to reduce fouling is anticipated to improve expected life of RO modules. In addition, the development of a urine brine processor on ISS provides an existing infrastructure for processing RO brine, thus reducing the impact associated with RO brine mass. RO technology can potentially be implemented within the WPA either as an MF bed replacement or by serving as a contaminant buffer upstream the MF beds and reactor. Implementation benefits could potentially decrease upmass due to the lightweight designs of RO modules tested and/or improve the life expectancy of the MF beds and minimize required MF bed replacements due to reduced influent contaminant load.

Studies were completed at MSFC to quantify the correlation between pressure drop, RO module performance, and percent water recovery (%REC). RO module designs provided by Aquaporin and Toray were tested in various configurations. The Aquaporin membrane was procured from Danish Aerospace based on previous testing performed by Ames Research Center.<sup>6</sup> Aquaporin membranes are of hollow fiber construction with a patented Aquaporin coating intended to provide improved rejection of lightweight organics. This feature was specifically desirable for ISS application since a reduction in volatile organics and DMSD could have a measurable impact on the overall WPA performance and design of the Catalytic Reactor. The Toray membrane is a commercially available hollow fiber module that was selected based on coupon tests performed at Johnson Space Center in support of the overall effort to evaluate RO for ISS WPA application. Each Aquaporin module provided 2.3 m<sup>2</sup> of effective membrane area while the Toray module provided 1.1 m<sup>2</sup>.

The MSFC test configuration utilized a single-pass configuration of RO modules, since a recirculation loop could not be reasonably implemented in the existing WPA architecture. Figure 4 provides the mechanical schematic of the test configuration. Based on preliminary tests performed with deionized water, multiple RO modules in series were required to achieve acceptable water recovery. Modules were integrated such that the brine from the first module is feed to the downstream module, while permeate from each module is combined as an aggregate product.



**Figure 4. Mechanical Schematic for RO Technology Evaluation. Shown are process pressure and conductivity sensors. System pressure was maintained downstream the process pump using backpressure regulators.**

### 1. System Backpressure & Configuration Evaluation

RO modules were first evaluated in three configurations to maximize water recovery with varied system backpressure and membrane surface area. Tests utilized the same challenge Ersatz wastewater used for Ambersorb certification. The Ersatz wastewater had a theoretical TOC target of approximately 57 mg/L and a conductivity target of 170  $\mu$ mhos/cm. This formulation also included 22 mg/L of DMSD. All Ersatz water tanks were quality controlled by the MSFC ES62 Chemistry Laboratory to verify TOC and conductivity parameters were within 10% of the target values. Table 2 displays the measured water recovery at varied backpressures for a single Toray module and two or three Aquaporin modules connected in series flow. As expected, higher system backpressure resulted in higher water recovery with additional

**Table 2. Percent water recovery (%REC) for RO Modules.**

	Backpressure (psid)				
	15	20	25	30	34
Configuration	%REC				
2 Aquaporin	-	-	-	90.5	-
3 Aquaporin	69.1	92.9	98.1	99.2	-
1 Toray	-	-	-	-	87.6



gains attained from increased surface area. However, increased water recovery also resulted in degraded permeate quality by allowing more TOC to pass through as shown by Figure 5. Based on these results, module configurations and test conditions were selected for further water quality performance evaluation.

## 2. RO Water Quality

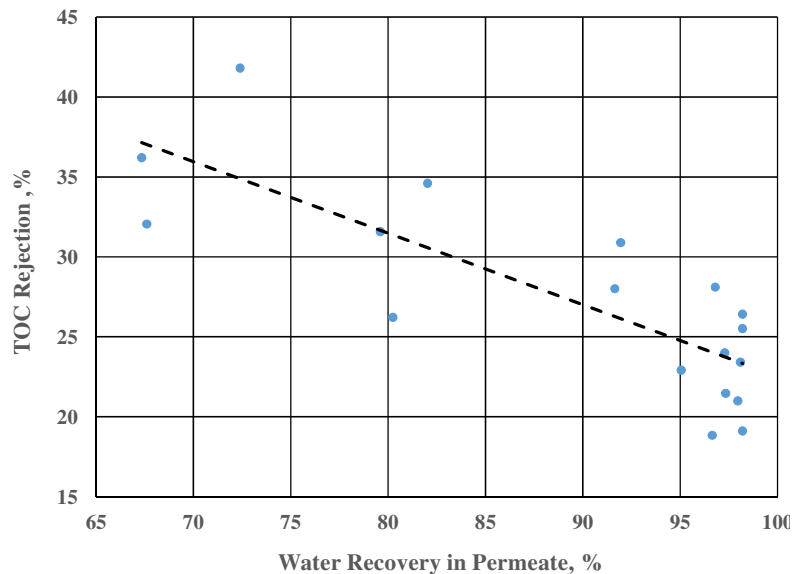
Module permeate and brine streams were sampled and analyzed to evaluate RO system performance by comparisons of TOC, conductivity, pH, as well as specific ionic and organic loads. Table 3 displays measured water quality parameters of three Aquaporin and one Toray module operated at system backpressures selected to achieve comparable percent water recovery. As shown by Table 3, the Toray modules typically performed better than Aquaporin when operated with a similar water recovery rate. Although TOC rejection was only slightly better for the Toray, its ionic rejection was significantly improved. This is a critical data point since the primary objective of implementing RO is to increase MF Bed life by reducing the ionic load. Conversely,

little to no rejection of volatile organics was observed for either module type. Although better organic water quality was observed for the Toray modules, minimal DMSD rejection was seen as compared to the performance of the Aquaporin modules. In fact, of the 22 mg/L DMSD load influent to the RO modules, only 17% was rejected for the Toray module compared to 57% rejection by the Aquaporin modules.

Unfortunately, for either RO technology evaluated, insufficient permeate quality was achieved at viable water recovery rates to outweigh the disadvantages associated with integrating RO technology into the WPA. Specifically, additional plumbing and instrumentation would be required to process the substantial amounts of brine produced in a

**Table 3. Water quality comparison between Aquaporin and Toray RO modules. Aquaporin Test Conditions – 3 modules, 20 psid, 92.9% REC. Toray Test Conditions – 1 module, 34 psid, 87.6% REC.**

Parameter	Units	Permeate Quality		Brine Quality	
		Aquaporin	Toray	Aquaporin	Toray
Methanol	mg/L	18.9	19.4	20.4	19.1
Ethanol	mg/L	13.8	12.6	17.3	16.4
Acetone	mg/L	3.41	2.48	-	3.9
DMSD	mg/L	9.5	18.3	250	175
Methyl Sulfone	mg/L	106	67.8	597	581
Propylene Glycol	mg/L	10.7	9.42	86.2	92.1
TOC	mg/L	40.7	29.7	279	232
Acetate	mg/L	11.2	4.08	112	138
Chloride	mg/L	9.66	2.80	188	172
Ammonium	mg/L	4.93	1.81	30.4	46.1
Potassium	mg/L	15.8	3.45	141.5	163
Conductivity	µmho/cm	90.2	27.7	1,080	1,060
pH	-	7.00	6.75	6.59	7.07



**Figure 5. Total membrane TOC rejection as a function of water recovery for the 3 module Aquaporin configuration.**

single-pass configuration. Though the parallel development of a Brine Processor on ISS was initially anticipated to minimize this impact, a trade study showed that the RO technology would only save approximately 30 - 70 lb upmass over a 2 year mission. This mass savings, while significant, was still determined to be insufficient to offset the impact to overall WPA process reliability associated with integrated RO technology.

### **C. Biocide Effectiveness Screening Study**

Biofilm growth in ISS wastewater systems has already resulted in loss of hardware, impact to operations, and the need for increased resupply.<sup>2</sup> The current approach of periodic hardware replacement is not viable for a manned Moon or Mars mission that provides limited to no resupply capability and must also survive a dormancy period. Multiple approaches are currently being evaluated for maintaining control of biofilm growth in this waste tank. One concept currently under consideration at MSFC is chemical biocide additives. MSFC has obtained a series of chemical additives from Aequor, Inc. for evaluation. In consultation with Aequor, candidate inhibitor formulations were selected that may be effective against biofilm growth in ECLS water systems. Minimum Inhibitory Concentration (MIC) measurements are ongoing to determine the required concentrations of biofilm growth inhibitors. Screening is underway utilizing ersatz wastewater containing a microbial population representative of that present in the WPA waste tank believed to be responsible for producing biofilms. These species include *Ralstonia pickettii*, *Cupriavidus metallidurans*, and *Burkholderia cepacia*. Turbidity measurements and microbial plating were used to compare the inhibitory and bactericidal capability of the candidate inhibitors. Once the most promising inhibitor formulation is identified, full-scale bellows tank testing will ensue.

### **D. WPA Catalyst Life Testing**

Based on reactor performance matrix testing,<sup>4</sup> an advanced candidate WPA catalyst developed by UTAS<sup>7</sup> was downselected for life duration testing at MSFC. The UTAS catalyst exhibited a high TOC oxidation efficiency of 97.9 % and remarkable DMSD oxidation efficiency of 92.6 % during performance phases. For life testing, the catalyst was operated daily against the Challenge Ersatz formulation [alcohols, aldehydes, acetone, glycols, formic acid, urea; TOC = 64.8 ppm]. This ersatz water formulation was chosen as this was the chemistry used to qualify the current ISS WPA catalyst. Approximately 4,671 lb (2,119 L) of Challenge Ersatz was processed during the life testing phase. The measured effluent TOC levels were at or near the instrument detection limit for the entire duration of this test phase indicating good long-duration catalyst life stability against historical ISS WPA development standards.

### **E. Implementation Path Forward**

The adsorbent currently used in the ISS MF Beds (Barnebey Cheney 580-26) has been obsolete for several years. An excess of media was procured by the ISS Program and stored at Umpqua Research Company to provide sufficient media to continue delivery of MF Beds until a replacement could be identified. Successful completion of the Ambersorb evaluation will allow the next pair of MF Beds to be assembled with the Ambersorb media, albeit with one inch less media to accommodate media swell during use on ISS. In addition to replacing the obsolete 580-26, the Ambersorb provides greater adsorbent capacity and thus more margin for organic removal in the MF Beds. Given the current flight schedule, the next pair of MF Beds is expected to be packed in 2018.

The UTAS development catalyst evaluated at MSFC has been approved for use with the WPA Catalytic Reactor. The ISS Program Office has authorized Boeing and UTAS to evaluate modifications to the Catalytic Reactor in response to the limited life of the rubber o-rings previously observed on ISS.<sup>2</sup> Polymer o-rings will be replaced with metal seals to return the Catalytic Reactor to a minimum 5 year life. This upgraded Catalytic Reactor will also include the development catalyst<sup>7</sup> to provide the reactor with increased capacity for organic oxidation. This catalyst also has improved performance for DMSD destruction, which has been a challenge for WPA since operations began on ISS. Ground testing<sup>4</sup> at MSFC showed the UTAS development catalyst will improve DMSD removal efficiency from 75% to 92%, which may be beneficial to insure DMSD no longer impacts WPA operations. The specific schedule for the new catalytic reactor has not been defined, but it is expected to be delivered in 2020 for operation on ISS.

## **II. Conclusion**

Testing performed at NASA MSFC in the past year has completed the assessment of Ambersorb media and verified a viable approach toward packaging the MF Beds to accommodate swelling of the Ambersorb media as it is saturated with organic contaminants. These results are immediately applicable to the assembly of the next pair of MF Beds required for use on ISS. Developmental catalyst testing performed at MSFC since 2016 has culminated in the selection of the UTAS catalyst for future use on ISS. The ISS Program Office is currently authorizing Boeing and UTAS to deliver a new Catalytic Reactor with this new catalyst to provide increased capacity for organic oxidation on ISS, including the problematic DMSD. Evaluation of biocides to control biofilm growth in the WPA waste tank has been initiated, and this effort is expected to expand in the next year to include ultraviolet concepts. Finally, development

testing of the RO technology has been completed. Though RO provides the opportunity to reduce consumable upmass, NASA has decided to not pursue it as a WPA upgrade due to the complexity required to integrate this technology.

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