

Humidity Condensate Treatment using a Hybrid Life Support System

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Treatment of space habitation wastewaters to produce potable water is a requirement for sustainable space habitation. Current micro-gravity systems use only physical or chemical processes. In addition, wastewaters must be stored prior to treatment. For future space habitats particularly in reduced gravity a variety of wastewaters may be produced including shower, hygiene, and laundry, but for any space habitat in micro-gravity or reduced gravity, humidity condensate and urine will always be produced. On station humidity condensate makes up about fifty percent of the produced wastewater. Storage of this wastewater prior to processing in the WPA is problematic because it is biologically active. Biomass produced in the storage tank or which grows downstream can and has caused failures due to clogging of filters or valves. The root cause of the growth is the presence of organic carbon which supports growth. Removal of this organic carbon would prevent system failures and produce a near potable water. This research effort evaluated the use of a hybrid treatment system which included a membrane aerated bioreactor coupled to a low-pressure reverse osmosis system to treat humidity condensate. For this study, the bioreactor acted as both the collection tank and RO recycle tank, which allowed the system to operate without production of brine. The system was run for over 200 days and treated 1,100 L and the RO process produced 1,100 L of permeate with a DOC < 10 mg-C/L and TDS < 100 mg/L for 170 days. Consumables consisted of only the RO membrane (260g/1000kg of treated water) and prefilter (227g/1000kg of treated water) and consumed O₂ (162g/1000kg of treated water). While the system could not operate indefinitely due to the increase in TDS, it does highlight the ability to remove organic carbon and operate for an extended period with brine production.

Nomenclature

| | |
|------------------------------|---|
| BOD | = Biochemical oxygen demand |
| C-d | = Crew member per day |
| COD | = Chemical oxygen demand |
| DO | = Dissolve Oxygen |
| DOC | = Dissolved Organic Carbon |
| GWBR | = Greywater Membrane Aerated Biological Reactor |
| HC | = Humidity Condensate |
| ID | = Inner Diameter |
| ISS | = International Space Station |
| L/d | = Liter per day |
| L/min | = Liter per minute |
| N | = Nitrogen |
| NH ₃ | = Ammonia (Aqueous) |
| NO ₂ ⁻ | = Nitrite (Aqueous) |

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| | |
|------------------------------|---|
| NO ₃ ⁻ | = Nitrate (Aqueous) |
| OC | = Organic Carbon |
| PGH | = Partial Gravity Habitats |
| RO | = Reverse Osmosis |
| SSA | = Specific Surface Area |
| STD | = Standard Deviation |
| TDS | = Total Dissolved Solids |
| TAN | = Total Ammoniacal Nitrogen |
| TN | = Total Nitrogen |
| TOC | = Total Organic Carbon |
| TSS | = Total Suspend Solid |
| UMABR | = Urine + Flush Membrane Aerated Biological Reactor |
| U+F | = Urine Plus Flush Water |
| WPA | = Water Process Assembly |
| HC-MABR | = Humidity Condensate Membrane Aerated Biological Reactor |

I. Introduction

The treatment of space habitation waste waters to produce potable water is a requirement for sustainable space habitation. Current micro-gravity systems use only physical or chemical processes and treat only urine+ flush water and humidity condensate (HC). This study evaluates a hybrid treatment system combining membrane aerated bioreactors and reverse osmosis to improve humidity condensate processing. Waste waters must be stored prior to treatment as the inputs are variable. For future space habitats, particularly in reduced gravity, a variety of wastewaters may be produced including shower, hygiene, and laundry; but, for any space habitat in micro-gravity or partial gravity, humidity condensate and urine will always be produced. On station humidity condensate makes up ~fifty percent of the wastewater produced. Storage of this wastewater prior to processing in the WPA is problematic because it is biologically active. Biomass is produced in the storage tank, or which grows downstream can and has caused failures due to clogging filters or valves. The root cause of the growth is the presence of organic carbon which supports growth. Removal of this organic carbon would prevent system failures and produce a near potable water. Currently, there are ongoing efforts at Marshall Space Center to evaluate technologies to mitigate this growth, one of which is the use of a biological reactor to replace the HC storage tank and remove the OC by biological oxidation.

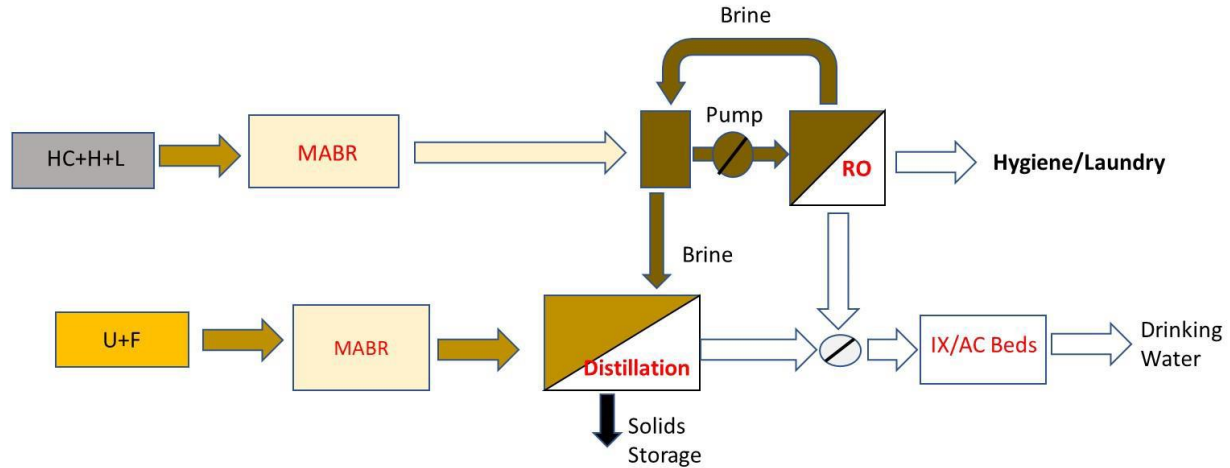
Biological treatment can be used to oxidize organic carbon and total ammoniacal nitrogen + organic nitrogen (TAN), which are all substrates capable of supporting microbial growth. It can also be used to remove NO₂⁻ or NO₃⁻, which are products of biological N oxidation. Extensive work has been conducted demonstrating the performance of biological reactors to treat space based wastewaters including, urine + flush, humidity condensate, and grey water (shower, laundry, and hygiene)^{3,4,5,6,8,9}. These studies have primarily used membrane aerated bioreactors (MABR) as they can operate in either micro-gravity or reduced gravity environments and do not require diffuse aeration which can lead to foaming and stripping of odors and volatiles. MABRs have been continuously operating for over 5 years without failure. These studies^{3,6} demonstrate oxidation of more than 90% of organic matter and 50% of the TAN and produce a biologically stable effluent with a pH of 6-7. However, habitation wastewaters still require desalination.

Previously^{3,6}, we demonstrated a hybrid recycling system (Figure 1) consisting of two full-scale gravity dependent MABRs, Reverse Osmosis (RO), and distillation systems. Greywater was collected and treated as produced (no storage tanks) in a MABR (Greywater Reactor) (Figure 1). This MABR operated in variable volume mode which allowed the system to collect all grey waters on demand but released effluent to the RO system once per day. The RO system processed the treated greywater, and the final brine (10% of greywater) was released to the static distillation system.³ The Urine + flush MABR (UMABR) acted as a collection tank for urine plus flush water (U+F) and oxidized organic nitrogen (50%) and organic carbon (>95%) and controlled the pH (6-7.5). The urine MABR was able to accept and treat U+F for multiple days without release if needed; but as needed, it released effluent to the static distillation system. The static distillation system processed the RO brine + urine MABR effluent.⁶

The greywater MABR was used as the sole collection tank for all greywater sources and removed >90% of the OC and the effluent was able to be desalinated using a low-pressure RO producing near potable water (TDS ≤ 10 mg/L, DOC ≤ 5mg/L, and TN ≤ 2 mg/L)³. Over 3000 L of greywater was able to be treated with one (260 g) RO membrane which could meet the processing requirements (4 crew/d or 41.5 L/d) for up to 60 days.³ Building on this

prior research, we designed and tested a hybrid biological reactor coupled with reverse osmosis to evaluate its performance in treating humidity condensate. The following section describes the experiment setup and operation conditions. These results suggested that it should also be possible to use a similar system to treat humidity condensate to prevent biomass production in the HC storage tank.⁹

This research effort evaluated the use of a hybrid treatment system which included a membrane aerated bioreactor coupled with a low-pressure reverse osmosis system to treat humidity condensate (Figure 2). For this study the bioreactor acted as both the collection tank and RO recycle tank which allowed the system to operate without production of brine.



MABR = Membrane Aerated Bioreactor; HC = Humidity Condensate; H = Hygiene; L = Laundry; U+F = Urine and Flush; UF = Ultrafiltration; RO = Reverse Osmosis; IX = Ion Exchange; AC = Activated Carbon

Figure 1. General flow diagram of hybrid architecture.

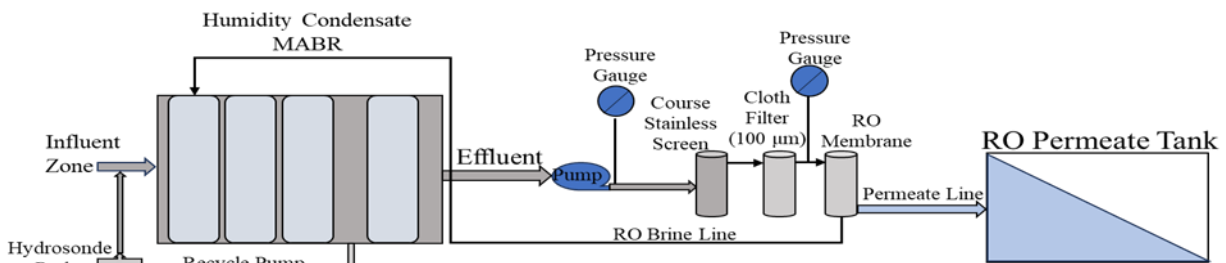


Figure 2. Diagram of a hybrid processing system treating Humidity Condensate and using the HC MABR as the RO recycle tank without brine production.

II. Materials and Methods

A. Humidity Condensate Membrane Aerated Biological Reactor (HC-MABR), Reverse Osmosis Systems Description and Operation

Previous papers^{3,6,8,9} describe the characteristics of the integrated Greywater MABR (Figure 3) with Reverse Osmosis (RO) system, which was also used here for humidity condensate testing. Reactor specifications are listed in Table 1. The HC-MABR (Figure 4) has a total volume of 238 L with a design working volume of 169 L (Table 1). The reactor has four membrane modules, and each module has an inlet and outlet air header which are connected to an oxygen tank with a flow rate of ~50 mL/min. A centrifugal pump located in the recycling line provided mixing.

The HC stream for 4 crew/d consists of 8 L/d and was continuously added to the reactor. The HC was produced using an ersatz recipe based on recent values from ISS⁷ (Table 2).

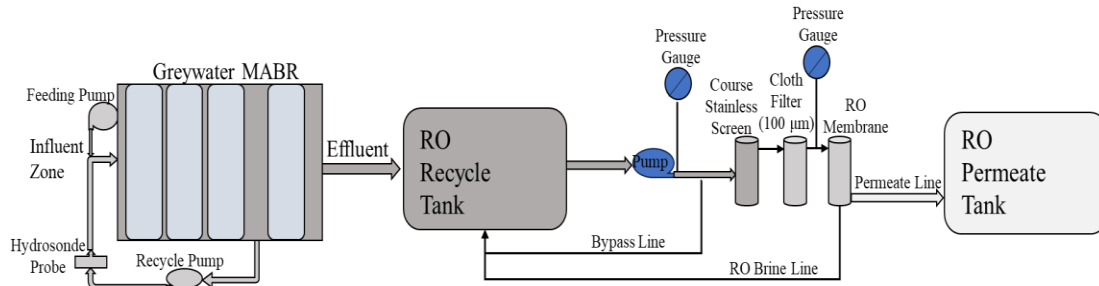


Figure 3. Diagram of a hybrid processing system treating Greywater and using the Greywater MABR as the RO recycle tank without brine production.

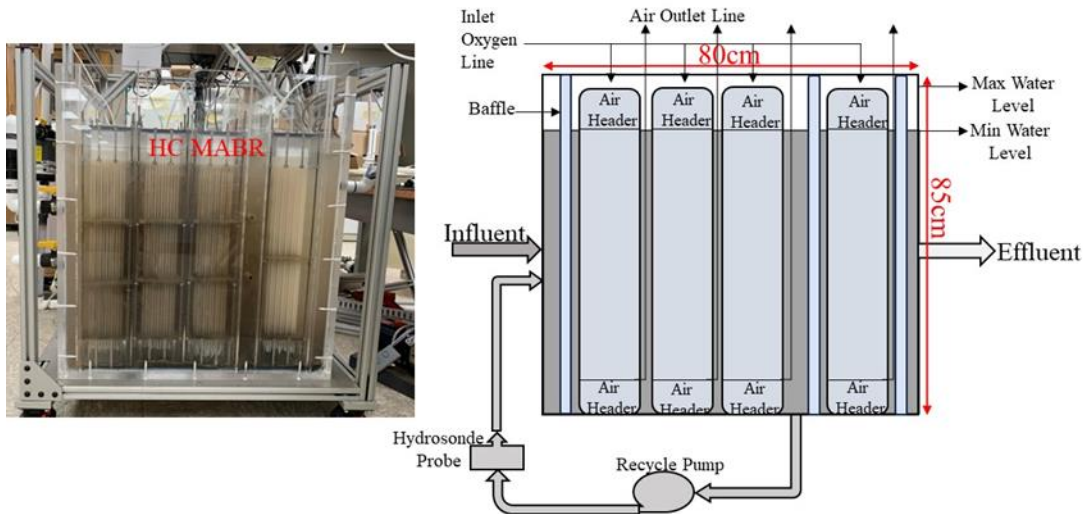


Figure 4. Humidity Condensate membrane aerated bioreactors HC-MABR

Table 1. Humidity Condensate Membrane Aerated Biological Reactors Specifications.

| MABR | L × W × H (cm) | V _{wet} (L) | V _{total} (L) | Number of Membranes | SSA | Retention Time (d) | Crew/day | Flow rate (Q) (L/d) |
|------|----------------|----------------------|------------------------|---------------------|-----|--------------------|----------|---------------------|
| HC | 80 × 45 × 85 | 169 | 238 | 1496 | 100 | 21 | 4 | 8 |

Table 2. Humidity Condensate Ersatz for Ground Testing of Water Processors ⁷

| Inorganic Compounds | | | | | |
|----------------------------|--------|---|---|----------------|--------------------------------|
| No. | g/mole | Cation | Anion | μM | Concentration of Compound mg/L |
| 1 | 79.06 | NH ₄ ⁺ | HCO ₃ ⁻ | 2,509 | 198.4 |
| 2 | 124.43 | Zn ⁺ | CH ₃ COO ⁻ | 121 | 15.0 |
| 3 | 45.08 | NH ₄ ⁺ | CH ₃ COO ⁻ | 329 | 14.8 |
| 4 | 117.74 | Ni ⁺⁺ | CH ₃ COO ⁻ | 50 | 5.9 |
| 5 | 32.06 | NH ₄ ⁺ | CHO ₂ ⁻ | 91 | 2.9 |
| 6 | 37.04 | NH ₄ ⁺ | F ⁻ | 37 | 1.4 |
| 7 | 162.11 | Ca ⁺⁺ | (HCO ₃ ⁻) ₂ | 8.4 | 1.4 |
| 8 | 136.09 | K ⁺⁺ | H ₂ PO ₄ ⁻ | 4.3 | 0.6 |
| 9 | 84.01 | Na ⁺ | HCO ₃ ⁻ | 4.0 | 0.3 |
| Organic Compounds | | | | | |
| No. | g/mole | Formula | Compound | μM | mg/L |
| 1 | 46.07 | C ₂ H ₆ O | Ethanol | 1,449 | 67 |
| 2 | 59.04 | C ₂ H ₃ O ₂ ⁻ | Acetate | See inorganics | |
| 3 | 76.09 | C ₃ H ₈ O ₂ | Propylene glycol | 357 | 27 |
| 4 | 32.04 | CH ₄ O | Methanol | 204 | 6.5 |
| 5 | 108.14 | C ₇ H ₈ O | Benzyl alcohol | 135 | 15 |
| 6 | 45.02 | CHO ₂ ⁻ | Formate | See inorganics | |
| 7 | 62.07 | C ₂ H ₆ O ₂ | Ethylene glycol | 73 | 4.5 |
| 8 | 58.08 | C ₃ H ₆ O | Acetone | 45 | 2.6 |
| 9 | 113.16 | C ₆ H ₁₁ NO | Caprolactam | 21 | 2.3 |
| 10 | 60.10 | C ₃ H ₈ O | 2-Propanol (Isopropanol) | 17 | 1.0 |
| 11 | 122.12 | C ₇ H ₆ O ₂ | Benzoic acid | 16 | 2.0 |
| 12 | 138.16 | C ₈ H ₁₀ O ₂ | 2-Phenoxyethanol | 14 | 2.0 |
| 13 | 162.23 | C ₈ H ₁₈ O ₃ | 2-(2-Butoxyethoxy)ethanol | 12 | 2.0 |
| 14 | 87.12 | C ₄ H ₉ NO | N,N-Dimethyl acetamide | 11 | 0.9 |
| 15 | 222.24 | C ₁₂ H ₁₄ O ₄ | Diethylphthalate | 5.4 | 1.2 |
| 16 | 90.20 | C ₃ H ₁₀ OSi | Trimethylsilanol | 4.6 | 0.41 |
| 17 | 44.05 | CH ₃ CHO | Acetaldehyde | 3.7 | 0.16 |
| 18 | 30.03 | CH ₂ O | Formaldehyde (100 % purity) | 2.7 | 0.081 |

Figure 2 displays the RO configuration in which the HC-MABR was used as a RO recycle tank. The RO pump circulates treated HC from the bioreactor's effluent zone through the RO module and back to the reactor's influent zone at a constant RO inlet pressure of 50 PSI at a flow rate ranging from 4.2 to 2.5 L/hr to maintain a constant pressure. The RO permeate is collected in a permeate tank. The RO system was operated discontinuously. The reactor was operated in variable volume mode, ranging from a liquid volume of 100 L to 169 L (Table 1). The RO operated approximately every 3-4 days processing ~ 24-32 L over a period of < 24 hours. During this test no liquid was wasted from the HC-MABR (e.g. no brine was produced).

B. Treatment Systems Operation

The HC-MABR + RO system using the MABR as the RO recycle tank (Figure 4) was evaluated for ~200 days. The RO system was operated as described above. The RO permeation rate and the RO module pressure were monitored periodically throughout each run. A commercial RO membrane was tested for this configuration. Samples were collected for water quality (TDS, DOC, TN, Cl⁻, NO_x⁻, SO₄²⁻) analysis from the initial wastewater, reactor effluent, and RO permeates.

III. Results and discussion

A. HC Membrane Aerated Biological Reactor and Reverse Osmosis Performance

Throughout the experiment, the HC-MABR treated approximately 1,100 L of humidity condensate (HC). The ranges of the pH and DO in the reactor were 3.5-6.8 and 12-22 mg/L, respectively. The average influent concentrations of COD (200 mg/L), and DOC (~100 mg/L) were relatively constant over the test point (Figure 6). The HC-MABR reduced the influent DOC and COD by 80% with steady state concentrations in the HC-MABR ~ 40 and 20 mg/L, respectively. There was no increase of either in the reactor with time, even though the brine was returned to the HC-MABR. Influent TN concentrations varied between 30 to 50 mg-N/L. TN in the RO permeate remained constant throughout the test even though the reactor TN concentration increased significantly. Reactor TN concentrations increased from ~30 mg-N/L to ~ 80 mg-N/L by day 125, remained constant and then increased to ~120 mg-N/L by day 200. TN in the reactor was largely composed of NO_x^- due to ammonium oxidation by nitrifying bacteria. The relative % of NO_x^- increased from 50% to nearly 90% by the end of the test point. The oxidation of the ammonium produced a decrease in the pH to ~ 4 through most of the study. The increase in TN and NO_x^- concentration in the reactor is due to rejection of NO_x^- by the RO system and subsequent accumulation. This also caused an increase in TDS in the reactor from ~130 mg/l on day 1 to ~ 500 mg/L on day 38 due to the accumulation of NO_x^- as well as other salts (e.g. Cl^- , SO_4^{2-} , Na^+).

Although the TDS concentrations in the reactor increased throughout the study, the RO permeate TDS only slowly increased. Permeate TDS was generally stable (~20-40 mg/L) until day 77 when it slowly increased to ~ 100 mg/L (Figure 7). The TDS in the RO permeate was still substantially lower than untreated HC on ISS (~ 400 mg/L). Concentrations of TOC and COD in the effluent were less than 5 mg/L. TAN was the only species that was elevated (~20 mg/L) but still lower than the influent TN concentration. The single RO membrane (~260 grams) produced ~ 1,100L (Kg) of permeate, approximately 500 crew days of HC. Initially, the permeation rate was high (97 L/day) but after an initial rapid decline stabilized (~68 L/day) and then slowly decreased throughout the remaining study to 60 L/day. At the cessation of the test the permeation rate was still able to treat a 4 crew HC load in 3 hours.

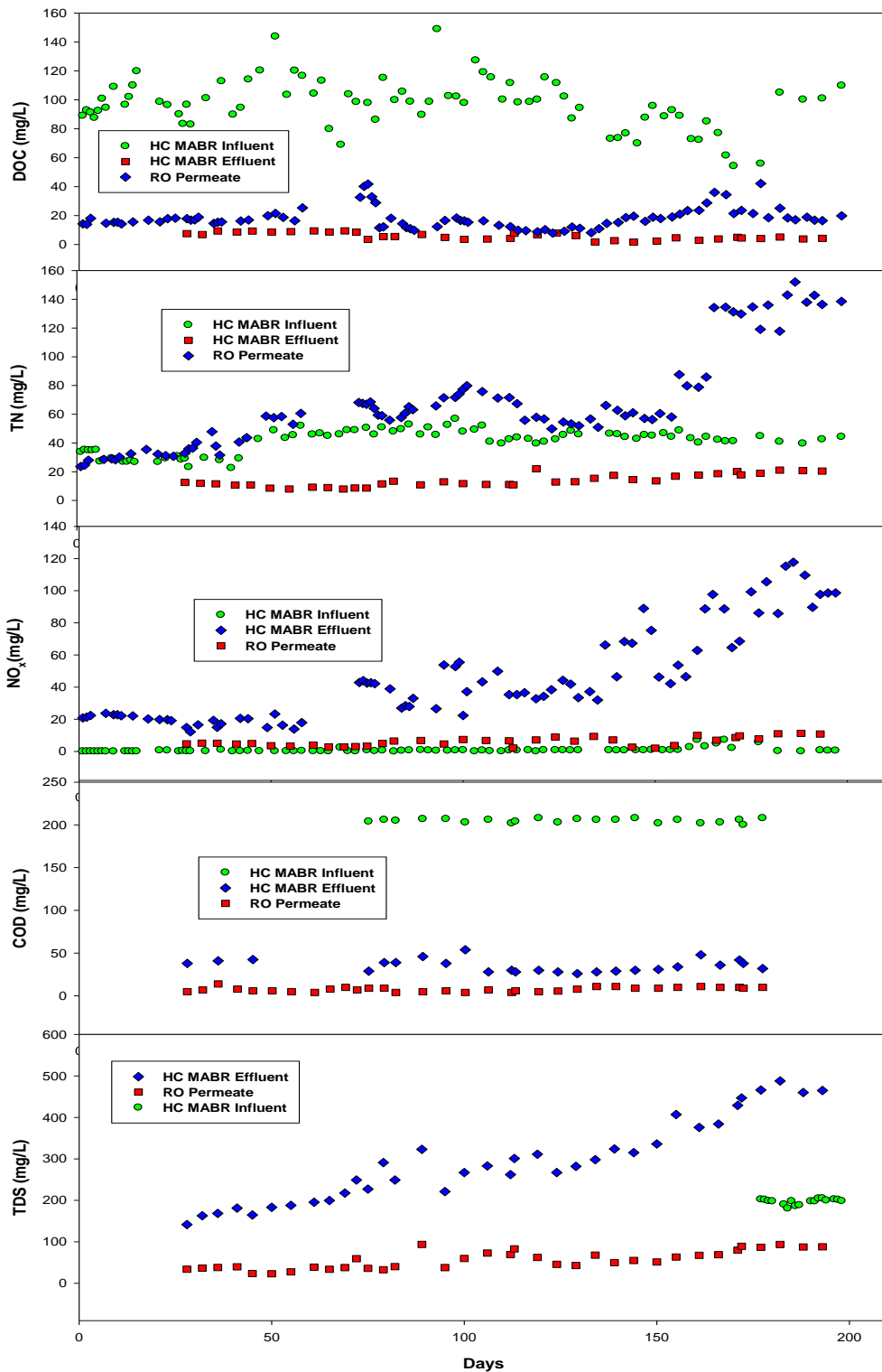


Figure 6. Water quality measurements, including dissolved organic carbon (DOC), total nitrogen (TN), and total dissolved solids (TDS) concentrations for the influent to the Humidity Condensate Membrane Aerated Biological Reactor (HC-MABR), concentrations in the MABR , and concentrations of the reverse osmosis (RO) permeate over a 200-day operation period.

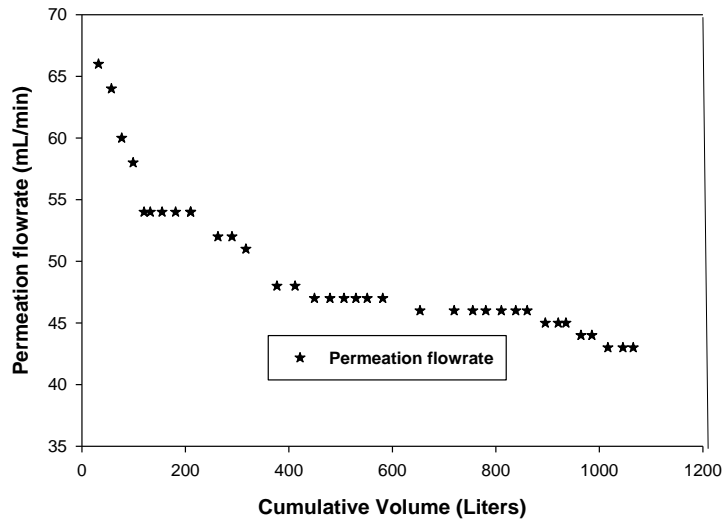


Figure 7. Reverse Osmosis system performance treating biologically pretreated humidity condensate without brine generation or a RO recycle tank.

IV. Conclusion

The results of these experiments showed that the small-scale, low-pressure, commercial RO module was able to remove more than 90% of COD, DOC, and 80% of the TDS to produce near potable water. The system uses the HC-MABR as a HC storage tank to stabilize the humidity condensate, as well as the RO recycle tank. Total consumables included the prefilter (225 grams), RO membrane (260 grams), and O₂ (178 grams) per 1,100 Kg of produced near potable water. In addition, the mass of the whole non-optimized system (258 Kg) may be comparable to the mass of the HC storage tank, suggesting that this configuration could be a significant mass savings and eliminate the current problems on ISS with biomass sloughing in the bellows tank. However, operating in this configuration could not be sustained indefinitely, due to the increase in salinity with time, due to the lack of any brine waste. One solution would be to operate until a TDS was reached that caused an unacceptable RO permeate TDS, at which time the HC-MABR volume could be processed through the distillation system and the process restarted. Alternatively, a small volume of brine could be removed from the HC-MABR daily (~10% of the daily input), which would allow the system to reach a steady state. Future work will evaluate the same process, but rather than use the HC-MABR as the recycle tank, will include an RO recycle tank that would allow the brine to be wasted after each RO batch. This would prevent any increase in TDS in HC-MABR.

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