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Brine Processor Assembly 2023-24: Operational Successes and Challenges on the International Space Station

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The Brine Processor Assembly (BPA), developed by Paragon Space Development Corporation as a one-year technology demonstration, has now been in operation onboard the International Space Station (ISS) for three years. BPA recovers available water from urine-brine produced by the ISS Urine Processor Assembly (UPA) via forced convection of cabin air coupled with a patented membrane distillation process. A dual-layer ionomer and microporous membrane-based bladder retains the liquid brine while water vapor pervaporates into the cabin, for collection as humidity condensate. This paper will discuss updated performance results as well as the practical operational challenges of maintaining hardware on the ISS.

In August 2023, BPA operations were automatically halted when the Brine Leak Alarm annunciated. Crew opened the BPA to confirm that there was no actual leakage of brine, upon which it was discovered that corrosion had developed on the Brine Leak Sensor. Paragon has been working with NASA to extend the life of the sensor and safely operate BPA, as well as to launch the spare replacement component. As of May 2024, 41 full operational runs have been completed spanning 612 days of active operations, recovering an estimated 741 kg (L) of water from urine-brine. This represents a cost savings of over $80 million from the mass of water that has not needed to be launched to or discarded on ISS, minus the cost of consumables (bladders and odor filters). The BPA currently has an impressive 6x water-to-up mass recovery ratio, meaning BPA has recovered 6x as much water as the mass of the BPA hardware itself and all consumables (bladders, spares, and odor filters). This has helped NASA to claim 98% water recovery on ISS, achieving an essential capability to enable human exploration of deeper space.

Nomenclature

%REC = % recovery
AES = Advanced Exploration Systems
Alt = Alternate
ARFTA = Advanced Recycle Filter Tank Assembly
BPA = Brine Processor Assembly
EDV = Russian acronym for Urine Tank
ENIG = electroless nickel immersion gold
ETHOS = Environmental and Thermal Operating Systems
HEPA = High Efficiency Particulate Air (Filtration)
ISS = International Space Station
IWP = Ionomer-membrane Water Processor
FIT = Failure Investigation Team
FOD = Foreign Object Debris
JSC = Johnson Space Center

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MSFC = Marshall Space Flight Center
NASA = National Aeronautics and Space Administration
PCB = Printed Circuit Board
RH = Relative Humidity
SMAC = Spacecraft Maximum Allowable Concentration
UPA = Urine Processor Assembly
VCD = Vapor Compression Distillation

I. Introduction

CLOSING the water loop on long duration spaceflight missions is a key aspect of reducing mission mass and logistics support for orbiting facilities and interplanetary spacecraft.[1] Urine water recovery on the International Space Station (ISS) is performed by the Urine Processor Assembly (UPA) via Vapor Compression Distillation (VCD). The VCD process is restricted to the solubility limit of various compounds in pretreated urine such as calcium phosphate for Alternative (Alt) Pretreatment (or calcium sulfate for Baseline Pretreatment), thus producing concentrated brine that requires further processing for water recovery. The Brine Processor was developed to demonstrate increased water recoveries on the ISS up to 98% and helps to enable long duration human exploration missions beyond low earth orbit. The Brine Processor is based on Paragon's patented[2] Ionomer-membrane Water Processor (IWP) technology which is a membrane-distillation based water recovery system. BPA operates in an open loop with cabin air and utilizes existing spacecraft systems such as the cabin-condensing heat exchanger and trace contaminant control system to minimize mass, volume, and complexity. The IWP membrane significantly limits contaminant permeation from the brine to the recovered water, purge gas, and cabin atmosphere.[3,4,5] The Brine Processor was developed by Paragon and NASA Advanced Exploration Systems (AES) Life Support Systems project as an integrated technology demonstration on ISS. This technology represents the state of the art for exploration mission brine water recovery beyond the limits of distillation, which is the current ISS technology. Flight hardware was successfully delivered to NASA in Fall 2020, launched to the ISS in February 2021, and installed in March 2021. On-orbit operations are ongoing and will continue to be evaluated to best understand BPA performance in a spacecraft environment.

A. Background

The Brine Processor Assembly utilizes forced convection of spacecraft cabin air coupled with Paragon's patented IWP membrane distillation process to purify and recover >80% of available water from 21.8 liters of brine within a 14-day cycle. The IWP membranes are formed into a disposable bladder (Figure 1) to contain and process this brine. The dual-layer bladder serves two purposes: 1) a method of containment of the high toxicity level (Tox 2) brine and 2) the technology by which water is recovered. The inner bladder retains solids and liquids but allows water vapor and some trace contaminants to pass through its microporous membrane. The outer ionomer bladder is also permeable to water vapor and fewer trace contaminants. Because the membranes are extremely lightweight, the entire IWP membrane structure is disposable with the brine, maintaining brine containment throughout the life of processing and disposal. At 0.5 kg total weight, the consumable bladders are well within the AES exploration program goal of brine processing consumables mass of 25% or less of recovered water mass.

The disposable BPA bladder accepts the brine from the UPA's Advanced Recycle Tank Filter Assembly (ARFTA) via a brine transfer hose. The urine brine received from ARFTA has been pretreated with the Alternative (Alt) pretreatment formulation (phosphoric acid). A heater warms the air, which passes over the bladder and collects the vapor. The vapor is condensed in the existing spacecraft condensing heat exchanger(s), which recover metabolically produced water vapor as humidity condensate. Condensate is then further processed to potable water utilizing the existing spacecraft Water Recovery System.[6]

Figure 1. Brine processor bladder (unused).

II. BPA Operational Performance

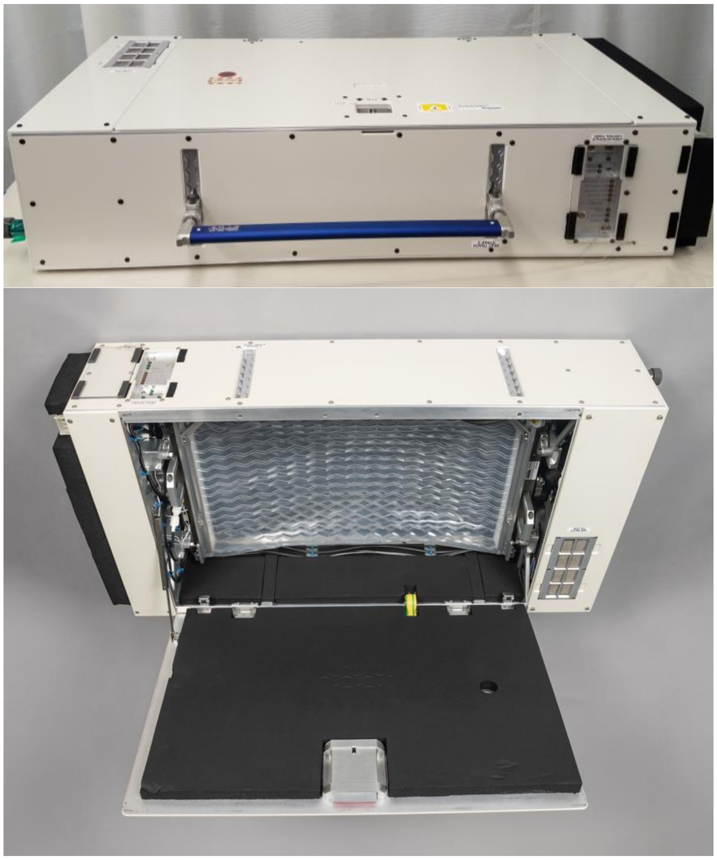

Figure 2. Brine processor assembly in a closed position (top) and open position (bottom).

Images of the flight hardware are shown in Figure 2 with the lid open to show the internal Detrusor and with the lid closed. Operational details of BPA have been published previously.[7,8] Briefly, ISS cabin air is drawn in through a heater, passes over a brine-filled IWP bladder in the central cavity, and water is evaporated out of the brine through the semi-permeable outer membrane of the bladder due the lower partial pressure of water outside versus inside the bladder. Effluent air exhausts out of the aft face through an outlet filter, not shown in Figure 2, for odor mitigation prior to release into the cabin. These operations continue until the extractable water is removed, as indicated by the difference between the inlet and outlet temperature telemetry.

Crew time for the end of a BPA cycle is relatively minimal, and includes the brine supply line attachment, bladder change out (i.e. used bladder removal, packaging for stowage and disposal, new bladder installation), brine fill of the new bladder, and disconnection of all brine lines after the bladder has been filled. All start/stop commanding of BPA is done remotely by NASA flight command. Active crew time for a bladder change out is scheduled as a 25 minute activity.

Select on-orbit telemetry data for the first dewatering run with a permanent filter can be seen in Figure 3. The temperature profile during a dewatering cycle remains steady for the beginning stages of operations. The inlet and outlet temperatures converge as less water is available to recover, thus decreasing the evaporative cooling due to the water's latent heat of vaporization. Dewatering cycles are concluded once the delta temperature across the inlet and outlet plenums of the BPA reach a certain known value based on the heater setting. The BPA's inline heater consists of three independent heater coils. The Heater receives 28V power and can be set to seven discrete temperatures (based on ambient conditions) by selecting different combinations of heater coils to be powered. Operational cycles run at higher heater settings, for example, will be terminated at a higher delta temperature value (i.e. Inlet – Outlet temperature). The maximum power draw of BPA, which is currently nominal operation, is 195 Watts.

In 2021, an extensive experimental trial was conducted in ground testing to demonstrate the capability of the exhaust filter. The performance of the exhaust odor filter has now been proven out on orbit for over two years with great success.

In 2023, the leak sensor was found to be corroded and was successfully cleaned by the crew, as detailed in Section II.B and C. As of May 2024, the BPA has successfully completed 41 full dewatering cycles, recovering an estimated 741 L of water.

A. On-Orbit Dewatering Performance & Analysis

Estimating the water recovered from the on-orbit runs relies on selecting the appropriate input parameters. Ambient temperature and humidity (i.e. dew point) are also kept as averaged constants for simplicity of modeling. On-orbit operations and parameters do not allow for precise estimates of volume and starting mass, so these values are also kept as consistent assumptions. For these reasons, the % mass of water recovered is always given as an estimated range, as seen in Table 1. Operating parameters, including heater settings, brine concentration, days of operation, and estimated water recovery for all 41 operational runs can be seen in Table 1. The brine that is dewatered in the BPA is generally received directly from the UPA's Advanced Recycle Filter Tank Assembly (ARFTA), although it is sometimes transferred from storage vessels such as Russian EDVs. The concentration of brine used in the BPA is dependent on many variables, including the amount of U.S. versus Russian urine that is processed, as well as how many process cycles it goes through to remove water. The brine concentration is generally referred to as % recovered (%REC), the percentage of water recovered by volume during UPA processing. Brine concentration is also represented as solids fraction in Table 1, which indicates what amount of the brine is not water (i.e. non-recoverable). The concentration of brine that is processed in BPA ranges from 78-87 %REC: 78 %REC brine is more dilute with more water available to recover while 87 %REC brine is more concentrated with less water available to recover. Brine starting concentration, heater setting, and the number of days of operation are the main determinants of how much water is recovered in an operational cycle. The % water recovery by BPA for an operational cycle is represented in Table 1 (in reverse chronological order) as a percentage of available water by mass, a percentage of total mass (i.e. water and solids) and a percentage by volume.

Table 1. On-orbit water recovery summary for 41 operational runs through May 2024.

		Cycle time	Water recovery (On Orbit estimate)				Telemetry (at end of ops)			Brine concentration	
Run	Heater	Days	~L	~% water b.m.	~% total b.m.	~% by volume	Delta T	Tin	Tout	%REC as received (from UPA)	~ Initial solids fraction
41	2+3	16.9	18.4	90-95+%	75-80%	85%	11.8	48.9	37.1	80.7%	0.21
40	1+2+3	12.9	17.8	90-95+%	70-75%	82%	13.4	54.1	40.7	84.6%	0.24
39	1+2+3	12.8	19.4	90-95+%	80-85%	89%	12.7	53.3	40.5	70.3%	0.15
38	1+2+3	16.3	18.2	90-95+%	75-80%	83%	12.5	52.3	39.8	82.7%	0.22
37	1+2+3	12.8	18.1	90-95+%	75-80%	83%	14.3	54.4	40.1	82.9%	0.23
36	1+2+3	14.0	18.6	90-95+%	75-80%	85%	11.9	51.1	39.2	79.6%	0.20
35	1+2+3	15.2	18.3	90-95+%	75-80%	84%	13.1	52.8	39.7	81.5%	0.22
34	1+2+3	14.3	18.5	90-95+%	75-80%	85%	12.3	49.6	37.3	80.4%	0.21
33	1+2+3	16.0	19.1	90-95+%	80-85%	88%	11.4	49.4	38.0	74.2%	0.17
32	1+2+3	14.9	18.7	90-95+%	75-80%	86%	12.5	50.2	37.7	78.2%	0.19
31	1+2+3	9.5	15.9	85-90%	60-65%	73%	12.9	48.5	35.6	87.0%	0.27
30	1+2+3	13.5	18.4	90-95+%	75-80%	85%	9.9	48.5	38.6	81.0%	0.21
29	1+2+3	11.6	18.0	90-95+%	70-75%	83%	10.3	50.1	39.8	83.4%	0.23
28	1+2+3	15.8	17.4	90-95+%	70-75%	80%	9.5	49.7	40.2	87.0%	0.27
27	1+2+3	14.0	18.1	90-95+%	70-75%	83%	9.6	49.3	39.7	83.4%	0.23
26	1+2+3	13.0	17.4	90-95+%	70-75%	80%	9.0	48.9	38.9	86.9%	0.27
25	1+2+3	11.8	18.7	90-95+%	75-80%	86%	9.0	47.8	38.8	78.6%	0.20
24	1+2+3	13.4	18.2	90-95+%	75-80%	83%	9.1	49.7	40.6	81.0%	0.21
23	1+2+3	13.5	18.2	90-95+%	75-80%	83%	8.6	47.2	38.6	82.5%	0.22
22	1+2+3	14.4	18.5	90-95+%	75-80%	85%	10.7	51.3	40.6	80.5%	0.21
21	1+2+3	13.1	17.7	90-95+%	70-75%	81%	8.9	47.4	38.5	85.2%	0.25
20	1+2+3	14.2	18.4	90-95+%	75-80%	84%	9.5	48.6	39.1	81.4%	0.21
19	1+2+3	14.65	17.9	90-95+%	70-75%	82%	8.9	46.5	37.2	84.0%	0.24
18	1+2+3	14.96	18	90-95+%	70-75%	83%	9.0	47.2	38.2	83.6%	0.23
17	1+2+3	16.6	18.2	90-95+%	75-80%	84%	9.3	48.1	38.8	82.2%	0.22
16	1+2+3	12.7	18.7	90-95+%	75-80%	86%	10.3	49.3	39	78.1%	0.19
15	1+2+3	15	18.7	90-95+%	75-80%	86%	9.7	47.6	37.9	78.9%	0.20
14	1+2+3	13	18.5	90-95+%	75-80%	85%	9.1	47.7	38.6	80.1%	0.21
13	1+2+3	14	18.4	90-95+%	75-80%	84%	9.7	49	39.3	81.2%	0.21
12	1+2+3	14	18.6	90-95+%	75-80%	85%	8.7	47.6	38.9	79.5%	0.2
11	1+2+3	14	19	90-95+%	75-80%	87%	9.6	48.6	39	76.0%	0.18
10	1+2+3	14.2	18.3	90-95+%	75-80%	84%	10.4	48.4	38	82.0%	0.22
9	2+3	15.8	18	90-95+%	70-75%	83%	8.0	42.8	34.8	84.0%	0.23

		Cycle time	Water recovery (On Orbit estimate)				Telemetry (at end of ops)			Brine concentration	
Run	Heater	Days	~L	~% water b.m.	~% total b.m.	~% by volume	Delta T	Tin	Tout	%REC as received (from UPA)	~ Initial solids fraction
8	1+2	17.2	17.9	90-95+%	70-75%	82%	4.1	36.3	32.2	82.0%	0.24
7	1	20.6	17.8	90-95+%	70-75%	81%	2.1	27.3	25.2	84.0%	0.24
6	1	20.1	17.4	90-95%	70-75%	80%	2.2			85.5%	0.25
5	1	17.5	16.8	85-90%	65-70%	77%	2.9	27.1	24.2	82.8%	0.23
4	1	19.5	16.5	85-90%	65-70%	76%	2.4	26.7	24	87.0%	0.27
3	1	20	18.2	90-95+%	75-80%	84%	2	27.2	25.2	80.0%	0.20
2	1	17.4	17.3	85-90%	70-75%	80%	2.5	28.5	25	79.0%	0.20
1	1+2+3	4.28	7.7	43%	31%	35%	16	49	33	87%	0.27
	1	6.68	6.7	38%	28%	31%	4.6	27.5	22.9		
	1	5.79	2.7	14%	11%	12%	3	28.9	25.9		
	Averages	**14.9**	**18.1**	**95%**	**75%**	**83%**	**9.1**	**46.1**	**36.8**	**82%**	**0.22**
	Total	**611.8**	**741.3**								

Since the %REC of water from urine-brine by the UPA is determined by the complex needs of ISS water recovery logistics, the BPA receives brine at whatever %REC it is available at. This means the only mechanisms available to modify BPA operations are heater setting and operational duration. Regardless, the BPA has continued to meet its end goal of reclaiming at least 40% of water by volume, and has exceeded this parameter for every run as shown in Table 1. In total, it is estimated that in 612 days of active operation the BPA has recovered 741 kg of water. The impact of the BPA can be visualized by comparing the water recovered over the last three years against the hardware launches for BPA, as shown in Figure 4. This includes all spares, bladders, bladder containment bags, and odor filters launched, including those that have not yet been used by BPA. The BPA currently has a hardware-to-upmass ratio of 6x, meaning it has saved 6 kg of upmass for every kg of hardware launched to support it. At the current operational cadence, BPA will have an upmass ratio of 10x within 2 years. The upmass ratio does not factor in the reduced reliance on EDVs to store or trash urine, which has additional cost/logistical savings.

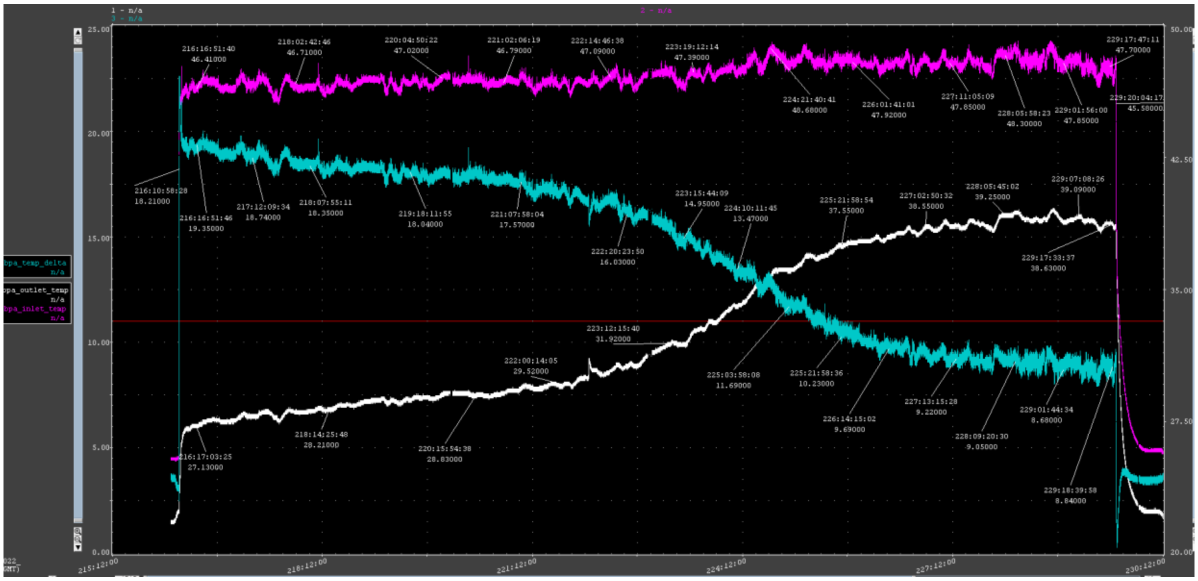

Figure 3. Telemetry for operational dewatering cycle # 14 indicating the beginning and end of the run as a raw data downlink. *Pink trace is inlet temperature, white trace is outlet temperature, and blue trace is delta temperature.*

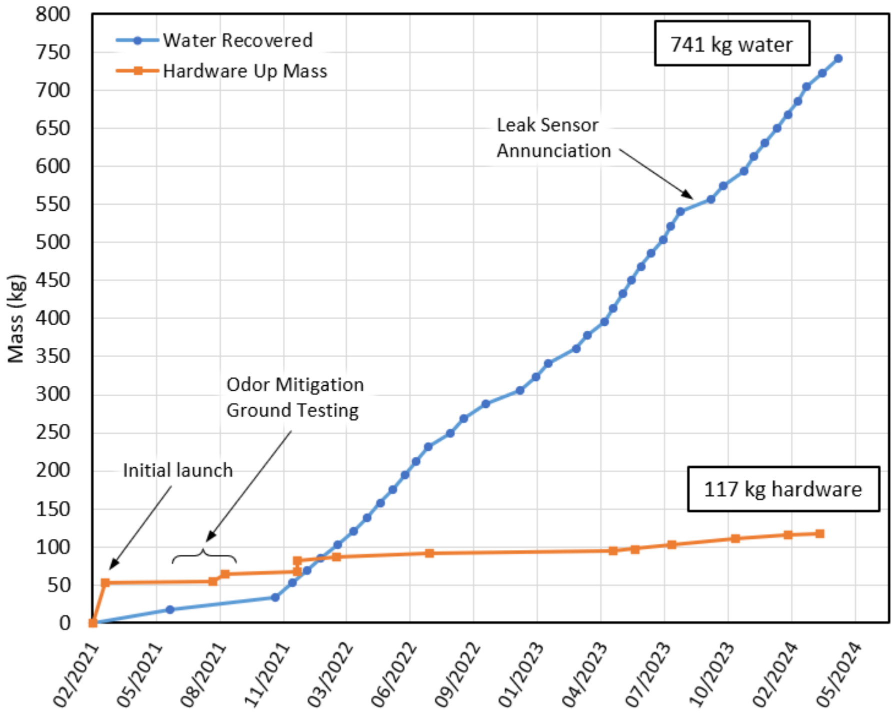

Figure 4. BPA water recovered vs. hardware up-mass since launch. *Includes all spares and consumables launched as of May 2024.*

After 41 full operational cycles, Paragon's thermal model for predicting dewatering performance has been further refined, especially based on brine concentration. In particular, a recent focus has been on coordinating BPA and UPA cycles. The BPA has been typically running through a complete cycle of 13-14 days, but the UPA operational cycles last only ~8 days, making BPA cycles somewhat offset from UPA cycles most of the time. Work is being conducted by NASA and Paragon to investigate running BPA for reduced cycle lengths to better align with UPA and reduce the need to pump brine to EDVs for temporary storage in-between brine cycles. The primary trade is between the different "costs" of each concept of operations: when BPA runs to completion the most water is removed from the brine, but recoverable water might be lost if brine needs to be trashed in-between cycles because the BPA is not available. Therefore, a shorter cycle where less water is recovered per brine batch may actually recover more water in the long run. This potential trade is demonstrated with Figure 5, which shows a sample run of the BPA dewatering cycle's water recovery metrics. Note that the water removal rate declines rapidly after the 8 day mark, and essentially very little to no water is being removed after 12 days for this run. These estimates help assess when to cease an operational run; now that there is a large set of operational data on-orbit, the BPA team can more confidently assess when to end BPA operations. Further optimizing the cadence of BPA operations with UPA operations on ISS will allow for the most efficient water recovery and storage on-orbit.

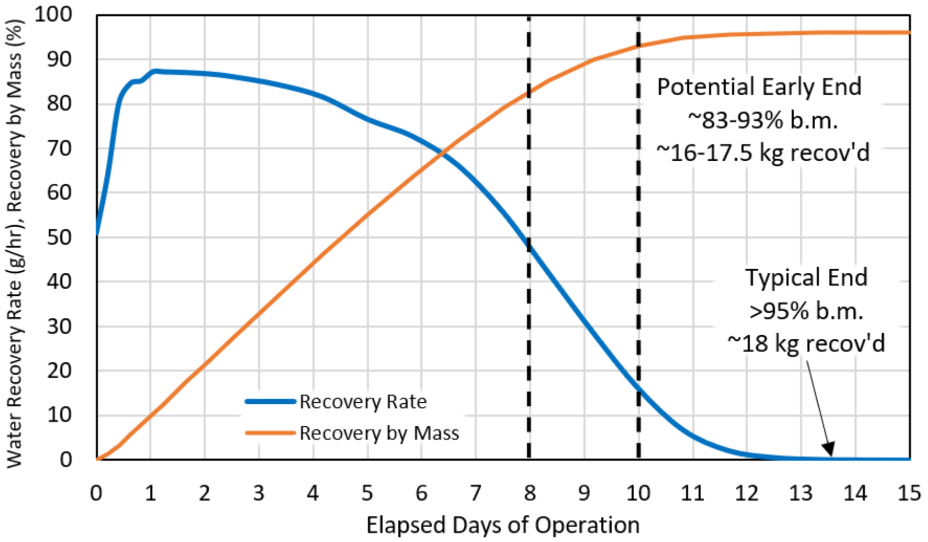

Figure 5. Dewatering model recovery metrics and illustration of short-cycle benefits.

B. Leak Sensor Annunciation

On August 16, 2023, soon after the start of operational Cycle 31, the BPA automatically halted operations when the Brine Leak Alarm annunciated. Upon inspection by the crew, there was no evidence of an actual brine leak event, but crew did find blue-green discoloration on several of the traces of the Brine Leak Sensor inside the BPA Detrusor, which is generally indicative of copper corrosion. The corrosion/discoloration was evident all around the sensor and not localized to any particular area. This even distribution hints at an oxidation mechanism which likely has been occurring over a significant period of operations (which is unknown).

The Brine Leak Sensor is comprised of two conductive metal traces built onto a printed circuit board (PCB). It is designed to detect a brine leak via a change in capacitance between the two wire traces, located on the face of the detrusor outlet plenum. When a highly conductive fluid (such as urine brine) contacts the metal traces, the inner trace is bridged to the outer traces ($^{---}$v^{---} shapes shown in Figure 6), the circuit is completed and the alarm trips. A Brine Leak Alarm will automatically put BPA into a Stop state, shutting down the heater and fan, and ceasing active dewatering operations to prevent any potential brine from escaping the Detrusor cavity.

In the case of this false Brine Leak Alarm annunciation, it is presumed that the corrosion (and the hydration of the corroded material) caused enough of an increase in conductivity (decrease in resistivity), bridging the circuit to cause a false positive alarm trip. The Brine Leak Sensor was originally manufactured as a copper electrode with electroless nickel immersion gold (ENIG) plating, which is designed to reduce corrosion. The original gold layer was 3 millionths of an inch thick (i.e. 3 micro inches) and the copper layer was 2-3 thousandths of an inch thick (0.002 inches). After discussions with the sensor manufacturer, it was determined that the protective gold layer had likely reacted with and/or migrated through the nickel and copper layers due to the harsh environmental conditions (high heat and humidity) within the Detrusor. After the protective (inert) gold layer was compromised, it allowed heat and humidity to react with the copper material, which lead to copper corrosion.

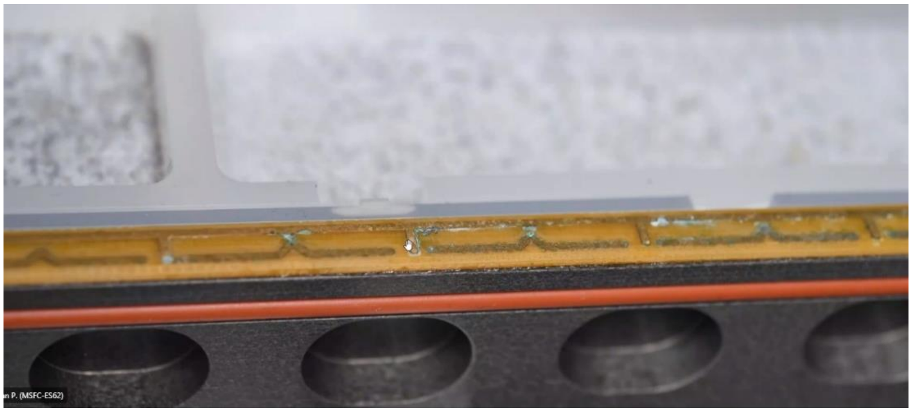

Figure 6. Image of the BPA brine leak sensor after false leak alarm, including where the electrical traces (darkened lines on yellow circuit board) show signs of copper corrosion (blue/green discoloration). Photo credit: NASA ISS Imagery Online.

The underlying cause of the corrosion is suspected to be the warm, humidified air (maximum temperature ~45°C, maximum relative humidity ~80%) that is flowing through the outlet plenum during the entirety of BPA operation (note: humidity is maximized near the beginning of the dewatering cycle, while temperature is maximized at the end of the cycle). From extensive ground testing, the humidity condensate is known to have an acidic pH due to trace amounts of additional compounds that are also transported across the ionomer membrane along with the water.[3] This certainly adds to the corrosive nature of the environment within the BPA Detrusor.

When a significant hardware or software failure is experienced on the ISS, a NASA interdisciplinary group of relevant subject matter experts, called a Failure Investigation Team (FIT) is assembled, including but not limited to safety, flight surgeon, operations, materials and process. An initial FIT meeting was held on August 17, 2023, at which time it was agreed that a leak did not occur, and that the most likely cause of the fault was identified as a short of the brine leak sensor due to corrosion developing on the sensor. A second FIT on August 23rd reviewed options for getting BPA operational again, and recommended cleaning the corrosion from the Brine Leak Sensor to restore the leak detection capability.

As the Brine Leak Sensor was still functional, it was decided that BPA operations could continue in this impaired, but still safe-to-operate state. It is important to note that all flight bladders are acceptance tested to the maximum design pressure for any potential leaks prior to launch and use, resulting in a very low risk of actual brine leakage from a bladder. The leak sensor annunciated a total of three more times over several subsequent runs, and for crew safety, operations were always stopped and the Detrusor interior was inspected, but no brine leak ever actually occurred. The BPA team decided that the best path forward would be to attempt to clean the corrosion in order to extend the life of the sensor as much as possible. It was decided that as long as the leak sensor annunciation was not a significant nuisance, and the sensor itself was still functional, BPA operations would continue with the imperfect sensor. Paragon worked with the sensor manufacturer and NASA to understand the best cleaning tools and methods based on their likelihood of success in removing metal corrosion and what was available on Station.

C. Leak Sensor Operational Mitigation

Downlinked video of the cleaning activities on ISS was requested to be able to monitor cleaning progress and give feedback to the crew during cleaning activities. This afforded the Paragon and NASA BPA teams the opportunity to observe and work around the logistical difficulties crew experienced during cleaning procedures. Despite the live camera footage, there was some appreciable delay between communication among the BPA team, NASA Ground Communications, and the transmittance of audible commands to crew. These practical delays in communication necessitate thorough preparedness for off-nominal crew procedures, so multiple if/then contingency plans and instructions were included during the development of the cleaning procedures. A snapshot of American astronaut Jasmin Moghbeli during a cleaning activity is shown in Figure 7.

As the electrodes are well-adhered to the PCB, it was decided that the best option was to attempt to remove the corrosion between electrode traces and clean the electrode surfaces to bare copper. A procedural outline was written for methods of cleaning the Brine Leak Sensor using mechanical and/or chemical cleaning. The intent was to start with the gentlest cleaning process and, if ineffective, increase the intensity of the cleaning method. The primary goal was to effectively remove the corrosion bridging the gap between electrodes while minimizing damage to the underlying metal of the electrode itself. The sensor's manufacturer confirmed that it would be very difficult to remove the base electrode from the board itself, and would require something such as steel wool or a metal pick, which were deemed last resort cleaning tools.

Figure 7. Image of BPA leak sensor cleaning activities showing ISS crewmember Jasmin Moghbeli working on the BPA. Photo credit: NASA ISS Imagery Online.

The general cleaning methodology was to target one area for cleaning efficacy, and, if corrosion was not removed, to try next removal method/tool in the same area. All cleaning methods were paired with a water dampened rag to wipe the area clean of any residue that could cause further corrosion or reaction with subsequent cleaning steps and to reduce the potential release of foreign object debris (FOD). The crew was asked to visually inspect the area for removal of corrosion and note the efficacy of each cleaning method and use best judgement to determine if additional pressure would be effective or to move on to the subsequent cleaning method. The tools and methods included a deionized water-dampened dry wipe, a dampened microfiber cloth, a weak acid dampened swab, a toothbrush or soft brush, and a metal pick as a last resort. Disinfecting wipes were eliminated as an option because they could create unwanted residues or potentially contain oxidizers that would lead to additional corrosion. A mild acid and light mechanical abrasion (i.e. elbow grease) was the most effective option, paired with a dampened dry wipe. Multimeter readings of resistance across the two electrical leads were taken prior to and after all cleaning activities to indicate the success of the cleaning (e.g. demonstrating higher resistivity/reduced conductivity between the electrodes).

Ultimately, through multiple cleaning activities with various crew members, the corrosion on the BPA Leak Sensor was significantly reduced, almost eliminated in many areas, as shown in Figure 8. A test to short the sensor by laying a screwdriver across the two leads was successful, immediately setting the alarm and confirming that its basic functionality was still intact. This gave further confidence that the sensor would indeed work in the case of an actual brine leak. Now that the protective gold layer has been compromised, it is inevitable that additional corrosion will continue to develop as the copper surface is exposed to elevated humidity and temperature during regular operations. Maintenance steps have been added after each dewatering cycle, during bladder change outs, to wipe down the sensor in an attempt to remove any additional corrosion that has developed. The crew also takes photos of the Brine Leak Sensor between each cycle to monitor its condition. As of May 2024, eleven additional operational cycles have been completed with the BPA and all its original (non-consumable) piece/parts. The original Detrusor is still installed, the Brine Leak Sensor continues to function and, with routine wipe-downs after every dewatering cycle, BPA has not incurred any additional false Brine Leak Alarms.

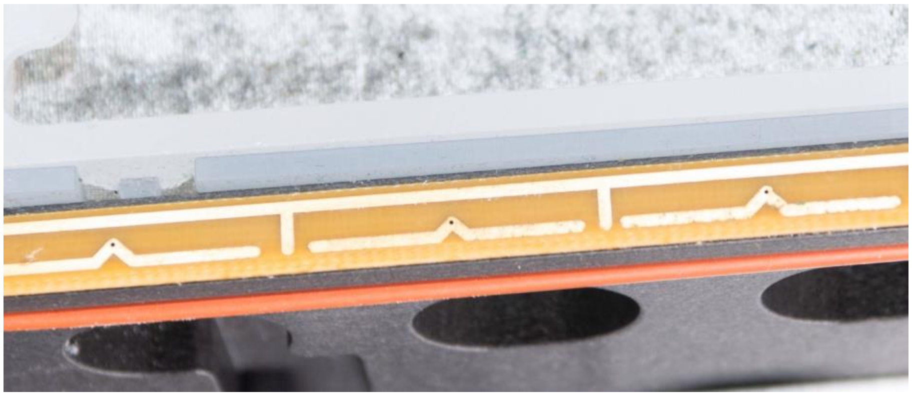

Figure 8. Image of BPA leak sensor after several rounds of cleaning activities showing significant reduction in corrosion. Photo credit: NASA ISS Imagery Online.

In March 2024, the BPA set off a different alarm, indicating a high temperature signature on the thermostat hardwired to the outside of the Heater. This alarm is to monitor and protect against over heating of the Heater itself. This alarm immediately followed an Adlink (ISS software connectivity) failure, and was originally presumed to be a BPA firmware glitch related to the loss of Adlink. Upon investigation into BPA telemetry and performance curves, it was found that the Heater over temperature alarm was real, and likely due to reduced air flow through the unit. The reduced air flow was suspected to be due to three years of use with the same Inlet high efficiency particulate air (HEPA) Filter as well as a small, known air leak that had developed internally. Neither of these conditions posed safety hazards to crew or BPA operations. BPA could continue to operate in the lower air flow condition, and the Heater temperature was reduced (Heaters 2+3 only) to continue operations without risk of overheating.

On May 7, 2024, after three years of operation, the original Inlet HEPA Filter was removed and replaced with a new spare. This was a much needed exchange, as evidenced by the dusty used filter shown in the left image of Figure 9. The new HEPA filter is shown on the right, just after being installed in the BPA, prior to reinstallation of the housing that retains it in place. The fine mesh on the top face of the Inlet HEPA Filter is meant to keep out large debris, and is vacuumed weekly as a part of regular crew maintenance. This is the only regular ‘housekeeping’ activity for BPA. After installation of the new Inlet HEPA Filter, BPA operations were resumed at max heater settings (all 3 heater coils operational). The inlet temperature dropped by ~4°C from previous operational Max temp runs, confirming that the clogged inlet filter was reducing the overall flow of air into BPA and thus increasing the temperature at the Heater.

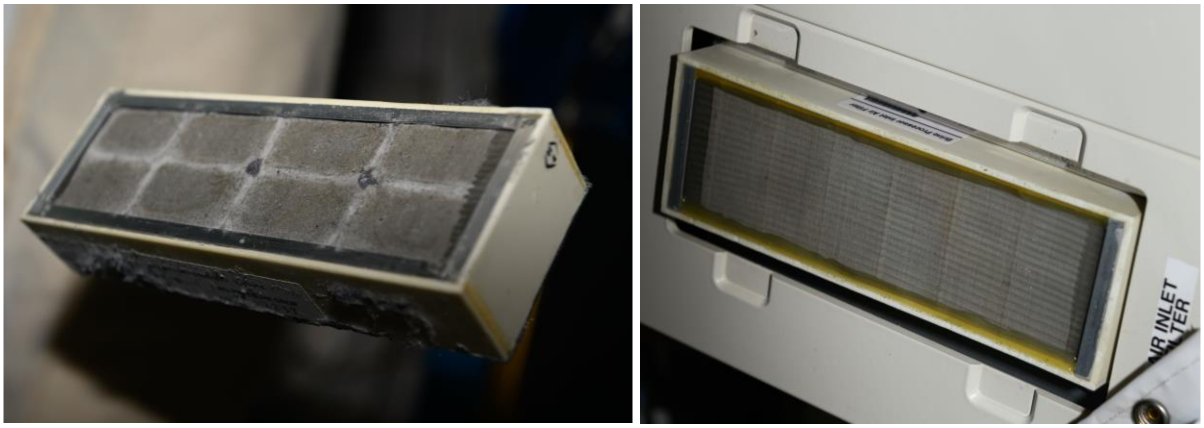

Figure 9. (Left) Image of used BPA Inlet HEPA Filter immediately after removal from BPA. (Right) Newly installed replacement Inlet HEPA Filter, as shown installed in BPA (before housing to hold in place is reinstalled). Photo credits: NASA ISS Imagery Online.

BPA was originally built as a one-year technology demonstration on ISS, so the continued use of BPA for three years is a significant success. Paragon believes that this is largely due to the simplicity of BPA's operations, with a fan being the only moving part to sustain. Knowing that the leak sensor was still compromised and would not last forever, a spare Detrusor was launched to ISS in late 2023. This is currently being held in stowage in preparation for removal and replacement once the original Brine Leak Sensor is no longer operational. Because the Brine Leak Sensor itself was not designed as an individually replaceable spare, the entire Detrusor must be replaced. This is a design improvement being considered for future Brine Processor Assembly hardware. The BPA requires minimal active crew time for bladder installation and removal, which is scheduled as a 25 minute activity. After use, bladders are placed into a triple layer Odor Containment Bag prior to stowage, until they can be disposed of, or in limited cases, returned to Earth for study. The Odor Containment Bag was originally designed as additional layers of containment for brine, with the bonus feature of odor containment. In practice, though, these bags did not successfully mitigate the odor of a used bladder. New Odor Containment Bags have been designed for both brine containment and more effective odor containment, which are being launched to the ISS in August 2024. The Odor Containment Bags were not designed or built by Paragon.

III. Conclusions and Forward Work

At the time of this writing, it is estimated that in 612 days of active operation the BPA has recovered 741 kg of water on orbit at an estimated launch and trash cost savings of roughly $80 million. BPA has far exceeded its levied water recovery requirements, facilitating the NASA overall goal of 98% water recovery on ISS.

During regular operations in August 2023 the Brine Leak Alarm annunciated, and it was discovered that corrosion had developed on the electrical traces of the Brine Leak Sensor. After multiple rounds of cleaning, a significant amount of the corrosion was removed, and with regular maintenance during bladder change outs the leak alarm has not annunciated since. It is believed that high humidity and higher temperature operations have likely degraded the original protective gold coating and led to corrosion (i.e. oxidiation) of the base copper layer of the electrode. As the BPA was designed and built as a one-year tech demo on the ISS, after 3 years of operation, it has long surpassed its original operational lifetime. BPA has now recovered over six times the mass in water as the original upmass of the hardware and all associated consumables.

Forward work will focus on extending the lifetime of the current hardware and using lessons learned from three years of BPA operations to design the new and improved version of components whose performance has degraded more quickly. An additional area Paragon is exploring is the reusability of bladders. This could be manifested by refilling after the initial dewatering cycle, or as a constant process of refilling as dewatering progresses. The dewatering process currently operates as a batch process, i.e. each bladder is one time use. Despite the low ratio of mass of the discarded bladder (0.5 kg for the empty bladder) to the mass of water recovered (16-19 kg) per cycle, an extended usage lifetime of the bladder would be highly desirable for long term lunar or Mars missions.

The continued on-orbit operations of BPA contribute significant knowledge to the most efficient use of energy to recover water, informing best practices for future implementation of membrane distillation-based water reclamation technologies. The ability to observe crew members conducting real time BPA maintenance activities has also afforded a better understanding of opportunities for hardware design improvements. Three years of sustaining engineering of the Brine Processor Assembly has lent incredibly useful and practical knowledge on hardware performance and maintenance impacts in reduced gravity operations. Despite some areas for optimization, the simplicity of BPA's operational function and design has required little overall maintenance to keep the hardware operational well beyond its originally designed lifetime on the International Space Station.

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