Treatment of Simulated Shipboard Gray Water in a Lab-Scale Membrane Bioreactor

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December 2005

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **DEC 2005**	2. REPORT TYPE	3. DATES COVERED **00-00-2005 to 00-00-2005**

4. TITLE AND SUBTITLE **Treatment of Simulated Shipboard Gray Water in a Lab-Scale Membrane Bioreactor**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Coast Guard Academy ,31 Mohegan Avenue ,New London ,CT,06320-8103**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**31**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Acknowledgments

This project was made possible by funding from the U.S. Coast Guard Engineering Logistics Command (ELC) in Baltimore, MD. We appreciate the invaluable technical support and advice provided by Mr. Hari Bindal of ELC and LTJG Andy Goshorn at CG Headquarters. In addition, we are very grateful for the technical expertise and sludge provided by Mr. Steve Banks of the Highlands Wastewater Treatment Facility in Ledyard, Connecticut. We also thank Mr. Kevin Cini and Mr. Jim Bowdy of the Groton WPCF for their technical advice and for the use of their microscopy equipment. We extend our thanks to Mr. Steve Grenier of CGA for his advice and assistance in laboratory procedures, reactor modification, and procurement. We thank Bill and Kathy Georgian of KB Analytical for their expert sample analysis and technical advice. We appreciate Bernie Mack of Ionics, inc. for promptly providing advice and a new filter curtain to get our system up and running after some initial difficulty. Rachel Jacobs of NAVSEA Carderock provided invaluable advice on reactor seeding and start-up. We are also grateful to the Coast Guard cutter personnel who took time from their busy schedules to provide shipboard wastewater flow rate data.

We also extend many thanks to the shipboard wastewater capstone project students from the CGA classes of 2001, 2002, 2003, and 2004. Their creative ideas and hard work helped pave the way for this year’s project.

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Executive Summary

The Coast Guard is challenged to operate its fleet of ships in an environment of increasingly stringent shipboard wastewater discharge standards. Under the Uniform National Discharge Standards (UNDS) now in development, standards will be set for several non-sewage discharges from ships including gray water. Shipboard generated gray water contains high levels of typical wastewater pollutants including biochemical oxygen demand (BOD), total suspended solids (TSS), total nitrogen (TN), and total phosphorous (TP). Since gray water is typically produced at rates much greater than that for black water, ships will have very limited capacity to store untreated gray water when operating in regulated waters.

The U.S. Coast Guard Academy has been involved in a multi-year project supported by Engineering Logistics Command to investigate the feasibility of treating shipboard black water and gray water in membrane bioreactors (MBRs). MBRs with submerged membrane modules are considered a promising wastewater technology for use aboard ships since significant treatment can occur in a small space and the use of a filter for solids separation eliminates the need for gravity separation which would be infeasible on a ship. In past years, a lab-scale MBR system was designed, constructed, and used for three successive years to treat shipboard gray water and black water in various combinations.

This report contains the results of an experiment conducted in Spring 2005 to treat simulated shipboard gray water in the lab-scale MBR for simultaneous removal of BOD and TN. Initially an experiment was performed to identify a recipe for shipboard gray water that most closely matches the composition of gray water from Coast Guard ships. The simulated gray water was treated for 29 days in a lab-scale MBR system, which consisted of an equalization tank, an MBR with submerged hollow fiber membranes, and a UV disinfection system. The reactor was operated in continuous flow mode with an effective hydraulic retention time (HRT) of 34 days. The aerators, which were built into the membrane filter assemblies, were cycled on and off (two hours on and one hour off per three hour cycle) to achieve removal of TN in a single tank. No effluent was permeated through the membranes during non-aeration periods to avoid fouling of the membranes. During aeration periods, permeate was drawn through the filters at a rate of 20 mL/min with the suction pump turned off for 2 minutes during every ten minute period.

The results show excellent removal of BOD, TN, TSS, and turbidity throughout the experiment. BOD removal started immediately, indicating an effective seeding and start-up protocol and a good environment for biological activity. Removal of TN was very effective indicating that the HRT and SRT and other reactor conditions were conducive to nitrification and denitrification in a single

tank. As expected with a well operating membrane filter, removal of TSS and turbidity was very effective. The following table shows the ranges of influent, effluent, and removal efficiencies for various parameters.

Pollutant Removal Efficiencies for
Shipboard Gray Water Treated in a Lab-Scale MBR (2005)

Pollutant	Avg. Influent Conc. (mg/L)	Avg. Effluent Conc. (mg/L)	Avg. Removal Efficiency (%)
BOD	361	9.62	97
Total Nitrogen	10.6	1.06	90
TSS	271	2.92	99
Turbidity	217	1.33	99

A full-scale MBR system with the same HRT and flow regime was designed to fit on a 225’ Juniper Class buoy tender. The full-scale system was designed to process 1500 gallons/day of gray water in 287 ft^3 of reactor space. Although the lab-scale system appears to fit in the available space of the buoy tender, it is unclear whether a full-scale system under shipboard conditions would achieve the level of treatment efficiency observed on a lab-scale.

The research results suggest that BOD and TN removal can be removed in a single MBR tank using a long HRT and by cycling the aerators on and off. Future testing should explore whether such treatment is achievable under actual shipboard conditions and whether a similar system could be used to treat a blend of gray water and black water in various ratios expected on ships. Future research should also focus on optimizing dissolved oxygen levels and aeration cycles and improved methods for monitoring microbial activity and population dynamics in the reactor. The reasons for poor TP removal should also be explored in future experiments. An MBR system capable of removing BOD, TN, and TP from shipboard wastewater would be most protective of the environment and likely to meet current and anticipated discharge standards. Further testing of various types of membrane filters should help identify filters and operational techniques that will lead to reliable and efficient removal of solids from shipboard wastewater. Finally, full-scale MBRs should be tested on Coast Guard cutters to evaluate whether this treatment technology is feasible and reliable under actual shipboard conditions.

1. **Background and Project Goals**

Project History:

Faculty and cadets at the Coast Guard Academy have been engaged in a multi-year project to identify and evaluate promising shipboard wastewater treatment systems for Coast Guard cutters. The project has included an ongoing research component using a lab-scale membrane bioreactor (MBR) system, designed and constructed by cadets in 2002, to evaluate the feasibility of treating various compositions of shipboard gray water and black water. In 2002 the system was tested for one week and found to be hydraulically stable. In 2003, combined gray water and black water in 10:1 and 6:1 ratios were treated in the lab-scale reactor in sequencing batch reactor (SBR) mode for close to one month. The results, which can be found in detail in Zelmanowitz (2003), showed very effective removal of TSS throughout the experiment and reliable filter operation. BOD removal ranged between 75 and 95 %, however, due to high influent BOD levels, effluent BOD were often above 100 mg/L. There were indications that inadequate microbial acclimation may have limited removal of BOD. In 2004, simulated shipboard gray water was treated in the lab-scale MBR in SBR mode. Reactor seeding techniques were improved to shorten the microbial acclimation period. Both TSS and BOD were removed to well below 30 mg/L and treatment was effective after one week of operation.

In addition to lab research, faculty and cadets worked to gather actual shipboard wastewater quality and quantity data to help in the development and selection of appropriate treatment systems. A full-scale MBR design for a 225’ buoy tender was completed based on the gray water and black water flow rate data collected. In 2004, students and faculty at CGA evaluated the operation and treatment effectiveness of a fixed activated sludge system (FAST) on the USCGC Hollyhock installed to treat combined black water and gray water generated on the ship.

Removal of Total Nitrogen in a Single Reactor:

A literature review of removal of BOD from domestic and shipboard wastewater in MBRs can be found elsewhere (Zelmanowitz, 2002). In recent years, removal of total nitrogen (TN) and total phosphorous (TP) has become critically important as regulations continue to reflect the need to reduce the discharge of nutrients into surface waters. Much research and application has focused on achieving nutrient removal in a manner that minimizes the need for additional space, detention time, and expense. Researchers and treatment plant operators have recently demonstrated success removing both BOD and total nitrogen (TN) in one reactor, in most cases, by alternating aerators off/on or by using aerated and anoxic zones in a single tank with various patterns of recycling. Simultaneous nitrification and denitrification in a single tank can result in significant removal of TN when high HRTs and SRTs are provided even though nitrification and denitrification rates are reduced. Rittman and Langeland (1985) removed greater than 90% TN from municipal wastewater in an activated sludge system with an HRT above 25 hours and DO levels below 0.5 mg/L. It is believed that denitrification may be enhanced with a high MLVSS concentration that is typically found in a single reactor system (Yeom et al., 1999). The Highlands Wastewater Treatment Facility in Ledyard, Connecticut consistently achieves effluent BOD below 10 mg/L while removing over 80 % Total Nitrogen using an SBR by cycling the aerators on and off (Banks, 2005). Yeom et. al. (1999) optimized removal of TN in an intermittently aerated MBR with submerged hollow fiber membranes. They achieved an average TN removal of 83 % with a hydraulic residence time (HRT) of 8 to 15 hours and a long solids retention time (SRT). Various anoxic mixing periods were followed by various aerated periods with filtration including 90 minutes anoxic mixing/ 60 minutes aerated, 40 minutes anoxic mixing/ 25 minutes aerated, 60 minutes anoxic mixing/ 90 minutes aerated, and 70 minutes anoxic mixing/ 50 minutes aerated. Excellent chemical oxygen demand (COD) removal (over 95%) was achieved in all reactors. TN removal ranged from 77.2% removal for 40 minutes anoxic/ 25 minutes aerated to 90.7% removal for 60 minutes anoxic/ 90 minutes aerated. Removal of total phosphorous (TP) was most effective for the 60 minutes anoxic/ 90 minutes aerated reactor at 70.9 %. They observed a linear relationship between measured specific denitrification rate (SDNR) and the ratio of BOD to TN. From this they proposed a model for estimating the appropriate length of the anoxic phase. Ahn et al. (2003) used the sequencing anoxic/anaerobic membrane bioreactor (SAM) process to enhance biological phosphorous removal from toilet flushing water. The system involved a sequence of anoxic/ anaerobic zone and aerobic zone that contained a flat sheet micro-filtration membrane. Recycling from the aerobic zone induced anoxic conditions in the first zone. To induce anaerobic conditions in the first zone recycling from the aerobic zone was suspended. Removal of TP averaged 93% for the system. A TN removal of 60% was achieved which is slightly less than that typically achieved in modified Luzack-Ettinger (MLE) systems in which mixed liquor is recycled continuously from the aerobic to the anoxic zone with an HRT 2.3 times lower in the SAM process compared with MLE processes.

Project Goals for Spring 2005:

This report contains work done in Spring 2005 to further evaluate the potential use of MBRs for treatment of gray water generated on Coast Guard cutters. A major goal of the research was to evaluate the removal of BOD and TN in a single reactor using alternating anoxic/aerobic cycles.

The major goals of the project were:

1. To refine the lab-scale MBR to run in continuous flow mode rather than in sequencing batch reactor.
2. To fully automate the operation of the MBR system so that minimal operator intervention would be needed.
3. To refine the recipe for simulated shipboard gray water so that it more closely matches the strength and the ratio of BOD: Nitrogen: Phosphorous in actual shipboard gray water.

4. To refine start-up and seeding procedures to obtain treatment soon after start-up.
5. To evaluate the ability of the lab-scale MBR to remove TSS, BOD, and Total Nitrogen (TN) from simulated shipboard gray water with aerators cycled off and on.
6. To monitor microbial activity in the reactor using specific oxygen uptake tests and daily microscopic examination.
7. To gather wastewater flow rate data for a variety of Coast Guard cutters.
8. To design a full scale version of the lab system to treat gray water onboard a 225’ buoy tender.

2. Treatment of Wastewater in a Lab-Scale MBR: Experimental Methods

An existing lab-scale MBR system was modified to operate in continuous flow mode. Several timers were used to automate operation with minimal intervention. The system included a feed tank with a mixer that alternated on/off in 5 minute intervals, an influent pump, an MBR tank with two submerged membrane filter assemblies each with three filter curtains, an effluent pump that pulled permeate through the filters under a negative pressure, an effluent carboy, and an ultraviolet (UV) disinfection unit.

Details on the design and construction of the lab-scale MBR can be found elsewhere (Zelmanowitz, 2002). The lab-scale filter used was a Mitsubishi Rayon Sterapore-L ultramicro hollow fiber filter. Each filter unit consisted of three filter curtains and a built-in aeration unit below the filter curtains. Permeate was collected on both ends and exited through two permeate ports located on the upper end of the module. Two ports on the lower portion of the module connect to the air supply. The properties and specifications for the filter are listed in Table 2.1.

Table 2.1: Properties and specifications for the lab-scale membrane filter.

Property	**Specification**[#]
Composition	Polyethylene
Nominal Pore Opening	0.4 micro meter
Surface Area per Filter Curtain	0.03 m^2
Number of Filter Curtains per Unit	3
Recommended Negative Pressure	4 psi (10 psi maximum)
Average Flow Rate	0.25 m^3/m^2/day
Dimensions of Each Filter Unit	2 in deep, 6.2 in wide, 7.8 in high
Recommended MLSS in MBR	4000 to 12,000 mg/L

[#] Specifications for the filter unit were provided by Ionics, inc. in Watertown, Ma.

Figure 2.1 shows the membrane filter assembly from front and side views.

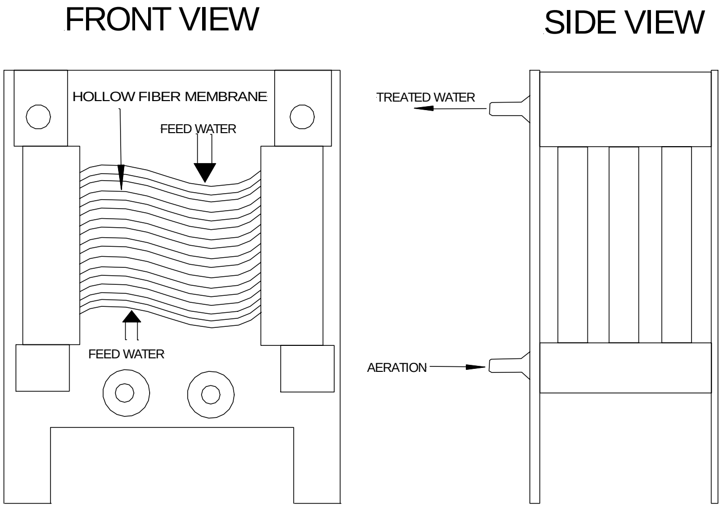


Figure 2.1: Front and side views of the membrane filter assembly.

The dimensions of the MBR tank were 10 inches diameter by 24 inches high with a maximum water level of 17 inches to provide freeboard. Two filter modules were set into polypropylene channels at the reactor bottom. Figure 2.2 shows a diagram of the lab-scale MBR.

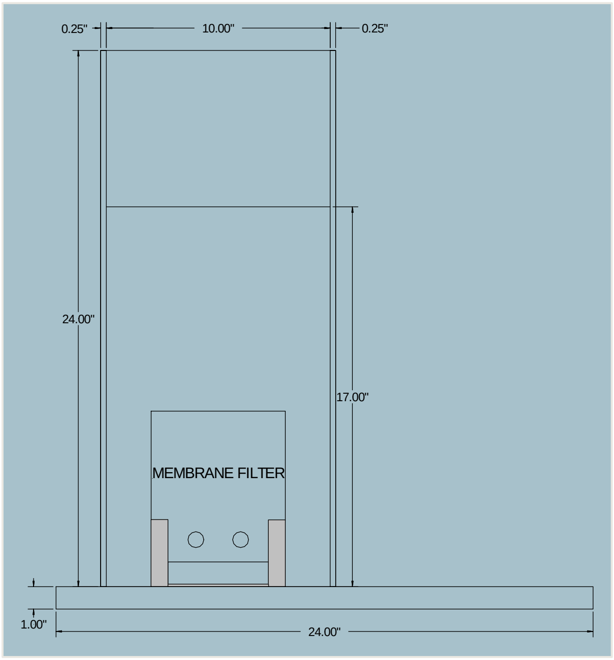


Figure 2.2: Lab-scale MBR design.

In previous years, the MBR was operated as an SBR. In 2005, the system was modified to operate in continuous flow mode with alternating aeration/non-aeration cycles for removal of TN. The hydraulic retention time (HRT) used was dictated by the maximum permeation rate recommended by the filter manufacturer and the size of the tank. With an inside tank diameter of 10 inches and an operational depth of 17 inches, the tank volume was determined to be 0.773 ft^3 (22.0 liters). The HRT was then determined using a recommended permeation rate of 20 mL/min and a requirement that in every ten minute period the permeation pump be turned off for 2 minutes to keep the filters from fouling. To optimize total nitrogen removal, it was necessary to cycle the aerators in the MBR on and off. After consulting the literature on biological nitrogen removal and speaking with Mr. Steve Banks of the Ledyard WPCA who operates an SBR with alternating aeration cycles to remove TN, it was determined that the aerators in the MBR should be cycled two hours on and one hour off. As such, eight complete three-hour cycles would occur within a 24 hour period. In addition, the permeate pump had to be off when the aerators were off to avoid clogging of the membranes. Because the permeate pump operated only 2/3 of the day and during operation the permeate pump was cycled 8 min on/ 2 min off, the average flow rate over a day was actually 10.7 mL/min or 0.0107 liters/min. Since HRT = V/Q, the HRT was calculated to be 34.3 hours. This long HRT may help in removal of TN in a single tank. Rittman and Langeland (1985) removed greater than 90% of TN from a municipal wastewater with an HRT above 25 hours.

The system also included a cylindrical plastic container capable of storing over 20 gallons of feed. The feed tank helped equalize the composition of influent gray water to avoid shock loading of microorganisms and also allowed storage of two or more days of simulated gray water. The feed tank contents were mixed 1 minutes on / 5 minutes off with an EMI Inc. PM6015 mixer.

A Masterflex variable speed peristaltic pump was used to pull a vacuum for permeation. Air was delivered to the built-in aerators in the filter module with a Gast DOA series laboratory diaphram compressor capable of delivering up to 60 psig. A pressure gauge measured air supply to the MBR in psi and this was converted to cfm using tables provided by the compressor manufacturer. A variable speed Masterflex peristaltic pump was used to add gray water to the MBR from the feed tank. A vacuum gauge with a maximum reading of 30 inches Hg was attached to the permeate line to monitor the vacuum pulled for permeation.

Three Fisher Brand timer/controllers were used to automate the feed tank mixer, the permation pump operation, and the cycling of the aerators. The timer was connected to the permeate pump and maintained the 8 minutes on and 2 minutes off cycle. A picture of the final MBR system in operation is shown in Figure 2.3.

Figure 2.3:
The lab-scale MBR in operation.

In previous experiments with the lab-scale MBR, the simulated shipboard gray water used was slightly low in BOD and had a high TKN:BOD ratio compared to typical shipboard gray water composition reported in the literature. As such, prior to the main experiment, several variations to the gray water recipe were mixed, analyzed, and compared with typical gray water composition for cutters. The two recipe ingredients that were varied were the beef soup and the shampoo. Other ingredients were the same as were used in experiments in spring 2004 according to Table 2.2. For a 5 gallon batch of gray water, the four recipe variations tested included:

Sample A:	20 mL of beef soup with 3.5 g of shampoo
Sample B:	20 mL of beef soup with 2.5 g of shampoo
Sample C:	10 mL of beef soup with 3.5 g of shampoo
Sample D:	10 mL of beef soup with 2.5 g of shampoo

The results of the gray water recipe test, actual shipboard gray water data from the UNDS report on gray water, the simulated gray water used in the lab-scale experiment in 2004, and the average composition of the feed used in 2005 are shown in Table 2.3.

Table 2.2: Recipe for 5 gallons of simulated gray water (2005).

2 gallons of tap water mixed with 2.5 g shampoo and 2.0 g body wash
1 gallon dishwater collected from the dishwasher using 60 g powdered detergent
0.5 gallons of tap water mixed with 0.5 mL Lime-a-way, 0.25 g instant coffee crystals, 0.1 g shave gel, 0.6 g toothpaste
1 gallon tap water with 2.35 g powdered laundry detergent
2.4 liters (0.6 gallons) of tap water with 0.5 mL soybean oil, 0.5 mL vegetable oil, 20 mL orange juice, 15 mL chunky beef soup pureed

Table 2.3: Gray water testing results, actual gray water collected in 2004, actual shipboard gray water from the literature, and simulated gray water used in 2005.

Sample	BOD_5[1] (mg/L)	TKN (mg/L)	Nitrate (mg/L)	Ammonia (mg/L)	TP (mg/L)
A	444	8.93	BDL	1.05	6.2
B	287	8.20	BDL	0.95	20.3
C	323	7.17	BDL	0.88	18.9
D	436	9.81	BDL	0.78	20.8
Shipboard Data 2004[2]	292	21.6	Not Measured	Not Measured	8.2
Gray water Underway[3]	323	12.9	0.8	0.1	2.5
Gray water In Port	344	14	0.8	0.1	3.14
Laboratory Data 2005[4]	357	10.8	BDL	0.1	7.3

[1] BOD_5 = 5-day Biochemical Oxygen Demand, TKN = Total Kjeldahl Nitrogen (ammonia plus organic N), TP = Total Phosphorous.
[2] Shipboard data for gray water were collected in 2004 from the USCGC Willow and Juniper.
[3] Gray water underway and in port are taken from UNDS data (EPA, 1999).
[4] Laboratory data 2005 represents the average composition of feed gray water for 2005.

High TP concentrations in samples B, C, and D may have occurred because the dishwasher crystals were not run through the dishwasher for those samples. The chosen recipe for the 2005 experiment used 15 mL beef soup and 2.5 g of shampoo (see Table 2.2).

In addition to refining the gray water recipe, the reactor seeding procedure was refined to minimize acclimation time. This was important due to the short duration of the experiment (4 weeks) and the fact that rapid acclimation of microorganisms would be highly desirable onboard ship. The seeding procedure was based on discussions with Ms. Rachel Jacobs of NAVSEA Carderock and a review of the literature. The reactor was seeded by obtaining mixed liquor from the Highlands Wastewater Treatment Facility in Ledyard, Connecticut. Seed material from this facility was considered ideal because the Highlands WWTF practices TN removal in an SBR by alternating between aerobic and anoxic cycles. The reactor was seeded by filling it half way with activated sludge from the plant and then filled to volume with tap water. This mixture was aerated for 24 hours and then the experiment was initiated by feeding simulated gray water at the targeted flow rate.

Several parameters were measured to assess conditions in the reactor and treatment effectiveness. A YSI 550 portable dissolved oxygen (DO) meter was used to monitor DO and temperature in the aeration tank on a regular basis. When a reading was needed, the probe was plunged into the reactor to mid depth until the reading stabilized. The DO probe had a built in temperature sensor that allowed for simultaneous monitoring of DO and temperature. Permeation rate was monitored up to several times per day using a graduated cylinder and stopwatch. The vacuum pulled on the membranes was measured at least once a day using a vacuum gage to check for signs of filter fouling. An airflow meter was used to measure the amount of air delivered to the reactor in psi. The pH of the mixed liquor was monitored periodically using a Fisher brand Accumet pH meter with combination electrode.

In addition to in situ measurement of tank conditions samples were taken from the feed tank, the reactor, the effluent tank (pre disinfection), and from the tubing leaving the UV disinfection process. In-tank samples were taken using a small beaker with a long handle attached. This allowed for gentle mixing of the reactor contents prior to retrieving a sample of 20 to 30 mL. Table 2.4 shows the various analytical tests run on each type of sample. Ammonia-N, nitrate-N, nitrite-N, fecal coliform, and TP were measured periodically (approximately 2 xs per week). BOD, TSS, and turbidity were measured daily. Mixed liquor volatile suspended solids (MLVSS) were measured once per week.

Table 2.4: Sample locations and parameters analyzed.

Sample Location	**Parameters Analyzed**
Feed Tank	Turbidity, TSS, BOD, TKN, NO_3^-, NO_2^-, Ammonia, TP, Fecal Coliform
Membrane Bioreactor	TSS, VSS, pH
Effluent (pre-UV)	Turbidity, TSS, BOD, TKN, NO_3^-,NO_2^- Ammonia-N, TP, Fecal Coliform, COD
Effluent (post-UV)	Turbidity, TSS, BOD, TKN, NO_3^-, NO_2^-, Ammonia-N, TP, Fecal Coliform, COD

Table 2.5 shows the analytical technique used or method reference and the location of the testing.

In addition to monitoring the growth of TSS in the reactor over time, specific oxygen uptake rate was measured periodically to assess microbial activity. In addition, the mixed liquor was examined under a phase contrast microscope daily to monitor the relative population of various wastewater organisms and to assess the relative amounts of floc-forming and filamentous bacteria in the reactor. Diluted and undiluted sludge volume index tests were also performed on the mixed liquor.

Table 2.5: Analytical methods and testing lab.

Parameter	**Method**[#]	**Lab**	**Detection Limit**
Turbidity	HACH (2002)	CGA	-------
TSS, VSS	SM	CGA	1 mg/L
BOD_5	SM5210B	KB Analytical	1 to 3 mg/L
TKN	SM4500-N_{org}B	KB Analytical	0.2 mg/L
Nitrate-N	SM4500NO_3E	KB Analytical	0.1 to 0.5 mg/L
Nitrite-N	SM4500NO_2B	KB Analytical	0.01 mg/L
Ammonia-N	SM4500-NH_3D	KB Analytical	0.1 mg/L
TP	SM4500PE	KB Analytical	N/A
Fecal Coliform	SM9221B	KB Analytical	10 col/100 mL
COD	SM5220D	KB Analytical	N/A

All standard methods (SM) are from APHA (1992).

The experiment was initiated on March 18th 2005 and was suspended after two days due to apparent filter failure. After replacing one filter curtain, replacing rubber o-rings that had disintegrated, and reinforcing the permeate ports with glue, the experiment was restarted several days later and was run successfully for 4 weeks.

3. Results of Laboratory-Scale Experiments

Environmental Conditions in the MBR:

Dissolved oxygen (DO) in the reactor was measured both during aeration cycles and when the aerators were turned off. During aeration the DO varied between 5.2 and 7.5 and was consistently well above 2 mg/L. During the anoxic phases (aerators were turned off for 1 hour per 3 hour period), and DO levels consistently fell to below 0.1 mg/L by the end of the anoxic period. This was determined by monitoring DO every few minutes after the aerator shut off. The high DO levels during aeration were followed by a rapid decline in DO levels with the aerator off providing time for denitrifiers to convert nitrate to nitrogen gas. This may explain the high efficiency of total nitrogen removal observed in the experiment. The pH of mixed liquor was also monitored to make sure that levels were within a reasonable range for the microbes to thrive. The pH was consistently between 6.6 and 8.0 with an average value of 7.2 indicating a good pH for the microbes needed. Since temperature affects microbial activity, the temperature was measured and recorded daily. The temperature in the reactor ranged between 19 and 22 ^{o} C over the course of the experiment.

Indications of Membrane Performance:

Throughout the experiment the negative pressure on the membranes were monitored at least once per day because a sharp increase in vacuum could indicate filter fouling. The vacuum measured consistently between 18 and 28 inches Hg with an average value of 23 inches Hg which is within range for normal operation. The effluent flow rate was also monitored daily to ensure that influent and effluent flow rates were consistent. A sudden decline in flow rate could also indicate filter clogging. The flow rates through the filters were consistently between 17 and 23 mL/min throughout the experiment with an average at the target value of 20 mL/min. The major indication of good filter performance is the effluent TSS and turbidity which was very low throughout the 4 weeks as will be discussed later.

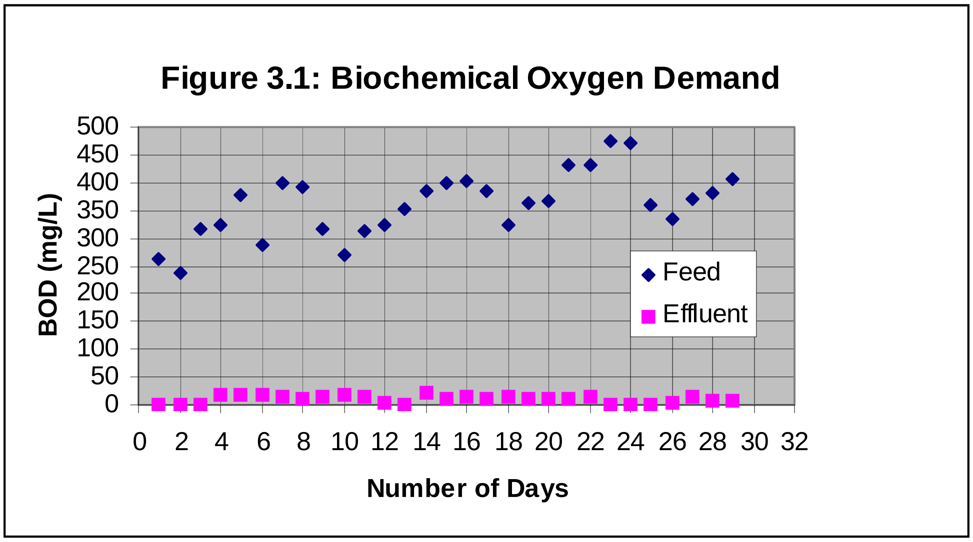
Air Supply to the Reactor:

An air flow meter was attached to the compressor to measure air supply to the reactor. The gage read consistently at approximately 1 to 2 psi. The needle on the gage was unsteady so only an approximate reading could be made. Using tables provided by the compressor manufacturer, the air supply in psi can be estimated as equivalent to about 0.9 cfm. Judging from the DO level in the reactor and the high level of BOD removal, the air supply was sufficient for treatment but may have been greater than necessary. Excess air delivery would be undesirable on a ship due to energy costs and available air pressure considerations. In this case excess aeration may have been partially responsible for the poor settling characteristics of the sludge noted during the experiment.

However, the advantage of an MBR is that high quality effluent can be achieved regardless of sludge settling properties.

Removal of Biochemical Oxygen Demand:

The removal of biochemical oxygen demand (BOD) was monitored by analysis of BOD in feed (influent) and effluent samples each day. Figure 3.1 shows influent and effluent BOD_5 during the experiment. BOD values plotted at zero are actually below the detection limit of 1 to 3 mg/L. BOD removal rates ranged from 93% to over 99% with all effluent BOD values well below 30 mg/L. Efficient BOD removal was noted from the first day of treatment indicating the success of the seeding technique. High BOD removal was very consistent despite fluctuations in influent BOD which ranged between 236 and 476 mg/L. Effluent BOD values plotted as zero represent data below the detection limit.



Removal of Nitrogen:

The experimental design involved alternating between aerobic and anoxic conditions to promote removal of TN in the reactor. The results indicate excellent removal of TN (estimated as TKN + nitrate-N + nitrite-N). Removal of TN ranged from 71% to greater than 99% with TN removal rates consistently above 95% after two weeks had elapsed. Figures 3.2, 3.3, and 3.4 show TKN, ammonia-N, and TN for the feed and the effluent over the course of the experiment. Nitrate-N and nitrite-N concentrations were not plotted since they were generally near or below detection limits. Figure 3.2 illustrates that TKN (ammonia-N plus organic-N) was significantly reduced in the reactor. Figure 3.3 shows that ammonia was significantly removed in the reactor. This indicates that most of the organic nitrogen in the feed was mineralized to ammonia and then the ammonia was nitrified in the reactor. Since most of the effluent samples also showed negligible nitrate and nitrite, there must have also been significant denitrification in the reactor resulting in effective removal of TN as seen in Figure 3.4.

Figure 3.2: Total Kjeldahl Nitrogen

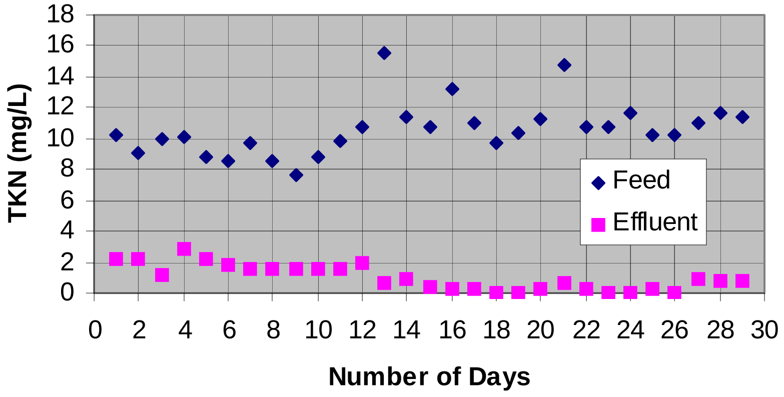
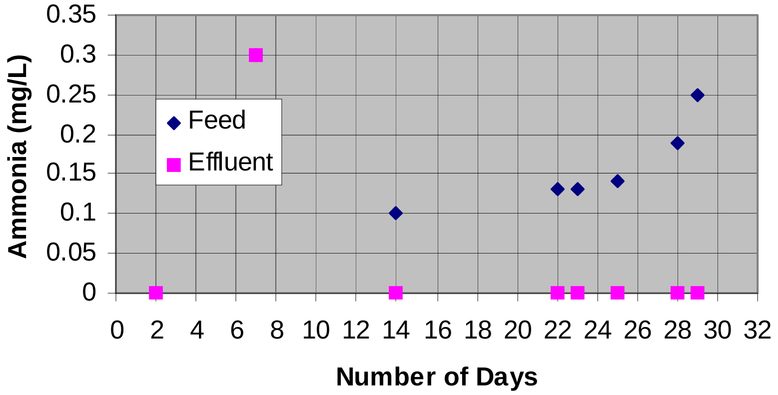


Figure 3.3: Ammonia Nitrogen



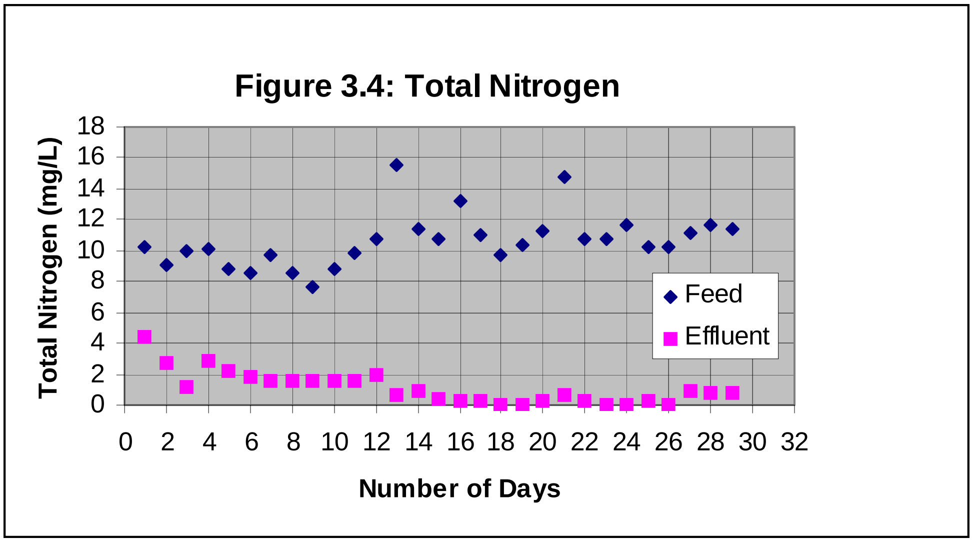


Figure 3.4: Total Nitrogen

Removal of Turbidity and Total Suspended Solids:
For the purposes of evaluating treatment effectiveness, both turbidity and TSS were measured on influent and effluent. The influent and effluent turbidity measurements are shown in Figure 3.5 and indicate consistent turbidity removal in excess of 98 %. Removal of TSS also indicates a high degree of filter effectiveness as shown in Figure 3.6. Effluent TSS concentrations plotted as zero indicate that the effluent was below quantification limits for the procedure.

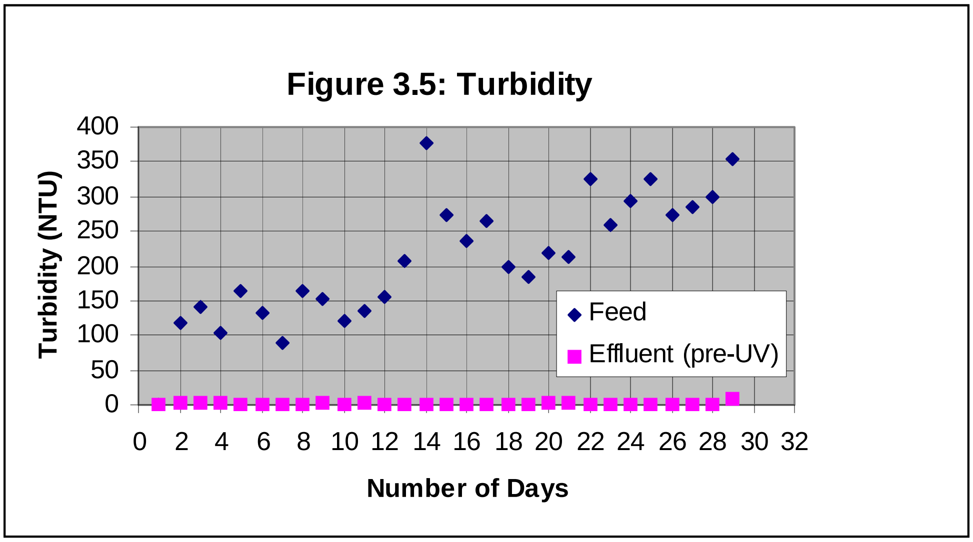
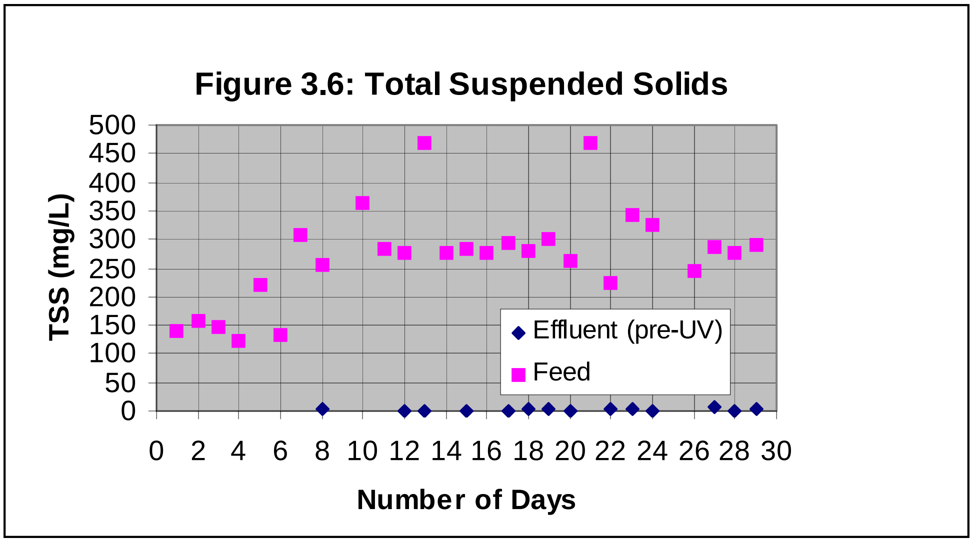
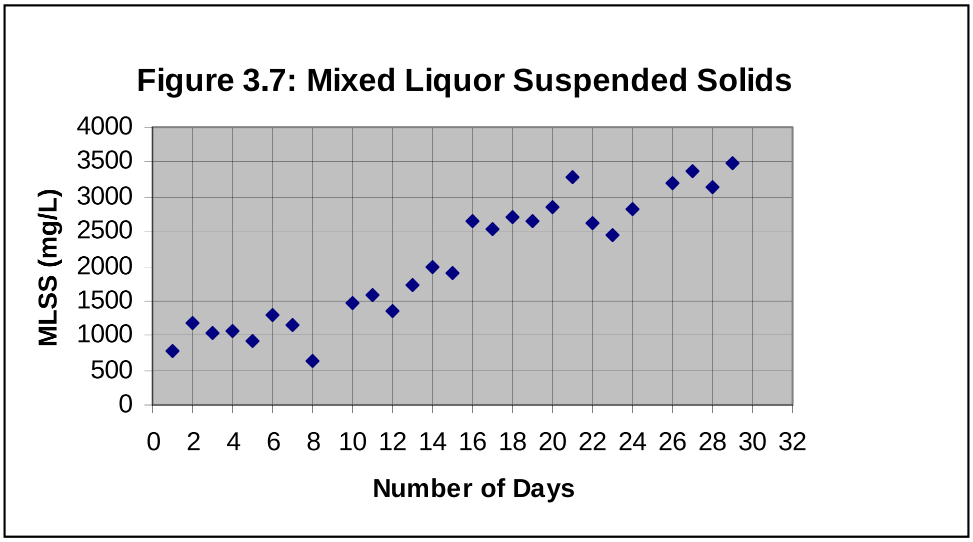


Figure 3.5: Turbidity



Indications of Microbial Growth and Activity:
The mixed liquor suspended solids (MLSS) was measured daily as one indicator of microbial growth during the experimental period. The MLSS concentrations (as shown in Figure 3.7) rose significantly as the experiment progressed until it was between 2,500 and 3,500 mg/L. The rise in MLSS that corresponds to a similar rise in mixed liquor volatile suspended solids (MLVSS) indicates a growth in microbial population over time. Periodically, MLVSS (mixed liquor volatile suspended solids) in the tank were also measured as a more accurate indication of microbial mass. However, due to insufficient sample sizes that were used to avoid affecting the tank volume significantly during the experiment, many of the MLVSS tests yielded negative masses rendering the results invalid. However, the five VSS tests that yielded reasonable results showed that MLVSS averaged at 80% of MLSS which is within expected values for a biological treatment system using domestic-type wastewater.



Two other indications of microbial activity are Specific Oxygen Uptake Rate (SOUR) measurements and daily microscopic examination of the activated sludge in the reactor. The SOUR test can give an approximate measure of respiration rate of the microbes and may indicate toxicity in the tank. Four SOUR tests were conducted on March 22nd (day 1 of the experiment), March 29th (after one week), April 5th (after 2 weeks), and April 12th (after 3 weeks). Dissolved oxygen of the activated sludge was measured each minute for 15 minutes or more and the daily TSS value was converted to VSS using the average value of VSS/TSS = 0.80 for the sludge. The SOUR data were determined according to the following equation and results are presented in Table 3.2:

$$\text{SOUR (mg/g)/h} = \frac{\text{(DO initial – DO final) mg/L}}{\text{(\# of minutes)}} \times \text{60 min/h} \times \frac{\text{1000mg/g}}{\text{VSS mg/L}}$$

Table 3.2: Specific Oxygen Uptake Results

Days into Experiment	**DO $_{\text{initial}}$ (mg/L)**	**DO $_{\text{final}}$[1] (mg/L)**	**VSS[2] (mg/L)**	**SOUR (mg/g)/h**
1	7.56	5.41	624	13.8
8	6.19	3.86	518	18.0
15	8.04	4.12	1526	10.3
22	8.13	4.91	2088	6.17

[1] DO final measurements were taken at 15 minutes.
[2] VSS was approximated as 0.8 x TSS

Guidelines for SOUR values are provided in the literature (http:/www.ne-wea.org/LabManual/sour.htm). A SOUR between 12 and 20 (mg/g)/h usually indicates a good BOD removal and a good settling sludge. Values above 20 (mg/g)/h may indicate too few solids to handle the BOD loading. SOUR values below 12 may indicate that the microorganisms have encountered a toxin or there are too many solids in the reactor. The SOUR values for day 1 and day 8 are within the desirable range. As the TSS and VSS increased in the reactor the SOUR values dipped into a less desirable range. This was probably due to excess solids since no solids were wasted from the reactor. BOD and TN removal continued to be effective while the SOUR values fell, so it is unlikely that toxicity was the issue.

A Leica model CME microscope was used to monitor the microbial population in the activated sludge each day. The sludge started out similar to the seed activated sludge with a good mix of bacterial floc, free swimmers, stalked ciliates, and some tardigrads (known as water bears). The activated sludge then took on the characteristics of a typical young sludge with an abundance of free swimmers such as lionotus. Mid-way through the experiment, the sludge appeared to have qualities of a medium age sludge with a mix of free swimmers and stalked ciliates. Toward the end of the month-long experiment, when the sludge was over 3 weeks old, an abundance of stalked ciliates were present and rotifers began to proliferate. Throughout the experiment, it was observed that the bacterial floc had a moderate level of filamentous bacteria but not excessive levels.

Sludge volume index (SVI) tests were conducted to quantify the settling properties of the sludge, although it was apparent during non-aeration periods that the sludge had poor settling characteristics. The SVI sample had to be diluted due to the poor settling properties. A dilution factor of 8 yielded the only usable SVI reading of 298 mL/g reflecting a poor settling sludge. Because the solids in an MBR are not separated by gravity, poor settling sludge is not necessarily a problem as long as treatment is effective. However, the reasons for poor sludge settling were explored to better understand the system.

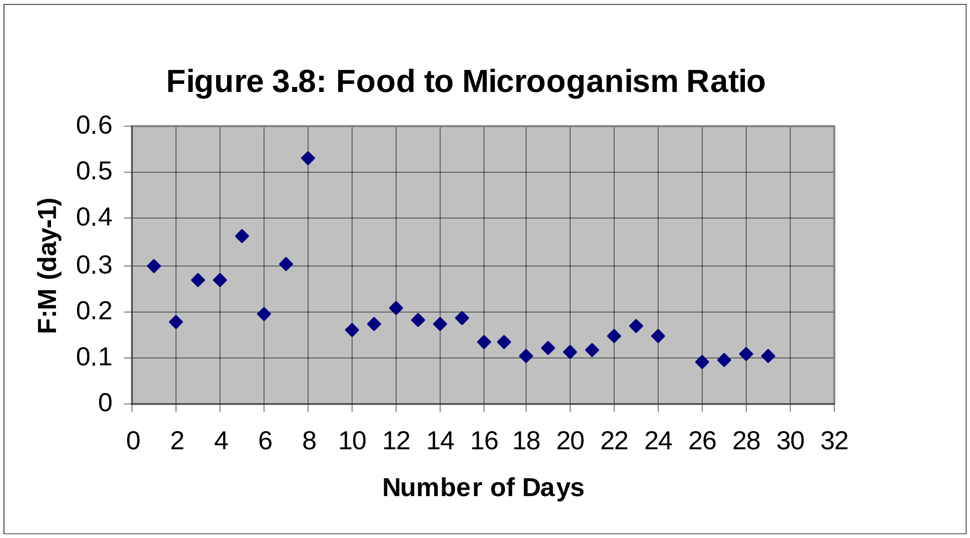
Sludge bulking or poor settling is typically caused by excessive growth of filamentous bacteria or by water trapped in the floc. For most of the experiment, the bacterial floc appeared to have only a moderate level of filamentous bacteria and less than would be typical of a poor settling sludge when filamentous growth is the cause of sludge bulking. In addition, there was no excessive foaming noted as might be observed in a reactor with filamentous growth. Reactor conditions that can cause excessive levels of filamentous bacteria includes low F:M ratio, low DO levels, and completely mixed conditions (Metcalf and Eddy, 2003). The flow regime used could have encouraged sludge bulking. In addition, even though high DO levels were maintained during aeration, the DO was low in the tank during anoxic periods.

Food to microorganism ratio (F:M), which can affect sludge settleability, was calculated daily. F:M is calculated as follows:

$$F{:}M = \frac{Q \times So}{V \times X}$$

Where: Q = volumetric flow rate
So = feed BOD concentration
V = reactor volume
X = MLVSS

The F:M for the experiment ranged from 0.092 to 0.532 day $^{-1}$ with most values in the range of 0.1 to 0.2 day^{-1} after the 10th day of reactor operation. Figure 3.8 shows the change in F:M as the concentration of microbes in the tank increased with time. Typical F:M for a completely mixed activated sludge system is 0.2 to 0.4 day $^{-1}$. However, the lab reactor had a high HRT of over 30 days similar to that of an extended aeration system which tends to have F:M of 0.04 to 0.10 day^{-1} (Metcalf and Eddy, 2003). The lab system, which alternated between aeration and no aeration for biological TN removal differs from a typical extended aeration system so it is unclear whether the F:M ratio achieved was appropriate. If it were deemed necessary to raise the F:M ratio, sludge could be wasted periodically, however, poor sludge settling did not affect wastewater treatment for the MBR.



Removal of Fecal Coliform:
Fecal coliform was analyzed at CGA using the membrane filtration technique to determine whether the UV disinifection system was effective. The feed samples were never diluted sufficiently to get a valid test. The effluent fecal coliform was measured before and after UV disinfection periodically. In general, disinfection was effective in reducing or eliminating fecal coliform as shown in Table 3.3.

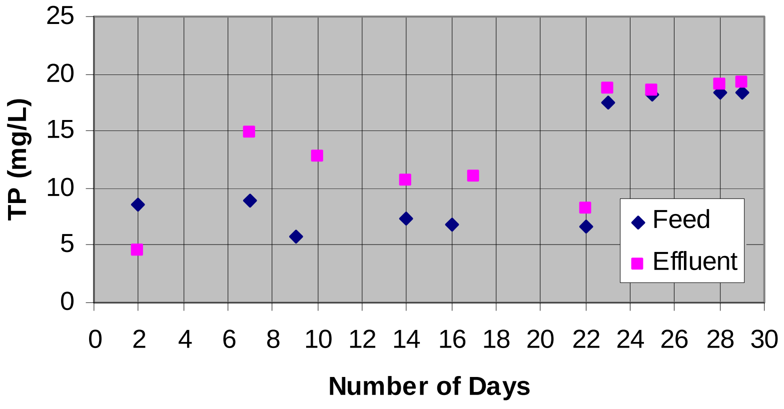
Table 3.3: Fecal coliform before and after ultraviolet disinfection.

Date	Volume Filtered (mL)	FC /100 mL Pre-UV	FC/100 mL Post-UV
March 24	100	1	1
March 24	100	Too Many	1
March 27	100	0	0
March 27	100	15	0
March 31	100	47	2
March 31	100	62	2
April 7	100	0	0
April 7	100	2	0
April 10	100	0	1

Other Parameters:
COD and TP were analyzed periodically to determine their fate during treatment. Although the experiment was not designed for removal of phosphorous, some removal of TP would be highly desirable considering the high concentrations of TP in the feed gray water and the potential deleterious effects of excess TP on receiving streams. As indicated in Figure 3.9, TP was about the same or slightly higher in the effluent compared with the influent. The increase in TP may have been within analytical error. In order to achieve biological phosphorous removal,

the growth of phosphorous accumulating organisms (PAOs) is necessary. The proliferation of PAOs typically requires a separate anaerobic zone with little nitrate and low DO ahead of an aeration zone. Systems that provide for both biological N and P removal are designed to avoid significant amounts of nitrates recycled into the anaerobic reactor (Metcalf and Eddy, 2003). As such, one would not expect TP removal in the single tank system used for simultaneous removal of BOD and TN.

Figure 3.9: Total Phosphorous



COD was analyzed for samples generated on April 12th and 13th. The COD feed samples were 786 and 946 mg/L representing a BOD:COD ratio of approximately 1:2. Effluent COD values were 46 and 74 mg/L indicating well over 90 % removal of COD in the reactor.

4. Full Scale MBR Design for a 225' Juniper Class Buoy Tender

The results demonstrated in Chapter 3 indicated excellent removal of BOD and TN using a lab-scale MBR operated with alternating aerobic and anoxic cycles in continuous flow mode. However, it is important to evaluate whether this reactor could be scaled up to fit and operate on a ship. The 225' Juniper Class buoy tender was chosen for design of a scaled-up system because data had been collected on available spaces and these ships operate close to shore and would benefit from gray water treatment.

The full-scale reactor was sized using the HRT of 34.3 hours used for the lab-scale system and a flow rate of 1500 gallons/day estimated from previous research. A required reactor volume of 287 ft^3 was designed to fit within available space on the auxiliary machinery deck. Figures 4.1 and 4.2 contain sketches of the full scale MBR system in plan and profile views, respectively.

Figure 4.1: Full scale MBR design for a 225' buoy tender – plan view

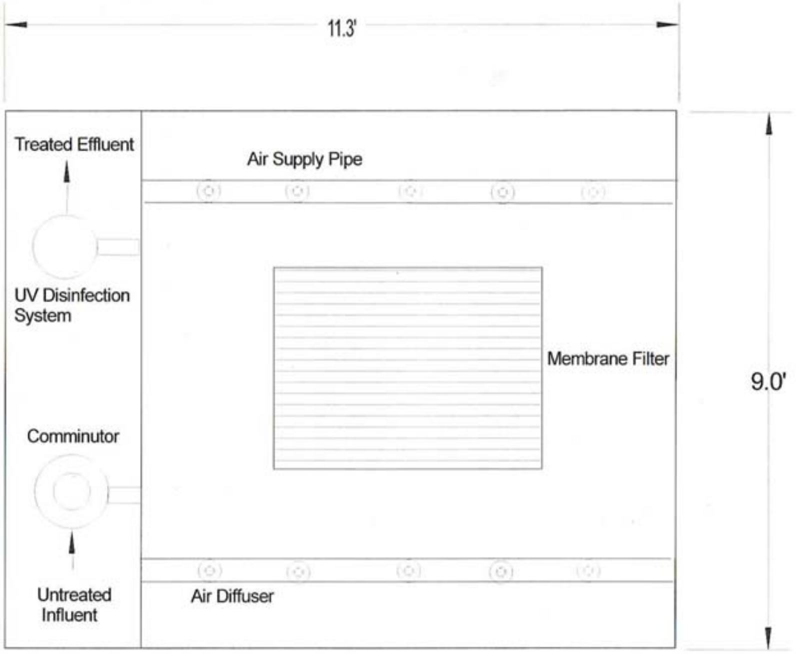
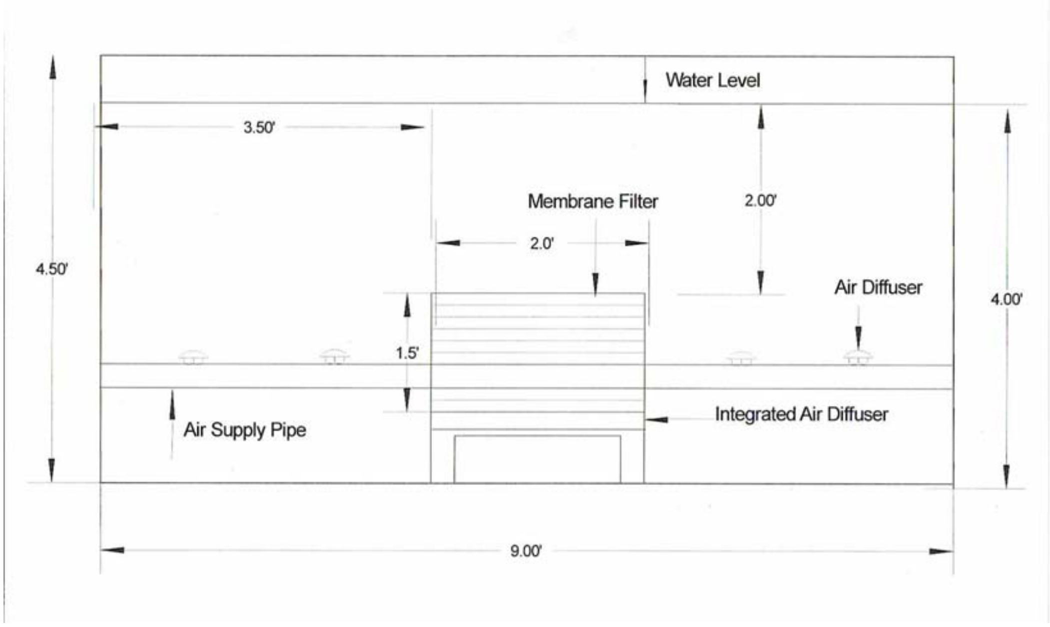


Figure 4.2: Full scale MBR design for a 225' buoy tender – profile view



The MBR system includes a comminuter for pretreatment to grind up large solids and a UV disinfection system as post treatment. The MBR is designed to fit a submerged Mitsubishi-Rayon hollow fiber Sterapore filter, product number MHFL1234 which is similar to the lab scale filter used in the experiment. The filter has a design flow rate of 15 to 20 m^3 per day and is 456 mm (1.5 ft) x 606 mm (2.0 ft) x 1483 mm (4.9 ft) in size. The system is outfitted with eight air diffusers to supplement the aerator built into the membrane filter which supply approximately 27 m^3 per hour of air. It is not certain the same treatment effectiveness observed in the lab would be achieved in a full scale shipboard situation. Factors such as temperature fluctuations, pitch and roll of the ship, fluctuating quality and quantity of gray water and minimal available trained operational staff would make actual shipboard treatment more challenging.

5. Black Water and Gray Water Flow Rate Data for Various CG Cutters

Table 5.1 contains flow rate data reported by crew members on CG cutters.

Table 5.1: Gray water and black water flow rate data for various CG cutters.

Cutter (size)	Crew Size	Gray Water (IP)	Gray Water (UW)	Black Water (IP)	Black Water (UW)	GW:BW Ratio
Ridley (87’)	11	40 gpd	100 gpd	10 gpd	20 gpd	5:1 IP[#] 4:1 UW
Biscayne Bay (140’)	17	80 gpd	300 gpd	10 gpd	30 gpd	8:1 IP 10:1 UW
Katherine Walker (175’)	26	400-500 gpd	600-700 gpd	50 gpd	200 gpd	10:1 IP 4:1 UW
Dauntless (210’)	75	1500 gpd	2500 gpd	300 gpd	No Data	8:1 IP 8:1 UW
Tampa (270’)	110	No Data	No Data	1500 gpd	2500 gpd	No Data
Mackinaw (290’)	84	1000 gpd	3500 gpd	100 gpd	300 gpd	10:1 IP 10:1 UW
Dallas (378’)	150	1000 gpd	5000 gpd	200 gpd	1000 gpd	5:1 IP 5:1 UW
Rush (378’)	170	No Data	9000 gpd	No Data	2000 gpd	9:2 UW
Boutwell (378’)	190	2100 gpd	6000 gpd	700 gpd	2000 gpd	3:1 IP 3:1 UW

IP = in port; UW = underway

The flow rate data were likely obtained in different ways for each ship and, in many cases, flow rates were measured for very limited periods of time. The data in table 5.1 highlights the great variability in flow rates between ships and between in port and under way conditions. Other research on actual shipboard wastewater shows that this variability is also seen in the composition of shipboard wastewater. The fluctuations in quantity and quality of shipboard gray water and black water present additional challenges for designing and operating wastewater treatment systems for ships.

6. Conclusions

The results of the research indicate that excellent removal of BOD, TN, and TSS were obtained in a laboratory scale MBR using simulated shipboard gray water. Effluent BOD concentrations were consistently well below 30 mg/L with levels below 1 mg/L on many days. BOD removal efficiency ranged from 93 to over 99 % throughout the month long testing period. Over 95 % BOD removal began in the first few days of the experiment indicating the effectiveness of the reactor seeding and start-up procedures. The alternating aerobic and anoxic cycling appeared to be a successful strategy for nitrification and denitrification in one tank. Removal of TN was above 70% from the first days of treatment and TN removal efficiencies were consistently between 90 to greater than 99 % after two weeks of reactor operation. Removal of turbidity and TSS were consistently well above 98% indicating excellent filter operation. Although TP was not removed and actually seemed to increase in concentration following treatment, removal of TP was not a goal of the experiment. The reduction in fecal coliform before and after UV treatment confirmed the effectiveness of the disinfection system.

Treatment effectiveness is consistent with many indications of microbial growth and activity. A diverse and active microbial community was noted through microscopic examination. The F:M ratio was between 0.1 and 0.4 day^{-1} for most of the experimental period. Although the sludge had poor settling properties as evidenced by a series of SVI tests, this did not hinder treatment efficiency or solids separation by the membrane filter.

Overall, the experiment demonstrated that BOD and TN were effectively removed from simulated shipboard gray water in a single membrane bioreactor tank by alternating aerobic and anoxic cycles. As such, it is likely that effluent BOD and TN concentrations achieved would meet or exceed any future limits set for gray water from ships. It is unclear whether the level of treatment noted in the laboratory experiment could be achieved on a ship considering the non-ideal conditions that would be encountered such as vessel motion, changing temperatures, fluctuating flow rates, changing quality of gray water, and minimal staffing and training for reactor operation and maintenance.

7. Recommendations

Based on the results of this research and the need to identify and test shipboard systems for treatment of gray water and black water, the following recommendations are made:

a. Modify the system tested in the lab to maintain removal of BOD and TN while effectively removing TP.
b. Evaluate the ability to treat various ratios of shipboard gray water and black water to identify whether it is feasible to treat combined black and gray water on CG ships.
c. Refine lab techniques for supplying air and measuring air supply to avoid excess DO levels during aeration cycles.
d. Refine techniques for measuring and monitoring microbial activity.
e. Determine optimum sludge removal practices for shipboard MBR systems to maintain good F:M ratios without compromising overall treatment.
f. Continue to collect data on shipboard wastewater quality and quantity to support design of MBRs for Coast Guard cutters.
g. Evaluate the treatment of shipboard gray water and/or blended gray water and black water in an MBR on a Coast Guard cutter. Operational issues with the full scale system should be monitored and documented.

Appendix A: List of Symbols and Acronyms

BNR	Biological Nutrient Removal
BOD_5	5 Day Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
F:M	Food to Microorganism Ratio
HRT	Hydraulic Retention Time
MBR	Membrane Bioreactor
MLSS	Mixed Liquor Suspended Solids
MLVSS	Mixed Liquor Volatile Suspended Solids
PAO	Phosphorous Accumulating Organism
SBR	Sequencing Batch Reactor
SOUR	Specific Oxygen Uptake Rate
SRT	Solids Retention Time
SVI	Sludge Volume Index
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TP	Total Phosphorous
TSS	Total Suspended Solids

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