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A Two-Stage Biological Reactor for Treatment of Space Based Waste Waters

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Previous works on Membrane Aerobic Biological Reactors (MABR) CoMANDR 1.0, CoMANDR 2.0, and R-CoMANDAR have demonstrated their ability to stabilize various space based waste streams over operating periods of ~1 year. Biological pretreatment by MABR systems can stabilize space based waste streams. Biological stabilization includes reducing the pH, conversion of organic N to NO_x^- and oxidation of dissolved organic matter to CO_2. These processes produce a more stable waste product (brine), facilitate the distillation processes, and enable evaporative or membrane based systems. An alternative to aerobic operation would be to include anoxic operation to promote denitrification and production of N_2 gas. This results in a reduced O_2 demand and increases ammonia oxidation efficiency. Denitrifictaion can be accomplished in either a single reactor (Simultaneous Nitrification Denitrification) or in a two-stage system with separate aerobic and anoxic reactors. We evaluated the performance of both architectures in pilot scale systems (1-2 crew/d). Each system was continuously operated for over 2 years during which they processed a variety of habitation waste streams (ISS, Transit, and EPB) in both a continuous and on production feed mode. Here we report the results of the two stage system. Results indicate that the two stage system can successfully remove organic carbon, lower pH and convert organic N to N_2 gas. Organic carbon and organic N oxidation reaction rates for the two stage system are similar to past studies for single stage aerobic systems. The two stage system is more complex and requires an additional pump. While no maintenance was required on the system during the nearly two year period of operation, the packed bed did produce N_2 gas for many operational test points. The performance and comparison of operational conditions are detailed below.

Nomenclature

MABR = Membrane Aerated Bioreactors
CoMANDR = Counter Diffusion Membrane Aerated Nitrifying Denitrifying Reactor
HC = Humidity Condensate
ISS = International Space Station
EPB = Early Planetary Base
C = Continuous
P = Pulse
N = Nitrogen

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N_2 = Nitrogen gas
NO_2^-& NO_3^-=Nitrate and Nitrite species (aqueous)
NH_3 = Ammonia (aqueous)
TN = total nitrogen
DOC = dissolved organic carbon
SNDN = Simultaneous Nitrification Denitrification
DO =Dissolve Oxygen
OD = Outer Diameter

I. Introduction

Development of life support systems to provide the requirements for space habitation is necessary as the National Aeronautics and Space Administration (NASA) is expanding the presence of humans in space[1]. Water accounts for 65% of the daily mass input per crew member and is a critical factor in these systems[2]. As such, much effort and research has been employed in order to provide technologies capable of producing reliable reused water. Chemical pretreatment, desalination and post processing technologies developed for the International Space Station (ISS) have an overall water recovery efficiency which currently does not exceed 90%, a key goal for sustainable habitation outside low Earth orbit. Higher water recovery can result in eliminating mission dependence on resupply by regenerating water from waste streams. The ISS waste stream consists of pretreated urine, flush, and humidity condensate which has a loading rate of ~6.9 L/d per crew member. As future missions have longer habitation periods, shower, laundry, and hygiene (e.g. handwash, shave, oral) may be added to the ISS waste stream and the total waste volume could increase to ~14 L/d per crew member. The Early Planetary Base (EPB) wastewater has a lower influent carbon and nitrogen concentration (~600 mg-C/L and ~700 mg-N/L) than the ISS waste stream (~2200 mg-C/L and 3000 mg-N/L)/ although the influent loading is similar. Inclusion of more diverse waste streams and larger wastewater volumes will require changes to the current ISS wastewater recycling process.

Biological treatment systems can provide more sustainable water recovery. Biological treatment has significant advantages including low cost, transformation of organic matter to produce more stable effluent, conversion of organic N to N_2 gas or NO_x^-, and a reduction in pH which is important in desalination processes to prevent precipitation and NH_3 volatilization. Organic N oxidation or nitrification (conversion of NH_4^+ to NO_2^- and/or NO_3^-) plays an important role as it reduces NH_3/NH_4^+, producing more stable and easier to remove products (NO_2^- and NO_3^-) that can allow for conversion of NO_2^- and NO_3^- to N_2 gas and producing of H^+ which lower pH of system.

Different configurations of biological water treatment processes have been studied for more than 20 years. Membrane Aerated BioReactors (MABRs) have been a focus, as they can achieve desired levels of waste water treatment and can be operated in a gravity independent manner. The membrane surface of MABRs allow biofilm attachment and the electron acceptor (O_2) can be transferred from the base of biofilm without two phase flow. Previous studies have demonstrated bioreactors can treat space-based waste streams successfully. MABRs have been evaluated in single reactor systems operating in aerobic conditions. Some studies investigated two reactor systems including a pre-anoxic reactor to convert NO_x^- to N_2 driven by carbon oxidation and a second reactor to convert ammonium to NO_x^- [3,4]. However, production of N_2 gas in a packed bed requires that the bed be pressurized and that the gas be stripped from solution in order to prevent bubble formation.

As part of a larger ongoing study, we evaluated a pilot scale (1-2 crew), two stage system consisting of a MABR in combination with a packed bed reactor. We studied performance and rates of C and N removal for treatment of ISS, EPB, and Transit waste streams. We also evaluated the impact of continuous or on production feeding (waste water fed directly to the system as it is produced) on system performance.

II. Methods

A. Reactor characteristics

A two-stage system includes a membrane bioreactor and a packed bed. The MABR has overall dimensions of **L= 81cm**, **W= 44cm**, and **H= 40 cm** and a total volume of **0**.14 m^3 (**Figure 1**). It consists of a liquid compartment (0.11m^3) and two air plenums (0.006m^3 each) on opposite sides of the reactor that are connected by 1552 siloxane tubes (**OD=0.55cm**) which pass from one plenum through the liquid compartment and into the opposite plenum. There is an inlet and outlet zone at each end of the liquid compartment that is separated from the membrane section by baffle walls to distribute flow. The liquid flow enters and exits through two 2.54cm ports in each zone. The inlet and outlet are connected by a recycle line (2.54cm) and centrifugal pump (~4 l/min). There is a HACH Hydrosonde multi-probe for online measurements of DO, pH, TDS, and temperature located in the recycle line. The inlet air header is supplied by compressed gas cylinders (O_2 and air) and the flow rates of each gas controlled by mass flow controllers. The packed bed is connected to the recycle line using a peristaltic pump which pulls water from the recycle line and pumps it to the PB, which allows the recycle flow to the PB to be independently controlled. The packed bed is an acrylic cylinder with dimension of 25cm in OD and 85cm long. Wastewater(s) is pumped into the PB reactor using a peristaltic pump(s). Effluent from the packed bed is displaced into the recycle line on the suction side of the recycle pump. Effluent is displaced from the outlet zone on the MABR. Both systems operate at elevated pressure (5-10 PSI) with the packed bed liquid pressure 1-2 PSI greater than the MABR. The gas headers also operate at above ambient pressure (2-4 PSI). Gas was supplied by oxygen and/or air tanks and the flow controlled by mass flow controllers.

B. General operation

Two-stage bioreactor operation requires supplying daily influent. The feed recipe depending on waste stream included urine, flush, hygiene, HC, shower, and laundry. The composition and rate of feeding is based on previous studies[5] but is reproduced here for clarity. In this study, we used donated urine and increased the volume produced per crew member and reduced the flush water in order to simulate the more concentrated urine on ISS. Laundry was produced using an ultralow volume washing machine and washing soiled clothes with a detergent (7th Generation). Other waste streams (Hand Wash, Shaving, Oral rinse, Shower) were prepared using published ersatz recipes or by volunteer donation using approved products (Arm and Hammer Toothpaste, Neutrogena Shaving cream, No-Rinse Shampoo)[6]. The reactor was challenged with two feeding modes (continuous or on production feeding). Continuous feeding includes an influent tank that contains all components and the waste water is pumped to the reactor continuously. On production feeding is based on pumping produced waste directly to the reactor as it is produced. Details on schedule and volume of on production feeding waste stream have been described in detail elsewhere[7] but the number of events and volume of each event are detailed in Table 1.

Table 1. Composition and input mode and rate for all test points.

Waste Stream and Mode	**Loading Rate (L/C-d)**							**Total Flow (L/C-d)**
	U +F	**Hygiene**				**Laundry**	**HC**	
		O	**HW**	**S**	**SH**			
	1.8	**0.2**	**0.95**	**6**	**.075**	**3.75**	**1.95**	
	Input Rate: C=Continuous (l/C-d)); P=Pulse (Number of events (E) per time period per day)							
ISS-C	C						C	3.75
ISS-P	6 P/16 hr						C	3.75
Transit-P	6 P/16 hr	2 P/16hr (t=0,16hr)	6 P/16 hr	2 P/16hr (t=0,16hr)	2 P/16hr (t=0,16hr)		C	11.0
EPB-P	6 P/16 hr	2 E/16hr (t=0,16hr)	6 P/16 hr	2 P/16hr (t=0,16hr)	2 E/16hr (t=0,16hr)	1 E/d (t=0)	C	14.7
EPB-C	C	C	C	C	C	C	C	14.7

U=Urine; F = Flush; O= Oral Hygiene; S= Shower; SH = Shaving; HW= Hand Wash

C. Test points

The system was challenged with 3 waste streams (EPB, Transit, and ISS) for 2 loading conditions (continuous and on-production) (**Table 2**). All test points evaluated a 2 crew-d loading rate except one test point that evaluated 1 crew-d loading rate. Some test points were used to evaluate the impact of recycle flow to the packed bed on performance and N_2 generation. Treatment of transit waste water was only evaluated for continuous feeding and results of on production feeding for treatment of EPB wastewater are not yet available.

D. Data Analysis

An online monitoring system measured pH, temperature, DO, and TDS. Effluent gas O_2 and CO_2 concentration was monitored by a Quantek 902P analyzer. As all influent components are mixed in continuous feeding, influent was sampled from the feed tank for analysis. During on production feeding a fraction of each component was sampled and mixed proportional to its volumetric contribution to the total daily feed of the reactor. An effluent sample was directly collected from the effluent tank. After filtering (0.2 µm), influent and effluent samples were analyzed for total organic carbon (TOC) and total nitrogen (TN) using a Shimadzu TOC/TN analyzer. NH_3 was analyzed using a HACH ammonia probe. NO_2^- and NO_3^- were analyzed using a Dionex Ion Chromatograph.

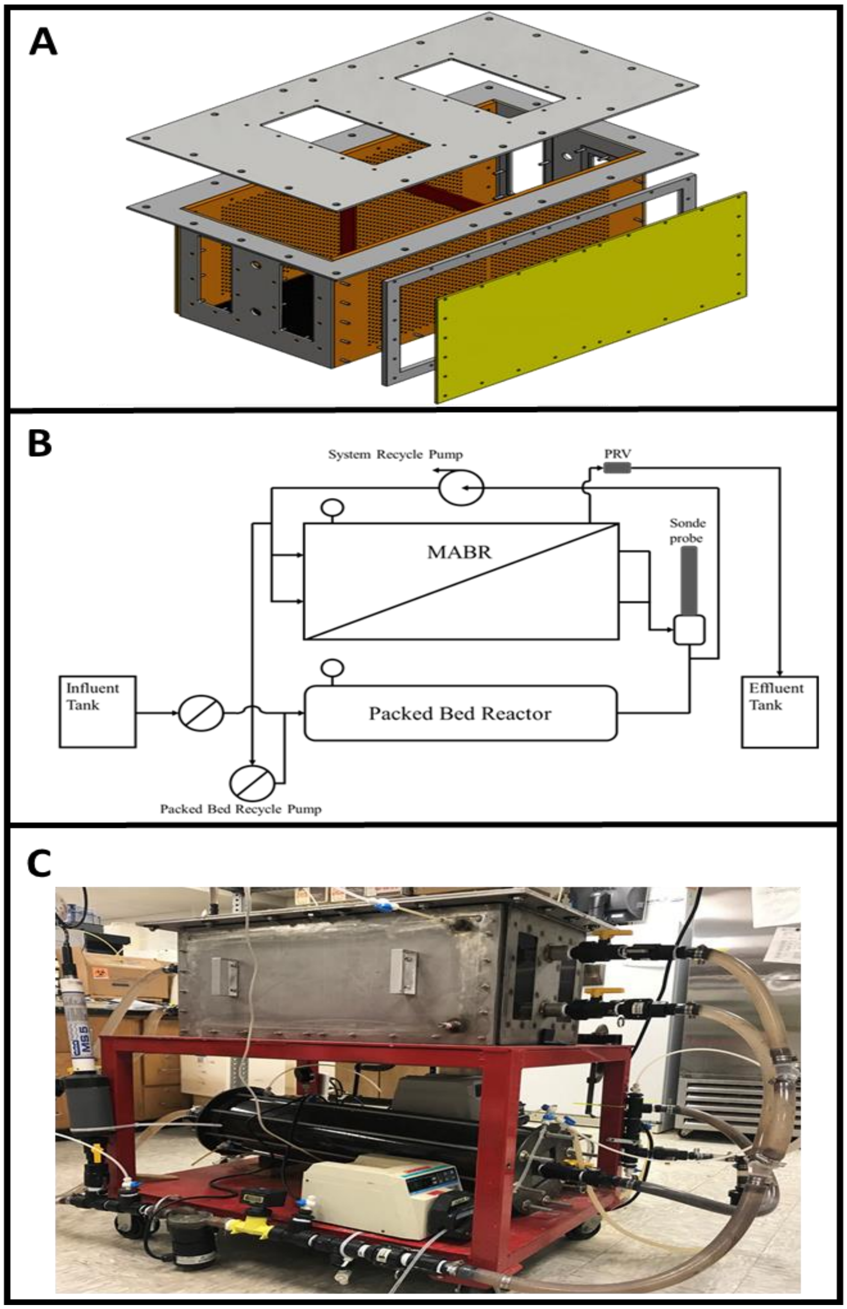

Figure 1. Two-stage MABR system, “A) design of Aerobic zone,” “B) Flow diagram of system,” “C) system operation in the lab”

Table 2. Summary of test points conducted. (C=continuous feed and P= on production feed)

Date	Waste Stream	Feeding Mode	Days Operated	Loading	Recycle flow (L/d)	Volume Treated (L)
07/26/2016	EPB	C	35	2 C-d (28.5 L/d)	30	855
08/30/2016	EPB	C	20	2 C-d (28.5 L/d)	60	570
09/19/2016	EPB	C	6	2 C-d (28.5 L/d)	120	171
09/25/2016	EPB	C	15	1 C-d (14.25 L/d)	120	213.75
10/11/2016	EPB	C	27	2 C-d (28.5 L/d)	120	769.5
11/07/2016	EPB	C	52	2 C-d (28.5 L/d)	346	1482
01/02/2017	ISS	C	39	2 C-d (6.9 L/d)	346	269.1
02/10/2017	ISS	C	80	2 C-d (6.9 L/d)	461	552
05/01/2017	ISS	P	39	2 C-d (6.9 L/d)	461	269.1
06/09/2017	ISS	P	23	2 C-d (6.9 L/d)	230	158.7
07/02/2017	ISS	P	11	2 C-d (6.9 L/d)	310	75.9
07/13/2017	Transit	P	40	2 C-d (21 L/d)	461	840
08/22/2017	Transit	P	56	2 C-d (21 L/d)	576	1176
11/11/2017	EPB	C	37	2 C-d (28.5 L/d)	576	1054.5
12/18/2017	Hibernation					
01/08/2018	EPB	C	49	2 C-d (28.5 L/d)	576	1396.5
02/26/2018	EPB	P		2 C-d (28.5 L/d)	576	In progress

III. Results

The two-stage system (separate aerobic and anoxic reactors) has operated for almost two years. Over this time, fifteen test points have been completed and one is ongoing. The two-stage reactor has treated more than 9,000 liters of various habitation waste streams. Test points varied due to waste stream (ISS, Transit, and EPB wastewater), feeding regime (continuous or pulse), and recycle flow. Change in recycle flow were mainly driven by either the desire to increase TN removal or to prevent N_2 gas accumulation in the packed bed. We evaluated the removal of C and N, oxidation of organic N, pH and mass loadings for each test point to determine the rate and efficiency of the overall treatment processes for each variable. As the main source of TOC and TN is urine and the volume fraction of wastewater from non-urine sources varied by waste stream, concentrations of DOC and TN and volume treated per day for each waste stream vary (**Table 3**).

A. Treatment of EPB Wastewater

Carbon oxidation-At the time of writing the evaluation of the on production mode of feeding was being completed and so only test points evaluating EPB continuous feed are available. Flow rate (28.5 L/d) was constant for all EPB test points (2 crew/d) except one test at 1 crew/d (14.25 L/d). Recycle flow varied from 30-576 L/d. DOC removal for continuous treatment of the EPB waste stream generally increased with the increase in recycle flow rate. DOC removal approached 90% for recycle flows greater than 120 L/d and varied only slightly 76-82% for lower recycle flows (**Figure 2**). DOC influent concentrations ranged from 520-700 g/m^3 and effluent DOC ranged from 70-150 g/m^3 (**Table 3**). Increasing recycle flow rate from 30-576 L/d resulted in lower DOC concentrations in the effluent.

Organic N oxidation- Organic N oxidation was generally greater than 70% with the exception of two test points (Flow = 2 crew/d and recycle ratio of 120 L/d and flow = 1 crew/d) (**Figure 2**). Two test points with the same flow rate (1 crew/d) and recycle flow (120 L/d), produced very different N oxidation efficiencies (46 and 72%), which could be related to an unusually low TN influent concentration (<600 g/m^3) compared to other EPB test points (>600 g/m^3). It should be noted that both the 1 crew/d and first 2 crew/d test point (120 L/d recycle) were conducted for a very short period (< 2 weeks) and so were unlikely to be at steady state. Changes in influent are due to collecting urine from a large group of donors and occasional supplements with synthetic urine on weekends and holidays when insufficient urine was donated. DO concentrations in the MABR were >6mg/l and the pH ranged from 5-7 with no relation to recycle ratio (**Figure 2**).

N Removal- N removal ranged from ~40-48% with two exceptions. The highest removal (51-58%) occurred at the highest recycle ratios and corresponded to higher DOC removals. The only test point with TN removal less than 40% was the same test point that had low DOC removal and the lowest organic N oxidation efficiency. This test point (2 crew/d and 120 L/d recycle flow) was characterized by the lowest influent DOC and TN concentrations.

B. Treatment of Transit wastewater

We only evaluated the Transit waste stream for on production feeding (feeding directly to the reactor) and for two recycle ratios (461 and 576 L/d). DOC removals were similar and ranged from 89-94% (**Figure 3)** with low effluent DOC concentrations (<100 g/m^3) (**Table 3**). Organic N oxidation was similar to the lower range for EPB waste water (65% to 71%). Total N removal was similar for both recycle flow rates (55%) and near the upper end of the EPB test points.

C. Treatment of ISS wastewater

Carbon oxidation- In treating ISS wastewater, both continuous and on production feeding were evaluated. The flow rate was constant in all tests (2 crew/d (6.9 L/d)) and recycle flow varied from 230-461 L/d in on production feeding and ranged from 346-461 L/d in continuous feeding mode. For continuous feeding, DOC removal was greater than 90% for all recycle flow rates and both feed modes (**Figure 4**). Effluent DOC was generally <100 g/m^3 (**Table 3**). There was no apparent impact from the feed mode on performance.

Organic N oxidation- Similar to organic C oxidation, N oxidation efficiency (71-78%) was on the upper end of those observed with no clear relation to recycle flow and a weak relationship for feed mode with on production feeding, producing slightly higher efficiencies (**Figure 4**). The pH for all ISS test points was less than or equal to 6 which were generally the lowest observed.

N Removal- for both continuous and on production feeding mode N removal ranged from 40-60% and decreased as recycle flow increased. Highest removal occurred for on production (60%) feed mode possibly due to the low recycle ratio.

Table 3. Overview of influent and effluent water quality data

Waste Stream	Mode	Recycle flow (L/d)	C/d	Q (L/d)	Volume Treated (L)	Concentration (Standard Deviation)							pH
						Influent (mg/L)		Effluent(g/m^3)					
						DOC	TN	DOC	TN	NO_x^-	NH_4^+	DO	
EPB	C	30	2	28.5	855	614.2(119)	683.1(146)	121.4(27)	391.1(29)	260.7(64)	162.4(54)	12(3.8)	6.2 (0.9)
EPB	C	60	2	28.5	570	656.3(113)	709.8(102)	156.5(49)	376.0(22)	190.8(19)	244.8(50)	10(3.4)	6.4(0.3)
EPB	C	120	2	28.5	171	615.9(140)	669.9(122)	108.5(17)	353.5(17)	176.1(20)	206.5(46)	14.8(3.5)	5.8(1.1)
EPB	C	120	1	14.25	213.75	666.7(59)	724.6(41)	131.5(23)	368.8(13)	127.5(30)	246.0(17)	13.7(4.8)	7.3(0.2)
EPB	C	120	2	28.5	769.5	525.4(76)	563.5(93)	113.5(18)	435.6(24)	139.6(12)	358.0(110)	6.2(1.7)	6.9(0.2)
EPB	C	346	2	28.5	1482	584.7(56)	649.4(70)	66.7(21)	357.2(73)	162.3(54)	260.9(107)	6.3(4)	6.1(0.4)
EPB	C	576	2	28.5	1054.5	672(129)	827.2(131)	83.0(27)	398.0(39)	223.0(40)	326.0(84)	6.6(2.8)	5.2(0.6)
EPB	C	576	2	28.5	1396.5	700(120)	834.0(109)	74.0(17)	357.0(44)	196.3(38)	241.0(89)	6.7(5.7)	6.1(0.5)
Transit	P	461	2	21	840	972.5(355)	1477.5(653)	50.5(7)	594.0(104)	200.0(93)	605.0(100)	0.48(0.8)	6.2(0.7)
Transit	P	576	2	21	1176	721(167)	1005.6(220)	75.0(26)	433.5(168)	98.2(53)	222.2(64)	0.9(1.3)	6.2(0.5)
ISS	C	346	2	6.9	269.1	3027.1(706)	3159.8(505)	78(14)	1538.7(228)	621.2(104)	681.0(127)	5(3.7)	6(0.2)
ISS	C	461	2	6.9	552	2341.7(343)	3046.6(439)	135.4(44)	1881.1(339)	1005.7(109)	1027.1(156)	5(3.4)	5.6(0.3)
ISS	P	461	2	6.9	269.1	2200(262)	2928(373)	73.0(9)	1718.0(104)	939.0(118)	1105.5(127)	4(3.5)	5.5(0.4)
ISS	P	230	2	6.9	158.7	2646.3(371)	4168.2(267)	70.8(18)	1914.5(186)	1009.4(193)	1423.1(156)	1.8(3.8)	6.1(0.6)
ISS	P	310	2	6.9	75.9	2588.0(727)	3612.2(1169)	59.8(10)	2180.0(110)	1294.0(151)	1588.0(155)	2.9(2.7)	5.2(0.6)

Table 4. Overview of influent and effluent loading rates, transformation and reaction rates for all test points

Waste Stream	Mode	Recycle Flow (L/d)	C/d	Loading (g/d)					Percent Transformation (Standard Deviation			Reaction Rate (g/m^3-d)		
				Influent		Effluent			DOC	N Oxidation	N Removal	DOC	N Oxidation	N Removal
				C	N	C	N Total	Organic N						
EPB	C	30	2	17.5	19.5	3.5	11.2	4.7	80(6)	75.2(7.5)	40.4(12.4)	90.5	94.8	47.6
EPB	C	60	2	18.7	20.2	4.5	11.2	5.3	76(7)	74(5)	46(70	103.5	108.6	71.1
EPB	C	120	2	17.6	19.1	3.1	10.1	5.1	82(5.2)	72.6(7.9)	46.1(9.4)	105.1	102.0	65.5
EPB	C	120	1	9.5	10.3	1.9	5.3	3.4	80(1.80	66.7(0.4)	494.7)	55.4	50.1	36.9
EPB	C	120	2	15.0	16.1	3.2	13.3	8.4	78(7)	46(10)	21(13)	85.3	55.4	26.5
EPB	C	346	2	16.7	18.5	1.9	10.2	5.6	88(40	69.6(10)	44.5(120	107.3	94.1	60.5
EPB	C	576	2	19.2	23.6	1.7	12.5	5.4	88(3)	77(5)	51(7)	126.6	157.0	110.9
EPB	C	576	2	20.8	23.1	2.0	8.4	4.4	89(3)	80(4)	57(70	129.6	139.5	98.8
Transit	P	461	2	20.4	31.0	1.1	20.3	8.3	94(2)	71(10)	55(18)	140.7	165.4	134.8
Transit	P	576	2	15.2	21.1	1.6	9.1	7.0	89(4)	65(160	55(19)	98.7	102.3	87.3
ISS	C	346	2	20.9	21.8	0.5	8.5	6.3	97(1)	71(5)	51(7)	109.9	112.4	81.3
ISS	C	461	2	16.2	21.0	0.9	13.0	6.4	94(2)	71(12)	37(15)	107.2	104.4	54.0
ISS	P	461	2	15.2	20.2	0.5	11.9	7.0	97(1)	73(5)	40(9)	106.7	107.8	60.7
ISS	P	230	2	18.3	28.8	0.5	13.2	6.1	98(1)	78(12)	59(15)	129.5	163.1	122.6
ISS	P	310	2	17.9	24.9	0.4	15.0	5.4	98(1)	73(8)	34(23)	126.8	136.7	71.8

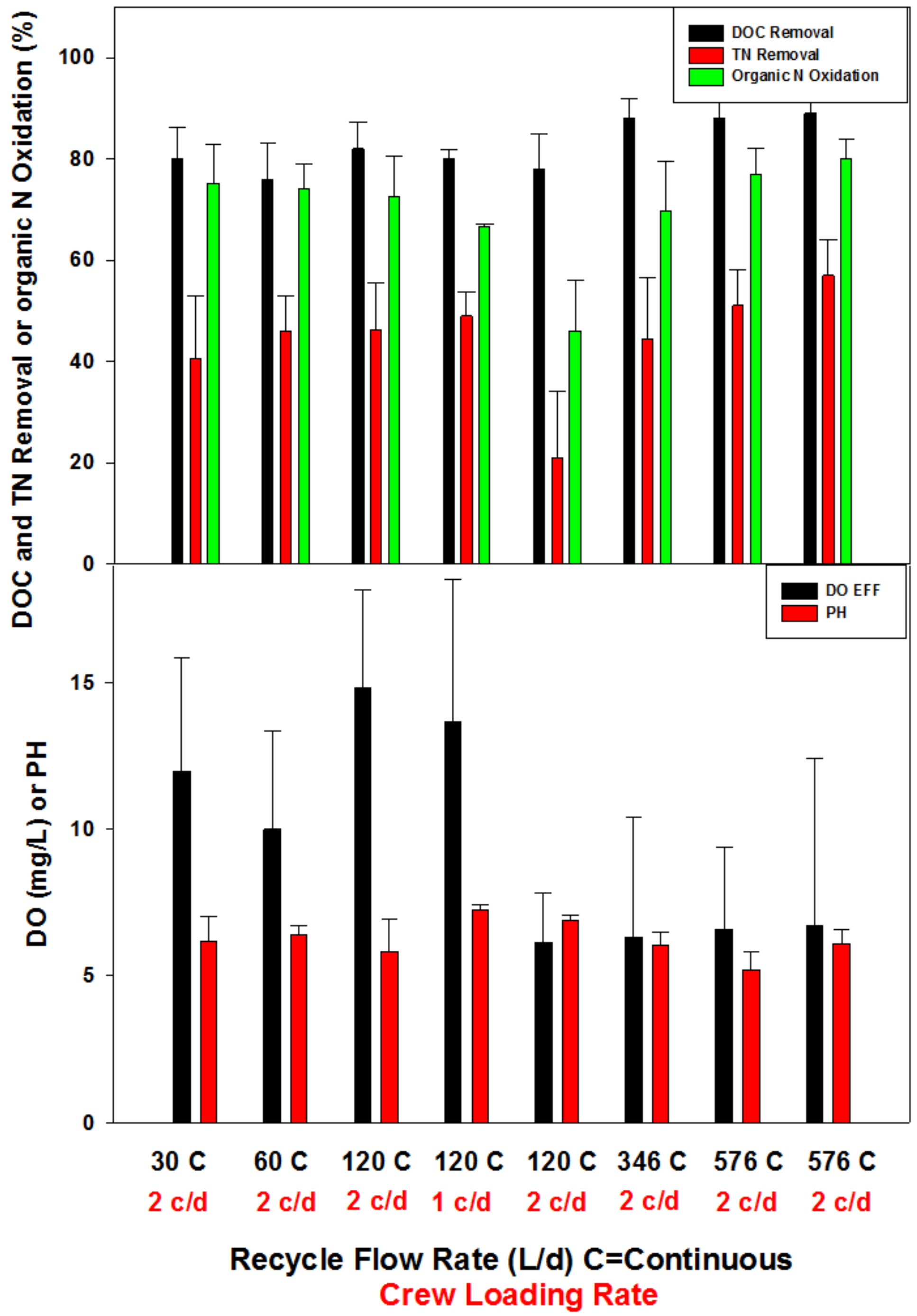

Figure 2. Transformation of carbon and N and organic N oxidation for EPB waste stream on continuous feeding for different recycle flow and loading rate conditions

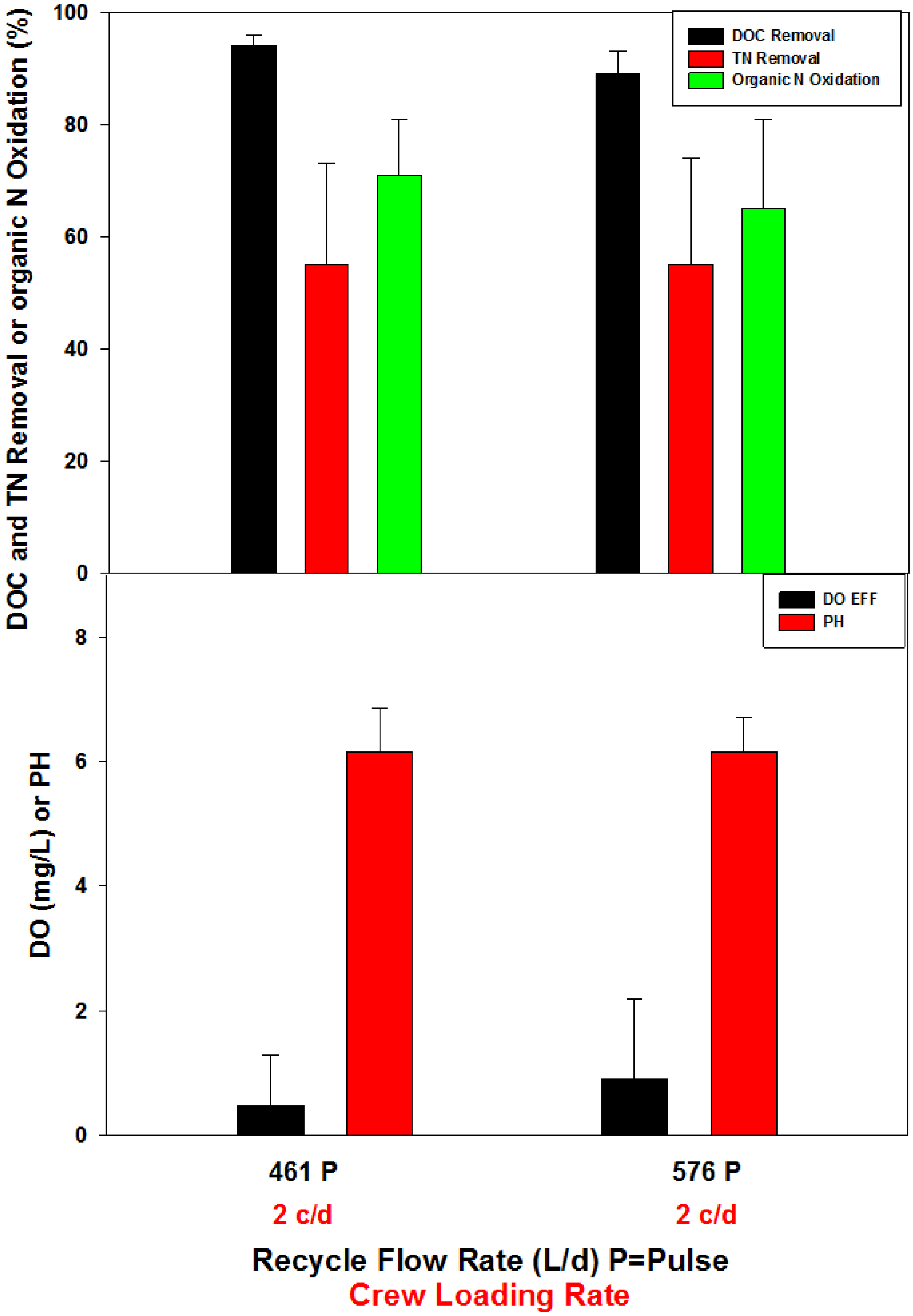

Figure 3. Transformation of carbon and N and organic N oxidation for Transit waste stream for on production feeding for different recycle flow and loading rate conditions

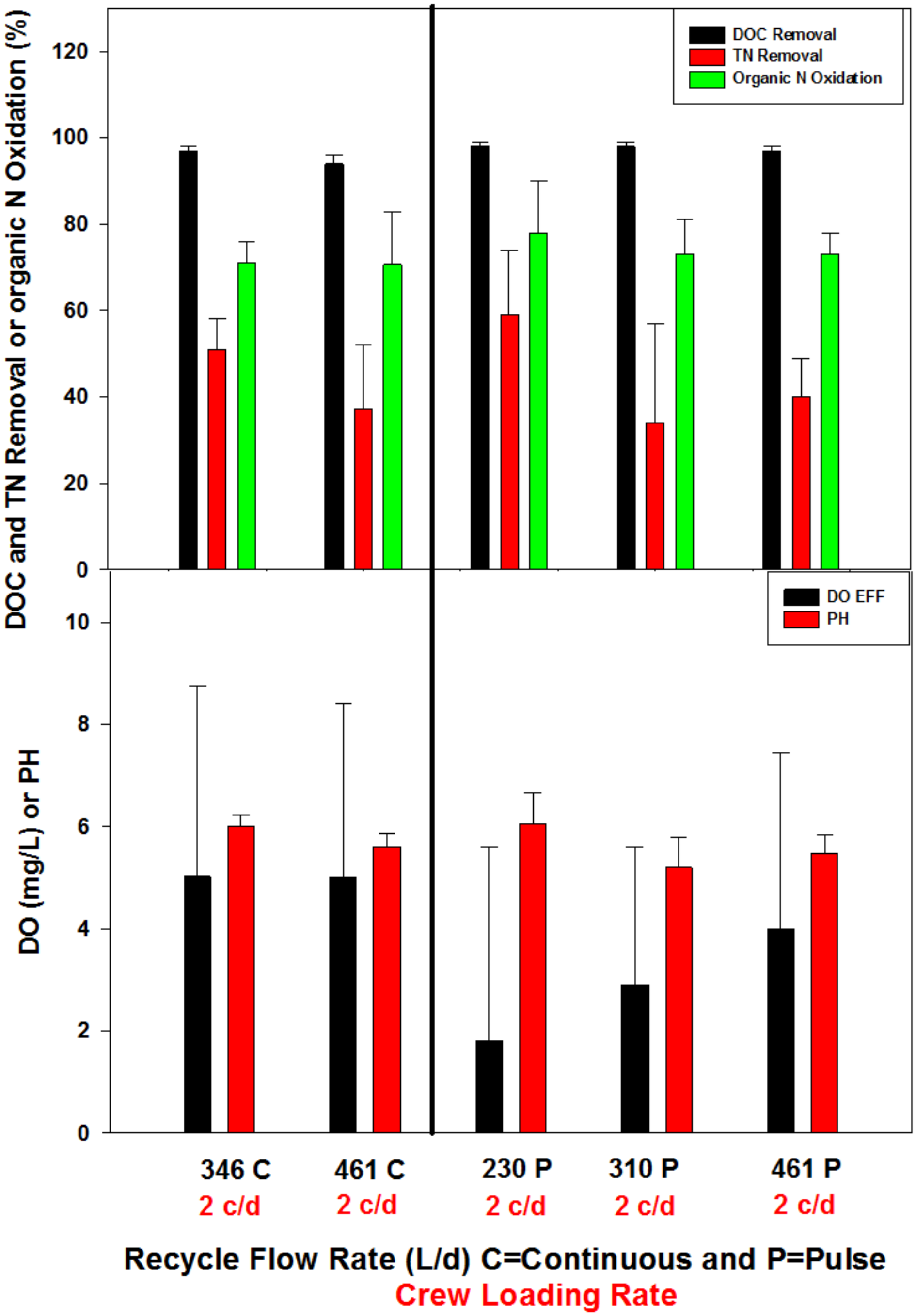

Figure 4. **Transformation of carbon and N and organic N oxidation for ISS waste stream for continuous and on production feeding for different recycle flow and loading rate conditions**

D. Loading and Reaction Rates

Carbon Oxidation- DOC influent loading rates ranged from ~15-20 g/d for all test points (EPB, ISS, and Transit) excluding one test point conducted at a loading of 1 crew-d. Similarity in loading given the more than two fold difference on volumetric flow rates is due to the urine, which dominates the C and N mass loading and is present in all waste streams. Effluent loading rates were generally very low (<2 g-C/d) for recycle ratios greater than 120 L/d. Recycle ratio impacted effluent loading at low flow rates and to a lesser extent at the highest flow rate. Effluent loading for treatment of EPB waste water was always greater than Transit or ISS recycle effluent loading, regardless of recycle ratio or influent loading. Although the organization of the data in Figure 5 appears to indicate that effluent loading decreased with subsequent test points, it should be noted that the test points were not conducted in this order (Table 3). Excluding test points with recycle ratios less than 230 L/d, volumetric DOC transformation rate ranged from ~100-130 g/m^3-d for all waste streams and all recycle ratios. Recycle flow rate did not appear to consistently impact reaction rate but reactions rates were generally higher for test points with higher C influent loadings. This suggests that the system is not rate limited for C oxidation. Carbon oxidation rates are similar but on the lower end of previously reported rates for pilot scale single stage MABRs treating EPB or ISS waste water at for a 2 crew-d volumetric load[8].

Organic N Oxidation- Influent N loading rates ranged from 16-31 g N/d for all 2 crew-d test points (EPB, Transit, and ISS), although all but three represented a smaller range of values (16-25 g-N/d). Influent N loading was similar between waste streams for reasons discussed above (e.g. urine contribution). Organic N effluent loading rate ranged from 2-8 g-N/d for all test points with no relation to recycle flow or influent N loading. Effluent N loading was slightly lower for EPB test points. There was also no effect of feeding mode on effluent N loading. With one exception (lowest influent N loading rate), the range of volumetric reaction rates (90-165 g-N/m^3-d) were similar for all waste streams, recycle flow rates, and feed modes for a 2 crew/d volumetric load. The higher range of reaction rates appear mainly to be due to higher influent organic N loadings, suggesting that the system can accommodate higher N loading rates as effluent N loadings did not relate to influent loadings. Volumetric reaction rates are very similar to rates from past studies on pilot scale single stage MABRs treating similar waste streams at a 2 crew-d load [8,9].

Total N Reduction- Influent N loading was previously discussed. In contrast to organic N effluent loading (excludes NO_2^- and NO_3^-), total N effluent loading was higher reflecting the contribution of NO_2^- and NO_3^-. Excluding one outlier with very high influent N loading, effluent total N loads for all 2 crew-d test points regardless of waste stream, recycle ratio or feed mode ranged from 8-15 g-N/d. Nitrogen removal rates (50-135 g-N/m^3-d) were lower than C oxidation rates but the ratio of C/N removal rates ranged from ~0.5 to nearly 1, reflecting the variation in C removal due to oxidation by O_2 rather than NO_x^-. There was a weak relation (r^2=0.44) between influent C loading and N reduction rate but a much stronger relationship (r^2=0.77) between organic N influent loading rate and N removal rate. Given that N removal is driven by carbon reduction and the observation that NO_x^- was available for reduction for all test points, the stronger relationship between N removal rate and N influent loading may reflect the impact of O_2 availability in the biofilm. N oxidation requires more O_2 per gram oxidized than organic C and elevated influent N loadings may have reduced O_2 availability allowing increased N removal.

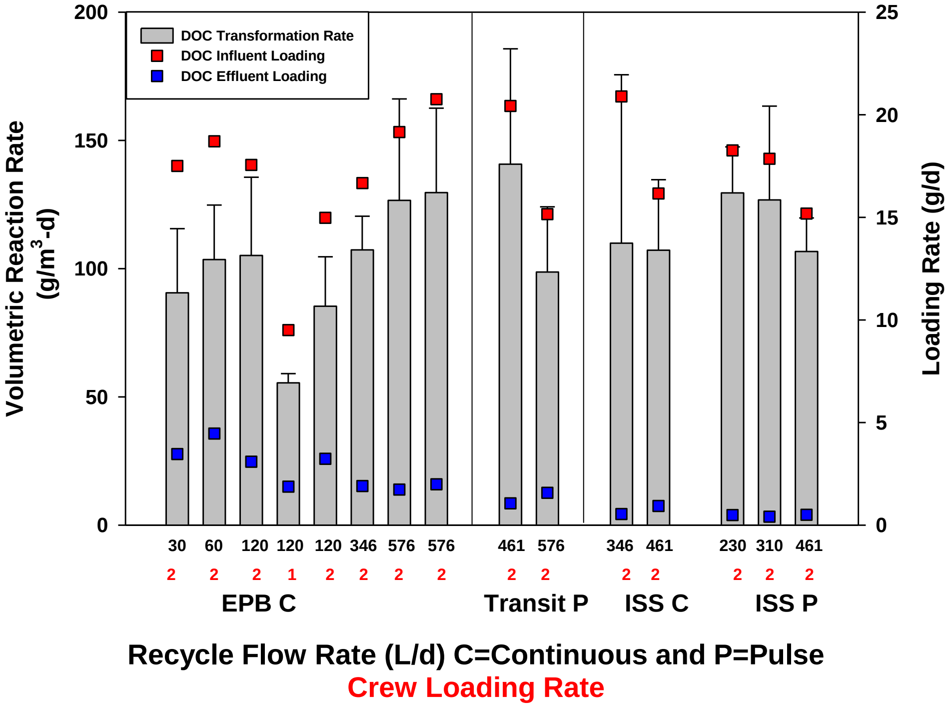

Figure 5. Volumetric reaction rate for carbon oxidation vs. influent and effluent loading rate for all test points

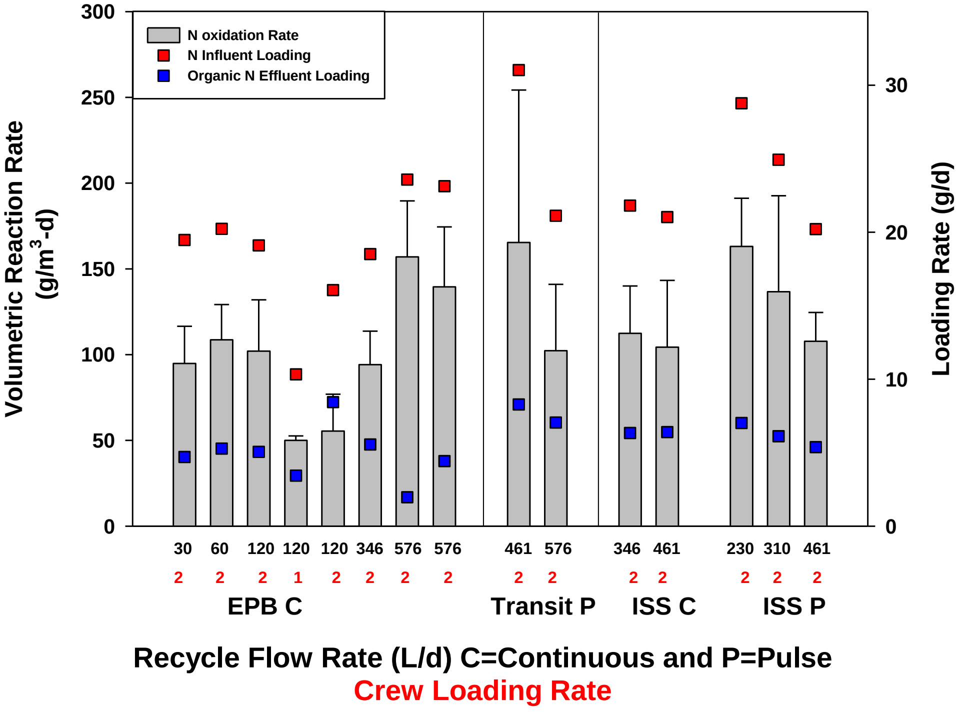

Figure 6. Volumetric reaction rate for N oxidation vs. influent and effluent loading rate for all test points

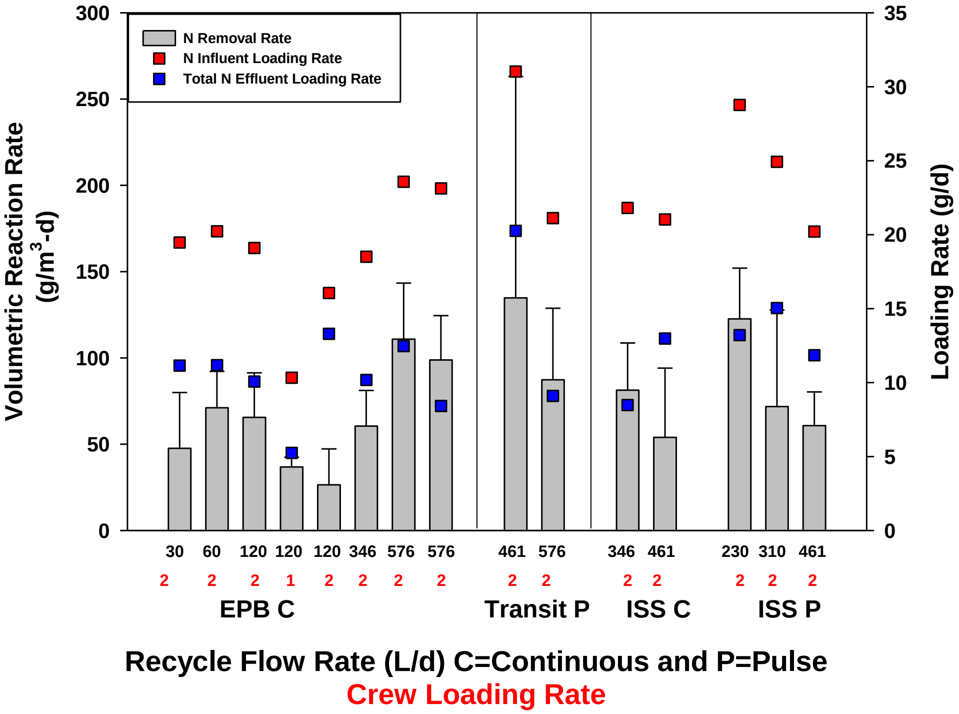

Figure 7. Volumetric reaction rate for N removal vs. influent and effluent loading rate for all test points

E. Peripheral Operation Issues

Treatment efficiency and rate of treatment are not the only issues that impact evaluation of biological reactors in life support systems. Operational issues are also important. The two-stage system rCoMANDR-PB was operated for almost 2 years. During that time no maintenance was performed on any part of the system excluding the in-line sensors and peristaltic pump tubing. The system is defined as everything downstream of the influent pump to the effluent tank. For instance, no recycling tubing or effluent tubing was changed or cleaned, the recycle pump was not cleaned or replaced, and no solids were removed from the reactor. One issue that was a consistent problem was build-up of gas in the packed bed reactor. While not reported here, low recycle ratios often led to increased gas build-up. It is possible that at higher pressures (>7 PSI), the N_2 would not have exceeded the bubble point. Past studies have been conducted as pressures as high as 25PSI, although operating at elevated pressures can produce other issues in terms of reactor operation. We also conducted one hibernation test lasting for 3 weeks in which the system was placed on recycle with a minimal air flow (~50ml/min). After hibernation period the system resumed treatment at the full pre-hibernation flow rate within 0-5 days.

IV. Conclusion

Overall, the two stage system appears to be a viable configuration for treatment of habitation wastewater. Once the current study is complete, the performance of the system will be compared to results from a single stage system which evaluated treatment of the same waste streams under oxic and anoxic conditions. Performance and sizing will need to be contrasted with system complexity and reliability. The 2 stage system may be overly complex for micro-gravity operation where N_2 production in the packed bed may be an unwarranted risk, while for an EPB gas generation would be less of an issue. Also not included in this paper are results of effluent stability testing and distillation testing. These tests evaluated the growth potential of treated wastewater and the quality of distilled wastewater as well as the potential recovery without solids formation.

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