

# Demonstration of a Full Scale Integrated Membrane Aerated Bioreactor- Ionomer-Membrane Water Purification System for Recycling Early Planetary Base Wastewater

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**Long term space habitation outside of low Earth orbit requires near complete recycling of wastewater. Current systems rely on chemical pretreatments and are not capable of treating the diversity of wastewaters expected to be produced from an early planetary base (EPB). Hybrid life support systems that combine biological treatment with advanced desalination systems can provide robust treatment systems with lower consumable mass and the capability to treat all proposed wastewaters as well as produce near potable quality. A habitation wastewater processing architecture was developed that combines three technologies: a Membrane Aerated Bioreactor (MABR), an Ionomer-membrane Water Purification (IWP) system, and a Gas-phase Trace Contaminant Removal (GTCR). The integrated system was continuously tested for 5 months. Testing included a baseline DI water run, three test periods utilizing an EPB wastewater, and a final DI water test period to characterize the extended testing impacts on the longevity of the system. The MABR acted as a variable volume universal wastewater collection tank and discharged wastewater to the IWP once per day. The distillation vessel continuously stored solids throughout each run (up to 54 days). Results of the first 5 test periods demonstrate an average water production rate of 14.6 L/day at a 46% desalination duty cycle. The quality of the water produced by the system was consistent with TDS, NO<sub>x</sub>, NH<sub>4</sub><sup>+</sup>, Cl<sup>-</sup>, and SO<sub>4</sub><sup>-2</sup> all within ISS potable limits. DOC satisfied terrestrial potable requirements but exceeded ISS limits while pH fell slightly below. The system had a water recovery rate of 95.1% including the initial wetting mass. Nominal test periods 2 and 3 surpassed that with recovery rates of 96.9% and 96.4%, respectively. Clean water production rates for the last test period after approximately 100 days of effluent processing equaled initial testing performance highlighting the robust performance of the design.**

## Nomenclature

<i>AC</i>	= Activated Carbon
<i>CO<sub>2</sub></i>	= Carbon Dioxide
<i>CCV</i>	= Condensate Collection Vessel
<i>DOC</i>	= Dissolved Organic Carbon
<i>DI</i>	= Deionized Water
<i>EPB</i>	= Early Planetary Base
<i>GEV</i>	= Gravity Evaporation Vessel
<i>GTCR</i>	= Gas Phase Trace Contaminant Removal
<i>HX</i>	= Heat Exchanger
<i>IRA</i>	= Integrated Water Recycling Assembly
<i>IWP</i>	= Ionomer-membrane Water Purification
<i>ISS</i>	= International Space Station
<i>MABR</i>	= Membrane Aerated Bioreactor

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<i>NASA</i>	= National Aeronautics and Space Administration
$NH_4^+$	= Ammonium
$NH_3$	= Ammonia
$N_2$	= Nitrogen Gas
$NO_x^-$	= Nitrite + Nitrate
$O_2$	= Oxygen
<i>SOA</i>	= State of Art
<i>TDS</i>	= Total Dissolved Solids
<i>TED</i>	= Thermal Exchange Device
<i>TN</i>	= Total Nitrogen
<i>WRS</i>	= Water Recycling System

## I. Introduction

Recovery of potable water from wastewater is essential to the success of long-duration human spaceflight. For human missions to Mars, the NASA goal is to recover >98% of the water from wastewater sources (urine, humidity condensate, etc.). Currently the state of art (SOA) for water recycling is the ISS Water Recovery System (WRS). This system is micro-gravity compatible and produces potable water from chemically stabilized urine and flush water as well as humidity condensate. The chemical pre-treat for urine has recently been altered and currently consist of adding concentrated  $H_3PO_4$  and  $CrO_3$ <sup>1</sup>. The chemically pretreated urine solution is first processed by the urine processing assembly (a micro-gravity compatible distiller which recovers ~80% of the wastewater). This condensate is then combined with the humidity condensate and passed through multi-filtration beds (activated carbon beds + ion exchange) and a catalytic oxidizer all of which must be periodically replaced. The urine brine produced is hazardous and contains high concentrations of organic carbon and organic N, the combination of which makes recovery of 100% of the water challenging, due to the consistency of the brine as it is dewatered<sup>2</sup>. The tertiary system has occasional issues with biofouling<sup>3</sup>. It is unclear if the current ISS SOA system would be compatible with other likely early planetary or even transit waste streams that include hygiene, shower, and laundry water. At a minimum, the ISS WRS would likely require chemical pretreat of a much larger volume of water increasing the required hazardous chemical consumption and storage requirements as well as other consumables. The ISS WRS could potentially be altered for an EPB as, much of the current design is dictated by micro-gravity requirements; but it would still require chemical pretreat in order to prevent urea hydrolysis and excessive  $NH_3$  volatilization during distillation. It would also still utilize the tertiary aqueous-phase treatment system. In either gravity or micro-gravity, the ISS WRS also does not recover useful products from the wastewater and results in a higher production of solid waste which is hazardous.

Reductions in mass, maintenance and consumables, and increases in robustness and reliability relative to the SOA is required without incurring significant increases in volume or power. Paragon Space Development Corporation® and partner Texas Tech University (TTU) developed a habitation wastewater processing architecture (Integrated Water Recycling Assembly (IRA)) that combines three technologies for graywater reclamation: a Membrane Aerated Bioreactor (MABR), Ionomer-membrane Water Purification (IWP) system, and Gas-phase Trace Contaminant Removal (GTCR) to produce potable water. The IRA could provide numerous advantages over the SOA. Biological pretreatment reduces the need for chemical pretreatment as it converts organic N to  $NO_x^-$  simultaneously reducing pH and preventing  $NH_4^+$  volatilization during distillation. It reduces organic carbon by 90% producing  $CO_2$  and can be operated to produce  $N_2$ <sup>4,5</sup>. The  $CO_2$  and  $N_2$  are resources, the  $N_2$  can be used to directly make up for atmospheric leakage and  $O_2$  can be recovered from the  $CO_2$  (e.g. via the Sabatier process). The reduction in organic carbon and pH reduces downstream biofouling and allows for higher distillation recoveries. The MABR itself can be designed to serve as the wastewater storage tank, which eliminates the need for additional tankage and any pretreatment that would be required. It should be noted that MABRs treating space based wastewaters (ISS and EPB) have operated continuously for over 5 years with no major failures and can endure hibernation periods upto 30 days without loss of function<sup>4</sup>. The IRA could result in a vastly simplified habitat wastewater recycling system that 1) significantly reduces consumables and eliminates/reduces the need for hazardous pretreatment chemicals, 2) accommodates transients in the wastewater generation rate and composition, 3) concentrates and stores non-volatile residual solids, 4) recovers other useful products in addition to water (e.g.  $N_2$  and  $CO_2$ ), and 5) produces hygiene and potable water. The objectives of this work were to develop and test the IRA system.

## II. System Description and Operation

The IRA system is illustrated in Figure 1. The MABR is the first component and acts to both biologically pretreat and receive all wastewaters directly as they are produced. The effluent is transferred to the Gravity Evaporation Vessel (GEV). Vapor from the GEV passes through an  $\text{NH}_3$  scrubber and then through the vacuum pump. After the vacuum pump, the water vapor passes through an evaporative heat exchanger (HX) and through the ionomer membrane (Nafion Array). Fluid that does not pass through the Nafion membrane is discharged to the retentate collection. Water vapor that has passed through the Nafion membrane is condensed in the condensing coils located on the outside of the GEV. Details of major subsystems are described below.

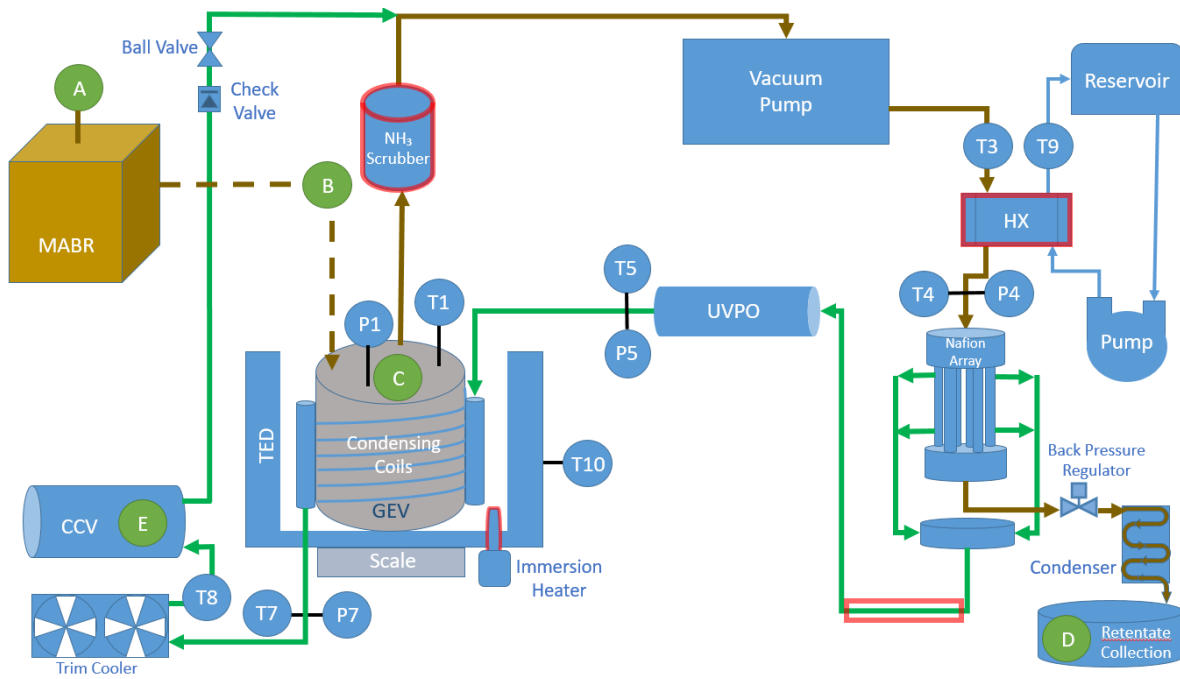


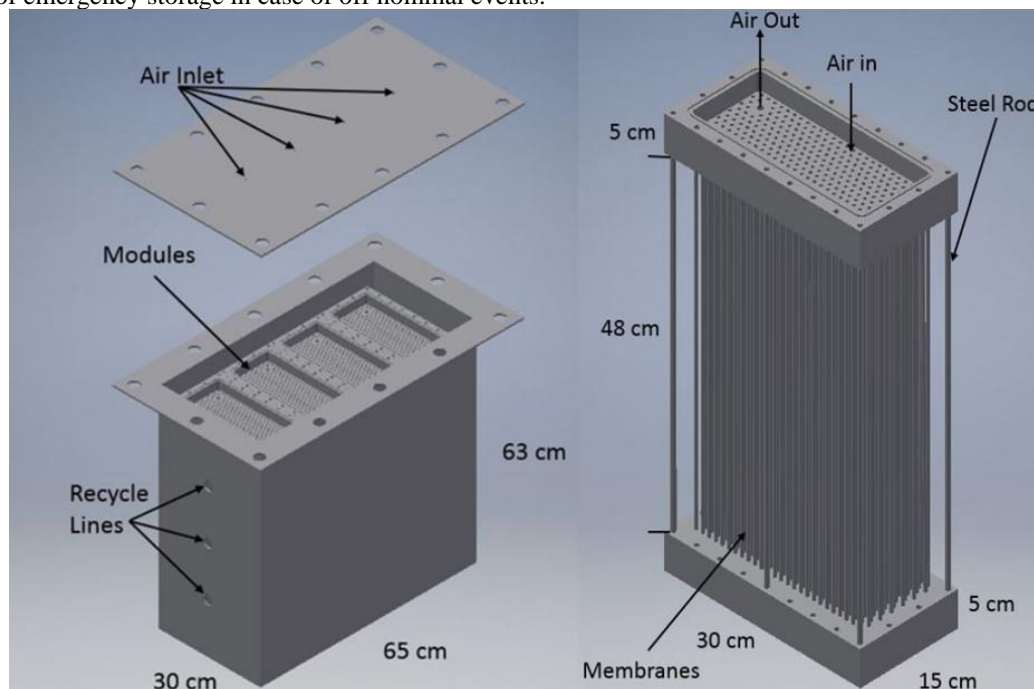
Figure 1. Overview Schematic of IRA.

### A. MABR

The MABR design features a stainless-steel tank with dimensions 30cm X 65cm X 63cm (W, L, H) and a total volume of 123 L and liquid volume of 96 L of which 77 L is contained within the membrane modules (Figure 2). Another 95 L is accounted for by the inlet and outlet zones, leaving 9 L above the air headers. The MABR contains four membrane modules. The MABR has an inlet and outlet zone (2.5 cm) separated from the membrane modules by a baffle wall. There are three (2.54 cm) liquid inlet and outlet ports that lead into and out of the inlet and outlet baffle zones. The liquid inlet and outlet zones are connected by recycle line (2.54 cm) that has an inline centrifugal pump to recirculate the fluid. The membrane modules each have 307 siloxane membranes that are 48 cm long and connect to the influent (top) and effluent (bottom) air headers. Each air header is 30 cm X 15 cm X 5 cm (W, L, H). The air headers are separated by 6 stainless steel 0.25 cm rods. The bottom air header has a collection tube on the bottom plate that connects through the bottom and top air header and exits into the head space above the membrane module (Figure 2). This allows the effluent air to force any condensation that collects in the bottom of the air header to exit into the tank. Effluent air is removed from the top plate of the reactor. The total surface area per each individual module is 2.2 m<sup>2</sup>, which brings the total surface area of membranes in the reactor to 8.82 m<sup>2</sup>. The modules allow easy access to the membranes to facilitate replacement or plugging of a failed membrane, while the MABR remains in operation. The

design also prevents wastewater release in case of a damaged membrane as any liquid that leaks into the membrane bottom air header would simply be recycled to the top of the interior of the tank.

The reactor is designed to operate with variable volume. The nominal operating condition is to operate with a liquid level below the top air header. Wastewater is continually collected as produced but the MABR only releases effluent to the GEV once per day. The system has a nominal 5.1 day residence time at the design flow rate of 15 L/d. The excess volume within the membrane modules above the 60 L required allows a safety factor for treatment in case of poor performance or short term high strength waste, while the volume above the air headers provides an additional ~0.5 days of emergency storage in case of off nominal events.



**Figure 2. IRA MABR Overall Dimensions and a view of one the four individual MABR membrane modules showing key dimensions and the Influent Air Header (and single Air/Water Outlet from the lower Outlet Air Header).**

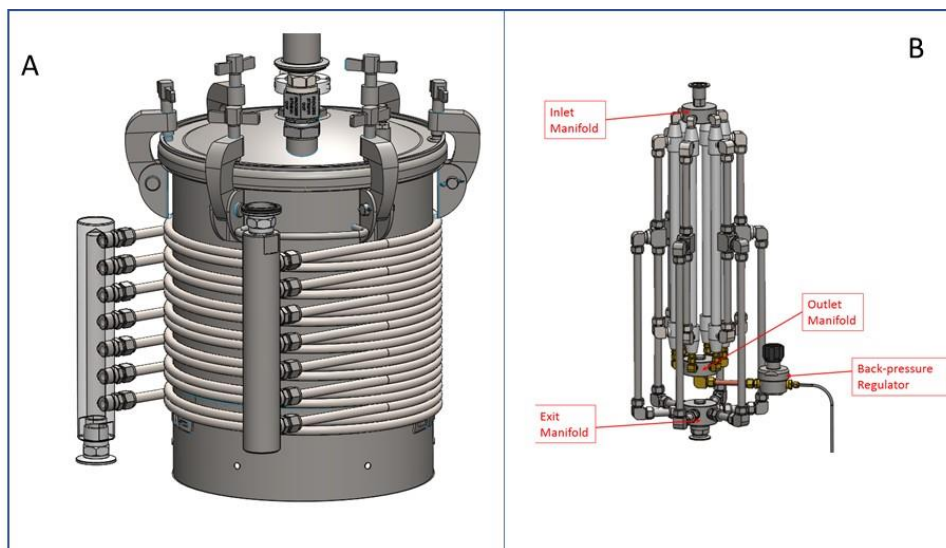
## B. Integrated Water Processor (IWP)

The Gravity Evaporation Vessel (ASME rated Binks® Pressure Tank) is encapsulated by the Condensing Coil, and sits inside of the Thermal Exchange Device, all of which rests on a scale when assembled into the IWP system and serves as the distillation chamber for the MABR liquid effluent (Figure 3). It is capable of maintaining a 15 psid operational vacuum and can hold up to 37 liters of effluent in its intended configuration. To ensure that trace  $\text{NH}_3$  volatilized from the MABR effluent did not impact the Nafion bed, which would reduce water transport, an activated carbon (AC) scrubber was placed in line between the GEV and Vacuum pump. The activated carbon bed housing is comprised of a chamber sized to hold 3.128 kg of Chemsorb 1425 for nominal system operation. The chamber is integrated with KF40 style vacuum flanges that mate to the GEV process outlet stream and equalization ports (upstream) and the vacuum pump (downstream). An air-cooled claw type pump was selected to meet the requirements which included exit temperature, capacity, pressure range, and oil-less operation.

Nafion is a copolymer of tetrafluoroethylene (Teflon) and perfluoro-3,6-dioxo-4-methyl-7-octene-sulfonic acid. Like Teflon, Nafion is highly resistant to chemical attack, but the presence of its exposed sulfonic acid groups confers unusual properties. Of relevance, the sulfonic acid group is immobilized within the bulk fluorocarbon matrix and cannot be removed, but unlike the fluorocarbon matrix the sulfonic acid groups do participate in chemical reactions. The presence of the sulfonic groups allows Nafion to readily absorb water from the vapor phase or from the liquid phase. Each sulfonic acid group will absorb up to 13 molecules of water. The sulfonic acid groups form ionic channels

through the bulk hydrophobic polymer functioning as a very selective, semi-permeable membrane to water vapor. The Nafion Bundle was composed of 6 24" Perma Pure PD-200T elements.

The TED consisted of a thermally insulated chamber capable of housing the GEV, Condensing Coil Assembly, as well as their associated fittings and manifolds. The container was a custom trimmed 55 gallon polyethylene bucket filled with DI water and insulated with 2.0" thick AP Armaflex foam insulation. The TED was placed on a scale for weight measurement and was fitted with a bulkhead pass-through for the exiting manifold. The TED was solely intended to provide a thermal exchange medium between the GEV and the Condensing Coil.



**Figure 3. Major components of the IWP. A) GEV and B) Nafion Array.**

### C. Operation and Testing

The system evaluated the treatment of an EPB wastewater. The EPB waste stream is composed of hygiene wastewater (effluent from showers, hand washing, shaving, and tooth brushing), laundry, urine plus flush water, and humidity condensate. Hygiene streams were simulated using published compositions; urine was donated by anonymous donors. Laundry effluent was produced by washing clothes with a low volume washing machine and detergent. For more details on EPB wastewater composition see Salehi et al.<sup>4</sup> The humidity condensate was simulated based on published compositions.<sup>6</sup>

The system was operated at a nominal 1.2 crew-day flow rate. The MABR system operated on a pulse loading cycle representing a 16 hour wake period and a 8 hour sleep period. Wastewaters were added to simulate their production rates and frequency. Urine, flush water, and hand wash were pulsed in the reactor 6X over the 16 hour loading period. Shower effluent was pulsed at the beginning and end of each wake period, laundry was loaded at the beginning of each wake period, and humidity condensate was continuously added to the reactor. Effluent was transferred to the GEV 1X per day just prior to the initiation of the wake period. While the MABR treated 18L per day, the GEV only processed 15L/d (1 crew/d). The effluent pH was adjusted to ~3 by addition of  $H_3PO_4$ . Addition of  $H_3PO_4$  would not be required for noperation but was done during testing to insure that  $NH_3$  did not reach the Nafion module and allow the system to be tested.

System performance was monitored in numerous ways. Temperature and pressure sensors were located throughout the system in order to characterize the two-phase flow. Water quality (TDS, DOC, TN,  $NO_3^-$ ,  $NO_2^-$ , TN, Cl<sup>-</sup>,  $PO_4^{3-}$ ,  $SO_4^{2-}$ , and pH) was monitored in the influent and effluent of the MABR and in the condensate and retentate collection. In addition, we monitored GEV water processing rate, produced water rate, and condensate collection rate, which enabled the total water recovery to be evaluated.

### III. Results

After a startup period, we ran a number of test points (Table 1). The test points included an initial run in which the GEV received DI water (Test Point 1) to establish a nominal production rate and operational characteristics absent the effects of the MABR effluent. Test Point 2 evaluated the use of MABR effluent as GEV feed but the GEV was cleaned daily and salts were not allowed to accumulate. Test point 3, consisted of a 68 day run in which the GEV was fed MABR effluent daily and the GEV was allowed to continuously accumulate salts. Test point 3 was terminated when the GEV unintentionally completely dried out. Test Point 4 was terminated due to concerns about processing rates as described below. The final Test Point (Test Point 5), was conducted after removal of the acid impregnated activated carbon filter which was found to have failed. This test point used DI water as feed to the GEV and was used to establish the processing rate change due to previous operation. The operation and results of each Test Point are described below in more detail.

**Table 1. A summary of Test Points.**

Test Period	Influent Source	Pump Speed [Hz]	Test Days	Runtime [hrs]	Feed Volume [L]	Processed Volume [L]	Produced Water [L]	Daily Acid Added [L/d]	Comments
1	DI	60	5	40	80	79	71	-	initial membrane distillation rate testing
2	MABR	60	13	114	201	213	192	0.014	no GEV cleaning throughout test period
3A	MABR	60	54	586	834	892	805	0.009	no GEV cleaning throughout test period
3B	MABR	50	11	235	170	187	160	0.011	reduced pump speed to evaluate effect on membrane distillation rate
4	MABR	60	12	171	203	211	178	0.011	stopped due to ammonia scrubber failure
5	DI	60	5	37	73	71	66	-	final membrane distillation rate evaluation
1 & 5 subtotal	DI	60	10	76	153	150	137	-	subtotals across test periods with DI water
2-4 subtotal	MABR	60 & 50	90	1106	1408	1503	1336	0.010	subtotals across test periods with MABR effluent (including scrubber failure in test period 4)
<b>Total</b>	<b>DI &amp; MABR</b>	<b>60 &amp; 50</b>	<b>100</b>	<b>1183</b>	<b>1560</b>	<b>1653</b>	<b>1473</b>	<b>0.010</b>	<b>totals across all test periods</b>

#### D. Test Period 1: DI Water

The GEV was filled daily (18 L) with DI water. The system was operated until the CCV (recovered water) increased in mass by ~15kg. After each run, the GEV and CVV were opened and the water volumes quantified. The volume of the Nafion retentate was also measured. During this test period a condenser was added to the Nafion retentate line to better capture any humidity in the off gas; however, there was little increase in condensate collected. On the last day of test period 1, the water bath was chilled and the collected retentate water increased from ~0.4 L/d to ~1.1L/d. The clean water production rate was consistent and averaged ~1.8 L/hr (Figure 4).

### C. Test Period 2: MABR Effluent Distillation with Daily GEV Clean Out

The system was operated similar to Test point 1 except that the GEV was filled daily with MABR effluent instead of DI water. The residual brine in the GEV was cleaned out each day throughout the test period. In order to lower the pH to <3 and ensure that NH<sub>3</sub> did not carry over to the Nafion module, the MABR effluent was acidified with small amounts of H<sub>3</sub>PO<sub>4</sub> acid (Table 1). The average volume of the acid added was 0.014 L/crew-d. It should be noted that the added H<sub>3</sub>PO<sub>4</sub> acid was a precautionary method only as the acid scrubber should be bale to remove any residual NH<sub>3</sub>. However even if need the amount fo H<sub>3</sub>PO<sub>4</sub> added was less than half of that used currently on ISS per crew member and treated ~7X more wastewater. The amount of effluent added was based on maintaining >2L in the GEV at the end of each of cycle. Effluent was added to fill the GEV to a total volume of 19L every day. The added volume varied but averaged 15.5 L/d (12.7 - 16.3 L/d), excluding off-nominal events. In order to ensure that there was always sufficient volume available to fill the GEV to 19L, the MABR processed 18L of EPB wastewater daily, which is greater than the design flow rate of 15 L/d (1 crew/d). Therefore, the MABR effluent water quality should be viewed as conservative values. The MABR removed >75% of DOC, 0% of TN and converted 41% of organic N to NO<sub>x</sub><sup>-</sup> during the test period. On average the effluent had a DOC, TN, NO<sub>x</sub><sup>-</sup>, and NH<sub>4</sub><sup>+</sup> concentration of 125, 580, 240, and 274 mg/L, respectively and a pH of 5.3 (Figure 5).

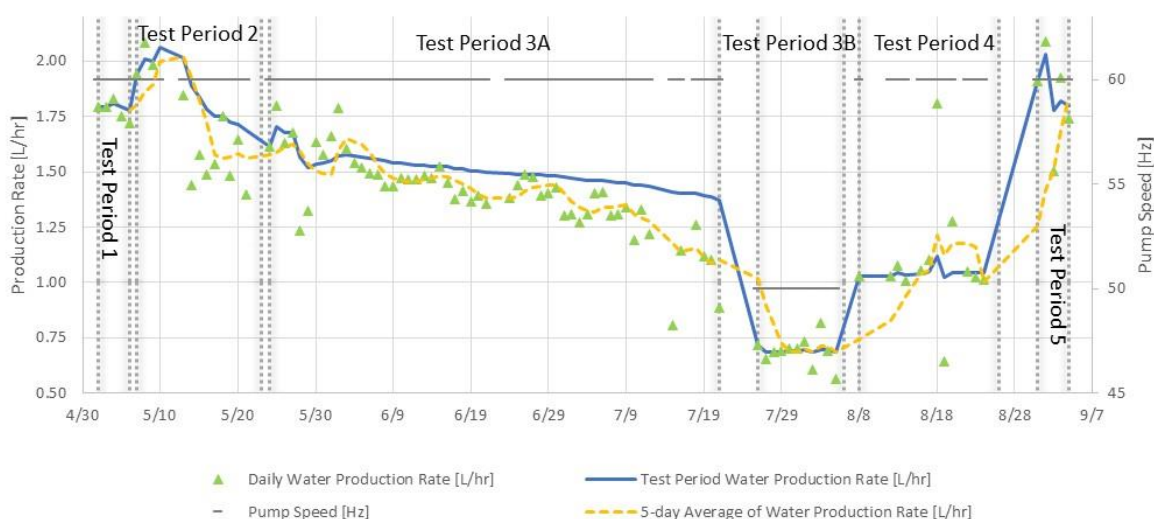


Figure 4. Clean water production rate of IWP distillation system for all test periods.

Table 2. IRA distillation system performance for all test periods.

Test Period	Influent Source	Pump Speed [Hz]	Daily Runtime [hrs/day]	Daily Feed Volume [L/d]	Daily Processed Volume [L/d]	Daily Produced Water [L/d]	Production Rate [L/hr]	Leak Rate [L/hr]	Water Recovery
1	DI	60	8.0	15.9	15.9	14.1	1.78	0.15	90.9%
2	MABR	60	8.8	15.5	16.4	14.8	1.69	0.05	96.9%
3A	MABR	60	10.9	15.4	16.5	14.9	1.37	0.04	96.9%
3B	MABR	50	21.3	15.5	17.0	14.6	0.68	0.03	96.4%
4	MABR	60	14.3	16.9	17.6	14.9	1.04	0.09	89.3%
5	DI	60	7.3	14.6	14.2	13.2	1.80	0.08	96.3%



<i>1 &amp; 5 subtotal</i>	<i>DI</i>	<i>60</i>	<i>7.6</i>	<i>15.3</i>	<i>15.0</i>	<i>13.7</i>	<i>1.79</i>	<i>0.12</i>	<i>92.1%</i>
<i>2-4 subtotal</i>	<i>MABR</i>	<i>60 &amp; 50</i>	<i>12.3</i>	<i>15.6</i>	<i>16.7</i>	<i>14.8</i>	<i>1.21</i>	<i>0.05</i>	<i>95.1%</i>
<b>total</b>	<b>DI &amp; MABR</b>	<b>60 &amp; 50</b>	<b>11.8</b>	<b>15.6</b>	<b>16.5</b>	<b>14.7</b>	<b>1.24</b>	<b>0.04</b>	<b>94.4%</b>

Water recovery during test period 2 was consistent (Figure 5). Water collected in the CCV ranged from 14.6-15.2 L/d excluding 2 days with operational issues. Water collected in the Nafion retentate ranged from 1.1-1.2 L/d. Water remaining in the GEV ranged from 1.5L - 5.2 L. Overall the water balance showed a small net loss of water across the system (0.4 L/d ~ 3%). Over the 15 day run, the system processed 201 L of MABR wastewater and recovered 192 L of clean water, a 95.8% recovery rate (Figure 6, Table 2). The water production rate averaged 1.7 L/hr (between 1.7 L/hr and 2.1L/hr), similar to the production rate using DI water in test period 1.

Produced water in the CCV was near potable quality. DOC was always less than 10 mg/L and averaged 6 mg/L and TN was less than 3 mg/L and averaged 2 mg/L (Table 3). It should be noted that the TN value is an estimate only, as the lower quantitation limit is 5 mg/L for this analysis. Concentrations of  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{PO}_4^{3-}$ , and  $\text{NO}_x^-$  were generally near or below detection limits (0.5 mg/L), with the exception of  $\text{SO}_4^{2-}$  which averaged (4 mg/L).

#### D. Test Period 3. MABR Effluent Distillation

The system was operated as described in the previous section except brine and solids remained in the CCV throughout the test period. The test lasted for 68 days during which the system processed an average of 16.5 L/d and a total volume of 1,079 L (Table 1). The average added  $\text{H}_3\text{PO}_4$  acid was 0.010 L/crew-d (14.9 L per year for a crew of 4). Less acid was added to the effluent than in test period 2, as the effluent generally had a lower pH (average of 4.2). The MABR removed 75% of DOC, 20% of TN and converted 58% of organic N to  $\text{NO}_x^-$ . On average the MABR effluent had a DOC, TN,  $\text{NO}_x^-$ , and  $\text{NH}_4^+$  concentrations of 150, 550, 250, and 205 mg/L, respectively and a pH of 4.2 (Figure 5).

Water recovery during test period 3 was relative consistent but did reduce slightly during the test period (Figure 6). Water collected in the CVV averaged 14.8 L/d (Table 2). Water collected in the Nafion retentate ranged from 1.0-2.1 L/d. Water remaining in the GEV averaged 3.4 L/d. Overall the water balance showed a small net average loss of water across the system (0.4 L/d). Over the 68 day run, the system processed 1,205 L of MABR wastewater and produced 1158 L of product water, a 96.1% recovery rate. These values include days in which there were small leaks in the CVV reducing recovery and so the actual product recovery would be higher.

It is unclear how much water vapor escaped from the Nafion back-pressure regulator even with the installed condenser coil, as the retentate off-gas flow rate was quite high (~12 L/min). The retentate off-gas flow rate was well above the design flow due to an issue with a vacuum-pump pressure relief valve feature that was designed to pull outside air in to cool the pump for typical commercial operations. This external air could introduce outside moisture, impacting the water balance, so the system was tested with no water in the GEV and 0.5 L of water was recovered over a typical run period of ~9 hrs. However, this was most likely residual water trapped in the system from past runs (e.g. in the ammonia scrubber activated carbon bed or condensate in lines), as the water that could have been produced from the ambient air was estimated at only ~0.009 L/hr. Additional tests are needed to evaluate the full impact of these leaks on water production.

The water production rate averaged ~1.4 L/hr for the first 57 days of the test period (Figure 4). For the last 11 days the system was operated at a reduced pump speed of 50Hz, lowering the water production rate to ~0.7 L/hr. Over the course of the first 57 days that the system was run at the nominal pump speed of 60Hz, the water processing rate generally declined (Figure 4). The decline in water production rate could be due to increased salinity in the GEV reducing the evaporation rate (Figure 5) or precipitate accumulation propagating an occlusion of the ammonia scrubber.

Produced water in the CVV was near potable quality. DOC was always less than 6 mg/L and averaged 5mg/L and TN was less than 3 mg/L and averaged 2 mg/L (Table 3). It should be noted that both of these values are estimates only as the lower quantitation limit is 5 mg/L for these analyses. Concentrations of  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ,  $\text{PO}_4^{3-}$ , and  $\text{NO}_x^-$  were generally near or below detection limits (0.5mg/L), with the exception of  $\text{SO}_4^{2-}$ , which averaged 4 mg/L.



At the conclusion of test period 3 the solids in the GEV were dissolved to determine the mass of TDS, DOC, TN,  $\text{NO}_x^-$  and  $\text{NH}_4^+$ . The organic carbon and TDS were largely recovered in the GEV solids (Figure 7). TN mass recovery in the GEV was slightly lower due the lower recovery of  $\text{NO}_x^-$ . The loss of  $\text{NO}_x^-$  is likely due to the production of NO and  $\text{NO}_2$  from the conversion of  $\text{HNO}_2$  to  $\text{NO}_3^-$  in the acidified GEV medium and possibly direct loss of  $\text{HNO}_2$ .

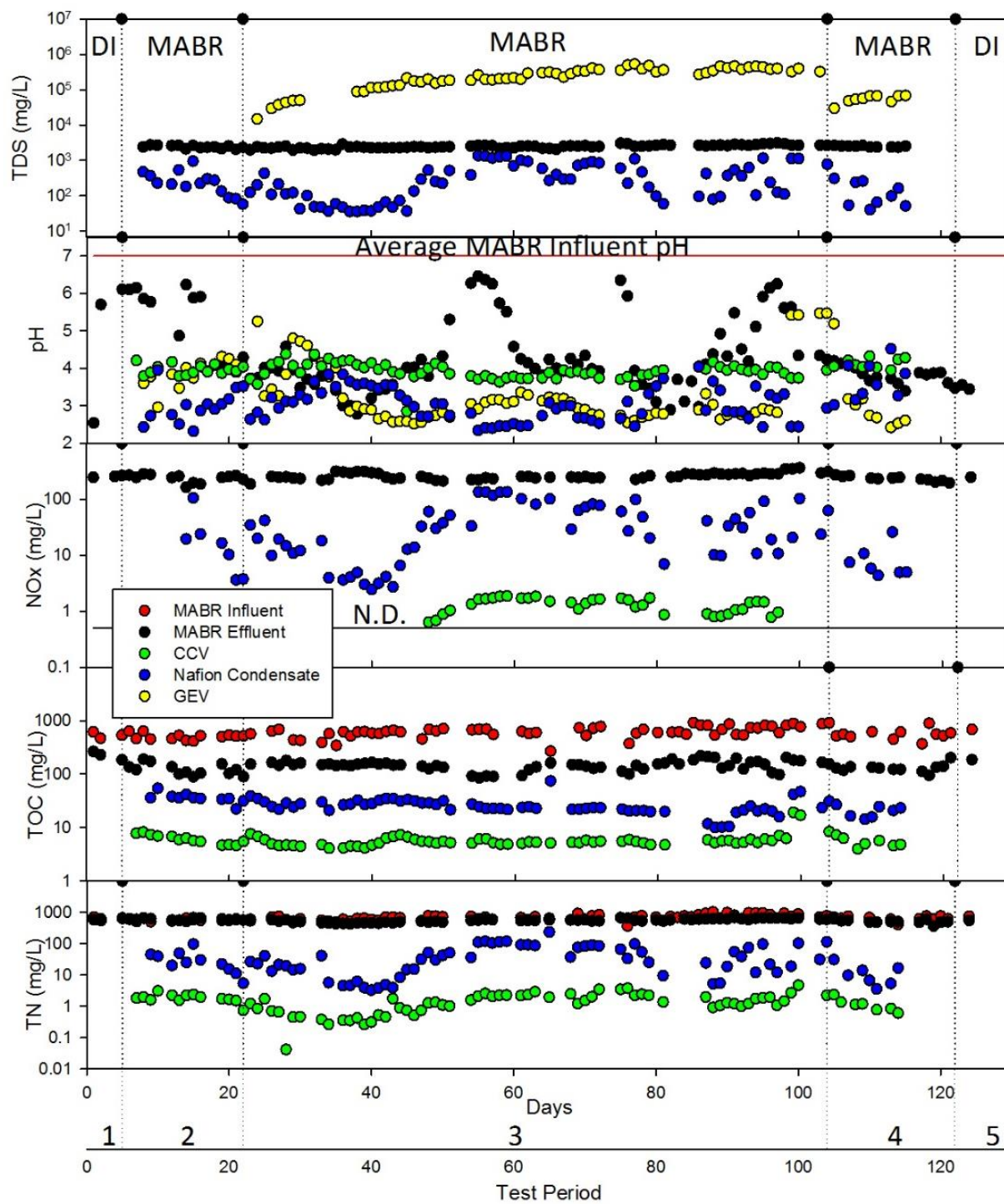
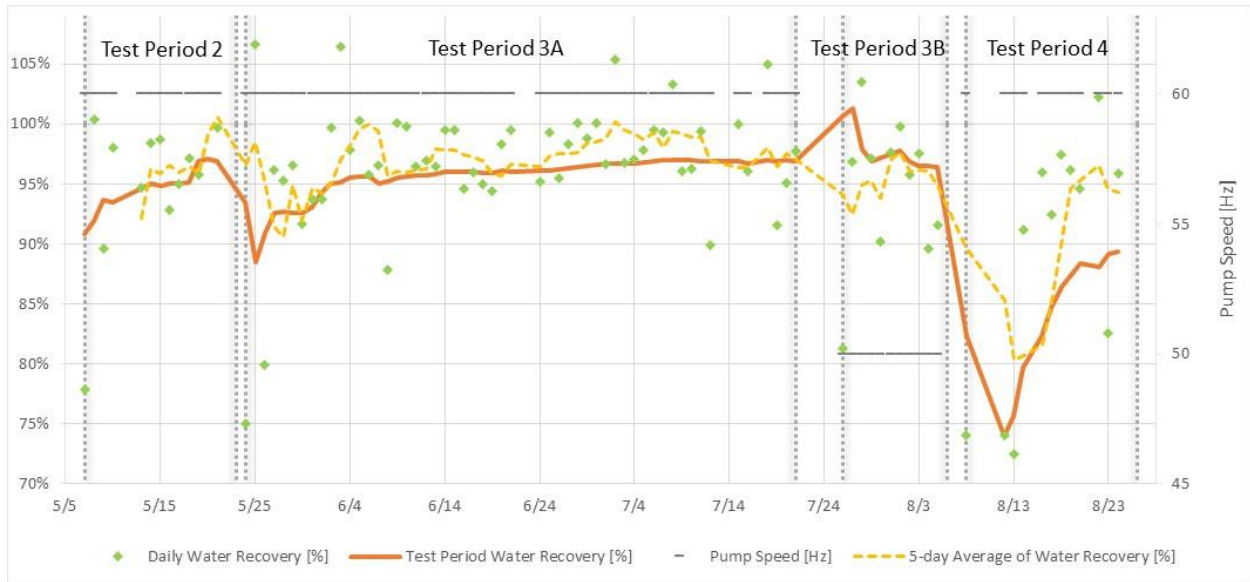


Figure 5. Water quality across the integrated system during all test periods.



**Figure 6. Clean water recovery of IWP distillation system from MABR effluent (test periods 2-4).**

**Table 3. IWP product water quality compared to potability limits from the ISS Crew Transportation and Services Requirements Document.<sup>i</sup>**

Test Period		pH	TDS [mg/L]	TN [mg/L]	DOC [mg/L]	Cl [mg/L]	PO4 [mg/L]	SO4 [mg/L]	NOx [mg/L]	NH4 [mg/L]
2	avg	4.0	15	1.9	6.3	<2.3	<0.5	<3.7	<0.5	0.1
	max	4.2	32	2.4	8.2	10.8	<0.5	7.2	<0.5	0.2
3A	avg	3.9	17	1.4	5.3	<0.8	<0.6	<2.8	<1.0	0.7
	max	4.4	34	3.7	7.6	2.6	1.5	6.9	1.9	1.8
3B	avg	4.0	20	1.4	5.6	<0.8	<1.4	<2.0	<1.1	-
	max	4.2	28	2.0	6.0	1.1	2.7	3.3	1.5	-
4	avg	4.1	18	1.5	7.3	<0.7	<0.5	<3.6	-	-
	max	4.3	35	2.7	19.1	1.4	<0.5	6.9	-	-
Totals 2-4	avg	3.9	18	1.5	5.7	<1.0	<0.7	<2.9	<0.9	0.6
	max	4.4	35	3.7	19.1	10.8	2.7	7.2	1.9	1.8
ISS Limits <sup>ii</sup>		4.5-9	500		3	250		250	11	1
Paragon Requirements (Appendix B)		5.5-9	500		20					

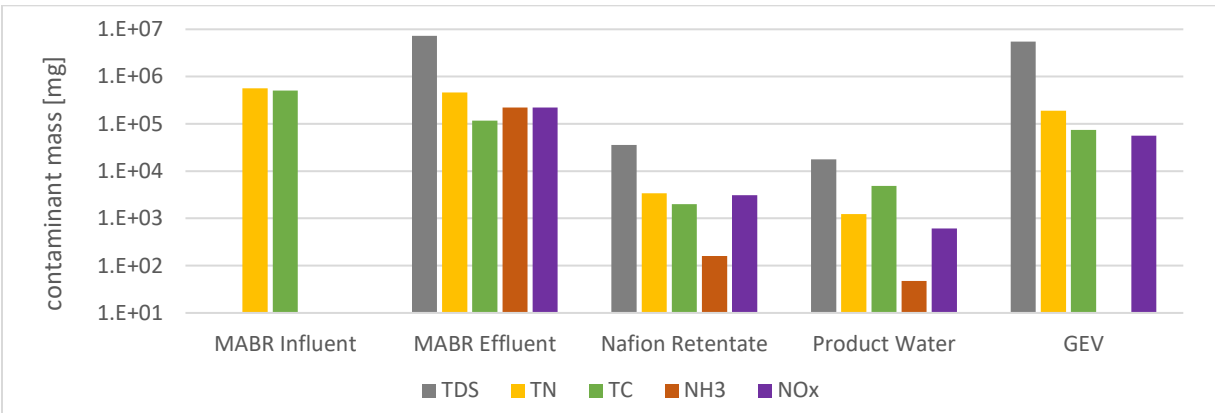


Figure 7. Mass recovery at the conclusion of test period 3.

#### E. Test Period 4: MABR Effluent Distillation without GEV Cleaning

Test period 4 used the same procedure as test periods 2 & 3A and lasted 10 days. It was terminated when the processing rate did not recover to values comparable to test period 3A. Upon inspection it was determined that condensate and GEV liquid, which had transported out the GEV due to boiling, was forming precipitates in the line between the GEV and ammonia scrubber. The condensate dissolved the acid impregnated on the carbon bed, forming a layer at the base of the reactor. Eventually, vapor transport was restricted. Future work should evaluate whether an acid trap is required. Given that the processing rate for DI water returned to initial values after the AC bed was removed in test period 5, it is possible that the decline in processing rate during test period 3 was due to the slow loss of through-flow in the AC bed. However, it is also possible that the increase in salinity led to the reduced processing rate.

#### F. Test Period 5: DI Water processing

After the identification of the failure of the ammonia scrubber, DI water was used again as influent to evaluate the water production rate and determine if the decline during test periods 3 and 4 could have been due to ionomer membrane degradation or was due to the AC bed failure. Processing DI water for 5 days with the scrubber removed, the processing rate increased to 1.8 L/d (Figure 4). This is comparable to test periods 1 and 2, which processed DI and MABR effluent, respectively, both at production rates of ~1.8 L/d. This suggests that at least some of the loss in water production rate in test periods 2, 3, and 4 was due to the AC bed failure.

### IV. Summary

MABR operation was stable and met requirements over all test periods. DOC in the effluent was consistently reduced to approximately 150 mg/L and greater than 50% of the TN was converted to  $\text{NO}_x^-$ . MABR performance was excellent, especially considering that it was treating 18 L/d and had been designed for only 15L/d (Table 23). Furthermore, the pH of the MABR effluent was generally close to 4, with only brief periods of higher pH values around 6. Low pH in the MABR effluent reduces the ammonia released from the GEV into the IWP working fluid and thus the strain on the ammonia scrubber. It should be noted that production of  $\text{CO}_2$  will increase the load on the  $\text{CO}_2$  air scrubbing system (0.012 kg/crew-day) but this increase is minimal compared to the  $\text{CO}_2$  load of the crew (~0.8 kg/day)

The water recovered by the IWP system from MABR effluent during test periods 2-4 satisfied the potability limits for the ISS except for pH (Table 4). The average and maximum sampled values for TDS,  $\text{NO}_x$ ,  $\text{Cl}^-$ , and  $\text{SO}_4$  were far below the limits for all test periods. The average concentrations for  $\text{NH}_4^+$  also satisfied requirements, and measured pH values fell only slightly outside of the range. Two instances of maximum reported  $\text{NH}_4^+$  were almost certainly due to sampling error as  $\text{NH}_3$  will not pass through IWP's Nafion membrane. Average and maximum DOC concentrations in the recovered water exceeded the stringent US-module ISS limits, but met those levied upon the Russian module. The IWP reduced TDS, TN, and  $\text{NO}_x$  by more than 96% compared to MABR effluent, and the integrated system decreased all contaminants by 99% or more relative to MABR influent. The Nafion membrane alone reduced TDS, TN, and  $\text{NO}_x$  by more than 95%, and the other contaminants by more than 75%, when comparing the quality of the

average contaminant concentrations of the recovered water to the retentate collected on the dirty side of the Nafion module.

**Table 4. Water quality measurements at sampling points throughout the integrated system across all test periods where MABR effluent was processed.**

<i>Test Periods 2-4</i>		pH	TDS [mg/L]	TN [mg/L]	DOC [mg/L]	Cl [mg/L]	PO4 [mg/L]	SO4 [mg/L]	NOx [mg/L]	NH4 [mg/L]
<b>MABR Influent</b> (point A)	avg	<b>8.5</b>	<b>3845</b>	<b>668</b>	<b>604</b>	<b>389</b>	<b>13</b>	<b>79</b>	<b>0</b>	<b>668</b>
	max	9.5	5000	1015	912	401	17	83	0	1015
	min	7.2	1872	362	268	377	7	75	0	362
	stdev	1.0	293	140	138	9	4	3	0	140
<b>MABR Effluent</b> (point B)	avg	<b>4.4</b>	<b>2463</b>	<b>551</b>	<b>152</b>	<b>517</b>	<b>159</b>	<b>301</b>	<b>256</b>	<b>229</b>
	max	6.5	3060	674	499	658	528	805	348	343
	min	2.8	1945	426	85	415	33	145	163	94
	stdev	1.0	242	63	66	59	117	149	32	71
<b>GEV</b> (point C)	avg	<b>3.3</b>	<b>213568</b>	-	-	-	-	-	-	-
	max	5.5	495000	-	-	-	-	-	-	-
	min	2.4	14770	-	-	-	-	-	-	-
	stdev	0.8	144682	-	-	-	-	-	-	-
<b>Nafion Retentate</b> (point D)	avg	<b>3.1</b>	<b>364</b>	<b>41.3</b>	<b>26.5</b>	<b>&lt;8.0</b>	<b>&lt;8.3</b>	<b>&lt;15.5</b>	<b>39.4</b>	<b>2.5</b>
	max	4.5	1357	234.8	74.3	301.7	300.3	161.2	134.8	24.2
	min	2.3	36	3.2	10.0	<0.5	<0.5	<0.5	2.4	0.5
	stdev	0.5	365	41.2	9.1	37.0	37.2	24.4	40.2	4.2
<b>Product Water</b> (point E)	avg	<b>3.9</b>	<b>18</b>	<b>1.5</b>	<b>5.7</b>	<b>&lt;1.0</b>	<b>&lt;0.7</b>	<b>&lt;2.9</b>	<b>&lt;0.9</b>	<b>0.6</b>
	max	4.4	35	3.7	19.1	10.8	2.7	7.2	1.9	1.8
	min	2.9	5	0.0	4.0	<0.5	<0.5	<0.5	<0.5	0.0
	stdev	0.2	8	0.8	1.8	1.4	0.4	1.5	0.5	0.7

The average daily feed and produced volumes met the threshold of 14.5 L/day for all test periods but the last one, despite relatively short daily runtimes. The cumulative production rate of 1.37 L/hr achieved over 54 days in test period 3A corresponds to 21.9 L produced during a 16 hour duty cycle. Had the system been operated the anticipated 16 hrs/day across all test periods, it would have produced approximately 20 L/day. Figure 6 shows that the recovery rate of clean water from MABR effluent exceeded the requirement of 95% during test periods 2 and 3, achieving a maximum water recovery of 96.9%. Note, that the presented water recovery rates include losses to wetting the system at start-up. Thus, water recovery exclusive of initial wetted mass is even higher. The system did lose some water through a back-pressure regulator, most of which was collected and then added to the GEV in the next batch. The associated water vapor leak rate stabilized at 0.04 L/hr, or <3%, during the longest test period. This is the single largest contributing factor to water loss from the system during testing. Entrained water entering the system through the vacuum relief valve was also estimated to be at most ~0.009 L/hr, or ~0.7%. The lowest production rates (test period 3B) occurred when the vacuum pump was operated at a reduced speed of 50Hz. Another period of lower production rates occurred during Test Period 4, which is attributed to the failure of the ammonia scrubber. A slow waning of the production rates during test periods 2 and 3A can be seen as well (Figure 4) and can be attributed either to reduced evaporation rate in the GEV due to the build-up of solids and/or slow occlusion of the ammonia scrubber.

With the ammonia scrubber removed in test period 5, water production rebounded to the same rate as in test period 1, which demonstrates the robustness of the ionomer membrane and the resilience of the membrane module design.

The cumulative water recovery rate improved the longer the system was operated without cleaning the GEV and was noticeably lower again at the onset of each successive test period (Figure 6). The presented cumulative water recovery rates are inclusive of initial wetted mass, which at least partially accounts for the lower recovery rates at start-up. Note, that the test period durations up to 57 days achieved in this phase never stressed the system to its failure point. There was a correlation between the GEV TDS concentration and the water production rates, although the effect was limited. After the GEV TDS rose from 0 to ~500,000 mg/L during the 57 days of operation in test period 3A, the average water production rate decreased only by ~0.2 4L/hr, or 15%. In test period 4 it remained roughly constant, despite rising TDS levels in the GEV. Other system parameters, like pump speed and ammonia scrubber throughput, have a much larger effect on production rates. Furthermore, the water recovery rate (Figure 6) was unaffected by the build-up of solids in the GEV. The experienced slight slow-down in production rate could thus be easily compensated by extending the daily run times without exceeding duty-cycle requirements.

Overall, the IRA was able to process EPB wastewater to essentially potable water. The MABR served as both collection tank for all wastewaters and stabilization system. It successfully operated with variable volume. GEV solids build-up during the accumulation periods tested did not significantly limit system operation. The system operated up to 57 days without cleaning; solids accumulation affected production rate only moderately and had no effect on the recovery rate. The IWP produced stable processing rates and achieved the 95% water recovery. Daily effluent processing and water production volumes met the threshold of 14.5L/day with average runtimes of less than 12 hrs/day. The quality of the water produced by the IWP was consistently excellent: TDS, NO<sub>x</sub>, NH<sub>4</sub>, Cl<sup>-</sup>, and SO<sub>4</sub> were within limits for the ISS; DOC satisfied terrestrial potability requirements but was above ISS limits; pH was slightly below ISS requirements.

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