Assessment of Membrane-Aerated Biological Reactors (MABRs) for Integration into Space-Based Water Recycling System Architectures

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ABSTRACT

This work investigates the suitability of membrane aerated biological reactors (MABRs) for biological treatment of a space-based waste stream consisting of urine, hygiene/grey water, and humidity condensate within an overall water recycling system. Water represents a critical limiting factor for human habitation and travel within space; thus, water recycling systems are essential. Biological treatment of wastewater provides a more efficient sustainable means of stabilizing the waste stream within water recycling system architectures in comparison to current chemical stabilization processes that utilize harsh chemicals, which represent both a hazardous and an unsustainable approach. To assess the capabilities of MABRs for providing microgravity compatible biological treatment and verify long duration operation and integration with desalination processes, two full-scale MABR systems were challenged with various loading rates and operational scenarios during sustained operation for over 1 year. The MABRs were able to maintain 196 g-C/m^3-d and 194 g-N/m^3-d volumetric conversion rates. Additionally the systems were able to handle intermittent loading and recover rapidly from system hibernation periods of up to 27 days. Overall, the use of MABRs within a wastewater treatment system architecture provides several potential benefits including minimizing the use of toxic chemical pretreatment solutions and providing an effluent solution that is easier to desalinate and dewater.

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INTRODUCTION

Human habitation in space is predicated on the advancement of the technologies necessary to support life in a highly challenging and constrained environment. As NASA and other space agencies seek to expand extraterrestrial human endeavors, sustainable and robust life support systems are a critical limiting factor (ISECG, 2011; NASA, 2011; NRC, 2012). Within these systems, water is a fundamental element, representing at minimum 65% of the daily mass input for crew members (Barta and Henninger, 1994). Efficient and reliable water recycling systems are a fundamental need. The International Space Station (ISS) water recovery system is able to achieve ~70% water recovery through chemical pretreatment paired with physical desalination and post processing of the water (Broyan Jr et al., 2011). For long term

habitation out of low Earth orbit, much higher water recovery and more sustainable systems will be required (98%) (NRC, 2012).

The concentrated waste stream produced in space-based environments is especially challenging for conventional treatment processes. The current ISS waste stream is composed of pretreated urine plus flush water and humidity condensate and is generated at a rate of ~4 L/crew-day. Future missions, particularly those with surface habitation (Mars or Moon), are proposed to have additional waste streams including shower, hygiene (e.g., oral, handwash, shave), and laundry, which would increase the wastewater production rate to ~15 L-crew/day. The waste stream itself far exceeds concentrations typically examined for terrestrial applications. Influent nitrogen and carbon concentrations from 800 mg-N/L and 600 mg-C/L for early planetary base type wastes to >2000 mg-N/L and 1500 mg-C/L for ISS wastes, both of which have C:N ratios <1. The carbon in the waste stream provides a continual microbial growth medium, which can result in biofouling throughout the system. The nitrogen is present initially as urea; however, hydrolysis converts the urea to ammonia, which is problematic for downstream physical distillation processes due to NH_3 volatility concerns and also the subsequent increase in pH that can lead to scaling issues.

On ISS, these impacts are mitigated by lowering the pH <2 using H_3PO_4 (10 g/L) and adding large doses of CrO_3 (0.4 g CrO_3/L urine) (Muirhead, 2010). Chemical pre-treatment, while enabling distillation type systems, has numerous drawbacks including storage of large volumes of hazardous material, large consumable demand, incompatibility with membrane-based desalination systems, and production of large quantities of hazardous brine, which is difficult to further dewater (Jackson et al., 2014).

Biologically based treatment systems have the potential to provide a more sustainable, less costly treatment system. Biological treatment transforms problematic compounds while recovering valuable resources in the process. Carbon removal stabilizes the waste stream to prevent unwanted microbial growth in the overall system. Nitrification transforms NH_4^+ to NO_2^- and/or NO_3^-. These ions can then be removed more easily than NH_4^+/NH_3 by downstream desalination processes.

Nitrification also produces H^+ ions that help lower the system pH, reducing NH_3 volatilization and scaling (Shon et al., 2004; Morse et al., 2007). Produced NO_2^- and/or NO_3^- from nitrification can be converted to N_2, a desired atmospheric gas component. Biological treatment of wastewater is a well-established terrestrial technology; however, space-based applications are much more complex due to potential microgravity conditions limiting two phase flow, volume limitations, high strength carbon and nitrogen coupled with low C:N ratio waste streams, and requirements for nearly closed loop operation with minimal solids processing.

Conventional biofilm processes are predicated on the co-diffusion of substrate and electron acceptor into the biofilm from the outer biofilm surface. This co-diffusion can lead to transfer limitations that necessitate larger volumes or higher biomass concentrations in order to achieve desired treatment levels. Membrane-aerated biological reactors (MABR) allow for counter diffusion in which the biofilm attaches to the membrane surface and the electron acceptor is transferred from the base of the biofilm while the substrate penetrates from the outer edge where the biofilm contacts the bulk liquid. In addition to increased efficiency and higher oxygen utilization in comparison to conventional processes, MABRs are also able to foster the growth of slower growing, more sensitive organisms such as nitrifiers. Nitrifiers are typically outcompeted in co-diffusion biofilms by heterotrophs. The presence of these organisms allow MABRs to be better at handling shock loadings and influent conditions that are considered challenging due to high strength or adverse characteristics such as high free ammonia or a low carbon to nitrogen ratio (Semmens et al., 2003; Terada et al., 2003). MABRs have been studied for treatment of wastewater for over 30 years and for incorporation into space habitation wastewater recycling systems for the last 15 or more years (Morse et al., 2004; Brindle and Stephenson, 2000, Casey et al., 1999). MABRs provide a means to utilize the benefits of biological treatment while meeting the additional constraints of the space-based environment. Microgravity compatible MABRs possess the following characteristics: 1) separate gas and liquid streams, 2) gas transfer via diffusion, 3) removal of

product gases downstream, and 4) immobilization of biofilm on membranes.

A number of bench scale studies have demonstrated successful treatment of space-based waste streams in microgravity compatible configurations (Morse et al., 2004: Landes et al., 2007; Jackson et al., 2010; McLamore, 2012). Single reactor systems composed of MABRs operating in either aerobic or anoxic conditions have achieved >90% carbon removal, up to 70% nitrification and in the case of anoxic operation up to 40% total nitrogen (TN) loss due to denitrification. For most systems, loading rates were limited by the inhibition of nitrification due to free ammonia toxicity at pH>8. Two reactor systems composed of an aerobic MABR and an anoxic packed bed have achieved overall transformation efficiencies and reaction rates equal to or exceeding single reactor systems. Although carbon removal was maintained across the studies, complete nitrogen removal via denitrification was not stoichiometrically possible due to carbon limitations as well as alkalinity limitations for the waste streams assessed (Morse et al., 2004; Morse et al., 2007; Chen et al., 2008; Jackson et al., 2009; Landes et al., 2011).

Although bench scale MABRs can successfully treat habitation waste streams in microgravity compatible configurations, several important questions remain for operation of full scale (~100 L) reactors in an integrated wastewater treatment system. The ability of full scale MABRs to be operated for long durations and in operational regimes that are compatible with downstream processes and habitation architectures is unknown. The impact of hibernation and changes in aeration gas composition and flow rates are also important areas in need of assessment.

The objective of this work is to assess the suitability of the MABR technology for integration into a space-based wastewater treatment architecture for water reuse applications. In order to accomplish these objectives two full-scale MABRs were operated for extended durations (>1 year) at a range of loading rates and operational scenarios. Several key parameters including effluent gas flow rate, gas composition, and influent flow mode (continuous, intermittent, hibernation) were varied to assess the impact on system performance.

MATERIALS AND METHODS

System Configuration

The reactors utilized in this work were an MABR designed at Texas Tech University (TTU) titled Counter-diffusion Membrane Aerated Nitrifying Denitrifying Reactor (CoMANDR). As depicted in Figure 1, CoMANDRs consist of a liquid chamber and membrane module. The two full size reactors, CoMANDR 265 and CoMANDR 200, utilized the same dimensions. Specifically, each had a 122 cm tall acrylic tube with an inner diameter of 40 cm for the 2.5 cm thick outer shell plus a submersible membrane module (SMM) that could be removed for maintenance or sampling (Figure 1). The SMMs varied slightly in membrane density between the two systems. The membrane modules consisted of two air plenums linked by Dow Corning hollow fiber siloxane tubes (0.49 cm and 0.26 cm outer diameter and inner diameter, respectively). CoMANDR 265 had 1775 tubes and 104 liters of liquid volume resulting in a specific surface area (SSA) of 265 m^2/m^3 and CoMANDR 200 had 1252 tubes and 109 liters of liquid volume for a specific surface area of 200 m^2/m^3. The liquid chamber was sealed via compression of 3.8 cm acrylic end plates with an O-ring compressed by 1.27 cm thick stainless steel threaded rods. The 2.5 cm influent ports were located 15.7 cm from the bottom of the reactor directly opposite each other. The 2.5 cm effluent ports were located 12.7 cm from the top of the reactor. The two reactors differed in the orientation of the ports. CoMANDR 265 had effluent ports located on the same vertical axis as the influent ports. CoMANDR 200 outlet ports were placed at a 90^0 rotation from the influent ports to help foster mixing within the membrane bundle and avoid preferential flow paths around the annulus. Figure 2 illustrates the assembled MABR configuration and the liquid and gas flow paths. Cole Parmer Mass Flow controllers connected to atmospheric air or O_2 compressed gas cylinders were used to control the blending of O_2 into the influent gas stream and to control the total flow and pressure on the effluent side of the system. Both the reactors were pressurized to prevent any gas bubble formation within the liquid volume. Gas pressure ranged from 10-15 psi (69-103 kPa) and liquid pressure ranged from 8-12 psi (55-83 kPa).

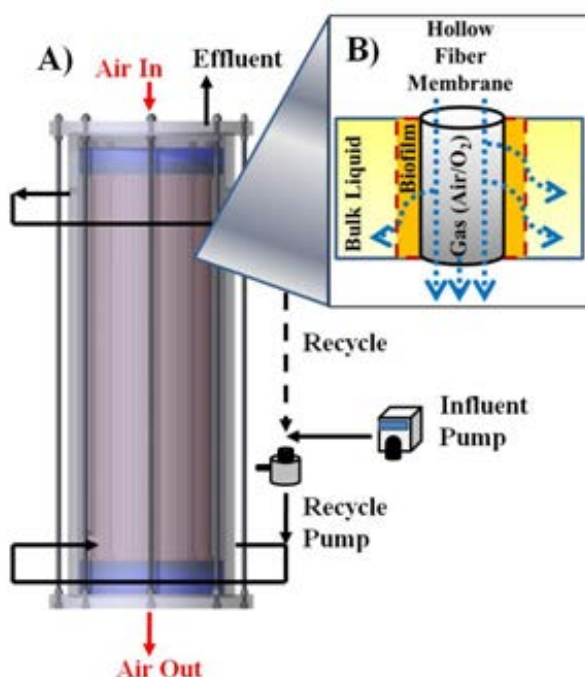The only exception was the hibernation test point in which the reactors were operated at ambient pressure.

Figure 1. (A) CoMANDR schematic and liquid and gas flow path and (B) expansion of single membrane to illustrate counter-diffusion.

Wastewater Composition

The feed solution for all test points consisted of space-based wastewater for an early planetary base scenario. The wastewater composition is summarized in Table 1 and consists of urine, flush water, humidity condensate, hygiene (toothbrushing, shaving, handwashing), shower, and laundry. The urine was donated by volunteers but all other solutions were chemical ersatz solutions based on the work of Verostoko (Verostko, 2009) and expanded to include laundry water ersatz (Table 1). Urine was either used from daily donations or from reserves kept at 4°C.

The hydraulic retention time (HRT) for various test points was represented by θ and calculated by dividing the liquid volume of the reactor by influent flow rate. To maintain complete mixing, a centrifugal pump recirculated liquid at a rate of >2 L/min. Influent flow was controlled by a Cole Parmer peristaltic pump.
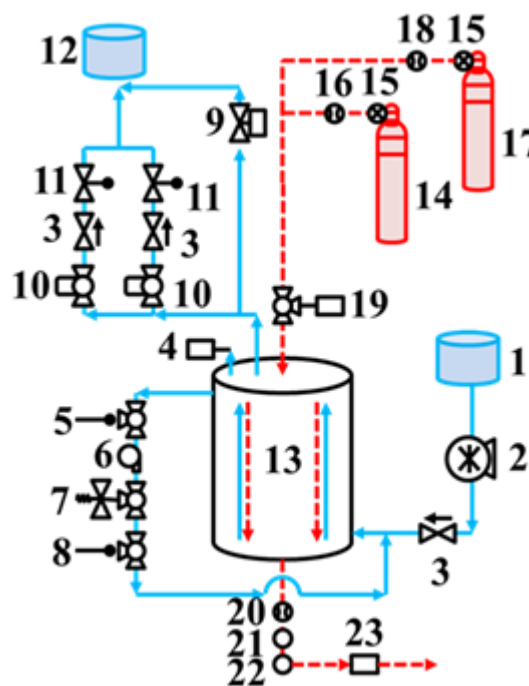

Figure 2. CoMANDR reactor and peripherals schematic (Christenson et al., 2013): (1) Influent Tank; (2) Influent Pump; (3) Check Valve; (4) Liquid Pressure Transducer; (5) pH probe; (6) Recycle Pump; (7) Liquid Pressure Relief Valve; (8) Sonde Multi-probe (pH, DO, TDS); (9) Pressure Dissipating Solenoid; (10) Screen; (11) Pressure Regulation Valve; (12) Effluent Tank; (13) Bioreactor; (14) O2 Cylinder; (15) Gas Cylinder Regulator; (16) Mass Flow Controller; (17) Air Cylinder; (18) Gas Mass Flowmeter; (19) Gas Relief Valve; (20) Gas Pressure Transducer; (21) Mass Flow Controller; (22) Desiccant Column; (23)% O2, %CO2 sensor.

System Operation

Each reactor was operated continuously for over a year. Reactor operation generally consisted of continuously pumping wastewater from the feed tank, which was refilled daily with fresh feed. The specific test points outlined in Table 2 represent different system operational conditions as described below.

Loading rate evaluation

Each system was operated at a range of loading rates (Table 2) to assess the system performance and develop a baseline for comparison purposes with additional test points.

Table 1. Wastewater Composition.

Wastewater Component	Volume/Day -Crew Member (L)	Constituents
Urine*	1.5	N/A
Hygiene#	7.2	**Organics**: Neutrogena shaving cream, Oragel or Arm and Hammer toothpaste, No-Rinse body wash, 13 other compounds** **Inorganics**: Sodium Chloride, Ammonium Bicarbonate, Sodium Sulfate, Potassium Phosphate Monohydrate Tribasic, Potassium Fluoride
Humidity Condensate#	1.95	**Organics**: Ethanol, 1-2 Propanediol, Acetic Acid, 2-propanol, 22 other trace organics** **Inorganics**: Ammonium Bicarbonate, Potassium Fluoride, Potassium Chloride, Calcium Chloride Dihydride, Sodium Sulfate
Laundry#	3.75	Seventh Generation Free and Clear Detergent
Total	14.4	

* Donor Urine, #Ersatz, ** (Verostko, 2009)

For the loading rate study, the loading flow rate was uniform 24 hours a day.

Intermittent loading evaluation

In order to evaluate integration with possible downstream processors (e.g., forward osmosis or distillation) that are more easily operated in intermittent mode, CoMANDR 200 was also operated in an intermittent mode. The system received the daily wastewater load (15.1 L crew/day) over 18 hours (wake cycle) and a recycle mode for 6 hours (sleep cycle).

Effluent gas flow rate and composition evaluation

When integrated into an overall system architecture, the flow rate and composition of gas discharged from and the mass of gas required by the CoMANDR system are important parameters. Minimizing gas flow may reduce excess O_2 returned to the cabin in cases where elevated partial pressure of O_2 is required for CoMANDR

operation. At the same time, reduced gas flow results in higher waste gas (CO_2, N_2O) concentration and could impact reactor performance. In order to assess the impact of gas flow rate, pressure, and composition on system performance, and to assess the impact on cabin atmosphere, the system was maintained at a constant wastewater loading rate (20 L/day), but operated at varying gas flow rates and O_2 partial pressures (Table 2).

Hibernation evaluation

Future missions will likely include periods of habitation dormancy due to mission gaps (crew changes) or extended extravehicular activities (EVAs). In order to evaluate the ability of the CoMANDR to tolerate such hibernation periods, each system was operated in a recycle mode for an extended period of time. Following a period of stable operation at a loading rate of 20 L/day, the flow to the system was stopped, the system was

depressurized, and the air flow was reduced to 100 mL/min. After 3 and 4 weeks, respectively, system feed and normal operation was resumed at the same flow rate used prior to hibernation and no start-up phase was initiated.

System Sampling and Analysis

Samples were collected from the influent and effluent tanks at a minimum 3 times per week. Influent and effluent samples were filtered (0.47 μm), and stored at 4^0C until preparation for analysis. Samples were analyzed for pH (HACH 301-C) and dissolved oxygen (HACH LDO 401). Anions (NO_2^- and NO_3^-) were determined using a Dionex AS14a column, and dissolved organic carbon (DOC) and total nitrogen were determined using a Shimadzu TOC/TN analyzer after acid addition to remove inorganic C. In addition to the grab samples, each CoMANDR included a Hydrosonde (MS5 minisonde) multi-probe in the recycle line which continuously monitored pH, dissolved oxygen (DO), and conductivity. Gas temperature, pressure, and flow were monitored by the Cole Parmer mass flow controllers. A Quantek 902-P gas analyzer was also utilized to monitor effluent gas O_2 and CO_2 concentrations (Figure 2).

Data Analysis

Carbon removal efficiency was calculated based on the percent difference of influent (inf) and effluent (eff) total organic carbon (TOC) concentrations (Equation 1). Nitrification efficiency was calculated from the overall change in total nitrogen (TN) concentration plus the concentration of NO_x^--N ($NO_x^- = NO_2^- + NO_3^-$) in the effluent (Equation 2). Areal reaction rates were calculated by dividing the mass removed/transformed divided by the membrane surface area (SA_{mem}) (Equation 3 and 4). Volumetric reaction rates were calculated by dividing mass removed/transformed by the liquid volume (V_{liq}) (Equation 5 and 6). Liquid flow rate is designated by Q.

Equation 1 $\frac{TOC_{inf} - TOC_{eff}}{TOC_{inf}} * 100 = carbon\ removal\ efficiency$

Equation 2 $\frac{TN_{inf} - TN_{eff} + NO_{x,eff}}{TN_{inf}} * 100 = nitrification\ efficiency$

Equation 3 $\frac{Q*(TOC_{inf} - TOC_{eff})}{SA_{mem}} = carbon\ removal\ areal\ reaction\ rate$ and

Equation 4 $\frac{Q*(TN_{inf} - TN_{eff} + NO_{x,eff})}{SA_{mem}} = nitrification\ areal\ reaction\ rate.$

Equation 5 $\frac{Q*(TOC_{inf} - TOC_{eff})}{V_{liq}} = carbon\ removal\ volumetric\ reaction\ rate$

Equation 6 $\frac{Q*(TN_{inf} - TN_{eff} + NO_{x,eff})}{V_{liq}} = nitrification\ volumetric\ reaction\ rate$

RESULTS

Loading Rate Evaluation

The two systems were fed similar waste streams and were tested over a range of HRT (2.5-5.5 days). Each system was tested at a given regime for varying time periods but generally >14 days (Table 2). The waste streams' carbon and nitrogen load is dominated by the urine fraction; thus, the concentrations of TOC (512-732 mg/L) and TN (710-1008 mg/L) varied within and between systems due to the use of donated urine and small donor pools (Table 2). C:N ratios were also <0.8 for all test points. Influent pH was generally >8 due to urea hydrolysis.

Effluent DOC and TN were generally constant for all systems and HRT (Table 2). TN loss ranged from 23–279 mg-N/L. Systems were operated with variable dissolved oxygen concentrations in the bulk liquid (1.5–40.5 mg/L); however, most test points had DO concentrations >2 mg/L (Table 2). Anoxic conditions were still possible in areas of thick biofilm. Effluent TN was composed of un-oxidized ammonia/ ammonium and NO_x^- with the primary NO_x^- species being NO_2^- (>92%). Little if any NO_3^- was present in the effluent for any system or HRT. The pH varied over a fairly large range (6-8) and

Table 2. Test Point Parameters. Key Influent and Effluent Parameters Along with Test Point Objectives and Characteristics for the CoMANDR 265 and CoMANDR 200 Modules.

Reactor Module	Test Point Objective	Days in Test	Hydraulic Retention Time (O)	Inf Organic Concentration (mg/L)	Eff Organic Concentration (mg/L)	Inf Nitrogen Concentration (mg/L)	Eff Nitrogen Concentration (mg/L)	Eff NO_2-N (mg/L)	Eff NO_3-N	Eff NO_x-N (mg/L)	Eff NO_2-N/ Eff NO_x-N	Eff pH	Dissolved Oxygen (mg/L)
CoMANDR 265	Loading Rate	32	2.6	529	47	710	642	231	25	256	0.90	6.73	40.48
CoMANDR 265		13	6.9	604	43	850	592	398	11	410	0.97	6.00	3.09
CoMANDR 265		24	3.5	539	49	1008	729	363	22	385	0.94	6.50	1.91
CoMANDR 265	Hibernation Study	21	5.2	550	43	824	643	378	12	390	0.97	6.24	1.59
CoMANDR 265		21					Hibernation: recycle only						
CoMANDR 265		25	5.2	489	57	858	643	368	37	405	0.91	6.44	2.55
CoMANDR 265	Intermittent Operation	16	5.2	635	42	935	722	359	17	376	0.95	6.57	2.37
CoMANDR 200	Gas Composition	32	5.5	398	56	828	748	343	25	367	0.93	6.55	7.24
CoMANDR 200		10	5.5	361	51	664	724	363	21	383	0.95	6.62	9.43
CoMANDR 200		7	5.5	314	48	763	694	344	20	364	0.95	6.73	10.28
CoMANDR 200		14	5.5	487	51	786	755	254	23	277	0.92	7.21	33.13
CoMANDR 200	Hibernation Study	9	5.5	361	130	906	819	279	79	358	0.78	6.68	5.87
CoMANDR 200		27					Hibernation: recycle only						
CoMANDR 200		26	5.5	484	93	854	782	351	21	372	0.94	6.53	31.71
CoMANDR 200	Loading Rate	10	5.5	337	61	744	664	325	19	344	0.95	6.60	8.17
CoMANDR 200		9	4.4	637	35	761	738	346	14	360	0.96	6.55	6.36
CoMANDR 200		13	3.6	732	44	884	844	164	9	173	0.95	7.27	2.39

varied inversely with respect to HRT but the overall range was similar between systems.

Carbon oxidation

As illustrated in Figure 3, carbon oxidation efficiency (>90%) did not vary regardless of SSA or HRT. The effluent DOC (generally <60 mg/L) was largely invariant particularly compared to the elevated concentrations in the influent (Table 2). This is likely due to nearly complete removal of biodegradable organic carbon with remaining DOC due to soluble microbial products and/or recalcitrant components of the influent DOC. Organic carbon reaction rates (0.24-0.9 g-C/m^2-d; 47-196 g-C/m^3-d) increase linearly with respect to decreasing retention time. This direct relationship indicates that the systems are not limited by SSA or HRT in regards to carbon removal. The maximum areal reaction rate of 0.9 g-C/m^2-d occurred at HRT=3.6 d. Although further increase in reaction rates for carbon oxidation would likely occur at HRT<3 d, the overall system performance (including ammonium oxidation) would be inhibited by the impact of increased pH on the nitrifying bacteria, if nitrification is desirable.

Previous studies of MABRs utilized for carbon oxidation/chemical oxygen demand (COD) removal of high strength waste streams have reported rates of 0.29 g COD/m^2-d to 42.7 g COD/m^2-d (Pankhania et al., 1994; Syron and Casey, 2008) with systems designed for carbon oxidation and nitrogen removal reporting rates in the range of 0.2 g-C/m^2-d to 6.3 g- C/m^2-d (Yamagiwa et al., 1994; Terada et al., 2003; Landes et al., 2007) for high strength waste streams with more similar C:N ratios. It is important to note that these systems, in addition to differences in waste stream concentrations and constituents, utilized biofilm control measures such as upflow velocity-induced sloughing or backwashing (Pankhania et al., 1994; Semmens et al., 2003) in order to maintain an optimal biofilm thickness and increase biomass growth, subsequently lower required retention times. The CoMANDR systems in contrast provide near infinite mean cell retention time (effluent total suspended solids (TSS) <100 mg/L) with no direct biofilm control. The absence of active biofilm control measures reduces the complexity of the overall system and eliminates the need for an additional solids management system.

Nitrogen

Both systems illustrate an increase in nitrogen oxidation efficiency as retention time increases up to a maximum of ~70% at θ>5d (Figure 3). Overall, reaction rates increased with loading and ranged from 75.3–194.3 g-N/m^3-d on a volumetric basis or 0.38-0.93 g-N/m^2-d on an areal basis (Figure 3). Throughout all test points, regardless of DO or pH, nitrite (NO_2^-) was the dominant NO_x^- species with only minimal NO_3^- present. These rates are in the lower range of rates reported for other nitrifying MABRs (0.1 to 6 gN/m^2-d) (Brindle et al., 1998; Brindle et al., 1999; Brindle and Stephenson, 2000; Semmens et al., 2003; Terada et al., 2003; Satoh et al., 2004; Landes et al., 2007; Morse et al., 2007; Lackner et al., 2008; Syron and Casey, 2008; Landes et al., 2011; Martin and Nerenberg, 2012; Wei et al., 2012; Li et al., 2015). The large range in rates is likely due to a number of operational differences for the various systems. While the waste streams included source separated wastewater treatment, industrial and livestock wastewater, and space-based wastewater, several of these systems utilized pH control or active biofilm management. Active pH control eliminates potential issues due to inhibition from either free ammonia or nitrous acid species leading to higher oxidation rates (5.4, 6.0 gN/m^2-d) (Brindle et al., 1998; Terada et al., 2003; Syron and Casey, 2008), but would increase consumables as well as require storage of large amounts of hazardous solutions. Active biofilm management by increasing fluid velocity and/or bubbling to shear biofilm and control biofilm thickness can increase reaction rates (6.0 gN/m^2-d) by maintaining the biofilm in an active growth stage. On the downside, this results in the production of solids which must be separated from the waste stream using non-gravity dependent means and must have a separate waste handling system to dewater and treat (Semmens et al., 2003; Syron and Casey, 2008). Other studies with higher rates (6.0 gN/m^2-d) only evaluated waste streams containing synthetic feeds or feeds with no influent carbon (Brindle et al., 1998; Semmens et al., 2003; Terada et al, 2003; Satoh et al., 2004; Syron and Casey, 2008; Martin and Nerenberg, 2012). Bench top systems with similar wastewater characteristics and no pH or biofilm control have achieved reaction rates similar to those reported here (Morse et al., 2003;

Landes et al., 2007; Jackson et al., 2009). It is important to note that the work performed here represents full scale operation with donor urine, no pH control, and high influent loading of both carbon and nitrogen. The use of donor urine allows for the variability inherent in real world applications in both space and terrestrial scenarios, thus broadening the applicability of these results.

pH

Bulk liquid pH varied directly with loading for CoMANDR 265. CoMANDR 200 operated over a narrow pH range so the relationship with loading is less evident. System loading directly impacts pH due to urea loading and subsequent hydrolysis which produces OH^-. Final system pH is a function of loading versus nitrification rate, which offsets the impact on pH by production of H^+ ions and the oxidation of NH_3 to NO_x^- species. This interdependence results in a decrease in pH with increasing HRT due to the increase in nitrification efficiency with increasing HRT and reduced urea loading. However, the impact of pH on organic nitrogen oxidation by nitrifying organisms is a complex process. Urea hydrolysis is the primary source of the ammonical nitrogen and also causes an increase in pH due to the production of ammonia. Nitrifying organisms oxidize the organic N, converting it into non-volatile species (NO_2^- and NO_3^-), and produce H^+ ions. Further, system pH has direct and indirect effects on the nitrifying organisms. pH>8 has been shown to directly inhibit nitrifiers (Van Hulle et al., 2007). The indirect effects arise from the speciation of the potentially inhibitory species of NH_3 and HNO_2^- as well as availability of substrate (NH_3). The competing, driving forces combined with the inhibitory influence of pH make system pH an essential indicator of system performance. Although effluent NH_3 and NO_x^- values also illustrate the system failure, pH is a reliable, strong, easily measured predictor. For space-based applications, pH is especially important as increasing pH directly impacts volatility of compounds such as NH_3 and causes additional issues with chemical precipitation. Space systems should be operated to produce as low a pH effluent as possible to minimize remaining NH_3 volatilization and reduce

precipitation potential while maintaining reasonable reaction rates to minimize reactor volume.

Intermittent Loading Evaluation

Integration with downstream treatment processes in comprehensive waste water treatment architectures will likely require CoMANDR systems to couple with desalination systems. These systems often operate in intermittent modes (batch feed) to allow for more efficient treatment. The ability of the CoMANDR system to maintain treatment efficiency when loaded intermittently prevents the need for an additional holding tank to allow for continuous CoMANDR feeding. During a recent integrated systems test at NASA Johnson Space Center, CoMANDRs were paired with a forward osmosis secondary treatment system (FOST) that required a 6 hour daily runtime (Vega et al., 2016). To assess the capability of an integrated CoMANDR/FOST system, COMANDR 200 was operated in an 18 hour feed and 6 hour recycle only mode. The full 24 hour wastewater loading was fed into the reactor over the 18 hours. Comparison of system efficiencies in Figure 4 illustrates that the system was able to maintain overall performance and effluent water quality during the discontinuous loading. There was no difference in carbon oxidation or nitrification efficiency between operational regimes. However, intermittent operation did produce dynamic changes in the system in response to changes in loading. Figure 5 illustrates the responses of several key effluent parameters over several 24 hour (18 feed 6 recycle) cycles. When feeding begins the pH immediately rises in response to the elevated pH of the influent and urea hydrolysis. System dissolved oxygen drops as the microorganisms respond to the loading of new substrate (carbon and nitrogen). Effluent gas DO decreases in response to the increased oxygen demand within the reactor and effluent CO_2 increases as the microbial respiration occurs. During the 6 hour recycle period the pH drops as nitrification rates exceed urea hydrolysis and dissolved oxygen in the bulk liquid increases in the absences of loading. The rapid response time of the system can allow for rapid changes to be made to control the system performance.
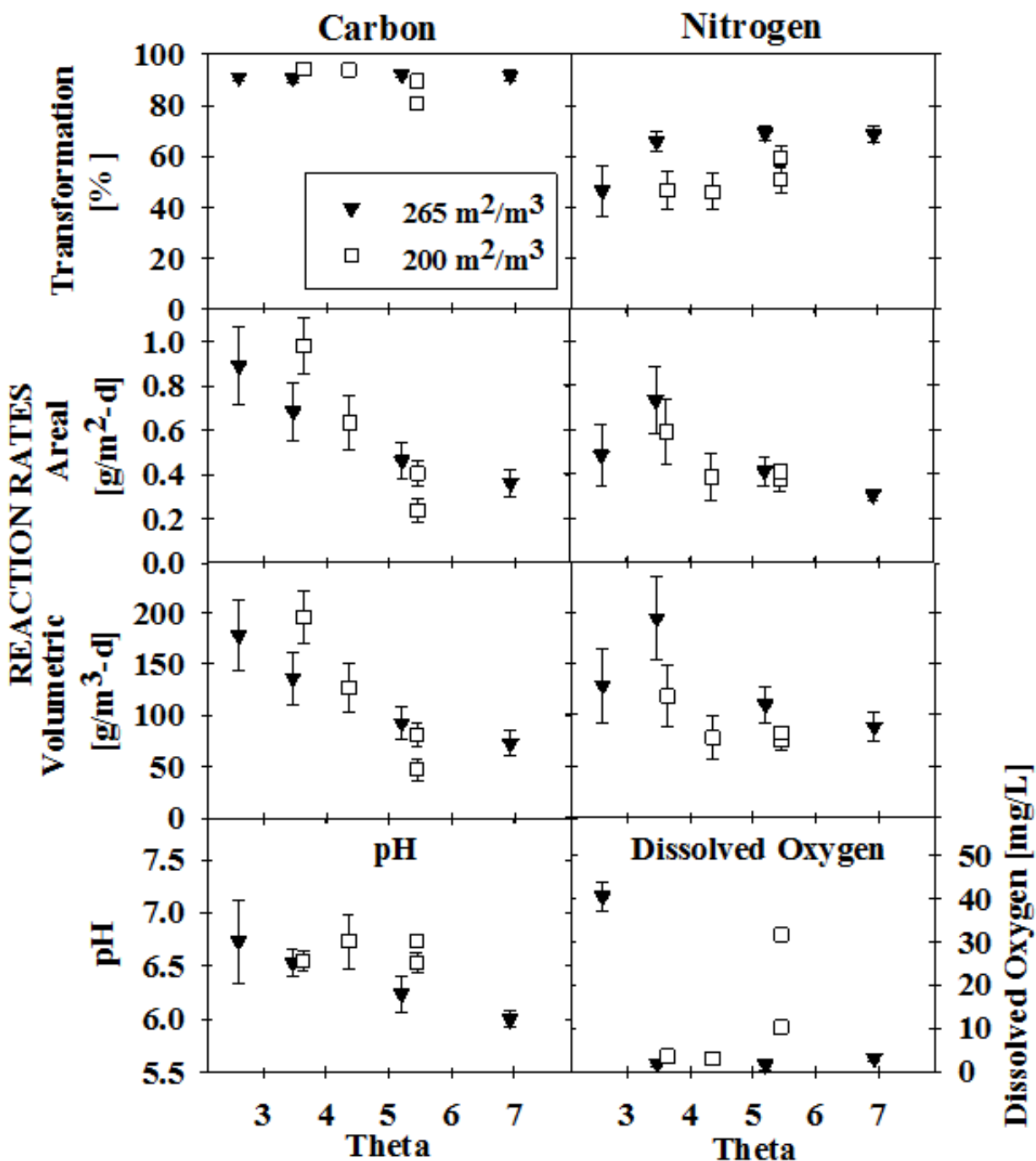
Figure 3. Overall carbon and nitrogen transformation efficiencies, reaction rates, pH, and dissolved oxygen vs. loading rate as indicated by hydraulic retention time (θ) for CoMANDR 265 and 200 treating an early planetary base wastewater.

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Integration with downstream treatment processes in comprehensive waste water treatment architectures will likely require CoMANDR

systems to couple with desalination systems. These systems often operate in intermittent modes (batch feed) to allow for more efficient treatment. The ability of the CoMANDR system to maintain treatment efficiency when loaded intermittently

prevents the need for an additional holding tank to allow for continuous CoMANDR feeding. During a recent integrated systems test at NASA Johnson Space Center, CoMANDRs were paired with a forward osmosis secondary treatment system (FOST) that required a 6 hour daily runtime (Vega et al., 2016). To assess the capability of an integrated CoMANDR/FOST system, COMANDR 200 was operated in an 18 hour feed and 6 hour recycle only mode. The full 24 hour wastewater loading was fed into the reactor over the 18 hours. Comparison of system efficiencies in Figure 4 illustrates that the system was able to maintain overall performance and effluent water quality during the discontinuous loading. There was no difference in carbon oxidation or nitrification efficiency between operational regimes. However, intermittent operation did produce dynamic changes in the system in response to changes in loading. Figure 5 illustrates the responses of several key effluent parameters over several 24 hour (18 feed 6 recycle) cycles. When feeding begins the pH immediately rises in response to the elevated pH of the influent and urea hydrolysis. System dissolved oxygen drops as the microorganisms respond to the loading of new substrate (carbon and nitrogen). Effluent gas DO decreases in response to the increased oxygen demand within the reactor and effluent CO_2 increases as the microbial respiration occurs. During the 6 hour recycle period the pH drops as nitrification rates exceed urea hydrolysis and dissolved oxygen in the bulk liquid increases in the absences of loading. The rapid response time of the system can allow for rapid changes to be made to control the system performance.

Effluent Gas Flow Rate Evaluation

Gas flow rate is another fundamental consideration when assessing CoMANDRs for integration into an overall system. The influent and effluent gas flow rates are essentially equivalent; however, effluent gas flow rate and composition could impact the cabin atmosphere. Minimizing the volume of gas discharged from the reactor is desirable whether the stream is treated and reintegrated into the cabin environment or directly discharged. Oxygen availability in the biofilm is the key parameter governing nitrification efficiency and is the
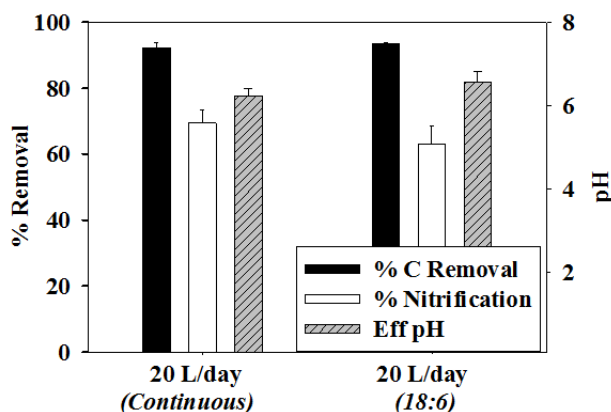

Figure 4. **Continuous vs. intermittent operation results on efficiency and effluent pH of CoMANDR 200 at uniform loading rate of 20 liters/day. Overall performance efficiencies were maintained during intermittent operation.**
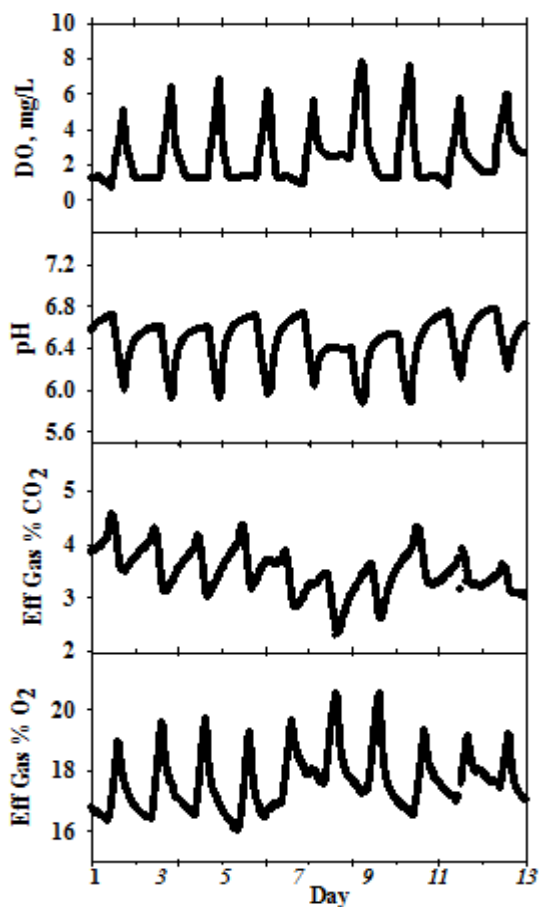

Figure 5. CoMANDR 200 effluent DO, pH, and gas O_2 and CO_2 % fluctuations in response to intermittent loading.

driving consideration when considering gas flow rate. Oxygen transfer to the base of the biofilm is governed by oxygen partial pressure in the lumen. Oxygen partial pressure is a function of total gas pressure and oxygen concentration. Oxygen concentration is influenced by influent gas composition and the rate of gas flow through the lumen with decreased concentration at low flow rates due to consumption. Figure 6 illustrates the ability of the CoMANDR system to maintain consistent treatment efficiency at gas flow rates varying from 80 to 600 mL/min. Within these flow rates, consistent oxygen partial pressure was maintained via changing the composition of the influent gas stream. The test points shown in Figure 6 are all at a similar total pressure (6-9 psi; 41-62 kPa); thus, O_2 concentration (%) in the gas provides an accurate estimate of oxygen partial pressure. Despite changes in effluent gas flow rate, the overall treatment efficiency of carbon oxidation and nitrification along with effluent pH remain relatively constant. This principle allows for control of the effluent gas flow rate and subsequent impact on cabin air quality if operated within a closed system. The buildup of CO_2 in the membrane lumen causes an elevated CO_2 concentration in the bulk liquid and subsequent drop in pH. This pH suppression can be favorable for handling shock loads or system interruptions that could cause a pH spike. Measurements of effluent gas O_2 and CO_2 concentration, pressure, and flow allow for the calculation of O_2 consumed and CO_2 produced on average per wastewater load per crew member. On average 32 g of O_2 consumed per crew member per day (~4% of O_2 consumed per crew member per day) and 12 g of CO_2 produced per crew member per day (~1% of CO_2 produced per crew member per day).
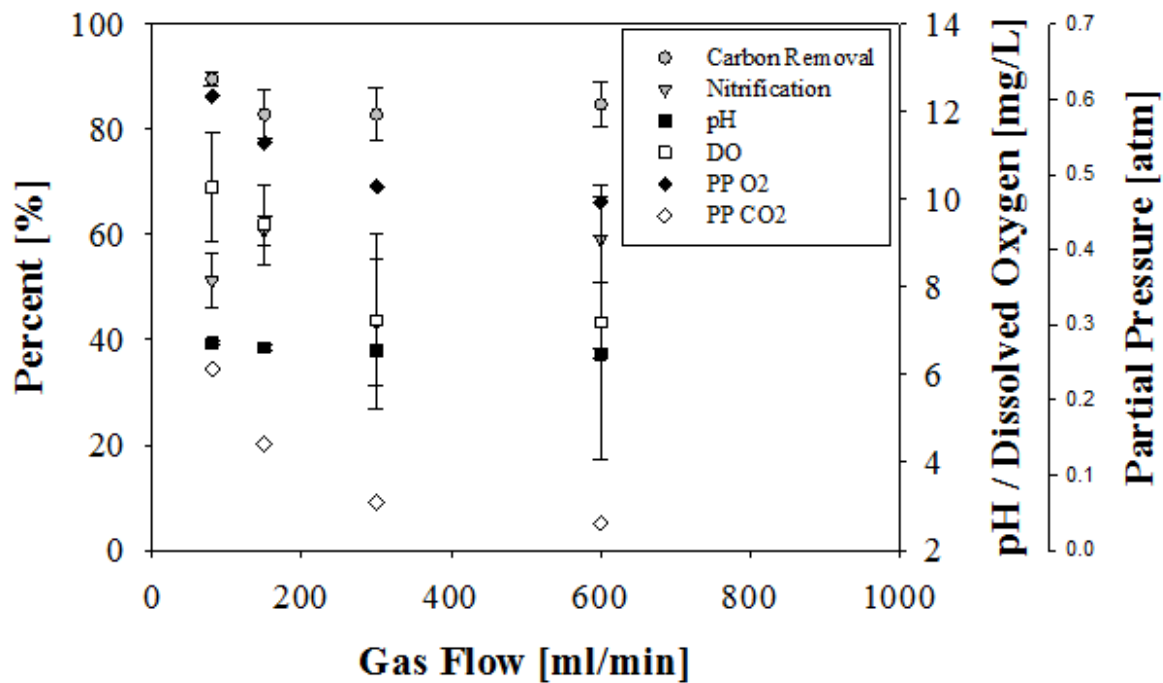

Figure 6. Total effluent gas flow vs. carbon and nitrogen efficiency and effluent liquid and gas composition.

Hibernation Evaluation

In addition to integration with the overall system architecture, components of a water re-use system also need to be able to handle longer term operational interruptions or hibernation periods. These may be necessitated by mission parameters such as an extended excursion by crew members away from base or possible inter-mission periods. The ability to hibernate systems could also be utilized to keep a spare system or to provide offline periods to allow for system maintenance. Both CoMANDR 265 and 200 were hibernated for extended periods (21 days for CoMANDR 265
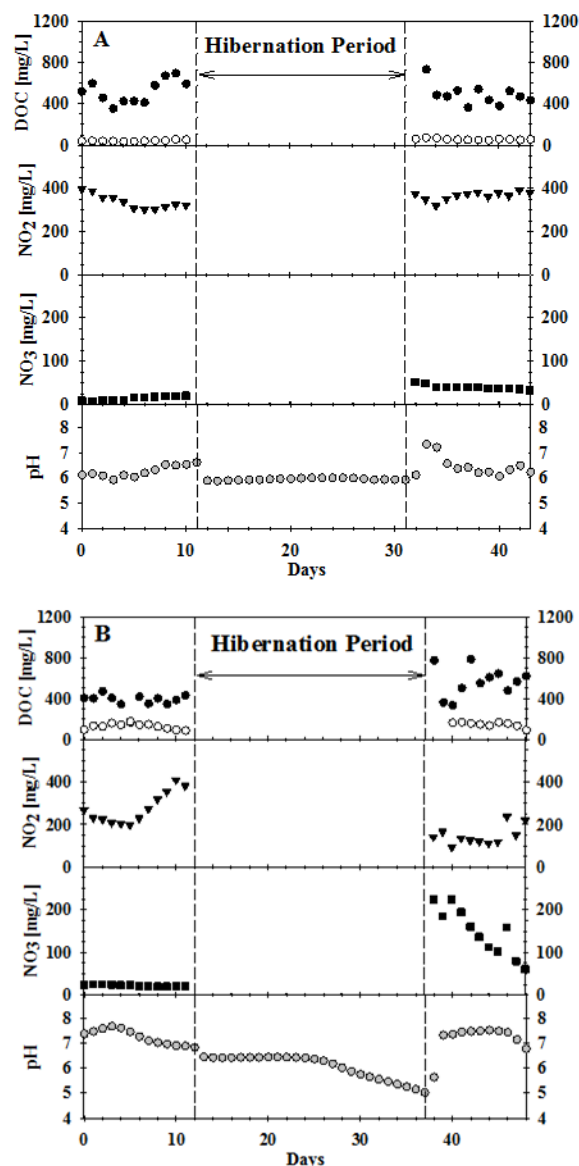
Figure 7. Hibernation performance: daily values of DOC, NO_2^-, NO_3^-, and pH for reactor systems (A) CoMANDR 265; (B) CoMANDR 200. Carbon oxidation and nitrification efficiencies are recovered within 1 week after resumption of operation.

and 27 days for CoMANDR 200). The systems were able to rapidly resume steady state operation (<1 week) and treatment efficiency (Table 1). Figure 7 illustrates the daily water quality of the reactors pre and post hibernation as well as pH during hibernation. Over the course of the hibernation period system pH drops as the nitrifiers continue to operate in the absence of a continued loading (Figure 7). The CoMANDR

200 system also illustrated a decrease in the NO_2^- concentration and increase in NO_3^-. The overall NO_2^- dominated NO_x balance resumes quickly (<2 weeks) upon restart of the system. The rapid recovery after short term hibernation supports the use of biological treatment, although longer term periods without inhabitants would need to be evaluated further.

DISCUSSION

This work provides important characterization of the performance and operational ranges of CoMANDRs to help facilitate integration of biological reactors into potential wastewater treatment architectures. Based on this work, treatment efficiencies of >90% carbon oxidation and 60% nitrification can be expected at ~3 day HRT. Volumetric conversion rates of 196 g-C/m³-d and 194 g-N/m³-d suggest that 0.05 m³ per crew member will be required for 70% conversion of NH_x and that SSA<200 m²/m³ are possible. Depending on constraints of the system, gas flow rates between 80–600 ml/min can be used without comprising treatment efficiency depending on the relative need to minimize effluent gas impacts on cabin. Oxygen consumption will likely not be a significant impact, requiring less than 5% of a crew member demand per day; CO_2 return will only add a 1% increase to crew load per day. Intermittent loading and hibernation studies illustrated the robust nature of the systems to handle discontinuous loading from an hourly to a weekly time scale. Effluent pH values <7.0 are favorable for integration with downstream processes and minimization of precipitation or scaling. For space-based applications, CoMANDRs offer sustainable, low energy input wastewater stabilization with minimal consumables and without the use toxic chemicals. The resulting brine from pretreated influent will also be significantly less toxic without the use of chemical stabilization and, due to lower DOC, TN, Chromium (Cr), and Phosphorus (P), the brine will be easier to dewater. Several key areas for further analysis remain in order to optimize the technology. Based on the favorable results from the intermittent loading study, future work should determine if a feed tank could be eliminated entirely by directly feeding wastewater into

reactor when the event occurs (i.e., urination, oral hygiene, laundry).

Biological treatment of a high strength waste stream allows for stabilization of a conventionally challenging stream without the use of toxic chemicals that represent potential downstream complications and, at minimum, are a consumable resource. CoMANDR technology allows for growth of the biomass necessary for treatment within a microgravity compatible and highly controllable environment. The capabilities of the CoMANDR technology when treating a high strength, low C:N, space-based waste stream also provide an increase in overall life support system sustainability with the potential to produce a nutrient-rich, stabilized effluent that could be used as a fertilizer source for plant systems in planetary base scenarios. The ability of CoMANDRs to produce N_2 when operated in simultaneous nitrification/denitrification mode could provide cabin make-up gas. Biological stabilization via a CoMANDR directly addresses several current operational issues in wastewater treatment on ISS by minimizing volatiles due to NH_x conversion and pH reduction and removal of volatile organics in humidity condensate, which reduce the efficiency of the post processors. Removal of the organic carbon in the wastewater minimizes regrowth potential in downstream tubing and orifices. The CoMANDR technology provides a sustainable and robust treatment option with the flexibility and control to handle diverse operational parameters including intermittent operation and hibernation.

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