Pilot Testing of a Membrane Bioreactor Treatment Plant for Reuse Applications

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New York State
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Final Report

Prepared for the

NEW YORK STATE ENERGY RESEARCH AND DEVELOPMENT AUTHORITY

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NOTICE

ABSTRACT

A combination of laboratory, bench, and pilot-scale studies were performed to evaluate the impact of coagulant and polymer addition on the efficiency of a novel wastewater treatment process. The New York State Energy Research and Development Authority (NYSERDA) funded research project was carried out through a partnership between Manhattan College, Rockland County Sewer District No. 1, and United Water of New York. The purpose of the study was to use a scale-up approach to select and test appropriate coagulants and coagulant aids (polymers, flocculants, etc.) aimed at enhancing settling and improving nutrient removal for the production of re-use quality water. The treatment process included a high-rate primary settling unit with coagulation to enhance settling and remove phosphorous, followed by a four-stage biological nutrient removal membrane filtration process provided by Zenon ®. The main goals of this one-year study were three-fold: 1) to determine if the combined enhanced settling and biomembrane filtration process could produce re-use quality water; 2) determine the effects of chemical coagulant addition on membrane performance and fouling; and 3) determine if membrane filtration processes can cost effectively be applied to treat municipal wastewater with varying BOD and nutrient loads and significant temperature variations.

Key words: Membrane bioreactor, reuse, fouling, nutrient removal, wastewater, pilot testing

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SUMMARY OF FINDINGS

The over-all goal of the project was to demonstrate that the piloted treatment train, specifically, and membrane bioreactor-based systems, generally, could cost effectively and reliably treat variable wastewater to meet stringent reuse criteria. Although the study encountered a number of set-backs, including severe weather, equipment failures, and loss of technical and financial support, the study was a success. All goals and objectives of the study were achieved, and most of the expected outcomes were realized.

Below is a list of the major objectives and issues addressed during this study, along with a brief description of the results from the study that address each issue/objective. The full report presents all of the results and discussion that support these objectives and, ultimately, concluded in a successful project.

1. **Evaluate the impact of different coagulants and polymers on membrane performance and operation.** Results from Phase I and Phase II indicate that the use of ferric chloride and, potentially, other coagulants (alum and some proprietary products) can actually enhance membrane performance. The results of this study support the theory that residual coagulant produces a larger and more structurally sound biological floc that, when accumulated around the membranes during vacuum operation, allows for a higher degree of porosity and less resistance to flow. In addition, biological floc conditioned with ferric chloride was more easily removed from the membranes during backwash. The net result was less severe membrane fouling during filtration cycles and less long-term clogging of membrane pores. The results imply that the use of coagulant prior to membrane filtration should reduce power costs associated with membrane operation (vacuum and back-pulse pressure) and membrane cleaning. Ultimately, the use of coagulant may increase the life-cycle of the membranes, resulting in fewer membrane replacements during the life of the plant. The results prove that the use of certain coagulants does not negatively impact membrane performance and most likely enhances membrane performance and reliability.

2. **Evaluate biological activity and flexibility in the reactor.** The activity and flexibility of the biological reactor was monitored throughout the study using standard methods (Biochemical Oxygen Demand - BOD, N and P). The Membrane Bioreactor (MBR) system operates at a high biomass concentration (> 10,000 mg/l mixed liquor suspended solids (MLSS) and long solids retention time (SRT) (30 days or more). Under these high biomass, long SRT operating conditions, maintaining a reasonable food to mass ratio (F/M) was difficult, especially when treating a wastewater that was relatively week and/or diluted by wet weather events. Under diluted BOD conditions, it was difficult to get enough BOD to the MBR system to support the high biomass operation. A low F/M ratio leads to foaming and reductions in nitrogen removal efficiency. Operating procedures to overcome this limitation included partial or total bypass of primary settling, increased sludge wasting to reduce MLSS, or increase in membrane flux capacity

(more membranes). Each solution has its own drawbacks, which are discussed in the report.

Another issue regarding the operation of a high-biomass MBR system is that under high-biomass operating conditions, the bacteria have a very low specific activity (BOD, nitrification, and denitrification). Specific activities can be further reduced by diluted wastewater and/or reductions in temperature. If the specific activity falls to critically low levels, the sludge may die-off resulting in an increase in soluble microbial products, which contribute to BOD and chemical oxygen demand (COD) in the effluent, increased fouling of membranes, and non-biological foaming events. One such event did happen during the pilot study. The event was blamed on prolonged and extremely low temperatures, incomplete weatherization of the pilot system, and diluted BOD in the influent wastewater. The impacts of low water temperature and incomplete weatherization would not be realized in a full-scale plant, and only the diluted BOD would impact the F/M ratio, which can be overcome using process control strategies as discussed in the report.

3. **Asses cleaning strategy requirements of the membranes**. The cleaning requirements of the membranes were minimal during the pilot study. The only time the membranes required a comprehensive cleaning was after a series of biological and non-biological upsets related to cold wastewater temperature, low F/M, and failed equipment (feed pump, internal pump). The result of this non-ideal operation was a significant reduction in membrane flux and an increase in vacuum pressure required to operate the system. After about eight months of non-ideal operation, the membranes were completely cleaned with a 300 ppm hypochlorous solution. The cleaning resulted in almost complete recovery of the membrane performance for the remainder of the study. In general, the membranes proved to be very strong, robust, and resilient.

4. **Evaluation of final effluent water quality, including nutrients and microbial contaminants.** The system was able to meet all of New York State's Level 3 and most of New York State's Level 4 reuse water quality criteria. This includes all BOD and nutrient criteria, all solids criteria, and all microbial contamination criteria. The only issue was with metals, when the effluent did not meet all of the Level 4 criteria. It is surmised that a full-scale, continuously operating system would perform better than the pilot, since there may be greater long-term process control and fewer impacts due to diluted wastewater and temperature extremes. Overall, the system performed extremely well, even under non-ideal operating and environmental conditions. An MBR system similar to the one piloted should have no problem meeting and exceeding New York State's Level 3 reuse standards and could likely meet Level 4 standards if specific attention were paid to optimizing phosphorous removal.

5. **Assessment of operating cost associated with this treatment train, including energy and solids management**. The piloted treatment train requires significant chemical costs, including coagulant (ferric chloride) to achieve required phosphorous removal (~65 mg/l) and methanol (~ 44 mg/l) for denitrification. In addition, sodium hydroxide or another base was periodically

needed to offset alkalinity loss caused by the nitrogen removal process. The membranes required some hypochlorous for membrane cleaning. Chemical costs could be significantly reduced if the plant was modified to include biological phosphorous removal and the primary clarifiers were replaced with a grit chamber and screens to allow more raw wastewater BOD to enter MBR to drive denitrification. The electrical costs compare favorably to a conventional tertiary plant, with the majority of electrical cost going toward aeration and membrane operation. The chemical and electrical costs will likely become more of a factor as the size of the plant increases (~ > 5 MGD). Other costs that need to be considered include replacement cost of the membranes every 10 years and periodic "dipping" of the membranes to reduce accumulated material and fouling. These increased O&M costs need to be considered, along with the potential cost savings and the reliability and efficiency of the MBR process. One limitation of the MBR systems for treating weak wastewater streams, such as those typically found in older cities, is the need for supplemental carbon to not only support denitrifcation, but also to support the high MLSS concentrations (> 10,000 mg/l MLSS) that most MBR systems require. Finally, once familiar with the MBR plant, there would be no need for extra labor to operate the plant.

The cost effectiveness of MBRs is currently highly site specific. If land cost and availability are a major driver and a high quality effluent is required, it is likely that MBRs will be competitive in comparison to traditional tertiary treatment technologies. As the need for water reuse grows across the US and the world, MBR systems will become increasingly more common. As the technology becomes more prevalent and the market place drives competition and innovation, it is likely that MBRs will become a technology that is commonly considered for many applications on both a cost and performance basis.

6. **Compliance with current and future regulations.** The results from the MBR pilot demonstrate that the MBR pilot system tested can meet the most strict effluent standards and that operational and process controls can be used to effectively optimize treatment to meet these standards. The MBR system can be easily upgraded to achieve even high effluent standards by simply adding a set of exterior ultra-, nano-, or reverse osmosis-membranes to further treat the high quality effluent that is produced by the micro-filtration process.

7. **Comparison between the pilot and conventional wastewater treatment plants**. The piloted system would require a significantly smaller footprint than conventional tertiary treatment processes and could produce a better quality effluent than most conventional tertiary treatment systems. In addition, the MBR system replaces three conventional treatment processes that would be needed to achieve Level 3 reuse quality effluent: the biological tanks, the secondary clarifier, and the sand filters. The MBR system will produce less sludge, since it is a high-biomass, low-yield, and low-specific-activity system. Different configurations of the MBR system should be considered to optimize cost and performance, but it is evident that a properly designed and operated MBR system can cost effectively achieve desired reuse water quality and compares

favorably to conventional systems. Table S-1 shows a general performance comparison between conventional activated sludge treatment and the MBR pilot system.

Table S – 1: Removal Efficiency of Conventional Plant vs. Pilot MBR

Process	Conventional Plant	MBR
SS, mg/l	<10	0.6
BOD_5, mg/l	<5	2
COD, mg/l	20-30	21
Total N, mg/l	<5	6
NH_3-N, mg/l	<2	0.8
PO_4 as P, mg/l	<1	0.1
Turbidity, NYU	0.3-3	0.3

8. **The water management applications of MBRs (e.g. combined sewer overflows (CSO), reuse, blending).** This pilot study demonstrates that MBR systems can be used to treat dilute and variable municipal wastewater streams to extremely high levels. MBR systems, like the one piloted, can be used for many types of reuse, including all four levels of reuse identified in the State of New York. The high-quality effluent could be blended with storm flow to meet the proposed US EPA blending policy and could have multiple beneficial reuse applications, including groundwater recharge, industrial reuse, agricultural reuse, and public access irrigation reuse. As has been demonstrated in other parts of the US, membrane systems can be used for a variety of reuse applications and are one of the technologies that are making reuse a financially and environmentally attractive option.

SECTION I

DESCRIPTION OF STUDY

The aim of the NYSERDA funded project, **"*Pilot Testing of an Innovative Small Footprint – High Efficiency Municipal Wastewater Treatment Plant*"** (**Contract #6603**), was to study the combination of an enhanced, high rate primary treatment process with a membrane bio-reactor (MBR). At the on-set of the project, an extension in time and cost was approved by NYSERDA to accommodate for the testing of a Biological Nutrient Removal Membrane Filtration Pilot Plant that was made available by Zenon, Inc. The combination of enhanced settling and BNR-MBR had not been previously tested or evaluated at the pilot scale. This project afforded the opportunity to study and demonstrate a novel, small foot print treatment train to produce reuse quality effluent, with potentially significant energy and operational cost savings.

The primary partners in this project were Rockland County Sewer District No. 1 (RCSD No. 1) and Manhattan College. United Water of New York was involved in the initial stages of the project and was responsible for securing the Zenon™ BNR-MBR pilot reactor and the original design and initial assembly of the pilot plant. United Water was also a major source of matching funds for the project. United Water's involvement in the project declined steadily as the project proceeded, with little or no participation in the last twelve months of pilot testing.

Project Objectives

The purpose of this project was to perform a full technical-economic study of this new treatment scheme. The evaluation was based on both pilot testing and existing data and future regulations. This project addressed the following issues:

Impact of residual polymer on membranes: Residual polymer in water is known to cause membrane fouling. The goal was to evaluate the impact of different polymers on the membrane and assess the role played by flocs in protecting the membrane.

Final water quality evaluation: The quality of the final effluent will determine whether opportunities exist to reuse the treated effluent. This includes nutrient removal (N and P), microbial quality, and all other water quality criteria proposed for Level 3 water reuse in New York State as shown in Table 1-1.

Process efficiency and reliability: The full-scale implementation of this design requires an assessment of the potential risks or failures associated with this design. Therefore, the applicability and reliability for full-scale application of this specific treatment system, and other similar systems using MBRs, was considered. Comments and suggestions based on the piloting results and the experience of operating and optimizing the system were made to potentially improve operation and performance of a full-scale MBR reuse plant like the one piloted in this study.

<u>Economic assessment:</u> Comparison to conventional wastewater design, including investment, O&M, energy savings, and chemical costs, was performed. Potential for beneficial reuse of the biosolids was also evaluated, since biosolids can be a significant cost in the operation of a wastewater treatment plant and can have environmentally beneficial applications.

Scope of Work

To achieve these objectives, the project was divided in the two primary phases, each with multiple tasks. Below is an outline of the phases and related tasks that were carried out over the duration of this study.

Phase I - Preliminary Work
- Task 1 – Analytical setup and jar testing
- Task 2 – Bench-scale testing
- Task 3 - Pilot plant development

Phase II - Pilot Plant Testing
- Task 1 - Pilot plant assembly, seeding, and start-up
- Task 2 - Pilot plant operations and testing
- Task 3 - Economic and operational evaluation and assessment

Table 1-1: New York State Department of Environmental Conservation Proposed Level 3 Water Reuse Standards

Parameter	Effluent Quality Goals
BOD_5 (mg/L)	<3
Total Suspended Solids (mg/L)	<3
Total Kjeldahl Nitrogen -N (mg/L)	<3
Ammonia, NH_3-N (mg/L)	<1
Nitrite-N (mg/L)	0
Nitrate-N (mg/L)	2-4
Total Nitrogen (mg/L)	5-8
Total Phosphate, P (mg/L)	0.2 (1)
Fecal Coliforms (no./l00 mL)	200/l00
Total Coliforms, MPN (no./l00mL)	2400/l00
Dissolved Oxygen (mg/L)	7
Settleable Solids (mL/L)	<0.1
Giardia Cysts	99.9% removal (1)
Enteric Viruses	99.99% removal (1)
Chlorine Residual (mg/L)	0.005 (2)
Turbidity (NTU)	0.5-3.0
pH	6.5-8.5
Temperature (^{0}C)	21 (estimated)
Aluminum (mg/L)	0.1 (3)
Iron (mg/L)	0.3 (3)
Manganese (mg/L)	0.3 (3)
Copper (mg/L)	0.0085 (3)
Zinc (mg/L)	0.078 (3)
Amenable Cyanide (mg/L)	0.0052 (3)
Total Mercury, Hg (mg/L)	0.0007 (3)

(1) Based on standards to discharge within the New York City watershed.
(2) Based on water quality standards for aquatic toxicity.
(3) Based on New York State ambient water quality standards and guidance values.

SECTION 2

PHASE I - PRELIMINARY WORK

This first phase of the MBR study involved three tasks carried out in parallel.

Task 1- Analytical Setup and Jar Testing

Manhattan College developed a modified jar testing protocol for evaluating various coagulants, flocculants, and polymer additions to determine their impact on settling and phosphorous removal. Jar testing is a standard methodology for testing and selecting coagulants. In addition, Manhattan College and RCSD No.1 developed sampling, operational, and analytical protocols for all testing done in Phases I and II. The majority of these protocols were taken directly from or adapted from Standard Methods.

Manhattan College carried out a series of jar tests to determine the best coagulant/polymer to use for the pilot treatment of the RCSD No.1 raw water using the high rate clarifier unit. The analyses performed during the jar test studies included:

- Turbidity Removal
- TSS Removal
- Phosphorous removal
- pH
- Alkalinity

Methods

The protocol used for the jar testing was similar to the standard jar test protocol presented by jar test manufacturers Phipps and Bird ™. Over 20 coagulants, flocculants, and polymers were included in the study. The initial screening of the chemicals was performed using concentration ranges suggested by the manufacturer. Certain combinations of coagulants and coagulant aids were not considered based on the literature and manufacturer experience and input. Each coagulant and coagulant/polymer combination was jar tested as directed by the manufacturer. The treated jars were analyzed for solids removal, final turbidity, and phosphorous removal.

<u>Results</u>

Over 50 jar tests were conducted during this phase of the study. Results showed that a commercially available alum blend, coagulant Nalco 8187, ferric chloride, and alum each performed very well over a relatively wide dosage range. Other chemicals that were tested showed similar removal results but either required high doses or were cost prohibitive for pilot or full-scale application.

The coagulant 8187 was determined to be the best for removing TSS and turbidity but was outperformed by both alum and ferric chloride in phosphorous removal, as shown in Table 2-1. Although alum removed more TSS, turbidity, and phosphorous than ferric chloride, it required about 40% more chemical addition than ferric chloride.

Table 2-1: Three Best Performing Coagulants of 20 Tested

Coagulant	Dose Range (mg/L)	% Removal TP	% Removal TSS	% Removal Turbidity
Nalco 8187	30-35	68	76	87
$FeCl_3$	35-40	78	73	83
Alum	50-55	82	75	79

Conclusions

Results from Task 1 indicated that Nalco 8187, ferric chloride, and alum were the three best additives to enhance TSS and phosphorous removal. The addition of coagulant aids and polymers did not appear to enhance removal efficiencies for any of the coagulants, so none were used in subsequent studies. The three best coagulants were evaluated at the bench-scale to determine their impact on membrane performance.

Task 2 – Bench-Scale Testing

The purpose of this task was to determine the impact of residual coagulant on the membrane fouling and MBR performance using a bench-scale testing system.

Description of the System

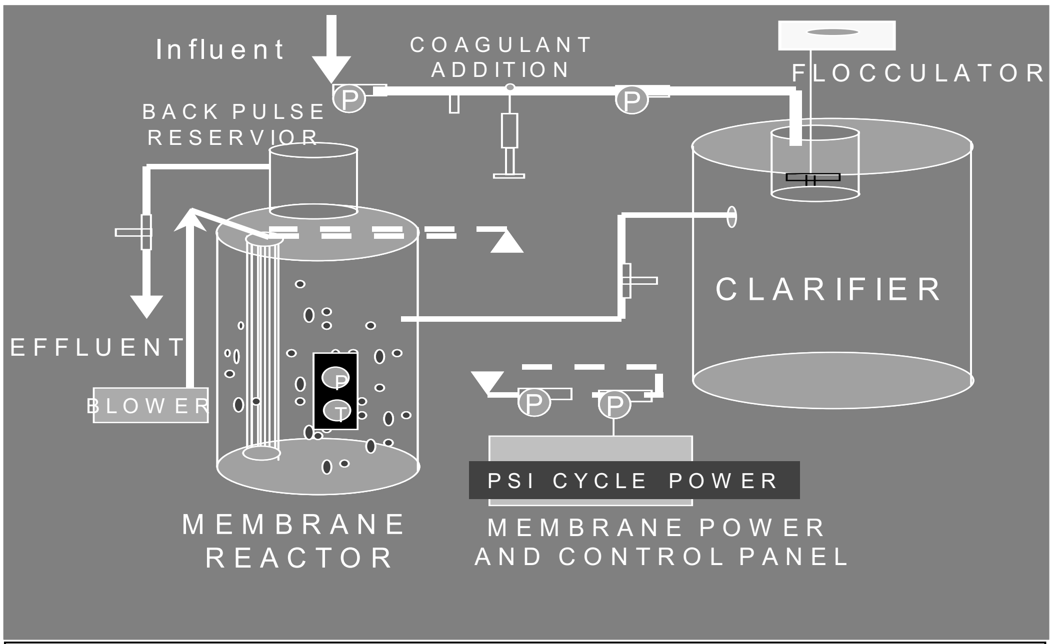
A bench-scale biological membrane reactor (model ZW-10) was provided by Zenon, Inc. (Toronto, Canada). This system was used to test the impact of the three chosen coagulants on membrane fouling. In addition, it was used to develop seeding, start-up, and operational protocols for the larger pilot system. The bench scale system included a 400-liter primary clarifier, a 100-liter biomembrane reactor, a 25-liter effluent holding tank, and all accessory equipment. The biomembrane reactor consisted of a module of about 100 hollow fiber membranes oriented vertically between two headers and arranged around a center aeration tube that supplies diffused air and coarse bubbles for membrane scouring. The top header had two holes: one for permeate, and one for pressure measurement.

Membrane pore size diameter was 0.04 micron, and the nominal surface area for the module was approximately 10 ft^2, which provided a permeate flow of about 0.5 - 0.75 liters/minute. The module was mounted directly inside the 100-liter reactor. The system also included an effluent pump, a syringe pump to deliver the coagulant, in-line mixers, a small flocculation tank, a control panel, and pressure and temperature gauges. Figures 2-1 shows a diagram of the bench scale system with the average operating characteristics. Figure 2-2 is a photo of the actual bench-scale system used for the study. Since the bench scale system consisted of only one continuous flow stir tank reactor, only BOD and ammonia removal (nitrification) were tested, along with chemical phosphorous removal and membrane fouling.

Bench-Scale Seeding and Operation

The MBR was seeded using concentrated sludge from the RCSD No.1 Wastewater Treatment Plant. It was started up in batch mode with RCSD No.1 raw wastewater used as the wastewater feed. The raw municipal wastewater from the Rockland Country Sewer District No.1 (RCSD No.1) was pumped into the system at a rate of 1.0 liter/minute. Table 2-2 shows the average characteristics of RCSD No.1 wastewater.

Figure 2-1: Diagram of Bench Scale MBR System



Reactor Volume: 100 liters	**Holding Tank Volume: 400 liters**
SRT: ~ 30 days	**HRT: ~ 100 hours**
MLSS: 7000 mg/l	**Flow: 0.6 L/min**

Figure 2-2: Photos of Bench Scale MBR System

Table 2-2: RCSD No. 1 Wastewater Quality

Parameter	Average
CBOD	130 mg/L
TSS	228 mg/L
Ammonia	22 mg/L
Phosphorous	5.2 mg/L
Alkalinity	230 mg/L as Ca CO3

Chemical coagulant was injected directly into the raw wastewater stream via a syringe pump and was mixed with in-line mixers. After the addition of coagulant, the wastewater entered a small flocculation tank, followed by the primary clarifier. Overflow from the primary clarifier was wasted, while 0.6 L/min was pumped to the biomembrane system. Manual sludge wasting from the reactor and clarifier occurred daily to maintain a 20 day SRT. The three chosen coagulants were tested in this system by applying a specific dose of a specific coagulant to the system for a 10-day period. The first five days allowed the system to reach a pseudo steady-state operation, while the following five days were used to test the effects of the coagulant on treatment and membrane operation. Testing started with low doses, and the dose increased with each 10-day test. The clarifier and membrane module were thoroughly cleaned at the conclusion of each 10-day test. Each coagulant dose obtained from the jar test results was tested in duplicate.

Bench-Scale Performance and Analysis

Initial testing began without chemical addition to establish baseline and control results. Since membrane performance is directly related to fouling, evaluation of the impact of coagulant addition on the membranes was based on four performance criteria: 1) maximum membrane vacuum pressure (VP) rate; 2) average membrane VP rate; 3) average applied VP; and 4) average back-pulse pressure (BP). Treatment performance was also evaluated, including BOD removal, solids removal, phosphorous removal, and ammonia removal.

Results

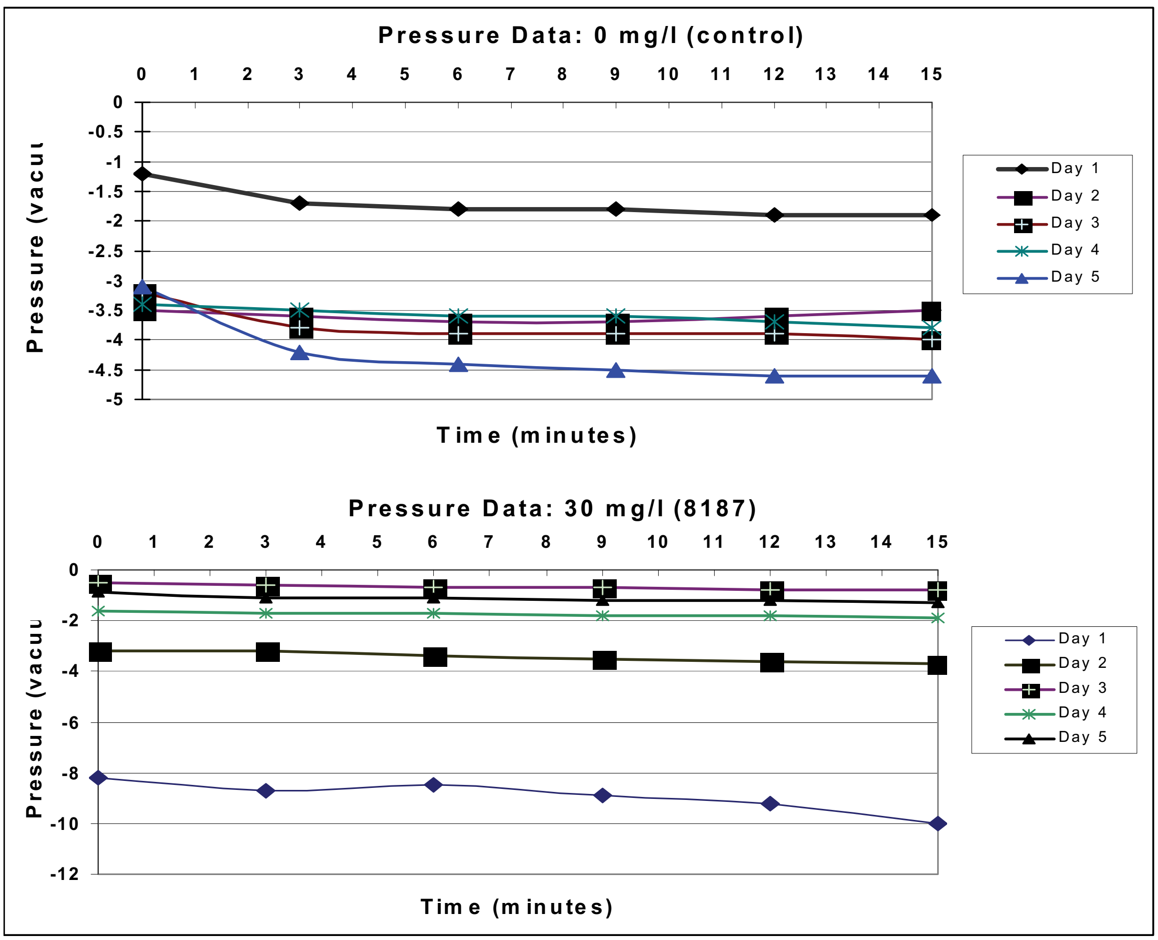
Coagulant Effects:

Coagulant effect on membrane performance was evaluated by measuring the increase in applied vacuum pressure over a 15-minute vacuum-pulse cycle. The biomembrane process uses a vacuum suction to pull the wastewater through the membrane, separating it from the biological and residual solids. The remaining solids cake to the membrane, fouling filter pores and creating a higher applied vacuum pressure demand in the system. Following the 15-minute vacuum cycle, a 30-second positive pressure back-pulse is applied, which cleans biological solids off the membrane, and the cycle is repeated. The applied membrane vacuum pressure data was collected over an average 15-minute cycle each day of a five-day test. Data was recorded every three minutes for a total of five data points per cycle. Figure 2-3 shows typical vacuum pressure profiles for a control (no coagulant) and a 30mg/l dose of coagulant 8187.

Max and Average VP Rate: The magnitude of the applied vacuum pressure indicates the degree of membrane fouling. Note that for each 15-minute cycle, as time increases, the degree of membrane fouling increases (slope increases). The increasing slope indicates that vacuum pressure is rising at an increasing rate, or the rate of membrane fouling is increasing. The steeper the slope, the quicker fouling occurs. Note also the difference between the control profile and the 8187 profile. For the control, as the five-day test progresses, the membrane vacuum pressure becomes greater at the start of each cycle, indicating that the initial degree of fouling increases. With the 8187, the membrane vacuum pressure becomes lower at the start of each cycle, indicating that the initial degree of fouling decreases as the test progresses. These observations imply that some type of activated sludge conditioning is caused by the residual coagulant, resulting in enhanced membrane performance and decreased membrane fouling rate.

<u>Back-pulse Pressure:</u> Back-pulse data was recorded daily at the end of the 15-minute vacuum cycle. This data was expressed as positive pressure and indicates the level of persistence of the cake, or fouling residual solids/ biological solids (MLSS), attached to the membrane surface. For example, a non-persistent cake would require less back-pulse pressure to be removed, and a persistent cake would require more pressure. The data demonstrated that the cake became less persistent when a coagulant was added to the system; therefore, a lower back-pulse pressure was needed to clean the membranes after every cycle.

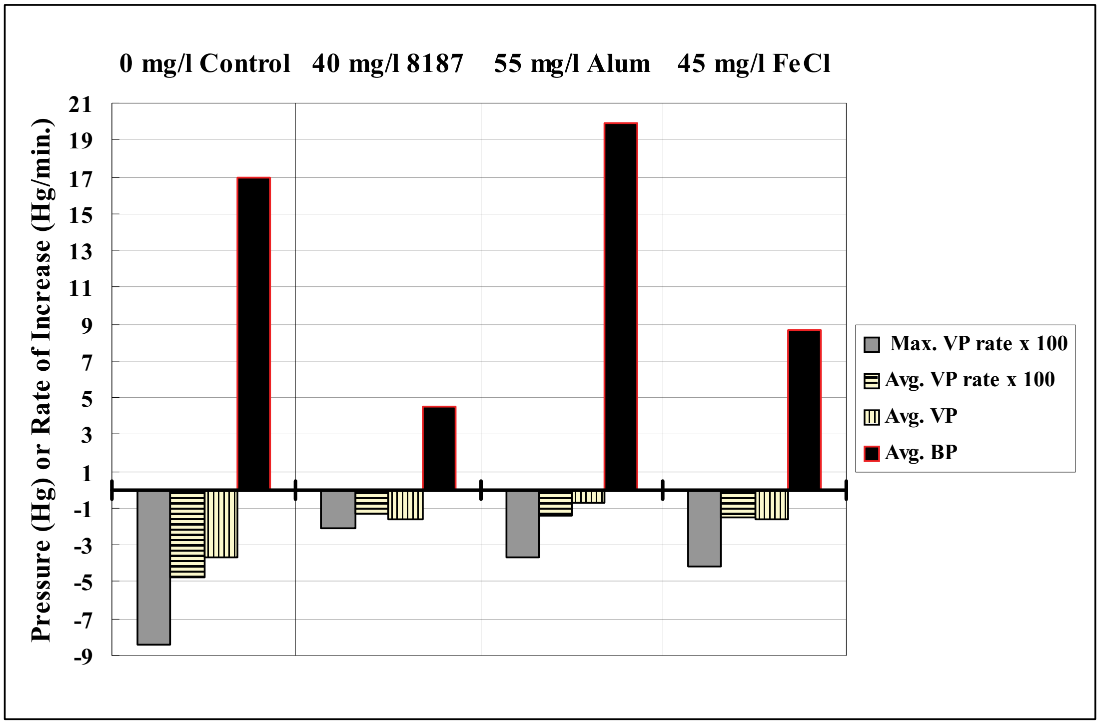
Figure 2-3: Membrane Pressure Profiles (VP) Without and With 8187 Coagulant



Membrane Performance Results:

Figure 2-4 compares membrane performance of the control (no coagulant) to each coagulant tested at its optimal dose. All three coagulants outperformed the control with regard to rate (average and max) and degree of membrane fouling, as well as the degree of cake persistence. The only exception was the greater degree of fouling persistence exhibited by Alum, which required a higher back-wash pressure to remove the caked solids.

Figure 2-4: Membrane Performance Using Different Coagulants



Based only on the effect of the coagulants on membrane performance, coagulant 8187 out performed the Alum and Ferric Chloride in each of the evaluation criteria. However, when taking into account solids removal, phosphorous removal, impact on membranes, and cost, ferric chloride proved to be the best coagulant to use in the pilot study. Table 2-3 shows a summary of the effects of ferric chloride dosing on membrane performance. Table 2-4 shows the percent reduction in each of the four membrane performance criteria compared to the control. Figure 2-5 shows the obvious positive impact of Ferric chloride on membrane performance.

Water Quality:

Removal of BOD, COD, and nutrients was monitored at three sample locations in the system; these included bench primary influent (BPI), bench primary effluent (BP1), and bench secondary effluent (BP2). In addition to monitoring the bench system, influent and effluent samples of the full-scale RCSD No.1 treatment plant (P2) also were analyzed, so comparisons could be made, and an initial set of full-scale performance data could be collected. Overall, the water quality produced by the bench scale system was very good and in some cases exceeded reuse quality standards (TSS, ammonia and BOD). For example, Figure 2-6 shows that the bench scale secondary effluent (BP2) had negligible ammonia concentrations and high nitrate concentrations as compared to the influent (BPI) and the RCSD No.1 effluent (P2). This indicates that complete nitrification was achieved during the bench scale testing.

Table 2-3 – Summary of FeCl Dose Versus Membrane Performance

WEEK	DOSE	AVG. INIT PRES.	AVG. FINAL PRES.	BP MIN	BP MAX	BP AVG	SLOPE	SLOPE	SLOPE
0	0 mg/l	-1.7	-4.83	2.9psi	7.8psi	4.9psi	-0.039	-0.0838	-0.0472
1	40 mg/l	-2	-3.95	2.6psi	5.5psi	4.3psi	-0.0171	-0.0124	-0.024
2	40 mg/l	-0.96	-0.88	3.4psi	5.6psi	4.5psi	-0.0076	-0.0162	-0.0133
3	30 mg/l	-1.95	-5.05	2.8psi	3.3psi	3.13psi	-0.0048	-0.0124	-0.0111
4	30 mg/l	-3.43	-1.13	0 psi	5.2psi	3.25psi	-0.1038	-0.0229	-0.0402
5	50 mg/l	-0.52	-2.4	4.1psi	4.1psi	3.65psi	-0.0181	-0.021	-0.0145
6	50 mg/l	-0.1	-0.3	4.1psi	6.1psi	5.1psi	-0.0124	-0.0076	-0.0133

Table 2-4: Percent Reduction vs. Control

Dose	Maximum VP Rate	Average VP Rate	Average Applied VP	Average Applied BP
40 mg/l 8187	75	72	57	74
55 mg/l Alum	56	70	80	-17
45 mg/l FeCl	50	68	56	49

Figure 2-5: Positive Impact of Ferric Chloride Addition on Membrane Fouling

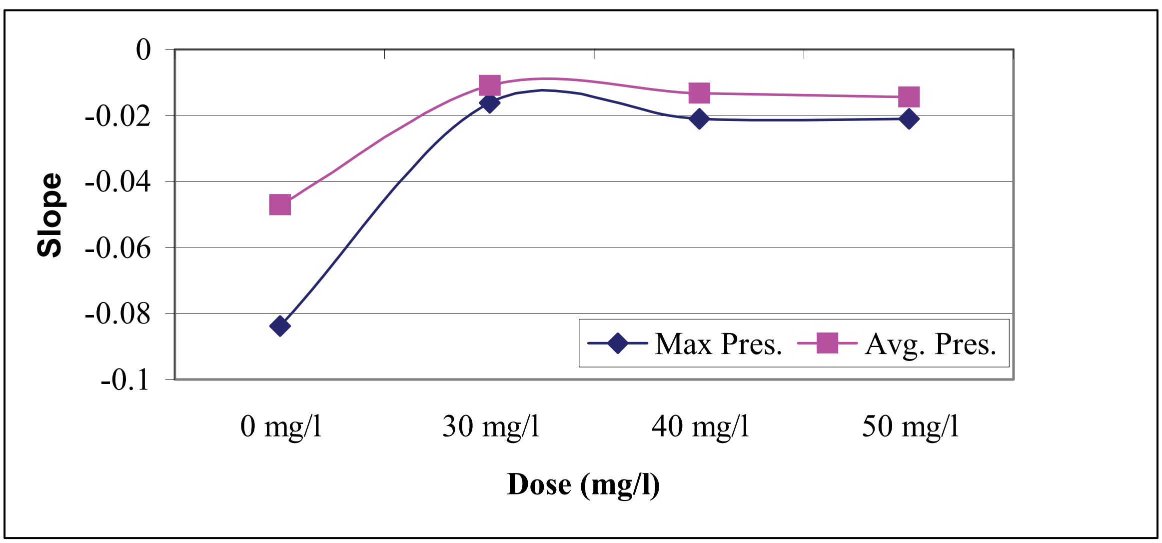


Figure 2-6: Nutrient Concentrations Across MBR Bench System

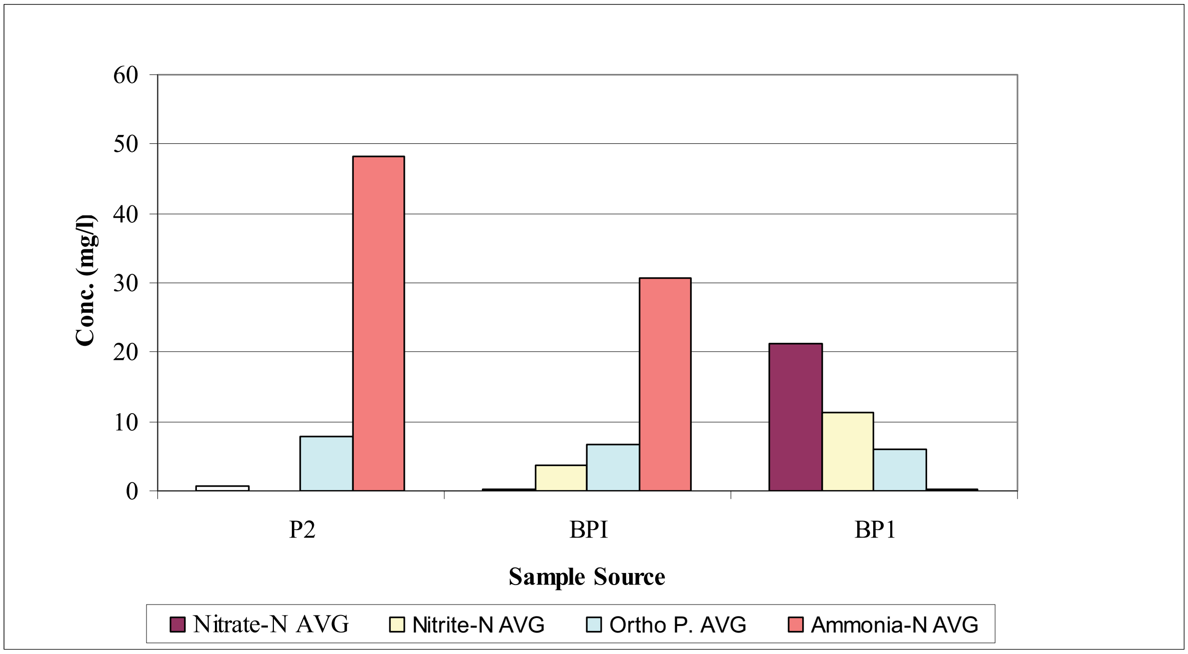


Table 2-5 shows complete water quality performance data for coagulant doses ranging from 30 to 50 mg/l and the percentages of removal for SS, BOD/COD, and ammonia, as compared to a control with no coagulant. Membrane processes consistently remove at least 97% of each constituent regardless of chemical dosage. Solids data for the bench scale system are shown in Table 2-6. The amount of solids removed in the primary clarifier was determined using two methods. The first method used a mass balance of solids across the clarifier using average flow rates and average influent/effluent solids concentrations. The second method measured the volume and concentration of primary sludge produced during each five-day test. Tables 2-5 and 2-6 show that a high percentage of the organic solids content was removed during operation, indicating that operational parameters such as SRT and F/M were at near optimal conditions for this system.

Conclusions

Independent of type or dose of coagulant addition, the bench system removed 98% of the influent BOD_5, and 99% of the suspended solids in the raw wastewater. As predicted by the jar test results, coagulant addition aided in removing an average of 85% of phosphorus from the treated water, and 98% of ammonia was effectively converted into nitrate, indicating full nitrification within the biological system.

More importantly, membrane performance improved significantly with coagulant addition. Results showed that doses greater than 30 mg/l enhanced operation by reducing the average and maximum membrane fouling rates by as much as 75% (Figure 2-4). In addition, the average degree of fouling decreased by 60%, and the back-pulse pressure requirement also decreased significantly. Only alum showed a deleterious effect on the back-pulse pressure, which indicated that residual alum may require more rigorous membrane cleaning. From the bench-scale studies it was determined that ferric chloride was an ideal coagulant to be tested at the pilot level, based on its high level of TSS and phosphorous removal, improvement on membrane performance, and relatively low cost compared to Nalco 8187. Figures 2-7a and 2-7b are conceptual representations of how residual coagulant may enhance membrane performance, as described below.

Table 2-5: Process Performance and Water Quality vs. Coagulant Dose

DOSE	TEMP (^{O}C)	Ph	AVG. Eff. SS mg/l	% Removal SS	FINAL BOD_5/COD	% Removal BOD_5/COD	Initial NH_3 mg/l	Final NH_3 mg/l	% Removal NH_3
0 mg/l	17	7.4	0.66	99.9	3.0/47	98.7/88.2	67.1	0.251	99.6
40 mg/l	16	7.4	0.33	99.9	3.0/46	98.7/90.6	31.5	0.218	99.3
40 mg/l	17	7.4	0.42	99.9	2.3/42	99.1/91.3	*	*	*
30 mg/l	14	7.4	0.42	99.9	2.0/33	99.3/92.1	25.5	0.539	97.8
30 mg/l	15	7.4	0.25	99.9	4.0/43	98.4/89.6	36	0.205	99.4
50 mg/l	16	7.5	0.8	99.9	2.0/30	99.2/95.4	41.5	0.441	99.1
50 mg/l	17	7.5	0.8	99.9	2.0/43	98.8/91.9	38	0.456	98.8

* Denotes no available data

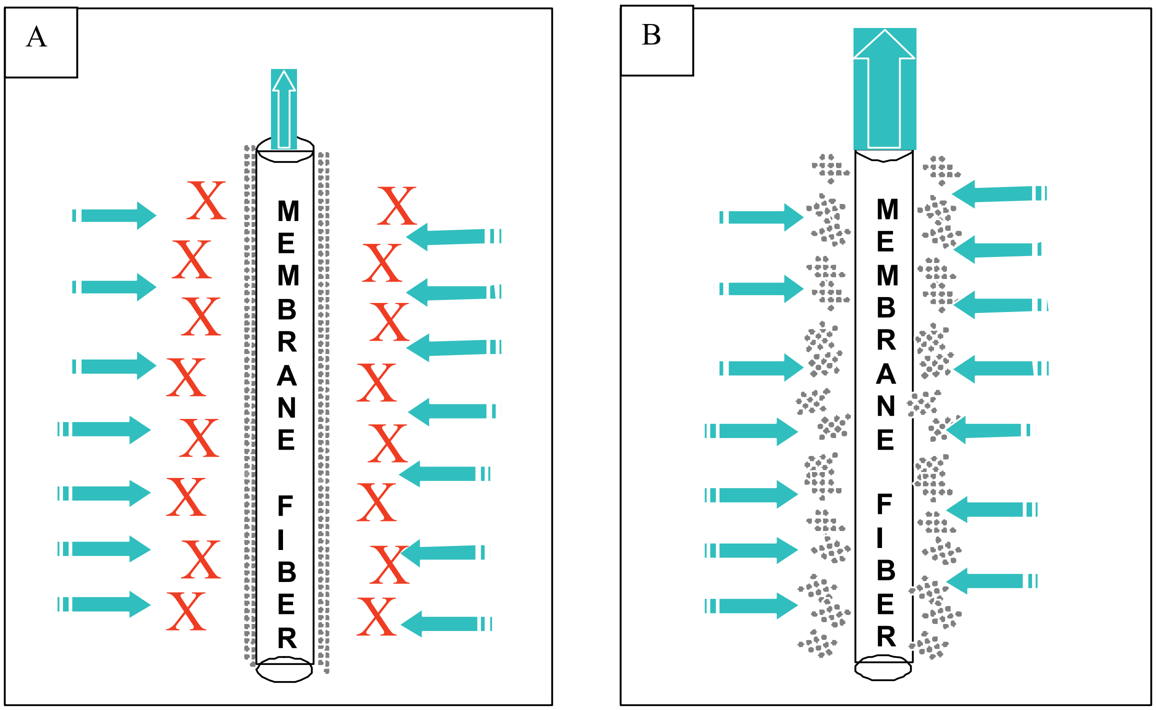
Table 2-6 Solids and Operational Data For Bench System

WEEK	DOSE	Q_{avg}	SS_0 mg/l	SS_1 mg/l	$\%_r$ Clar.	(SS_0-SS_1) mg/l	V_{ss}	[MLSS] mg/l
0	0 mg/l	1 L/min	785	255	67.5	530	76 L	11300
1	40 mg/l	1 L/min	2105	295	86.0	1810	114 L	7000
2	40 mg/l	1 L/min	1290	230	82.2	1060	114 L	6820
3	30 mg/l	1 L/min	1760	620	64.8	1140	114 L	9420
4	30 mg/l	1 L/min	1935	275	85.8	1660	114 L	7780
5	50 mg/l	1 L/min	1625	170	89.5	1455	114 L	5540
6	50 mg/l	1 L/min	805	445	44.7	360	114 L	9860

$TSS_1 = Q_{avg} (SS_0 - SS_1)$ and $TSS_2 = V_{ss} [SS]$

Without coagulant, solids and biomass remain very small, so when suction is applied, they fill the tiny pore spaces and create a dense and highly persistent sludge cake on the membrane surface. This impedes flow, which requires higher vacuum pressure to draw water through and higher positive pressure to blow the sludge cake off. However, when coagulant is added, membrane performance is enhanced by the aggregation of small particles into flocs that are larger than membrane pore spaces. The flocs create a porous cake on the membrane surface that is more conducive to flow through the membrane and is less persistent during back pulse. These improvements result in less wear on the membrane, which translates into less operational downtime for cleaning and lower cost to operate the system.

Figure 2-7: Conceptual Description of Coagulant Enhance Membrane Performance:
A) Premature Fouling: Without coagulant, membrane is coated with dense layers of persistent biomass. B) Reduced Fouling: Coagulated floc creates a porous biomass coat on membrane fiber, which results in less resistance to flow.



Task 3 - Pilot Plant Development

The original conceptual design for the pilot plant was to test a DensiDeg (Degramont) high-rate primary settling tank combined with a basic MBR capable of removing only BOD and nitrification. During Phase I of the study, it came to our attention that Zenon had a BNR (nitrification and denitrification) pilot plant available for a minimal increase in rental costs. United Water secured the lease for the BNR MBR from Zenon. The BNR MBR allowed an upgrade of the study to include the production of reuse quality water, which coincided with the desires of Rockland County Sewer District No.1 to evaluate treatment options for a discharge to groundwater treatment plant to service northern Rockland County Communities. However, a cost effective pilot scale DensaDeg® unit was unavailable, so the treatment train was revised by United Water to include chemically enhanced, short residence time primary settling, followed by the BNR MBR.

The treatment train combined two processes developed in the early nineties: an enhanced primary clarification process and a membrane bio-reactor (ZEEWEED®/ZENOGEM® PROCESS) provided by Zenon Environmental, Inc. This study is the first time these technologies have been combined for reuse application. [Note: Testing of the MBR system in this case will be on low strength, highly variable municipal wastewater that is heavily influenced by storm events and industrial inputs].

Originally, the pilot was to consist of a single settling unit that was built to accommodate the flow of the smaller Zenon pilot plant proposed in the original project. The availability of the BNR Zenon membrane pilot plant allowed for the extension of the project to include BNR and reuse. The larger Zenon unit required a higher flow rate, and a second settling tank was added to treat the higher flow rate. In the end, the high-rate primary clarification process consisted of two treatment vessels that were combined to produce a dense sludge, allowing for a high quality effluent while minimizing sludge handling. Chemical coagulant (Ferric Chloride) was used to enhance settling and provide for chemical phosphorus removal (See Phase I results). The complete pilot system was designed and initially constructed by United Water.

The ZenoGem® process is a patented, advanced treatment technology designed to provide superior treatment for municipal and industrial wastewaters. The process has been commercialized for over ten years, and it has been successfully applied in a number of private and public wastewater treatment applications. Like the ZW-500 pilot plant that was to be used for the current NYSERDA pilot study, the ZenoGem® process is based on a membrane bioreactor in which a microfilter replaces the clarifier found in conventional activated sludge biological treatment plants. However, unlike the ZW-500, the ZenoGem® has two custom-built, fully integrated aerobic and anoxic high-rate settling tanks preceding the biofiltration tank to provide primary clarified effluent and phosphorous removal prior to biofiltration. Figure 2-8 shows a process schematic of the ZenoGem® pilot plant. Figure 2-9 is a photo of the actual pilot plant in operation.

The ZenoGem® BNR pilot plant required a flow of approximately 12 - 14 gpm. The use of the ZenoGem® pilot unit required two rapid-settling systems, each with a capacity of 6-10 gpm. The original project required only one settling unit, so as part of the extension an additional settling unit was built.

The ZenoGem® pilot unit was a fully integrated BNR system with flexible aerobic and anoxic tankage, various staging and recycling options, and a host of process control and monitoring features. The specifications for the BNR pilot unit were as follows:

- Feed Pump – 24 gpm
- Skid mounted system –approximately 30’(L) X 8’ (W) X 12’(H)
- Tank (mounted on skid) – complete with baffles and a total volume of 7,000 gal to provide for the following reaction/treatment zones :
    - 1 - Anoxic zone
    - 2 - Aerobic zone
    - 3 - Anoxic zone
    - 4 - Aerobic (membrane) zone

- Aeration blower
- Permeate Pump
- Recirculation pumps (1-150 gpm)
- Magnetic flow meters for recirculation flow
- Diaphragm valves to control recirculation flows
- Submersible pumps for mixing in zones 1,2,3,4
- Methanol addition pumps
- Alum and other chemical pumps
- Effluent flow meter and totalizer
- Air flow meter
- Two (2) ZW-500 Membrane modules
- SCADA instrumentation and controls
- Electric power transformer
- Effluent turbidity meter
- Data logger (monitor 10 instruments, to be defined)

In addition to the unit, Zenon provided technical assistance for start-up and operation of the unit throughout the pilot study. The unit was equipped with remote monitoring capabilities to allow for Zenon representatives and project PIs to monitor pilot plant performance via internet access.

The membrane bio-reactor volume was a 7,000 gallon, suspended growth biological reactor equipped with a submerged microfiltration membrane system. The reactor tank consists of four zones separated by baffles: two anoxic zones, one aerobic zone, and one aerobic membrane zone (Figure 2-8). The system had internal recycle to enhance the dentrification process and external recycle to circulate biomass throughout the reactor and move accumulated biomass away from the membranes. The effectiveness of this system was enhanced by the use of immersed hollow fiber membranes submerged in the mixed liquor (ZeeWeed® 500). Each membrane was a reinforced fiber with a nominal pore size of 0.04 micron, capable of removing bacteria, turbidity, and most viruses (a vast improvement over conventional systems). Hundreds of membrane fibers, oriented vertically between two vacuum headers, make up a *module*; up to 36 modules make up a *cassette*. Two cassettes were used for this pilot system.

Figure 2-8: Schematic of Pilot MBR System

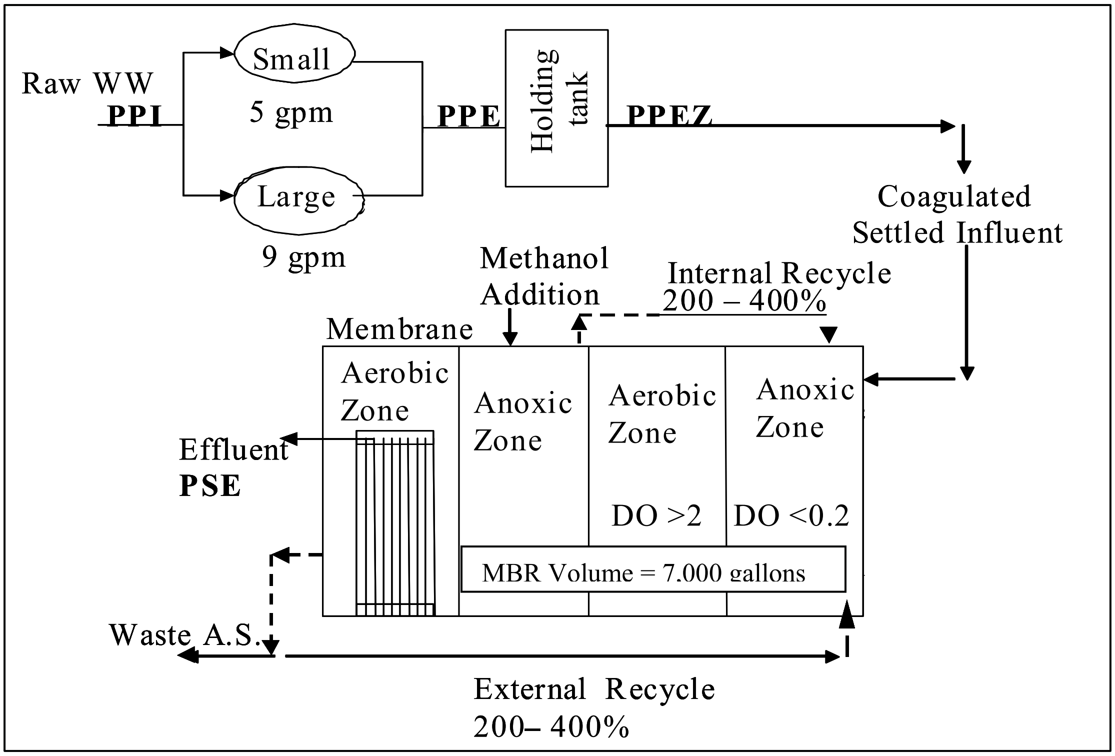
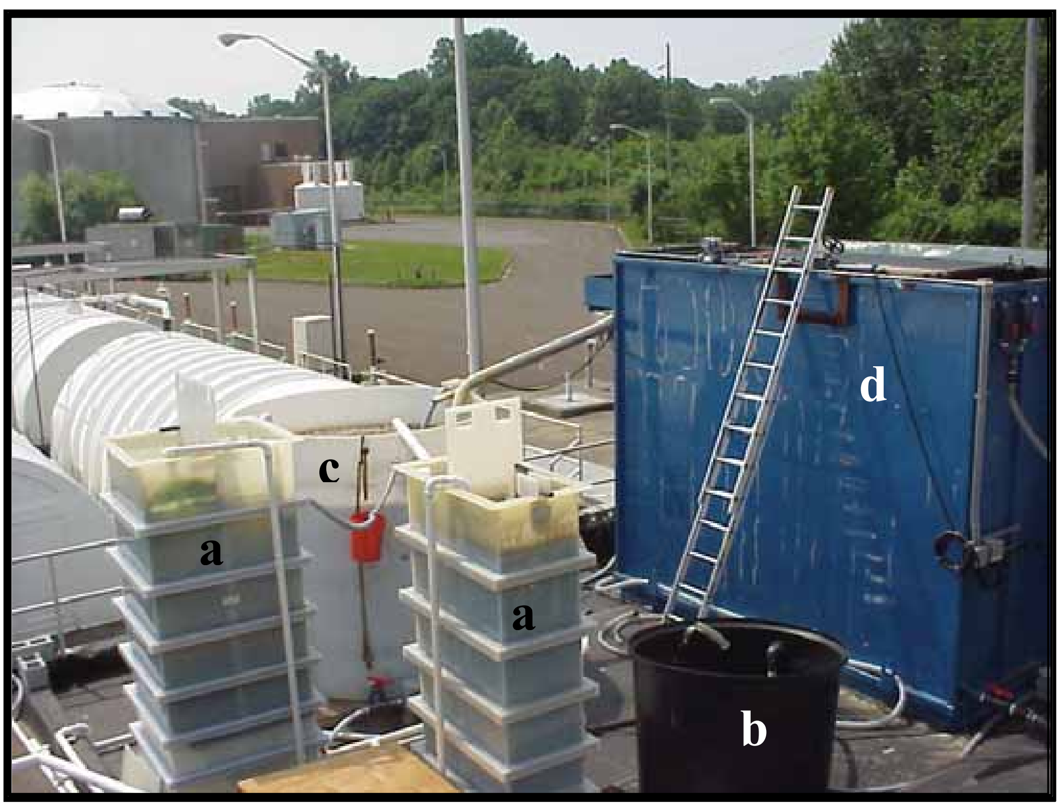


Figure 2-9: Photo of Pilot System: a) High-Efficiency Clarifiers, b) final effluent holding tank, c) 2000 gallon primary holding tank (white), d) 7000 gallon reactor (blue).



SECTION 3

PHASE II - PILOT PLANT TESTING

Task 1 - Pilot Plant Assembly, Seeding, and Start-up.

Set-up/Start-up

Due to the size of the pilot system, correct siting of the pilot plant at RCSD No.1 was important. A number of issues were taken into account when siting the pilot system, including: access to electrical and water supplies, structural integrity, spill and leak containment, and access to equipment needed to unload and position the pilot plant. In addition, the location could not interfere with the everyday operations of RCSD No.1. The chosen location of the pilot system allowed access to all needed utilities and had minimal containment requirements.

Once properly sited, the pilot system was assembled and started by representatives of Zenon®, United Water, and Manhattan College. Start-up and general operational protocols were developed by Zenon®, with input from RCSD No.1 and Manhattan College. Results and experience gained from the bench-scale (ZeeWeed® 10) testing played an important role in developing the pilot plant operational protocol. Following a one-week training period, pilot plant operators seeded the system with activated sludge taken from a local treatment plant. The pilot was fed raw wastewater from the RCSD No.1 grit chamber (See Table 2-2). The seed concentration at the time of start-up was approximately 6,000 mg/l MLSS. Start-up was quick with almost complete BOD removal and 90% nitrification occurring within the first four days.

Pilot Plant Operation

Once the pilot system was fully operational, a series of tests were carried out to determine what primary operational variables and parameters impact system performance. The testing focused on basic BNR operation, effect of coagulant dose on system performance, and optimization of nitrification and denitrification (denitrification carbon source: BOD or Methanol, solids management, F/M, and internal/total system recycle). Testing was carried out systematically to optimize each operational parameter of the process prior to chemical coagulant addition. The activated sludge target concentration of 10,000 mg/l MLSS was achieved after one month of operation and was maintained +/- 1500 mg/l MLSS throughout normal operation.

The process flow rate was set at 14 gpm based on the manufacturer's recommendation and the reactor and membrane design characteristics. Flow through the plant was increased to 18 gpm for initial flux tests, and to increase F/M ratios during biological upsets. The SRT averaged approximately 30 days, while the hydraulic retention time (HRT) stayed at approximately 8.3 hours. SRTs were adjusted to deal with problem microbial populations (e.g. *Nocardia*), and HRTs were adjusted based on the results of flux tests.

The MBR system was equipped with internal and external recycle pumps. The internal recycle pump maximized nitrification, while the external sludge pump circulated sludge throughout the system and moved accumulated sludge away from the membranes. Internal and external recycle rates were used to optimize treatment efficiency and maintain active solids and appropriate dissolved oxygen (DO) concentrations across the MBR system.

The SRT was controlled by sludge wasting from the reactor at a rate of 250 gallons per day. The sludge-wasting rate fluctuated as necessary to maintain the MLSS concentration at or near 10,000 mg/l. The DO concentrations were maintained above 4 mg/l in the aerobic zones, and below 0.2 mg/l in anoxic zones. DO variations occurred due to planned and unplanned changes in process parameters and internal pump failures but remained relatively constant throughout testing. Temperature was allowed to vary with ambient weather conditions and became a significant factor in overall system performance. The pH remained at 7.0 throughout the study; however, external controls were necessary to maintain a pH above 6.4 once ferric chloride was added.

System performance was examined by every-other-day sampling of the influent wastewater (PPI), the primary effluent taken from the clarifiers (PPE), the primary settled effluent taken from the holding tank (PPEZ), and the secondary effluent (PSE). The samples were tested for COD, BOD_5, TSS/turbidity, N, and P. Coagulant-enhanced final effluent samples were tested for total and fecal coliform counts, as well as heterotrophic plate counts. Samples of the mixed liquor were taken daily before wasting to check pH, MLSS, and MLVSS. [Note: All lab testing was completed in accordance with Standard Methods (APHA-AWWA, 1995) except for N and P, which were analyzed using an ion chromatograph]. All plant performance parameters were routinely monitored for the duration of the study.

Membrane performance was tracked via an automatic data collection system provided by the manufacturer. Performance parameters included turbidity, process flow, membrane flux, vacuum pressure, and permeability. Membrane operation was continuous and consisted of alternating cycles of vacuum pressure and positive back-pulse pressure. Vacuum pressure cycles lasted 30 minutes and were accompanied by coarse bubble aeration that scours the membranes and removes heavy solids from the membranes. Back pulse cycles lasted five minutes and were accomplished via positive pressure back flush of treated effluent through the membranes, removing more persistent solids embedded in membrane pores. Chlorinated back-wash automatically occurred once a day to thoroughly clean the membranes.

On a single occasion in the early spring of 2003, the system was shut down, and a full chemical cleaning of the membranes was performed when the operating pressure approached the maximum safe operating limit. This was done to protect the system and to restore membrane efficiency after damage caused by excessive down time and biological upsets. The comprehensive cleaning was carried out in the membrane zone according to the protocol provided by Zenon®. Typically, membrane cassettes require a comprehensive chlorine "dip" treatment every 4–8 months depending upon operation and membrane performance.

Process optimization was carried out by systematically maximizing the efficiency of each step of the nutrient removal process. For example, initial water quality results showed that nitrification was occurring at a rate sufficient to degrade greater than 99% of ammonia in the raw water. However, due to the mild characteristics of the influent (low strength, high variability, influence of storm events, and industrial inputs), "ammonia challenges" were conducted to evaluate the resiliency and reliability of the system. Spikes in ammonia concentrations are a regular occurrence at RCSD No.1. Methanol addition was evaluated to determine the optimal dosage for denitrification. The impact of various coagulant doses on primary settling efficiency, phosphorous removal, membrane fouling, and overall pilot plant performance also were evaluated.

The system ran continuously for more than 400 days, but a myriad of mechanical and weather-induced complications interrupted the normal operation and sampling protocol, resulting in process optimization setbacks and some data fluctuations. Most weather related difficulties would not be expected in a full-scale installation, since pipes and tanks would be naturally insulated, and the flow rates and volumes would be large enough to negate the impact of prolonged cold weather. In addition, at full-scale, most of the membrane system would be housed within a building, including most of the pumps, blowers, and other electrical equipment. During the pilot study, Herculean efforts were made to weatherproof the pilot system during one of the worst winters experienced in 20 years. Absent the bad weather and the occasional mechanical/power failures, evaluation of the pilot system was carried out systematically as follows:

1. BOD removal and Nitrification Optimization (including ammonia and flux challenges)
2. Denitrification Optimization – methanol dose, DO, and pH
3. Phosphorous Removal Optimization - FeCl dose, pH, membranes.

Task II – Pilot Plant Operation and Testing

Water Quality Results

Wastewater BOD Removal

Soon after start-up it was evident that the MBR system could easily remove greater than 98% of influent BOD. Typically, the BOD was less than 2.0 mg/l leaving the pilot system, as shown in Table 3-1. The primary clarifiers typically removed 40% of the influent suspended solids throughout the pilot testing period. Unlike conventional treatment systems, it can be assumed that the majority of the BOD in the membrane effluent is not associated with biomass leaving the system but with dissolved organic matter.

Solids Removal

Table 3-2 shows the average effluent quality in terms of solids and BOD removal. The data indicates that without the aid of coagulant, the system is capable of meeting reuse standards for TSS and BOD. The addition of coagulant made only a minor improvement in performance for these parameters. Note that with coagulant addition, the turbidity of the effluent was comparable to that required for *drinking* water filtration

(NTU < 0.3). Table 3-3 shows that the effluent solids, turbidity, and BOD_5/COD concentrations were well below NYS DEC Level 3 reuse requirements (See Table S-1).

Table 3–1: Mass Balance for BOD Across MBR System

Process	PPEZ	PSE	Removal	% Removal
with no FeCl3	130.4 mg/l	1.58 mg/l	128.8 mg/l	98.79
with 45 mg/l	125.8 mg/l	1.96 mg/l	123.9 mg/l	98.44
with 65 mg/l	130.5 mg/l	1.67 mg/l	128.8 mg/l	98.72

Table 3-2: Mass Balance for % Solids Removal Across the Primary Clarifier

Process	TSS of PPEZ	Turb. PSE	TSS of PSE	Removal	% Removal
with no FeCl3	124 mg/l	0.36	0.8 mg/l	123 mg/l	99.33
with 45 mg/l	142 mg/l	0.29	0.6 mg/l	141 mg/l	99.53
with 65 mg/l	111 mg/l	0.25	0.6 mg/l	111 mg/l	99.48

Table 3-3: Solids and Substrate Removal With Ferric Chloride Addition

Sample/ Dose	TSS (mg/l)	COD (mg/L)	BOD_5 (mg/l)	Turbidity
PSE/ 0 mg/l	0.33	35.87	1.66	0.14
PSE/ 45 mg/l	0.29	38.91	1.96	0.14
PSE/ 60 mg/l	0.25	20.67	1.67	0.13
Reuse Quality	3	45	3	0.35

It is believed that using more-efficient and better-designed primary clarifiers could have resulted in significantly better primary removal of solids, BOD, and phosphorous. The primary clarifiers were not properly sized for the pilot design flow and were prone to hydraulic difficulties, as well as temperature effects. However, shortfalls in primary clarification were partially made up in the intermediate holding tank. Finally, a highly efficient primary treatment could negatively impact tertiary treatment systems such as the MBR pilot, by removing too much BOD. If the BOD entering the MBR is too low, the F/M ratio can become too low to support the high biomass (~ 10,000 - 12,000 mg/L mlss) in the system. This condition can lead to biological upsets and or excessive biomass decay. These issues are discussed later in the results section. Secondly, it is more cost effective to have excess BOD enter the MBR to reduce the need of methanol for the denitrification process.

Microbial Analysis

Control and destruction of pathogenic microorganisms in the effluent is necessary to protect public health and the environment. The Level 3 and 4 reuse standards require a high degree of inactivation /removal of viruses, pathogenic bacteria, and protozoa (*Cryptosporidium* and *Giardia*). Table 3-4 shows the reduction in total coliforms across the pilot plant, and Table 3-5 shows the reduction in fecal coliforms. The very high reductions (99.999%) are indicative of membrane technologies and are one of the benefits of using membranes as opposed to using secondary clarification followed by sand filtration. Table 3-6 shows the average effluent total and fecal coliform results (cfu/100ml) achieved by the MBR **without** disinfection. Even without disinfection, these results exceed Level 3 and 4 reuse requirements for bacterial contamination.

Low microbial counts were achieved without post secondary disinfection. With low solids content in the effluent, a full-scale MBR plant would likely be equipped with UV disinfection as an additional barrier to deactivate and kill pathogens in the effluent. Since bacteria are significantly smaller than key protozoa pathogens (*Giardia* and *Cryptosporidium*), these results indicate that removal of protozoa would meet Level 3 and 4 reuse criteria (99.99% *Giardia*), especially when followed by UV disinfection. The ability of micro-filtration to effectively remove *Giardia* and *Cryptosporidium* has been demonstrated in both the wastewater reuse and the drinking water industries.

Table 3-4: Percent Removal for Total Coliforms

Date	#/100ml PPI	#/100ml PPE	#/100ml PPEZ	PSE #/100ml	PSE #/500ml	Removal	% Removal
2/24/03	6.7E+06	6.6E+06	4.5E+06				
3/24/03	3.7E+06	2.3E+06	4.0E+06	53		3.6E+06	99.99856
3/26/03	1.8E+06	1.4E+06	1.8E+06	7		1.8E+06	99.99962
3/28/03	3.9E+06	3.3E+06	3.3E+06	5		3.9E+06	99.99986
4/3/03	4.0E+06	2.1E+06	1.6E+06	36	76	4.0E+06	99.99910
4/14/03	3.7E+06	4.2E+06	2.4E+06	37	TMTC	3.7E+06	99.99901
4/16/03	4.5E+06	2.7E+06	2.4E+06	2	10	4.5E+06	99.99996
4/24/03	6.1E+06	2.6E+06	2.7E+06	3	18	6.1E+06	99.99996
4/30/03	1.0E+07	6.0E+06	6.6E+06	6	30	1.0E+07	99.99994

Table 3-5 Percent Removal for Fecal Coliforms

Date	#/100ml PPI	#/100ml PPE	#/100ml PPEZ	PSE #/100ml	PSE #/500ml	Removal	% Removal
2/24/03	3.0E+06	9.4E+06	7.5E+06				
3/24/03	2.5E+06	1.1E+06	1.1E+06	14		2.5E+06	99.99946
3/26/03	3.3E+05	2.7E+05	4.6E+06	1		3.3E+05	99.9997
3/28/03	3.9E+06	1.5E+06	1.2E+07	1		3.9E+06	99.99997
4/3/03	4.0E+05	8.0E+05	6.5E+06	7	22	4.0E+05	99.99825
4/14/03	9.2E+05	2.6E+05	3.7E+05	1	20	9.2E+05	99.99986
4/16/03	2.4E+06	4.7E+05	1.1E+06	0	3	2.4E+06	100.0000
4/24/03	2.0E+06	2.3E+06	5.2E+05	1	1	2.0E+06	99.99995
4/30/03	3.9E+07	2.0E+06	2.4E+05	1	4	3.9E+06	99.99997

Table 3-6: Microbial Quality of Pilot Effluent Compared to Level 4 Reuse Standards

Sample/ Dose	Fecal Coliforms (#/100mL)	Total Coliforms (#/100mL)	HPC (#/100mL)
PSE/ 45mg/L	3	20	6.22E+02
Reuse Quality	200	2400	n/a

Finally, two sets of enteric virus counts were performed by Source Molecular Corporation (Miami, FL), a private analytical lab that specializes in microbial analysis of environmental sample. Virus detection was carried out using the most probable number method on 757 liters of effluent sample (PSE). The results for sample #1 were completely negative, with numbers below the detection limit of 0.15 viruses/100 liters of sample. For sample #2, results were just at the detection limit of 0.15 viruses/100 liters. These virus counts are extremely low and were at or below the analytical detection limit for viruses. Typically, raw municipal wastewater has a concentration of 10 – 20 enteric viruses per 100/ml. The effluent virus counts are based on 100-liter samples and do not include kill associated with disinfection. Even without disinfection, an MBR system would meet the 99.99% removal of viruses required for indirect reuse.

Metals

Table 3-7 shows average metal concentrations in the effluent and compares these results to Level 4 reuse standards and drinking water maximum contaminant levels (MCLs). Results indicate that removal rates fail to meet Level 4 reuse quality standards for copper and zinc. When ferric chloride was used, both iron and aluminum also exceed Level 4 standards. The data also shows that ferric chloride addition did not significantly improve metals removal (Table 3-8). When coagulant was used, concentrations of almost all of the metals increased, especially copper and aluminum. The average concentrations of metals and cyanide in the effluent were highly influenced by a few samples that were an order of magnitude, or more, higher than the average throughout the project. These spike concentrations were likely caused by industrial inputs (10% of flow at RCSD No.1 is industrial), including flows from chemical manufactures, pharmaceutical companies, landfill leachates, and metal-finishing shops. As a quality control check, every other sample was analyzed by a certified commercial lab. The results of the commercial lab analyses are included in the average results. As can be seen in Table 3-7, the metals concentrations typically exceed drinking water MCLs and would meet Level 3 reuse standards.

Better long-term control of the coagulation process (flow adjusted dosing and pH adjustment) would significantly reduce residual iron and other associated metals such as aluminum, copper, and zinc in the effluent. Impurities in the ferric chloride may also contribute to the lower removal rates and supports the results. For systems without significant industrial flow, metals would be less of an issue. Finally, when using tertiary and MBR treatment technologies, effective SRTs range between 20 days and 60 days. Longer residence times produce fewer biological solids, which results in less wasted sludge and decreased metals removal. The key to operating tertiary and MBR treatment plants is to cost effectively balance solids production with adequate metals removal. Other potential solutions for reducing metals would be an equalization tank to dampen any spike concentrations attributed to periodic industrial inputs and/or implementation of a more stringent industrial pretreatment program.

Table 3-7: Average Metals and Cyanide Removal Data for Complete Study

Sample	Al	Fe	Mn	Cu	Zn	Hg	CN
PPI	0.079	1.59	0.642	0.24	0.64	0.001	<0.01
PPE	0.077	6.811	0.831	0.088	0.275	0.000	<0.01
PPEZ	0.080	5.452	0.788	0.077	0.505	0.000	<0.01
PSE	0.091	2.36	0.146	0.091	0.513	0.000	<0.001
Reuse Quality	0.100	0.300	0.300	0.009	0.078	0.0007	0.0052
DW MCL*	0.200	0.300	0.300	1.3	0.200	0.002	0.200

* US EPA Drinking Water Maximum Contaminant Levels

Table 3-8: Metals and Cyanide Removal with Coagulation

Sample / Dose	Al	Fe	Mn	Cu	Zn	Hg	CN
PPI	0.079	1.59	0.642	0.24	0.64	0.001	<0.01
PSE 0 mg/l	0.092	3.36	0.14	0.10	0.51	0.00	<0.01
PSE 45 mg/l	0.116	4.0867	0.1180	0.0852	0.7700	0.0005	<0.01
PSE 60 mg/l	0.168	1.1600	0.2400	0.1820	0.2550	0.0005	<0.001
Reuse Quality Level 4	0.1	0.3	0.3	0.0085	0.078	0.0007	0.0052

BNR Performance Results

Nitrification

Table 3-9 summarizes the nitrification result. Data taken after less than one SRT (~ 30 days) showed that the system was capable of removing enough ammonia to meet reuse standards. The average data is skewed higher by mechanical and weather related difficulties that occurred during the first eight months of operation. Table 3-10 shows results toward the end of the study, when the system was running consistently and the average ammonia concentrations were significantly below 1.0 mg/l.

Initial results of an ammonia challenge were acceptable (91% removal rate); however, two phenomena coincided with the challenge. First, a significant pH decrease in the secondary effluent (pH = 5.3), which likely resulted from low alkalinity in the influent wastewater and the consumption of alkalinity during the nitrification process. Second, a *Nocardia* foaming event likely caused by a low F/M ratio (0.04) and high suspended solids (12,400 mg/l MLSS). Future ammonia challenges were abandoned due to the potential for biological upsets and to protect the system. In the tenth month of operation, the system received a substantial industrial release of ammonia. The influent ammonia concentration was measured at 66 mg/l for a 36 to 48-hour period, compared to a ten-month average of 38.46 mg/l. Neither pH reduction nor biological foaming occurred in this instance, which likely is due to restored alkalinity via denitrification and a more favorable F/M ratio created by methanol dosing. Overall, the system was very responsive and efficient in removing ammonia and can easily produce an effluent with ammonia concentration below 1.0 mg/l as N (Table 3-10).

Table 3-9: Average Ammonia and Nitrification Results

Date	pH	PPI mg/l	PPE mg/l	PPEZ mg/l	PSE mg/l	% Ammonia Removal
One Month	6.96	28	20.35	*	0.1	99.64
Amm. Challenge	5.3	38.7	37.2	18.6	3.46	91.06
Tenth Month	7	66.2	62.9	50.5	4.16	93.72
Twelve Month Average	7.3	38.46	36.45	30.79	1.05	97.27
Reuse Standard	6.5-8.5				<1	

Table 3-10: Nitrification Results Before and During Phosphorous Optimization

Coagulant Dose	pH	PPI mg/l	PPE mg/l	PPEZ mg/l	PSE mg/l	% Removal
0 mg/l Ferric Chloride	7.32	38.46	36.45	30.79	1.05	97.27
45 mg/l Ferric Chloride	7.27	89.44	68.26	70.46	1.04	98.83
65 mg/l Ferric Chloride	6.92	62.77	50.40	49.33	0.76	98.78
Reuse Standard	6.5-8.5				<1	

Denitrification

Table 3-11 shows the denitrification results prior to coagulation. The average effluent nitrate concentration prior to methanol addition was about 15 mg/l. That amount was reduced by more than 75% once an initial dose of 44 mg/l of methanol was added to the system. To optimize denitrification, the internal recycle was set at 250% of influent flow rate (24 gpm), and external recycle was set at 300% of the influent flow rate (24 gpm). Increases in internal recycle by as much as 50% did not result in significant changes in effluent nitrate. However, relatively small decreases in internal recycle rate did reduce dentrification efficiency.

In an effort to minimize chemical costs, the methanol dose was reduced to 38 mg/l for two weeks and was then reset to 44 mg/l when nitrate levels began to rise above 4 mg/l. Winter operation showed poor denitrification results due to biological upsets and mechanical problems brought about by the extreme cold weather, including failure of the internal recycle pump. When the internal recycle rate could be maintained at or above 24 gpm, the reuse standard of 2-4 mg/l nitrate was easily met. The impact and potential causes of biological upsets are discussed later in the report. A methanol dose of 44 mg/l was used for the majority of the study. It is believed that if treating a more concentrated wastewater (medium- or high-strength BOD content), a lower dose of methanol could be applied to achieve the same level of denitrification.

Once the system was operating consistently in reasonable weather, the system was able to meet Level 3 and Level 4 reuse nitrate concentrations consistently, as shown in Table 3-12. Results also indicate that the addition of ferric chloride may have enhanced nitrate removal, but the majority of the effect is likely improved and consistent operating conditions. Table 3-13 shows a mass balance for nitrogen for the complete study.

Table 3-11: Denitrification Results During Cold Weather

Methanol Dose/ Date	Average NO_3 (mg/l)	% Removal
0 mg/l	15.05	
38 mg/l	3.23	78.51
44 mg/l	10.95	27.25
Reuse Standard	2-4	

Table 3-12: Denitrification in Final Six Months of Operation

Coagulant Dose	Average NO_3 (mg/l)	% Removal
0 mg/l Ferric Chloride	9.11	
45 mg/l Ferric Chloride	1.20	92.06
65 mg/l Ferric Chloride	0.84	94.40
Reuse Standard	2-4	

Table 3-13: Mass Balance of Nitrogen across the MBR

Process	NO_3 PPEZ mg/l	NH_3 PPEZ mg/l	TN PPEZ mg/l	NO_3 PSE mg/l	NH_3 PSE mg/l	TN of PSE mg/l	Removal mg/l	% Removal
no methanol	0.04	31.12	31.16	14.11	1.29	15.4	15.76	50.58
44 mg/l methanol	0.33	50.77	51.10	5.21	0.84	6.05	45.05	88.16

Phosphorus Removal

The MBR process without any coagulation was capable of removing only about 14% of the total phosphorus via biological synthesis and uptake. The average effluent phosphorous concentration was 6.44 mg/l, which indicated that inherent biological phosphorus removal was inadequate to meet the reuse quality goal of 0.20 mg/l. Since the system was not designed to carry out enhanced biological phosphorous removal, chemical methods were needed to achieve reuse phosphorous limits.

The results in Table 3-14 and Table 3-15, show average phosphorous removal with chemical addition in the primary and secondary treatment trains, respectively. The combination of the two removal processes did result in an effluent concentration that meets reuse standards. The best results were found when the applied ferric chloride dose was 60 mg/l. This dose was higher than the dose identified in the bench scale. The elevated dose was suggested by Zenon and was based on the stoichiometry of excessive ferric chloride addition. The key issue when using a coagulant in this system was to establish a working ferric chloride dose that produces an effluent that meets discharge standards and does not adversely impact membranes operation or residuals management. These results reinforce the applicability of MBR technology coupled with chemical precipitation to meet strict phosphorous reuse standards.

Table 3-14: Mass Balance of Phosphorous Across the Primary Treatment

Process	OP of PPI mg/l	OP of PPE mg/l	Removal mg/l	% Removal
with no FeCl3	5.46	5.32	0.14	2.56
With 45 mg/l	7.95	1.97	5.98	75.21
With 65 mg/l	6.23	1.47	4.76	76.39

Table 3-15: Balance of Phosphorous Across the MBR

Process	OP of PPEZ mg/l	OP of PSE mg/l	Removal mg/l	% Removal
with no FeCl3	4.19	4.11	0.08	1.91
With 45 mg/l	1.12	0.86	0.26	23.08
With 65 mg/l	0.29	0.14	0.15	51.16

Overall Pilot Performance

Table 3-16 compares conventional activated sludge BNR treatment systems to the performance of this pilot system. The MBR system is capable of meeting lower nitrogen and phosphorous levels, even when compared to an activated sludge system equipped with a porous media filter. These low levels may not be necessary for all applications, but they are becoming increasingly common as more municipalities practice water reuse.

Table 3-16: Removal Efficiency of Conventional Plant vs. Pilot MBR

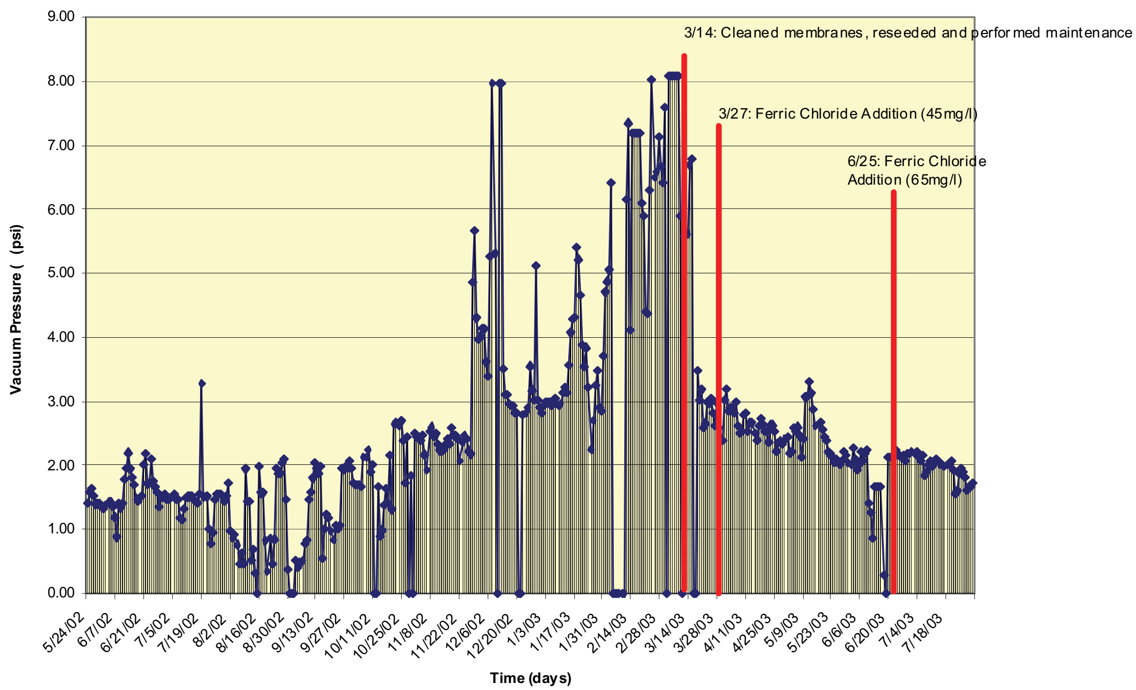
Process	Conventional Plant	MBR
SS, mg/l	10	0.6
BOD_5, mg/l	5	2
COD, mg/l	20-30	21
Total N, mg/l	8	6
NH_3-N, mg/l	2	0.8
PO_4 as P, mg/l	1	0.1
Turbidity, NYU	0.3-3	0.3

Membrane Performance

Coagulant impact on membrane performance was evaluated by measuring the changes in *applied vacuum pressure* and *membrane permeability* over time. Figure 3-1 depicts the average daily-applied vacuum pressure for the duration of the study. Results prior to coagulant addition show membrane vacuum pressure steadily increasing from 1.5 psi to about 8 psi, indicating significant fouling of the membranes. This significant and relatively rapid fouling coincided with the biological and weather related difficulties encountered in the winter (12/1 – 3/15). Because this value approaches the maximum safe operating pressure (12 psi), the membranes underwent a major cleaning to protect the system and to establish more favorable membrane operating parameters (low vacuum pressures, high flux rates, etc.) before adding coagulant. The cleaning coincided with the manufacturer's suggested cleaning every 6 –12 months.

Once cleaned, the vacuum pressure dropped to levels slightly higher (~3 psi) than when the study began. With 45 mg/l of ferric chloride, the vacuum pressure decreased by nearly 33% (~ 2.1 psi) and by another 20% (~1.7 psi) when the dosage was increased to 65mg/l. Times when the vacuum pressure drops very low (< 1.0 psi) indicate prolonged cleaning, system standby, or mechanical and electrical failures.

Figure 3-1: Variable Applied Membrane Vacuum Pressure



Permeability is the *aptitude* of the membrane to be passed through by a fluid and is inversely proportional to vacuum pressure. Figure 3-2 depicts daily-averaged membrane permeability during the study. The results show similar performance improvement when coagulant was added to the system. Prior to membrane cleaning and coagulant addition the permeability decreased from 8.5 to a low of about 1.7. After cleaning, the permeability increased to 4.5 and continued to increase when ferric chloride was added. By the end of the study, the permeability approached the initial value of 8.5. It should be noted that a slight improvement in both the vacuum pressure and the permeability occurred during the first three weeks of operation. This phenomenon also was observed in the bench phase and is not well understood, but it seems to be related to membrane conditioning, sludge age, and the presence of proportionally fewer volatile solids.

Temperature Effects

Warm Weather Foam Event

Figure 3-3 shows membrane operation data obtained during a warm-weather period (July 27 – August 27, 2002). Due to an increase in warm weather and a small decrease in influent BOD (dilution) during that time period, the MBR system experienced a biological foaming event as depicted in Figure 3-3. The event was confirmed as a biological foaming event using microscopy, which showed the ubiquitous presence of N*ocardia* like organisms in the sludge. This foaming event likely occurred due to the low F/M ratio caused by higher specific activities caused by increased water temperatures and lower influent BOD indicative of summer wastewater flows. To overcome the fouling problem, the water level in the MBR system was dropped to decrease hydraulic retention time by 15%, the biomass concentration was dropped by 30%, and the flux was increased from 14 gpm to 18 gpm to increase the supply of BOD. In addition, the foam was sprayed with a concentrated chlorine solution.

The effects of these operational changes are illustrated in the changes in flux. The foaming problem was brought under control; however, there was a residual impact on the membranes that results in a 23% decrease in permeability. In addition, the average vacuum pressure increased due to residual membrane fouling caused by the foaming event. It should be noted that the MBR system did continue to produce a high-quality effluent during this period and responded quickly to changes in operational controls.

Figure 3-2: Variability in Permeability Before and After Coagulant Addition.

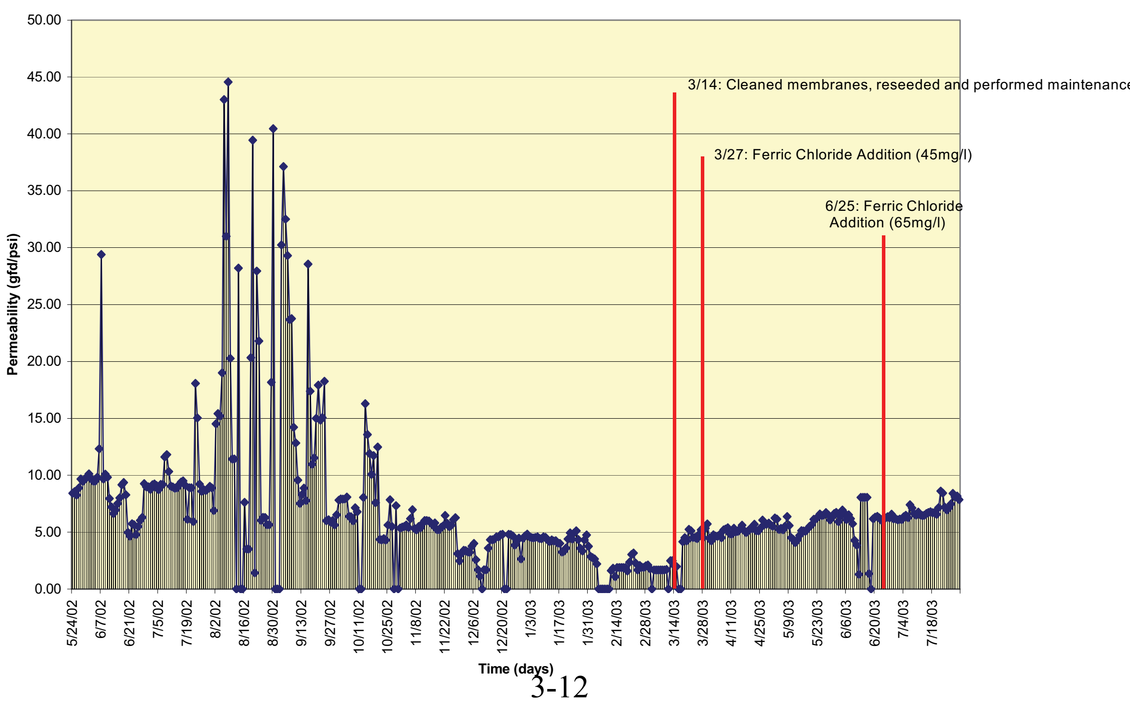
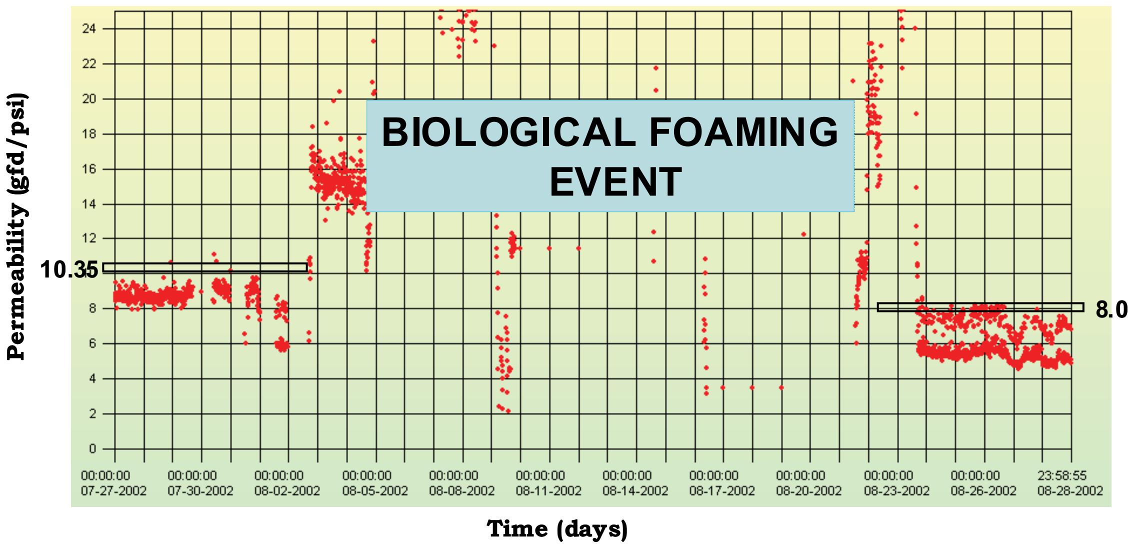


Figure 3-3: Impact of Biological Foaming Event on Membrane Permeability

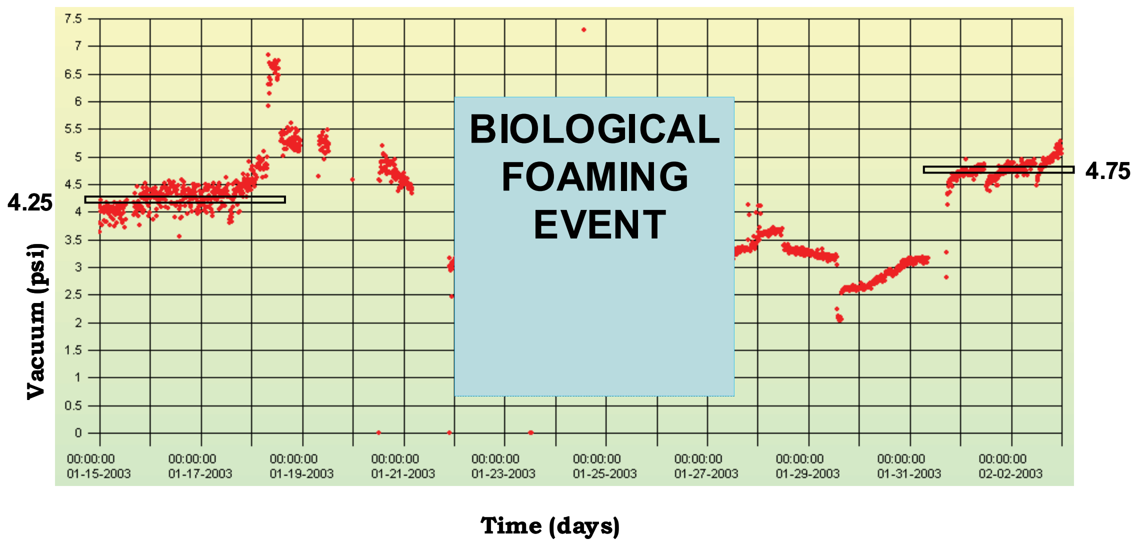


Cold Weather Foam Event

Figure 3-4 shows the impact of cold weather (January 15 – February 2, 2003) on membrane performance. The overall performance of the MBR was adversely impacted by the extreme cold weather. As depicted in Figure 3-4, the membrane performance was very erratic, and there was a non-biological foaming event. Microscopic analysis of the sludge during this event indicated that excessive-foam-causing microorganism populations (i.e. *Nocardia sp*.) were not present. Accompanying this foaming event, the rates of nitrification and denitrification decreased, which resulted in high ammonia and total nitrogen in the effluent. The probable cause for these effects was excessively cold water temperatures (5 – 6 degrees C), which reduced biological activity, and an increase in the viscosity of the water, which impacted membrane performance. The drop in biological activity translated to a high degree of cell decay, which in turn resulted in the increase in soluble microbial products (cell protein), which tend to foam. A cold weather upset resulted in an increase in applied vacuum pressure to maintain a constant flux. Decreasing the HRT by increasing membrane flux and decreasing SRT resolved these problems.

Since this pilot was built above ground and had a relatively small un-insulated volume (7,000 gallons), it was severely affected by the cold weather. It is reasonable to assume that a full-scale plant would be less affected by the cold weather. However, it was apparent that small changes in the temperature did impact the performance of the system as a whole. It also should be noted that soon after the system recovered from the foaming event and began to perform better, the system experienced numerous problems caused by the severe cold winter, including acute membrane fouling associated with extensive biomass loss (MLSS < 3,500 mg/l) and mechanical problems that were not related to the MBR system (frozen pumps, frozen feed and waste lines, etc.). In general, the membrane performance was adversely impacted when the MLSS concentration dropped below approximately 7,500 mg/l.

Figure 3-4: Impact of Cold Water On Vacuum Pressure.



Issues with High Biomass/Low Nutrient Reuse Treatment

Testing a MBR system to treat weak municipal wastewater to meet strict reuse standards poses a number of technical and operational issues. Municipal wastewater may be low in BOD content due to dilution caused by 1) combined sewers (NYC); 2) significant infiltration and inflow in to the sewer collection system (Rockland Co.); or 3) large clean water industrial flows (cooling water, boiler water, wash water, etc.). Treating a weak wastewater using high biomass systems such as MBRs can be difficult because the high biomass (> 10,000 mg/l MLSS) requires a significant BOD to maintain activity. Advantages of the high biomass MBR system are that it requires a much smaller foot print and can adapt quickly to changes in nutrient load. However, when treating weak wastewater using a high biomass system, relatively small fluctuation in influent BOD can have a large impact on biological activity and F/M ratio. Significant drops in activity can also be caused by seasonal changes in temperature. Table 3-17 compares typical values for operational parameters and microbial activity for a conventional activated sludge process (CAS) and the MBR-BNR system evaluated in this project.

When seasonal changes in temperature and dilution of weak wastewater are combined, a severe drop in biological activity can result in biological upsets. If the temperature increases the activity of the biomass, then the biomass will increase and the BOD in the system will be used quickly, resulting in a drop in F/M and the potential for problem organisms to flourish (filamentous and N*ocardia*). To combat these situations, the influent flow must be increased to provide additional BOD and the biomass concentration must be dropped by increasing the wasting rate. Operationally, these measures are similar to those that would be taken in a conventional plant. However, in an MBR plant, when the biomass drops below a certain level (7,000 – 8,000 mg/l MLSS), the membranes begin to foul more quickly; in addition, the membranes have a limiting flux rate that limits flow rate.

A less likely, but still important, treatment scenario that may occur when treating a weak municipal wastewater is when the temperature decreases significantly, resulting in a drop in biological activity. Since the MBR system already operates at a relatively low specific activity (Table 3-17), a small change in that activity caused by a drop in water temperature could cause an endogenous decay event that results in a non-biological foaming event. The foam is produced by soluble microbial products that are produced as cells lyse during decay. Such an event can impact membrane performance, as seen in this study. The best way to combat such a scenario is to maintain a relatively high specific activity and by protecting the MBR system from severe weather. This scenario is only an issue in colder regions and becomes less significant as the size of the plant increases.

In addition to operational difficulties, weak raw wastewater increases the cost of tertiary treatment by increasing the need for supplemental BOD to drive denitrification and enhanced biological phosphorous removal.

Table 3-17: CAS vs. MBR: Operational Parameters and Specific Activity.

Parameter	Units	CAS	MBR (Nite only)	MBR (N & P removal)
0_H	Hr	4-8	8.3	8.3
F/M	lb BOD$_5$ / lbMLVSS-d	0.2-0.5	3.39E-02	
MLSS	mg/l	2,000	10,000	10,000
Specific Ammonia Utilization Rate	Mg NH_3^{-+} / MLVSS-d	0.81	9.5E-03	1.14E-02
Specific Nitrate Utilization Rate	Mg NO_3 / MLVSS-d	0.045	6.64E-03	4.70E-04
Specific BOD Utilization Rate	Mg BOD$_5$ / g- MLVSS-hr	3-8	1.2	9-.5E-01

Design Solutions for Addressing Operational Issues

This particular pilot system was subject to the aforementioned operational difficulties due to its small volume and sensitivity to temperature changes, the use of primary clarification reducing BOD to the MBR, the relatively weak raw wastewater, and the limitations on membrane flux controlling the BOD feed to the system. These issues could be overcome by the following:

1. Partially or periodically by-passing primary treatment to increase the BOD seen at the MBR. This is one way to increase the F/M ratio during high temperatures or diluted flow periods.

2. Replacing the primary clarifier with a grinder pump and fine screens to maintain raw wastewater BOD entering the MBR. This is similar to how many MBR systems used for on-site and decentralized applications are designed. This would require a different approach to phosphorous removal, including either post-ferric addition with polishing membranes or biological phosphorous removal combined with chemical addition in the membrane zone.

3. Increasing the number of membranes in the system to increase the total flux capacity of the system so higher flux rates can be achieved when the wastewater is diluted by storm flow, and infiltration and inflow (I/I).

For newer sewer systems, systems without significant clean water industrial flows, or systems that have an aggressive and effective I/I program, biological upsets such as these will likely not be an issue. In addition, experienced operators should be able to use process-control strategies (e.g., increase flux, increase sludge wasting) to deal with any upsets that could be caused by long-term diluted influent.

Task 3 - Economic and operational evaluation and assessment.

Economic Benefits

Capital Costs

When comparing the costs of an MBR plant to that of a conventional activated sludge plant, the degree of treatment and the type/strength of wastewater must be considered. The biggest advantages of MBRs is the fact that the membrane unit can replace the need for both a secondary clarifier and a sand filter. Also, since an MBR operates at a higher MLSS (12,000 mg/l MLSS for MBR vs ~ 2,000 mg/l MLSS CAS), an MBR occupies considerably less space, which can be very valuable if the land upon which a plant is being built is valuable for development. This small footprint of the MBR system is one of the reasons it is such a popular technology for on-site treatment at housing developments where land is at a premium. MBRs have proven that they are capable of treating wastewater to the most stringent reuse standards. The design and operational variability will strongly influence whether or not MBRs are cost effective compared to conventional treatment. Many of the land development MBR systems do not have a primary clarifier but instead are equipped with grinder pumps and fine screens. Removing the primary clarifier from the plant design further reduces capital costs and footprint and also allows more of the raw wastewater BOD to enter the membrane unit to support the high-biomass operation. The BOD in the raw wastewater may also be used to drive denitrifcation and support enhanced biological phosphorous removal. However, there have been difficulties with clogging of the fine screens and maintenance of the high capacity grinder pumps.

The difference in capital costs of a MBR reuse quality plant similar to the one evaluated in this study and a conventional reuse plant (primary settling, activated sludge BNR, secondary clarifier, polishing filter) is difficult to quantify, since it will be a function of the size of plant, the value of land, and the local cost of labor. Other considerations that will impact costs include type of building, odor control, pumping and storage, etc. In general, capital costs for a conventional 1 MGD plant will range from $5.00/gpd to $8.50/gpd, while MBR plants producing the same quality of water will range from approximately $6.00 to $10.50/gpd. These numbers are based on values from the literature and experience in the field. These costs can vary greatly depending upon the degree of treatment required; however, as the degree of treatment increases, MBR systems become more competitive. For NYS Level 3 reuse standards, the difference in capital costs between a CAS-type system and an MBR system would be 10 – 15%. This difference could be recovered by reduced land costs and reductions in electrical and operating costs. In addition, if a plant is designed to produce a higher quality water with more reuse applications, expenses can be continuously recovered by selling the reuse water to specific users (farmers, golf courses, industry etc.) at a rate typically between 25- 50% of potable water rates. Regardless of the type of treatment, systems smaller than 1 MGD will incur higher costs due to the minimum cost needed to build any significant reuse quality treatment system. Some small (50,000 – 100,000 gpd) MBR plants may cost as much as $25/gpd to construct. These systems are typically used as on-site treatment for land development, and the costs are passed on to the home or business buyer. The cost per two-bedroom home is typically less than the cost of a quality septic system, without the maintenance and environmental issues.

Operational Costs

Typically, the largest operational costs associated with tertiary treatment are the chemical costs. Results from the pilot study were used to calculate chemical costs for a 1.0 MGD plant similar to the one that was piloted. The chemical costs would consist mostly of methanol (44 mg/l) and ferric chloride (65 mg/l). The methanol would cost approximately $210/day for a 1.0 MGD plant, and the ferric chloride would cost approximately $95/day. These costs are based on bulk purchase quotes provided by vendors in Spring 2004. The total annual chemical cost would be approximately $110,000. Other chemicals that may be needed would include pH adjust, if the raw water alkalinity is not high enough to offset alkalinity losses incurred by nitrogen removal, and ferric chloride addition. If an MBR were used to treat a stronger wastewater that is more indicative of typical municipal wastewater, the methanol costs could be reduced by more than half. In addition, if enhanced biological phosphorus removal were incorporated into the MBR process, the cost for coagulant and alkalinity addition could be greatly reduced.

A 1.0 MGD membrane plant could be operated by a single operator working an eight-hour shift, as long as the plant was equipped with adequate automation, PLC, and SCADA systems. The operator would likely have to be highly trained and experienced, which would require an annual cost of approximately $80,000. The less automation the plant has, and the more equipment and unit processes that need to be operated and maintained, the more operators will be needed.

The electrical costs for operating a 1.0 mgd MBR plant were provided by Zenon. The electrical costs are just for the MBR potion of the plant, and do not include costs for any primary treatment, sludge handling or disinfection. The costs include electricity for:

1. Membrane air scour blowers
2. Biological process air blowers
3. Internal recycle pumps
4. External or total recycles pumps
5. Permeate (membrane) pumps

The total annual energy requirement for a 1.0 MGD MBR unit would be approximately 1,114,160 kWh/annum, or $78,000/yr based on 24-hour operation and $0.07/kWh. However, energy costs in upstate New York can vary greatly depending upon location and season. RCSD No.1 pays an average of $0.15/ kWh in 2003/2004; this would increase the costs to approximately $167,000/year in energy costs to operate the MBR unit.

The O and M costs should not be that much different than that needed for a conventional plant. The only large difference is periodic cleaning of the membranes every 4 – 8 months and membrane replacement every 10 years. One concern is the lack of experience operators may have with MBR systems.

Environmental Benefits

The environmental benefits of reuse are well documented. Increasingly in the north east, municipalities are trying to move away from the use of septic systems and move toward tertiary treatment using both centralized and decentralized treatment plants. Reuse quality water can be used to supplement ground water supplies, decrease vulnerability to droughts, better manage natural water systems (riparian rights), and provide water for industrial and agricultural reuse that does not require a high degree of treatment, thus fewer chemicals are used.

Biosolids Quality and Potential for Reuse

As mentioned before, biosolids are waste material that have undergone stabilization treatment to reduce disease-causing organisms, odor, and conditions that attract vectors and flies, and they must meet specific standards for metals and chemical concentrations. MBR generates about 13 lb of biosolids per day. The metals found in the MBR biosolids can be seen in Table 3-18. Table 3-19 gives the standards for land application of biosolids. For more detailed description of the biosolids metals standards that apply to different land applications, refer to Table 3-20, which includes the complete metal limits for beneficial reuse of biosolids as established in the US EPA Part 503 Biosolids Rule.

Table 3-18: Average Metals Found in the MBR Biosolids

Type	**Zn Mg/kg**	**Cu mg/kg**	**As mg/kg**	**Ni mg/kg**	**Cd mg/kg**	**Pb mg/kg**
Small Clarifier	49.70	1.46	0.80	0.36	0.038	8.02
Large Clarifier	1.00	1.13	0.87	0.35	0.030	9.21
MLSS	46.86	2.62	1.22	0.33	0.020	6.33

Table 3-19: Ceiling Concentration limits for Land Applied Biosolids in NYS

Land Application	**Zn mg/kg**	**Cu mg/kg**	**As mg/kg**	**Ni mg/kg**	**Cd mg/kg**	**Pb mg/kg**	**Cr mg/kg**
Current	2500	1500	NL	200	25	1000	1000
Proposed	2800	1500	41	290	21	300	1200

Table 3-20: Limitation for Metals and Trace Substances for Land Application

Pollutant	Ceiling Limits for Land Applied Biosolids (mg/kg)	Limits for EQ and PC Biosolids (mg/kg)	CPLR limits (kg/ht)	APLR limits (kg/ht/yr)	Average Conc. In NVS
Arsenic	75	41	41	2	7.6
Cadmium	85	39	39	1.9	0.83
Chromium	3,000	1,200	3,000	150	
Copper	4,300	1,500	1,500	75	134
Lead	840	300	300	15	48
Mercury	57	17	17	0.85	<0.5
Molybdenum	75	--	--	--	1.38
Nickel	420	420	420	21	55
Selenium	100	36	36	5	1.69
Zinc	7,500	2,800	2,800	140	186
Applies to:	All land applied Biosolids	Bulk /bagged Biosolids	Bulk Biosolids	Bagged Biosolids	--
From US EPA Part 503:	Table 1 503.13	Table 1 503.13	Table 2 503.13	Table 4 503.13	--

CPLR- Cumulative Pollutant Loading Rate
APLR- Annual Pollutant Loading Rate
Molybdenum concentrations are currently being reconsidered by USEPA
Source: A plain English Guide to the EPA Part 503 Biosolids Rule

The concentration of the metals in the solids will increase as the sludge is processed via digestion and dewatering. Assuming that the original biological solids to be digested and reused will be 80% volatile and that the resulting digested and dewatered biosolids would have a solids concentration of 26%, the actual metals concentrations within the biosolids will be about 2 (1.96) times the levels that are found in the MBR sludge. This increase is caused by concentrating the sludge solids through digestion and dewatering. Even with the concentrating factor, the biosolids produced by the MBR systems should easily meet the beneficial reuse criteria set by NYS and Rockland County Solid Waste Authority as long as no large metal-laden industrial inputs are introduced to the system.

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Pilot Testing of a Membrane Bioreactor Treatment Plant for Reuse Applications

Final Report 08-16

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