RECLAMATION

Managing Water in the West

Desalination and Water Purification Research and Development Program Report No. 147

Evaluation of Newly Developed Membrane Bioreactor Systems for Water Reclamation

U.S. Department of the Interior
Bureau of Reclamation

February 2009

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
November 2007

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
October 2005 to October 2006

4. TITLE AND SUBTITLE
Evaluation of Newly Developed Membrane Bioreactor Systems for Water Reclamation

5a. CONTRACT NUMBER
Agreement No. 05-FC-81-1157

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
James F. DeCarolis
Zakir M. Hirani
Samer Adham, Ph.D.

5d. PROJECT NUMBER

5e. TASK NUMBER
Task C

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
MWH Americas Inc.
618 Michillinda Avenue, Suite 200
Arcadia, California 91007

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Department of the Interior
Bureau of Reclamation,
Denver Federal Center
PO Box 25007, Denver CO 80225-0007

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
DWPR Report No. 147

12. DISTRIBUTION / AVAILABILITY STATEMENT
Available from the National Technical Information Service
Operations Division, 5285 Port Royal Road, Springfield VA 22161

13. SUPPLEMENTARY NOTES
Report can be downloaded from Reclamation Web site:
www.usbr.gov/pmts/water/publications/reports.html

14. ABSTRACT ***(Maximum 200 words)***
This project evaluated the pilot scale performance of four newly developed membrane bioreactor (MBR) systems during the reclamation of municipal wastewater. The specific systems tested and participating MBR suppliers included Puron™ MBR from Koch Membrane Systems (KMS), Huber® MBR from Huber Technology, Kruger Neosep™ MBR from I. Kruger Inc., and DynaLift™ MBR from Parkson Corporation. Each system offers unique design features intended to increase overall operational efficiency. During pilot testing, the systems were evaluated under average operating conditions (i.e., flux, solid reaction time, hydraulic retention time, membrane air scour, and backwash/relaxation frequency) for both productivity and water quality performance. The impact of peaking on MBR performance was also assessed during this study by simulating typical diurnal peak flow rates over a 6-day period. The MBR systems were also evaluated for their ability to produce product water which meets the California Department of Public Heath Title 22 Water Recycling Criteria and is suitable for further treatment by RO. Lastly, previous full-scale MBR cost estimates (1 and 5 million gallons per day) performed by the project team were updated using information provided from the participating suppliers.

15. SUBJECT TERMS
membrane bioreactor, flux

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE	SAR	190	Bob Jurenka
U	U	U			19b. TELEPHONE NUMBER *(include area code)* 303-445-2254

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. 239-18

Desalination and Water Purification Research and Development Program Report No. 147

Evaluation of Newly Developed Membrane Bioreactor Systems for Water Reclamation

Prepared for Reclamation Under Agreement No. 05-FC-81-1157 Task C

by

Montgomery Watson Harza

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Water and Environmental Services Division
Water Treatment Engineering Research Team
Denver, Colorado

February 2009

MISSION STATEMENTS

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Acknowledgement

The authors would like to express their gratitude to the following individuals and organizations for their contributions to the successful completion of the project:

CITY OF SAN DIEGO

- ***Metropolitan Wastewater Department:*** Larry Wasserman, Neil Tran, and Steve Lagos for providing assistance in project coordination, data management, and pilot testing
- ***Point Loma Wastewater Treatment Plant (WWTP) Laboratory:*** Brent Bowman, Julie Webb, Maricela Coronel, Enrique Blanco, Margot Szeterlak, and Connie Mata for performing water quality analysis during the study
- ***Marine Microbiology Laboratory:*** Laila Othman, Ricardo Amador, George Alfonso, Sonji Romero, Aaron Russell, Joseph Toctocan, and Roxanne Davis for performing microbiological analysis during the study
- ***Industrial Wastewater Laboratory:*** Brad Ramstead, Miles Slattery, Armando Martinez, Salvador Coria, and Lee King for performing water quality analysis during the study
- ***Point Loma WWTP Operations and Maintenance Division:*** Joe Cordova, Kip Cooper, Ted Taylor, Jesse Parks, Ken Goebel, Kurt Hoeger, Dennis Jewell, Mitch Dornfeld, and rest of the Point Loma WWTP staff for their cooperation and support throughout the study

PARTICIPATING VENDORS

- ***Membrane bioreactor suppliers:*** Koch Membrane Systems, Huber Technology, I. Kruger Inc., and Parkson Corporation
- ***Reverse osmosis membrane supplier:*** Koch Membrane Systems
- ***Screen:*** Waste-Tech Inc./Roto-Sieve

MWH

- Stephen Lacy for serving as a technical advisor for the study
- Suvid Surendran and Lee Portillo for their assistance in pilot testing
- Brian Gallagher and Eric Bruce for setting up the pilot equipment

Finally, the authors would like to thank the Bureau of Reclamation for their support in the implementation of this project.

Acronyms and Abbreviations

BOD or BOD5	5-day biochemical oxygen demand
CDPH	California Department of Public Health
CFU	colony forming units
COD	chemical oxygen demand
CPI	consumer price index
DO	dissolved oxygen
ENRCCI	Engineering News-Record Construction Cost Index
F/M	food to microorganism
ft^2	square foot
gfd	gallons per square foot per day
g/L	grams per liter
gpd	gallons per day
gpm	gallons per minute
hr	hour
in	inch
kg	kilograms
L	liter
m^2	square meter
m^3	cubic meter
m^3/min	cubic meter per minute
m^3/day	cubic meter per day
MBR	membrane bioreactor
MF	microfiltration
mg	milligram
mg/L	milligrams per liter
mg/L-N	milligrams per liter as nitrogen
min	minute
mL	milliliter
MGD	million gallons per day
MLSS	mixed liquor suspended solids
MLVSS	mixed liquor volatile suspended solids
mm	millimeter
MWH	Montgomery Watson Harza
NaOCl	sodium hypochlorite

Acronyms and Abbreviations (continued)

NH_3-N	ammonia as nitrogen
NH_4Cl	ammonium chloride
NTU	nephelometric turbidity units
NO_2-N	nitrite as nitrogen
NO_3-N	nitrate as nitrogen
NWRI	National Water Research Institute
O&M	operations and maintenance
PES	poly ethyl sulfone
PFU	plaque forming units
PLC	programmable logic controller
PLWWTP	Point Loma Wastewater Treatment Plant
PO_4	ortho phosphate
ppm	parts per million
psi	pounds per square inch
PVDF	polyvinyl difluoride
RO	reverse osmosis
s	seconds
scfm	standard cubic feet per minute
SBWRP	South Bay Water Reclamation Plant
SDI	silt density index
TIN	total inorganic nitrogen
TKN	Total Kjeldahl Nitrogen
TOC	total organic carbon
TSS	total suspended solids
UF	ultrafiltration
VSS	volatile suspended solids
$\Delta\pi$	net osmotic pressure of the feed and permeate
°C	degrees Celsius
$K	thousands of dollars
µg	microgram

Acronyms and Abbreviations (continued)

µmhos	micromhos
µm	micrometer
µS	micro Siemens

Calculated Parameters

HRT	hydraulic retention time (hours)
J	membrane flux (gfd)
J@20°C	temperature corrected membrane flux (gfd)
J_{SP}	specific flux (gfd/psi)
P_{NET}	net operating pressure (psi)
Q_{NET}	net permeate rate (gpm)
R	salt rejection (%)
RR	recycle ratio
SRT	sludge retention time (days)
$SRT_{7\text{-}D}$	average sludge retention time over 7 days
TMP	transmembrane pressure (psi)

Table of Contents

Table of Contents (continued)

Table of Contents (continued)

1. Executive Summary

Membrane bioreactor (MBR) is a proven technology for wastewater reclamation that combines biological treatment with membrane filtration to achieve high quality effluent. Montgomery Watson Harza (MWH) and the city of San Diego have been conducting research on the MBR process since 1997 through various research projects (Adham et al., 1998, 2000, 2001). In the previous projects, the research was focused on the feasibility of the MBR process for water reclamation and optimization of MBR pilot units from different vendors that are currently well established in the United States market (Adham and DeCarolis, 2004). But due to the growing MBR market in the United States and worldwide, several new vendors recently have introduced their systems to the United States market. Pilot-scale evaluations of these MBR systems will help establishing these systems in the United States thereby encouraging competition within the MBR industry.

In 2005, MWH was awarded a grant from the Bureau of Reclamation (Reclamation) to evaluate four newly developed MBR systems for water reclamation. The primary objectives of this study were as follows:

- Conduct third-party performance evaluation of newly developed MBR systems
- Perform California Department of Public Health (CDPH) Title 22 approval testing of newly developed MBR systems
- Evaluate the performance of new generation desalting membranes after pretreatment by MBR
- Update and refine cost estimates for the newly developed MBR systems

As a primary goal of the study, the project team evaluated four pilot-scale MBR systems from new suppliers including Puron™ MBR from Koch Membrane Systems (KMS), Huber® MBR from Huber Technology, Kruger Neosep™ MBR from I. Kruger Inc., and DynaLift™ MBR from Parkson Corporation. Each MBR pilot system was operated for a target period of about 3,500 hours on raw wastewater from Point Loma Wastewater Treatment Plant (PLWWTP) located in San Diego, California. In addition, a reverse osmosis (RO) membrane provided by KMS was also evaluated while operating on MBR effluent.

Initially, Puron and Huber MBR systems were operated in parallel at different flux-rates to assess the membrane fouling trend and water quality. During this period, effluent from Huber MBR was fed to the RO pilot unit. Later, both Kruger Neosep and DynaLift MBR pilot units were operated in parallel to assess the membrane performance and water quality. During this period, the RO unit was fed by effluent produced from Kruger Neosep MBR. In addition, a peaking study was conducted on each system to assess the membrane performance during peak flows and to perform CDPH Title 22 testing of all four MBR systems.

Based on the results obtained from the pilot study, the food to microorganism (F/M) ratio for the MBR pilot systems ranged between 0.05–0.09 g BOD/g VSS.d[1] during normal operating conditions, which is within the desired range. A significant difference was observed in the operating flux of the submerged MBR systems and external MBR system. The median net flux for submerged MBR systems was measured between 13–16 gallons per square foot per day (gfd) whereas that for an external MBR system was measured at 27 gfd. The high-flux operation of external MBR system may be attributed to better turbulence available within the external membrane module due to a relatively higher recirculation flow requirement compared to submerged MBR systems. When comparing the frequency of maintenance cleans, the Kruger Neosep MBR system required fewest maintenance cleans during the same operational period as other MBR systems. The scouring air requirements per unit membrane area for MBR systems varied from 0.019–0.040 standard cubic foot per minute per square foot ($scfm/ft^2$). Both the Puron and DynaLift MBR systems had the lowest scouring air requirement at 0.019 $scfm/ft^2$. The Puron MBR system was able to achieve this by using intermittent scouring, while the DynaLift MBR system relied on air-lift assisted cross flow pumping for scouring, which requires additional energy for cross flow pumping.

All four MBR systems tested produced excellent water quality with effluent turbidity of less than (<) 0.1 nephelometric turbidity units (NTU) and effluent 5-day biochemical oxygen demand (BOD5) concentration of <2 milligrams per liter (mg/L). When tested for microbiological contaminants removal, all four MBR systems achieved more than 5-log removal of total and fecal coliforms and more than 3-log removal of inherent coliphage. The MBR systems also achieved ammonia levels of <0.5 milligrams per liter as nitrogen (mg/L-N) in the effluent, indicating complete nitrification. The denitrification efficiencies of the systems varied depending on the presence of an anoxic zone with permeate nitrate concentrations varying from 4.2–29.3 mg/L-N.

To determine the performance of the MBR systems at peak flux and to assess the permeate water quality for Title 22 testing, a 6-day peaking study was conducted on each MBR system. The operating parameters during the average and peak flux operation were recommended by the manufacturers. As per their recommendation, each MBR system was operated with either increased scouring air or recirculation flow rate or both during the peak flux operation with the exception of Huber MBR. During this peaking study, all four MBR systems were able to sustain the operation without a significant drop in the specific flux. However, a significant difference was observed between submerged and external MBR systems while operating at peak flux. All three submerged MBR systems

[1] Grams of biochemical oxygen demand per gram of volatile suspended solids-day.

(Puron, Huber, and Kruger Neosep) showed a temporary decline in the specific flux while operating at peak flux whereas no such trend was observed on the external MBR system (DynaLift). This could be attributed to the operation beyond critical flux for submerged MBR systems while operating at peak flux. For external MBR system, a relatively higher recirculation flow rate coupled with scouring air helped to maintain the flux in subcritical range, even when operating at peak flux. The Huber MBR system was able to sustain peak flux operation without any increase in the scouring air or recirculation flow rate. This advantage in operating performance for Huber MBR system could be attributed to the rotation of the membrane module within the bioreactor, which may have helped to mitigate the solids buildup across the membrane surface during peak flux operation.

From the results obtained during Title 22 testing, all four MBR systems were able to produce effluent with turbidity of less than 0.2 NTU for 100 percent (%) of the time and met the turbidity requirements by CDPH for recycled water. Even though the nominal pore size of all four membranes of these MBR systems fell within the ultrafiltration (UF) range, a significant difference (1.0–4.0 log) in the virus rejection capability of these systems was observed. The 50th percentile virus removal for Puron MBR was observed at 1.0 log whereas that for DynaLift MBR was observed at 4.0 log, even though both of these systems have UF membranes and use backwash after each filtration cycle. On the other hand, the Kruger Neosep and Huber MBR systems were able to achieve 3.0- and 4.0-log removal of virus respectively at 50th percentile. Both of these systems use relaxation at the end of the filtration cycle and also have a nominal pore size in the UF range. Based on the results obtained from the Title 22 testing of these MBR systems, all four MBR systems received conditional approval from CDPH in 2006.

During the course of study, the RO system was operated for more than 1,500 hours on effluent from two different MBR systems. The RO unit consisted of two single pass trains and was operated at 50% recovery and 12 gfd throughout the study period. The RO membranes operated for a period of more than 1,300 hours on MBR effluent without requiring a chemical clean. However, when a membrane breach occurred with one of the MBR systems, the RO membrane fouled overnight. As a result, the project team recommends that the membrane integrity of MBR systems should be checked periodically to avoid any problems with the MBR systems to pass to the RO system.

Cost estimates were developed for the MBR systems tested during this study at 1- and 5-million-gallon-per-day (MGD) capacities. These estimates included both capital and operational costs related to the MBR process and subsequent disinfection. Costs associated with the membrane portion of the MBR systems were obtained from the four participating MBR suppliers and were based on specific guidelines and criteria developed by the project team. All other costs of the MBR process components were derived from previous estimates (Adham et al., 2004) and updated using current Engineering News Record Construction Cost Index (ENRCCI) and Chemical Engineering Plant Cost Index (CEPCI). Results of the cost analysis (dollars per 1,000 gallons [$/1,000 gal]) revealed that 1-MGD MBR water reclamation systems, ranged from $2.02–$2.58. A comparison of the cost estimates for 1- and 5-MGD systems showed an economy of scale of approximately 17%. This is largely due to savings in construction and raw material costs associated with the larger size facilities.

To gain insight on the historical cost trend of MBR systems, cost estimates for the newly developed systems were compared to similar estimates made by the project team in 2000 and 2003 (Adham et al., 2000 and 2003). Overall results of this comparison showed the costs associated with the membrane system component of the MBR systems has decreased between 2000 and 2006 by approximately 33%, while nonmembrane MBR process component costs (i.e., headworks, process basins, blower/pump building, chlorine dosing system, and effluent storage) have increased by approximately 24% over the same time period. The rise in nonmembrane costs associated with the MBR system costs is due to the increased cost of concrete and other raw materials used for plant construction. The drop in membrane system costs may be attributed to advancements in manufacturing and increased competition in the market place. These trends suggest that the overall total cost for 1-MGD MBR systems was fairly level between 2000 and 2006.

2. Introduction

2.1 Background/Introduction

Due to the increasing population and limited freshwater resources around the world, water reclamation is becoming increasingly popular. Among the several techniques available for water reclamation, the membrane bioreactor (MBR) is a proven technology that combines biological treatment with a membrane separation process, thereby providing effluent low in particulate and organic matter. The advantages offered by an MBR compared to a conventional activated sludge process are reduced footprint, consistent and superior water quality, potential low sludge production, and solids separation independent of mixed liquor suspended solids (MLSS) characteristics. As the secondary clarifiers are eliminated in the MBR process along with reduced volume of aeration tank due to higher operating MLSS concentration, MBR offers a significantly reduced footprint compared to the conventional activated sludge process. The effluent produced from an MBR has to pass through a microfiltration (MF) or ultrafiltration (UF) membrane; hence, the water quality is superior and free of pathogens such as Cryptosporidium and Giardia. In addition, operation at long sludge age results in low sludge production. For the regions where wastewater can be used for indirect potable reuse after advanced wastewater treatment, the effluent produced from MBR can be used as a direct feed to reverse osmosis (RO) treatment.

The MBR systems are available in two different configurations: "external" or "submerged" (Adham, 1998). In the "external" configuration, sludge is recirculated from the aeration basin to a pressure-driven membrane system outside of the bioreactor where the suspended solids are retained and recycled back into the bioreactor while the effluent passes through the membrane. In the past, external MBR systems were limited to industrial applications due to high energy cost required to maintain proper cross flow velocities for external membrane modules (Morgan et al., 2006). But due to the recent advances, the external MBR systems are now operated with air-lift-assisted cross flow pumping, in which scouring air is introduced along with the sludge recirculation at the bottom of the vertically mounted membrane module to reduce the recirculation flow requirement. In this configuration, the membranes are regularly backwashed to remove suspended solids buildup and are chemically cleaned when operating pressures become too high. In the "submerged" configuration, a membrane module is submerged in an aeration basin and operated under vacuum. The membrane is agitated by coarse bubble aeration that helps prevent suspended solids accumulation at the membrane surface. The submerged membranes are either regularly backwashed or relaxed and are chemically cleaned when the operating pressures become too high.

Due to several advantages offered by a MBR process compared to a conventional activated sludge process, several full-scale MBR plants have been constructed in the last few years. The market for MBR in North America generated revenue of $32.2 million in 2003 and is projected to grow at a compound annual rate of 15.6 percent (%) for the forecast period of 2003–2010 (Frost and Sullivan, 2004). The number and capacity of full-scale MBR plants have steadily increased in the United States and worldwide within last few years, prompting many new MBR suppliers to market their product in the United States market. When compared to the established MBR systems, these new MBR systems have unique features which, when applied to full-scale plants, may prove cost effective.

Before implementing the newer systems entering the MBR market on a full-scale, it is very important to assess their performance on a pilot-scale to determine the potential advantages and drawbacks of each system. Among the performance assessment of MBR systems, membrane fouling trend and effluent water quality are two of the most important parameters to be determined. Membrane fouling trend could be determined by a drop in the specific flux over time and frequencies of maintenance cleans at different flux-rates, whereas effluent water quality can be evaluated in terms of particulate, organics, and microbial contaminants removal. As water reuse is one of the key applications of MBR, it is also important that these new MBR systems meet Title 22 water reuse criteria specified by the California Department of Public Health (CDPH).

Another concern while constructing full-scale MBR plants is the ability of the membrane to handle peak flows. These peak flows could be either diurnal or seasonal, but the additional flow has to pass through the membranes to be considered treated water. Most of the MBRs installed to date have a peaking factor (peak flow to average flow ratio) of 2 to 3 or have an equalization basin installed upstream of the MBR to handle peak flows (Chapman et al., 2006). Providing an equalization basin increases the overall footprint of the plant, leaving peak flow operation a desired choice for MBRs to maintain a small footprint. When designing MBRs with a peaking factor, it is very important that the operating pressure (or vacuum) of the membrane stays within an allowable range during peak flux operation. To date, very limited published literature is available on membrane performance of MBR systems during peak flux operation.

From previous studies, it is well documented that MBR systems can provide excellent pretreatment to RO membranes, as the silt density index (SDI) for MBR effluent is consistently less than 2 (MWH, 2004). With the arrival of these new MBR systems in the wastewater market, it is important to determine if these new MBR systems also can produce consistent water quality suitable for feed to the RO system. Also, a need exists to evaluate the new generation RO membranes, which specifically are designed for wastewater reclamation. These new generation RO membranes operate at significantly low pressure while offering high salt rejection.

Finally, a cost analysis of these new MBR systems is required to develop guidelines for estimating capital and operation and maintenance (O&M) costs for wastewater industry. Cost analysis of these new MBR systems will also provide an opportunity for the wastewater industry to compare them with the established MBR systems, thereby encouraging competition in the MBR industry. It is also important for the industry to have some insight on the overall historical costs trend of MBR systems applied to water reuse over the past 5-year period.

2.2 Study Objectives

In October 2005, MWH was awarded a grant from the Bureau of Reclamation (Reclamation) to evaluate four newly developed MBR systems. The four MBR systems evaluated during this study were Puron MBR from Koch Membrane Systems (Wilmington, Massachusetts), Huber MBR from Huber Technology (Huntersville, North Carolina), Kruger Neosep MBR from I. Kruger Inc. (Cary, North Carolina), and DynaLift MBR from Parkson Corporation (Fort Lauderdale, Florida).

The primary objectives of this study were as follows:

- Conduct third-party performance evaluation of newly developed MBR systems

- Perform California Department of Public Health (CDPH) Title 22 approval testing of newly developed MBR systems

- Evaluate the performance of new generation RO membranes after pretreatment by MBR

- Update and refine the cost estimates for newly developed MBR systems

To meet the above stated objectives, each MBR pilot system was operated for a target period of 3,500 hours. During this period, the membrane performances of each MBR system were assessed by recording the operating pressure and permeate flow rate. Peaking study was also conducted on each system to assess the fouling trend of membranes at peak flows. Water quality data was collected to assess the capability of these systems to remove particulate, organics, and microbial contaminants. As part of the Title 22 testing, turbidity and virus rejection data was collected and final reports were submitted to CDPH for review (DeCarolis et al., 2006 a, b, c, and d). The MBR systems were used as a pretreatment for RO membranes, and the performance of RO membranes was monitored in terms of operating pressure and conductivity rejection. Finally, capital and O&M cost estimates for 1- and 5-million-gallon-per-day (MGD) MBR installations were developed for the newly developed MBR systems.

3. Conclusions and Recommendations

3.1 Operational Performance

3.1.1 MBR Systems

3.1.1.1 Puron MBR

- The Puron MBR system was operated at flux of 10–16 gallons per square foot per day (gfd) during the study period and showed minimum to moderate fouling during average flux operation. During the study, KMS recommended operating the system at 24 gfd with permeate recycle by decoupling HRT and SRT due to bioreactor volume limitations. Later, the system was operated at 24 gfd without permeate recycle. When comparing these two runs, the system operated for a longer run time while operating with permeate recycle, which might be attributed to the absence of nonbiodegradable organic matter in the permeate whereas shorter run time while operating without permeate recycle might be attributed to low HRT operation.

- The Puron MBR pilot system was fully automated. The online solids' wasting mechanism on the pilot worked very well and was able to maintain the MLSS concentration within the desired range of 10–12 grams per liter (g/L) throughout the study period.

- After 500 hours of operation, KMS recommended changing the membrane module as the permeate turbidity was higher than expected by KMS. The feed line to the pilot got clogged twice, resulting in the reduction of the feed pump capacity. As a result, the system had to be stopped and the line had to be cleaned manually to get the desired flow rate.

3.1.1.2 Huber MBR

- The Huber MBR system was operated at flux of 15–16 gfd during the study period and showed minimal to moderate fouling during this period. However, due to a mechanical problem, the system had to be reseeded following which relatively shorter run time was observed at average flux operation. This could be attributed to the low MLSS concentration following reseeding, causing high food to microorganism (F/M) ratio in the bioreactor.

- The Huber MBR pilot system was easy to operate, and each of the pilot components could be operated either in manual or automatic mode via a simple touch screen.

- As there was no flowmeter on the sludge wasting line, the waste sludge volume had to be measured manually. Also, after about 2,000 hours of operation, an unusual mechanical problem occurred with the pilot requiring the membrane tank to be drained for repair. Also, two membrane plates were found compromised during this period, causing a slight increase in the permeate turbidity concentration. After these two plates were replaced, the permeate turbidity values were back to normal.

3.1.1.3 Kruger Neosep MBR

- The Kruger Neosep MBR system operated with minimum fouling at flux of 17–18 gfd during the entire study period.

- The Kruger Neosep MBR pilot system was fully automated and required little operator attention. Though the sludge wasting had to be done manually, Kruger provided a calibrated tank to calculate the volume of sludge wasted.

- The feed pump to the pilot system lost prime a few times due to a faulty check valve and had to be primed manually. Also, after about 1,500 hours of operation, the project team noticed an increase in the permeate turbidity concentration, following which the membrane module was inspected and four membrane plates were found defective. After isolating these defective plates, the permeate turbidity values were back to normal.

3.1.1.4 DynaLift MBR

- The DynaLift MBR system was operated at a flux of 25–30 gfd during the study period. The system operated with minimum fouling during the first run at 30 gfd. However, after the failure of the air compressor, the system operated with a relatively shorter run time.

- The pilot was fully automated and was designed with an automatic sludge wasting mechanism. But the flowmeter on sludge wasting line did not function, which required manual calibration of the sludge waste flow rate.

- The air compressor used to operate the pneumatic valves on the system failed twice during the study period and resulted in a downtime for 8–10 days.

3.1.2 RO System

- The Koch 4040 HR RO membranes operated with minimum fouling when operated at 12 gfd and 50% recovery on MBR effluent. The temperature corrected specific flux dropped from 0.13 to 0.11 gfd per pounds per square inch (gfd/psi) during 1,255 hours of operation.

- The median net operating pressure for the RO system during the pilot study was calculated at 102 psi, whereas the median temperature corrected specific flux was calculated at 0.12 gfd/psi. To avoid biofouling and scaling on RO membranes, chloramine (2 milligrams per liter [mg/L]) and antiscalant (2 mg/L of VTEC™ 3000 by Avista Technologies) were added to the RO influent.

- When the membrane breach occurred on one of the MBR systems, the RO membranes fouled overnight. During this event, a significant drop in the temperature corrected specific flux at 25 degrees Celsius (°C) was observed (0.12 gfd/psi to 0.08 gfd/psi), which was recovered by performing an acid clean.

3.1.3 Screening

- The 4024-40 Roto-Sieve screen provided by Waste-Tech Inc. operated for over 7,000 hours without any mechanical problem. Though the screen was designed to operate up to maximum flow rate of 300 gallons per minute (gpm), it was operated between 30–80 gpm during the study period based on the MBR pilot feed flow requirements.

- The Roto-Sieve screen produced consistent water quality without any breakdown when used to screen raw wastewater. The percent removal of 5-day biochemical oxygen demand (BOD5) and total suspended solids (TSS) by the screen was observed at 36% and 33%, respectively.

- The screen was equipped to clean itself automatically by a rotating brush and continuous water supply via a water hose connected to the screen. This cleaning mechanism was very effective and resulted in minimum operator attention.

3.2 Water Quality Performance

3.2.1 Particulate Removal by MBR Systems

- The MBR influent turbidity concentration ranged between 65–161 1 nephelometric turbidity units (NTU) with a median concentration of 112 NTU.

- All four MBR systems tested achieved excellent particulate removal with permeate turbidity concentration of less than 0.1 NTU under normal operating conditions.

- During few incidents, when membrane plates of Huber and Kruger MBR systems were compromised, permeate turbidity was recorded up to 0.3 NTU.

3.2.2 Organics Removal by MBR Systems

- The MBR influent BOD5 concentration ranged between 97–277 mg/L with a median concentration of 161 mg/L.

- All four MBR systems tested achieved excellent organics removal with permeate BOD5 concentration of less than the detection limit of 2 mg/L for all the samples collected during the study period.

- Even when the membranes were compromised for MBR systems, permeate BOD5 concentration was still less than the detection limit of 2 mg/L.

3.2.3 Biological Nutrient Removal by MBR Systems

- The MBR influent ammonia-nitrogen concentration was measured at a median value of 23.2 milligrams per liter as nitrogen (mg/L-N) and ranged between 17.6–32.5 mg/L-N.

- All four MBR pilot systems evaluated achieved complete nitrification with permeate ammonia-nitrogen concentration of less than the detection limit of 0.2 mg/L-N under normal operating condition.

- The denitrification efficiencies of each MBR system varied depending on the presence/absence of the anoxic zone. The permeate nitrate concentrations ranged from 4.2 to 29.3 mg/L-N.

3.2.4 Microbial Removal by MBR Systems

- The median influent concentration for total coliforms, fecal coliforms and coliphage was measured at 6.6E+07 CFU/100 mL,[2] 5.4E+06 CFU/100 mL, and 2.1E+04 PFU/100 mL,[3] respectively.

- The median permeate concentrations of total coliforms for Puron, Huber, Kruger Neosep, and DynaLift MBR systems were measured at 100 CFU/ 100 mL, less then (<)10 CFU/100 mL, <10 CFU/100 mL, and 20 CFU/100 mL, respectively. The median permeate concentrations of fecal coliforms and coliphage were measured below the detection limit of 10 CFU/100 mL and 10 PFU/100 mL, respectively, for all four MBR systems during normal operating conditions.

- The consistent presence of total coliforms in the Puron MBR permeate could be attributed to the pore size distribution of the membrane and backwash used by the system.

[2] CFU/100 mL = colony forming units per 100 milliliters.

[3] PFU/100 mL = plaque forming units per 100 milliliters.

3.2.5 Conductivity Rejection by RO System

- The median influent conductivity concentrations for the RO system was measured at 1,720 micro Siemens (μS) and ranged between 1,466–2,025 μS.

- The Koch 4040 HR RO membrane achieved greater than 98% of conductivity rejection with median permeate conductivity concentration measured at 32 μS.

3.3 Peaking Study

- During the 6-day peaking study conducted on all four MBR systems, no irreversible fouling was observed on any of the systems, indicating a stable operation. The peak flux for submerged MBR systems (Puron, Huber, and Kruger Neosep) ranged between 33–35 gfd, whereas that for external MBR system (DynaLift) was observed at 45 gfd.

- All three submerged MBR systems showed a temporary drop in the specific flux during peak flow operation, which could be attributed to the operation beyond critical flux at peak flows. No such trend was observed for an external MBR system, which uses relatively higher recirculation flow rate to sustain high flux operation.

- In order to mitigate fouling during peak flux operation, one or more of these parameters were changed as per manufacturer's recommendation: scouring air, recirculation flow rate, and flow rates following peak flux operation.

3.4 Performance Comparison of MBR Systems

- The F/M ratio for the MBR pilot systems ranged between 0.05–0.09 g BOD/g VSS.d,[4] which is within the desired range.

- The median net flux for submerged MBR systems ranged between 13–16 gfd whereas that for external MBR system was measured at 27 gfd.

- The scouring air requirement per unit membrane area for MBR pilot systems ranged between 0.019–0.040 standard cubic feet per minute per square foot ($scfm/ft^2$).

[4] Grams of biochemical oxygen demand per gram of volatile suspended solids-day.

3.5 Title 22 Approval Testing

- The Puron MBR system achieved permeate turbidity of <0.1 NTU for 95% of the time in addition to achieving 1.0-log removal of MS-2 phage at the 50^{th} percentile level.

- The Huber MBR system achieved permeate turbidity of <0.05 NTU for 95% of the time in addition to achieving 4.0-log removal of MS-2 phage at the 50^{th} percentile level.

- The Kruger Neosep MBR system achieved a permeate turbidity of <0.05 NTU for 95% of the time in addition to achieving 3.0-log removal of MS-2 phage at the 50^{th} percentile level.

- The DynaLift MBR system achieved a permeate turbidity of <0.05 NTU for 95% of the time in addition to achieving 4.0-log removal of MS-2 phage at the 50^{th} percentile level.

- As a result of the Title 22 testing, all four MBR systems evaluated met Title 22 water recycling criteria and received CDPH approval (appendix E).

3.6 Cost Analysis

- Cost estimates ($/1,000 gal) for newly developed MBR water reclamation systems (1 MGD) ranged from $2.02–$2.58.

- Cost estimates of the newly develped MBR systems showed an economy of scale of approximately 17% for 1- and 5-MGD facilties .

- Comparison of current cost estimates to previous estimates indicates the cost of MBR process components (excluding membrane system) for 1-MGD systems have increased by approximately 24% between 2000–2006.

- An evaluation of membrane costs associated with 1-MGD MBR systems adjusted to 2006 dollars shows a decrease of approximately 33% between 2000–2006.

- Results show that increased costs in construction and raw material has been offset by decreased membrane costs.

3.7 Recommended Future Work

The project team was able to identify various advantages and drawbacks about these new MBR systems through this project. Other than some minor issues experienced with these systems, all four new MBR systems operated well at the manufacturer's recommended operating conditions. With the arrival of these systems in the United States market, the number of MBR vendors have doubled, thereby increasing competition and benefiting the water/wastewater utilities. In addition to the above findings, the project team would be interested in several new research topics which are listed below:

- Conduct demonstration scale testing of MBR system to evaluate potential issues with full-scale implementation of these new MBR systems

- Study the long-term impact of peaking on MBR systems along with the difference in fouling trend at different operating parameters during peak flows

- Long-term operation and optimization of external MBR systems to determine their competitiveness with submerged MBR systems

- Optimization of MBRs to remove emerging contaminants such as Endocrine Disrupting Compounds and Pharmaceutical and Personal Care Products

4. Materials and Methods

4.1 Pilot Testing Site

During the entire study period, all four MBR systems were operated at a site specially designed for pilot operation at the Point Loma Wastewater Treatment Plant (PLWWTP) located in San Diego, California. The PLWWTP is a 240-MGD advanced primary treatment facility. The pilot units were operated on a concrete slab located at PLWWTP. The pilot site had easy access to raw wastewater, electrical power, and discharge channels for waste sludge, filtrate, and potable water. Separate electrical connections to each pilot unit were provided by the city of San Diego. The site had proper containment to avoid any sludge spill outside the pilot testing area.

4.2 MBR Influent Wastewater Quality

A schematic of PLWWTP showing the feed water supply line for MBR pilots is shown in figure 4-1 (all tables and figures are presented in appendix A). Raw wastewater entering the PLWWTP from nearby pump stations is first screened using 1-inch bar screen and passed to a grit chamber. The degritted wastewater is then passed into an influent channel during which 15–25 mg/L of ferric chloride is added to the water to initiate a chemical coagulation process. To enhance the coagulation process, the wastewater is dosed with approximately 0.1 mg/L of anionic polymer before being passed to the primary clarifier. Advanced primary effluent from the primary clarifier is then screened before being discharged to the ocean.

During the entire pilot study, raw wastewater with ferric chloride, but prior to the addition of polymer, was screened by 0.75-millimeter (mm) rotary drum screen before being fed to the MBR system. Wastewater quality for MBR influent during the study period is presented in table 4-1. MBR influent samples were collected after raw wastewater was screened by a 0.75-mm rotating drum screen. As shown, the BOD5 and TSS concentrations for the MBR influent were lower than expected due to the fine screening and coagulant addition prior to the intake. The average BOD5 concentration for the raw wastewater was measured at 252 mg/L (City of San Diego, 2005), whereas that, after fine screening, the concentration was measured at 161 mg/L, indicating a 36% removal of BOD5 by fine screen. The TSS concentration for the raw wastewater was measured at 274 mg/L (City of San Diego, 2005), whereas, after fine screening, the concentration was measured at 185 mg/L, indicating a 33% removal of TSS by fine screen. While using a 0.5-mm drum filter screen for screening MBR influent, 29% chemical oxygen demand (COD) removal and 63% TSS removal have been reported in a similar study (van der Roest, et al., 2002).

4.3 Description of Pilot Units

4.3.1 Puron MBR

The Puron MBR system, provided by Koch Membrane Systems (KMS), consisted of a 580-gallon aerobic tank, 406-gallon anoxic tank; and a 185-gallon membrane tank. Feed water to the system was screened by a 0.75-mm Roto-Sieve rotary drum screen before being passed to the anoxic basin. The anoxic basin was designed with fine bubble diffusers so that it can be used either as an aerobic or anoxic zone. Feed flow to the anoxic basin was controlled via a programmable logic controller (PLC) of the system using a submersible pump. As shown in figure 4-2, water from the anoxic tank flowed by gravity to the aeration tank for nitrification. Nitrified water from the aeration tank was recirculated back to the anoxic tank for denitrification. Water from the aeration tank was also recirculated to the membrane tank at a flow rate of four times the permeate flow. Overflow from the membrane tank flowed back to the aeration tank by gravity. Wastewater could be nitrified and denitrified before being filtered out from the membrane tank. Sludge wasting was done automatically from the aeration tank and it was controlled via a PLC after receiving an output from a TSS sensor submerged in the aeration tank. For the Reclamation study period, the system was operated in nitrification only mode. The photograph of the Puron MBR pilot system is shown in appendix D.

The membrane tank for the Puron MBR system consisted of one PSH 500C2 membrane module with total membrane area of 323 square feet (ft^2) (30 [square meters] m^2). KMS's PSH 500C2 membrane module consists of a L1 membrane, which is designed with an outside-in flow path and has a nominal pore size of 0.05 micrometer (µm) (as per the information obtained from KMS). Membrane specifications for KMS's L1 membrane are specified in table 4-2. The L1 membrane is a polyethersulfone (PES), hollow fiber membrane cast onto a braided support. The braided support is meant to provide high mechanical strength to the membrane fiber and makes the fiber resistant to tearing or breaking down during filtration. A unique feature of the Puron MBR is that the membrane fiber is sealed at the top and potted only at the bottom to potentially avoid hair and fibrous substances getting clogged at the top of the membrane bundle. Also, the scouring air, backwash flow rate, and filtration cycle time varied based on permeate flow rate, which is explained further in section 5.1.1. The photograph of the PSH 500C2 membrane module is shown in appendix D. The chemical cleaning procedures for the Puron MBR pilot system are provided in appendix B.

4.3.2 Huber MBR

The Huber MBR pilot system, provided by Huber Technology, was equipped with a 3,700-gallon aerobic tank and a 3,200-gallon membrane tank. Raw wastewater was screened using 0.75-mm Roto-Sieve screen and was fed to the aeration tank. A general schematic of the Huber MBR system is shown in **figure 4-3**. Feed flow to the aerobic tank was controlled via a programmable logic control (PLC), which receives output from the level sensor in the aeration tank that controls a submersible feed pump. After being nitrified, water from the aeration tank was pumped to the membrane tank via a recirculation pump at a flow rate of 3–5 times the permeate flow rate. The recirculation pump for the system was operated intermittently and was controlled by the permeate drawdown set point. Once initiated by a specified drawdown from the membrane filtration tank, the recirculation pump operates for a specified period, which could be optimized based on the permeate flow rate. This run time was set to 300 seconds during the study period. During this time, the wastewater from the membrane tank flowed by gravity to the aeration tank via an opening at the top of the wall between the aeration tank and the membrane tank. Water was filtered through the membranes using a filtration pump that creates a vacuum inside the membrane plate thereby having water flow from outside in. The photograph of Huber MBR pilot system is shown in **appendix D**.

The membrane tank of the Huber MBR system consists of one Vacuum Rotation Membrane 20 (VRM® 20) unit with total membrane surface area of 1,162 ft^2 (108 m^2). The Huber VRM® 20 membrane unit uses Huber Technology's NADIR P-150F flat-sheet ultrafiltration membrane. The NADIR P-150F is a polyethersulfone (PES) membrane with a nominal pore-size of 0.038 µm. Membrane specifications for Huber Technology's NADIR P-150F membrane are specified in **table 4-2**. The VRM® 20 unit consists of individual rotating plate membranes installed around a stationary hollow shaft. Two centrally arranged air tubes provided scouring air into the interspaces between the plates. Permeate was drawn from each plate via permeate tubes that collect permeate to a common pipe. These horizontal pipes eventually meet at a center manifold, from which permeate was taken out of the system. Because of the rotation of the membrane element within the membrane tank, membrane plates are scoured alternately. At high flux operation, the rotation of the membrane module also potentially reduces the air requirements for scouring from two centrally placed air tubes. The photograph of the Huber VRM® 20 membrane module is shown in **appendix D.** The chemical cleaning procedures for the Huber MBR pilot system are provided in **appendix B**.

4.3.3 Kruger Neosep MBR

The Kruger MBR pilot system, provided by I. Kruger Inc., consisted of a 1,300-gallon anoxic tank, 3,000-gallon aerobic tank, and 1,900-gallon membrane tank. A schematic of the Kruger MBR pilot system is shown in **figure 4-4**. As shown in the schematic, raw wastewater was screened using a 0.75-mm screen and fed to the anoxic tank. The feed pump was regulated by a PLC to maintain the desired tank level via a sensor detecting the water level in the anoxic tank. Wastewater from the anoxic tank was passed to the aerobic tank for nitrification by gravity. The aerobic tank and membrane tank were connected at the bottom to allow sludge from the aerobic tank to flow into the membrane tank by gravity. Sludge from the membrane tank was pumped back to the aerobic tank at five times the permeate flow rate. Nitrified wastewater from the aerobic tank was recirculated back to the anoxic tank for denitrification at three times the permeate flow rate. A permeate pump was used to create a vacuum inside the membrane module and filter water from outside in. Sludge wasting was done manually twice a day to maintain a target MLSS in the aeration tank. A telescoping valve, installed in the aeration tank, was used to waste sludge from the top of the aeration tank, thereby allowing the foam to be removed from the bioreactor. The photograph of the Kruger Neosep MBR pilot system is shown in **appendix D**.

The membrane tank of the Kruger Neosep MBR pilot system was equipped with one Neosep™ K100 membrane module, which contains 100 flat-sheet membrane elements with a total membrane area of 1,506 ft^2 (140 m^2). The Neosep K100 membrane module uses flat-sheet polyvinylidenefluoride (PVDF) ultrafiltration membrane with a nominal pore size of 0.08 µm. The standard deviation from the nominal pore size is very low at 0.03 µm. Membrane specifications for the Neosep K100 membrane module are shown in **table 4-2**. The manufacturer claims that this allows the fluid to be distributed equally along the membrane surface during filtration. It also allows the cleaning chemicals to be evenly distributed making the cleaning more effective. The photograph of the Kruger Neosep K100 membrane module is shown in **appendix D**. The chemical cleaning procedures for the Kruger Neosep MBR pilot system are provided in **appendix B**.

4.3.4 DynaLift MBR

The DynaLift MBR pilot system provided by Parkson Corporation consisted of a 1,400-gallon aerobic tank, 1,250-gallon anoxic tank, and an external membrane module. Screened wastewater was fed to the anoxic tank via a submersible pump controlled by a PLC to maintain a constant water level in the tank. Wastewater from the anoxic tank flowed by gravity to the aerobic tank for nitrification. Nitrified water was then recirculated to the external membrane module for filtration. Scouring air was injected at the bottom of the membrane module using an airlift pump along with sludge recirculation to maintain a turbulent cross flow. This innovative design feature helps to minimize the recirculation flow requirements for an external MBR. Finally, sludge from the membrane module overflowed back to the anoxic tank from the top of the module. The schematic of the DynaLift MBR pilot system is shown in figure 4-5. Sludge wasting was done automatically on desired intervals from the recirculation line and was controlled via a PLC after receiving input from the operator via set-points. The operator would set the wasting frequency and wasting duration and the PLC opened the wasting valve accordingly. For the entire study period, the system was operated in nitrification-denitrification mode. The photograph of the DynaLift MBR pilot system is shown in appendix D.

The DynaLift MBR pilot system consisted of one DynaLift 38 PRV external PVDF tubular membrane module with a nominal pore size of 0.03 µm and a membrane area of 312 ft^2. Specifications for the DynaLift 38 PRV membrane module are shown in table 4-2. These external tubular membranes provide a wide-channel, nonclogging design and can be operated at high MLSS levels of up to 15,000 mg/L. Because the membrane module is located outside the bioreactor, no membrane system components are submerged in the mixed liquor. To eliminate high pumping energies, membranes are placed in a vertical orientation and MLSS is kept suspended inside the module using air-lift assisted cross flow pumping. This air-lift assisted cross flow pumping minimizes the recirculation flow requirement for the system. The photograph of the membrane module is shown in appendix D. The chemical cleaning procedures for the DynaLift MBR pilot system are provided in appendix B.

4.3.5 RO System

An RO pilot unit was used during the study to treat effluent from the MBR systems. MBR effluent from MBR systems was collected in a single tank which served as a feed to the RO system. MBR permeate initially was chloraminated at a dose of 2 mg/L and then dosed with antiscalant ("VTEC 3000" provided by Avista Technologies) before being filtered through a 5-micron cartridge filter to prevent any upsets that may occur in the MBR systems from reaching the RO membranes. The effluent of the cartridge filters was then pressurized and introduced to the RO pilot unit, which was configured to operate with single stage train at a feed-water recovery of 50%. This single stage train consisted of two pressure vessels in series, each equipped with three RO membrane elements. Throughout the testing period the RO membranes were operated at a constant flux of 12 gfd. The concentrate of all the RO membranes was directed to waste.

To evaluate the performance of RO membranes while operating on MBR effluent, new generation RO membranes, specifically designed for wastewater reclamation, were installed in the RO pilot unit. These 4040 HR RO membranes were provided by Koch Membrane Systems, which is a leading RO membrane manufacturer. Table 4-3 provides specific details on the RO membranes evaluated during the study. This information was obtained from the manufacturers and is based on the specific test conditions provided.

4.3.6 Roto-Sieve Screening Equipment

A Roto-Sieve Model 4024-40 drum screen was evaluated during the study to screen raw wastewater before passing it to MBR pilots. Model 4024-40 drum screen had 0.8-mm perforations and had a flow capacity of 60–300 gpm. The roto-sieve drum screen consisted of a perforated drum with an internally fixed screw, which transports the separated particles out of the drum. Perforated drum screen helps to remove hair and fibrous materials from raw wastewater and prevents clogging of membrane in MBR systems. Raw wastewater was fed into the drum through an inlet pipe, which distributes the water over a large area of the drum's interior. During passage through the drum, the wastewater is screened through the drum's perforations and collects in the trough underneath. Separated particles are transported out of the drum through the screenings outlet. The screen was also equipped with a counter rotating roller brush and a spray header with spray nozzles. This brush, along with sprayed water, continuously cleaned the screen to prevent clogging of the perforated slots. The brush is fixed against the outside of the drum and rotates by friction between the drum and the brush. Specifications for the Roto-Sieve screen used during the pilot study are presented in table 4-4.

4.4 Water Quality Analysis

4.4.1 Onsite Water Quality Analysis

During the course of the pilot testing, water quality samples were collected and analyzed to assess the performance of the MBR systems and the RO membranes. As indicated, several water quality parameters including pH, conductivity, DO, and turbidity were monitored onsite. All onsite measurements were made using portable, batch, and online instruments.

4.4.1.1 pH

pH was measured for MBR influent, MBR aeration tanks, RO influent, and RO permeate using a handheld Hach SensION1 pH meter. The meter was calibrated once every 2 weeks using a three-point calibration with buffers 4, 7, and 10.

4.4.1.2 Turbidity

Turbidity of MBR influent, MBR permeate, and RO permeate were measured three times a week using a Hach 2100N desktop turbidimeter. Turbidity readings for MBR permeate were also measured online using a Hach 1720C turbidimeter.

4.4.1.3 Dissolved Oxygen (DO)

DO levels were measured in MBR aeration tanks three times a week using a handheld YSI 550A DO meter. DO was also measured in the aeration tanks using online DO meters equipped on the MBR systems.

4.4.1.4 Conductivity

Conductivity was measured for RO feed and RO permeate samples using handheld Hach sensION5 conductivity meter. Conductivity readings also were collected for RO feed and RO permeate from online conductivity probes installed on the pilot skid.

4.4.1.5 Temperature

The temperature of the aerobic tank/membrane tank of the MBR systems and RO feed were monitored using in-line temperature gauges. These values periodically were verified using a thermometer.

4.4.1.6 Free and Total Chlorine Residual

The total and free chlorine residuals for RO feed were measured three times a week using Hach’s colorimetric test kit.

4.4.2 Laboratory Water Quality Analysis

The remaining water quality parameters were measured by off-site laboratories in accordance to methods listed in the Standard Methods for the Examination of Water and Wastewater (SM), United States Environmental Protection Agency (EPA). Water quality samples were sent to four different State-certified laboratories to perform different water quality analysis. These labs consisted of: the city of San Diego's Point Loma WWTP Laboratory, Industrial Waste Laboratory at Alvarado, and Marine Microbiology Laboratory. The fourth lab used was Calscience Environmental Laboratory located in Garden Grove, California. Table 4-5 specifies the method and detection limits for each parameter evaluated by the laboratories.

All water quality samples were collected as grab samples using sample containers provided from the corresponding laboratory. All samples were transported to the lab in a cooler at recommended temperature and were processed within the allowable holding period. Before collecting samples, all sampling ports were flushed for a few seconds. The samples for microbiology analysis were collected after the sampling ports were properly flamed and flushed.

4.5 Quality Assurance/Quality Control

Appropriate measures were taken at the pilot site to attain the highest degree of quality assurance and quality control (QA/QC). Appendix C contains a technical memorandum documenting the QA/QC that was performed throughout the study to ensure the correct measurement of pilot operational data and water quality.

4.6 Calculation of Operating Parameters

Transmembrane Pressure (TMP) for MBR Systems

The transmembrane pressure for MBR pilot systems was calculated as follows:

For submerged MBR systems (i.e., Puron, Huber, and Kruger Neosep)

TMP (psi) = Static Pressure – Dynamic Pressure *(1)*

For external MBR system (i.e., DynaLift)

TMP (psi) =((Module Top Pressure + Module Bottom Pressure)/2) – Permeate Pressure *(2)*

Flux for MBR Systems

The flux of the MBR membranes was calculated as follows:

$$J = \frac{Q_p \times 1{,}440}{A} \qquad (3)$$

Where,

J = Membrane flux (gfd)

A = Total membrane surface area (ft^2)

Q_p = Permeate flow rate (gpm)

Temperature Corrected Flux for MBR Systems

Temperature corrected flux for Puron and Huber MBR systems were calculated as follows:

$$J_{@\,20\,°C} = J \times e^{-TCF \times (T-20)} \qquad (4)$$

Where,

$J_{@\,20°C}$ = Temperature corrected flux at 20 °C

J = Flux at T °C

T = Feed water temperature (°C)

TCF = Temperature correction factor as provided by the manufacturer

Temperature corrected flux for Kruger MBR system was calculated as follows:

$$J_{@\,20\,°C} = J - (TCF \times J) \qquad (5)$$

Where,

$J_{@\,20\,°C}$ = Temperature corrected flux at 20 °C

J = Flux at T °C

T = Feed water temperature (°C)

TCF = Temperature correction factor as provided by the manufacturer

Temperature corrected flux for DynaLift MBR system was calculated as follows:

$$J_{@\,20\,°C} = J \times 1.022^{(20-T)} \qquad (6)$$

Where,

$J_{@\,20\,°C}$ = Temperature corrected flux at 20 °C

J = Flux at T °C

T = Feed water temperature (°C)

24-hr Weighted Average Flux

$$J_{24\text{-}hr} = \frac{(J_{min} \text{ x } T_{min}) + (J_{avg} \text{ x } T_{avg}) + (J_{max} \text{ x } T_{max})}{24} \quad (7)$$

Where,

$J_{24\text{-}hr}$	=	24-hour (hr) weighted average flux
J_{min}	=	Minimum flux as recommended by manufacturer (gfd)
T_{min}	=	Number of hours system was operated at minimum flux during 24-hr period (hr)
J_{avg}	=	Average flux as recommended by manufacturer (gfd)
T_{avg}	=	Number of hours system was operated at average flux during 24-hr period (hr)
J_{max}	=	Maximum flux as recommended by manufacturer (gfd)
T_{max}	=	Number of hours system was operated at maximum flux during 24-hr period (hr)

Food to Microorganism Ratio (F/M)

F/M = (Influent BOD5 (mg/L) x Treated (filtered) water per day (L/d))/ (volatile suspended solids [VSS] concentration in the bioreactor (mg/L) x Bioreactor volume (L)) *(8)*

Specific Flux for MBR Systems

The specific flux for the membranes was calculated as follows:

$$J_{SP} = \frac{J}{TMP} \quad (9)$$

Where,

J_{SP}	=	Specific flux (gfd/psi)
J	=	Flux (gfd)
TMP	=	Transmembrane pressure (psi)

Likewise, the temperature-corrected specific flux can be calculated using the temperature corrected flux.

Hydraulic Retention Time (HRT)

The HRT of the MBR system was calculated as follows:

$$HRT = V / Q_p \quad (10)$$

Where,

V = Volume of the bioreactor (gallons)

Q_p = Permeate flow rate (gpm)

Anoxic HRT and total HRT were calculated using anoxic and total bioreactor volumes, respectively, in the above stated formula.

Solids Retention Time (SRT)

The SRT of the MBR system was calculated as follows:

$$SRT = V / Q_w \tag{11}$$

Where,

V = Volume of the bioreactor (gallons)

Q_w = Wasting flow rate (gallons/day)

Net Flux

Net flux for MBR systems using relaxation (i.e., Huber and Kruger) was calculated as follows:

$$J_{net} = (J \times T_F) / T_F + T_R \tag{12}$$

Where,

J_{net} = Net flux (gfd)

J = Membrane flux (gfd)

T_F = Filtration time (minute [min])

T_R = Relaxation time (min)

Net flux for MBR systems using backpulse (i.e., Puron and DynaLift) was calculated as follows:

$$J_{net} = [(J \times T_F) - (J_{BW} \times T_{BW})] / T_F + T_{BW} \tag{13}$$

Where,

J_{net} = Net flux (gfd)

J = Membrane flux (gfd)

J_{BW} = Backwash flux (gfd) = backwash flow/membrane area

T_F = Filtration time (min)

T_{BW} = Backwash time (min)

Estimated Membrane Area Requirements for 1-MGD

$$A_{1\text{-}MGD} = \frac{1{,}000{,}000\ (gal.)}{J_{net}\ (gfd)} \tag{14}$$

Where,

$A_{1\text{-}MGD}$ = Estimated membrane area requirements for 1 MGD

J_{net} = Net flux (gfd)

Scouring Airr per ft² of Membrane (scfm/ft²)

$$scfm/ft^2 = \frac{\text{Measured scouring air from pilot (scfm)}}{\text{Membrane area of pilot } (ft^2)} \tag{15}$$

Estimated Scouring Air Requirements for 1 MGD

Estimated scouring air for 1 MGD $= A_{1\ MGD} \times (scfm/ft^2)$ (16)

Recirculation Ratio

$$\text{Recirculation ratio} = \frac{Q_{A\ to\ M}}{Q_p} \quad (17)$$

Where,

$Q_{A\ to\ M}$ = Flow from aeration tank to membrane tank/module (gpm)

Q_p = Permeate flow

Log Removal

The log removal was calculated as follows:

$$\text{Log removal} = \text{Log}(c_f) - \text{Log}(c_p) \quad (18)$$

Where,

c_f = Concentration in the MBR influent

c_p = Concentration in the MBR permeate

Net Operating Pressure for RO Membranes

The average net operating pressure for the RO membrane system was calculated as follows:

$$P_{net} = \frac{(P_i + P_o)}{2} - P_p - \Delta\Pi \quad (19)$$

Where,

P_{net} = Net operating pressure (psi)

P_i = Pressure at the inlet of the membrane module (psi)

P_o = Pressure at the outlet of the membrane module (psi)

P_p = Permeate pressure (psi)

$\Delta\pi$ = Net osmotic pressure of the feed and permeate (psi)

The following approximation can be used to determine osmotic pressure of the feed stream:

1,000 mg/L NaCl solution ~ 11.5 psi of osmotic pressure, π

A correlation between NaCl and conductivity can be assumed as follows:

(1 micromho of conductivity = 1 mg/L NaCl)

Specific Flux for RO Membranes

The specific flux is the relationship between flux and the net operating pressure. The relationship is defined by the formula:

$$J_{SP} = \frac{J}{P_{Net}} \tag{20}$$

Where,
J_{SP} = Specific flux (gfd/psi)
J = Flux (gfd)
P_{Net} = Net operating pressure (psi)

Likewise, the temperature-corrected specific flux can be calculated using the temperature corrected flux. Temperature corrections to 25 °C for flux and specific flux of the RO membranes was made according to the manufacturers correction factors.

Feed Water Recovery

The parameter "feed water recovery" (FWR) represents the net water production of the RO system. The FWR will be calculated according to the following equation:

$$FWR = \left[1 - \frac{Q_{conc}}{Q_{perm}}\right] x\ 100\% \tag{21}$$

Where,
Q_{conc} = Concentrate flow rate
Q_{perm} = Permeate flow rate

Rejection

The rejection of contaminants by each treatment process was calculated as follows:

$$R = \left(1 - \frac{C_P}{C_F}\right) x\ 100\% \tag{22}$$

Where:
R = Rejection, %
C_P = Product water concentration, (mg/L)
C_F = Feed water concentration, (mg/L)

5. Results and Discussion

5.1 Operating Parameters for the Pilot Units

5.1.1 Puron MBR

The Puron MBR system was operated in nitrification only mode throughout the study period by converting the anoxic zone into an aerobic zone. **Figure 5-1** presents the MLSS concentrations in the aeration tank of the Puron MBR system. The system was seeded with sludge from the aeration tank of South Bay Wastewater Treatment Plant (SBWRP). As shown, the MLSS concentration increased from 4 to 10 grams per liter (g/L) in about 500 hours of operation. The MLSS concentration was maintained at the target concentration of 10–10.5 g/L during the rest of the operating period. This was achieved by an automatic wasting via a pneumatic valve that operated based on input received from an online TSS sensor submerged in aeration tank. The SRT 7-d and wasting rate are shown in **figure 5-2**. The Puron MBR system was operated at an HRT of 4–11 hours during the study period. The DO levels in the aerobic tank were maintained between 1–2 mg/L. **Figures 5-3** and **5-4** show the HRT and the DO concentrations for the Puron™ MBR, respectively.

The Puron MBR system was designed to operate in three different modes depending on the level in the aeration tank. The backwash flow rates, filtration cycle times, and scouring air frequencies varied based on the operating mode. The system operated in average-flux (F_{opt}) for most of the time during the day. For a certain period of time during a day, the system was designed to operate in a low-flux mode (F_{min}) to relax the membrane and to minimize membrane fouling. By controlling the feed flow to the system and, thereby, maintaining the desired water level in the aeration tank, the system could be operated in low-flux mode (F_{min}) for a desired period of time during a day. As shown in **figure 5-5**, membrane scouring air was provided intermittently at 10–12 scfm. The operating parameters for Puron MBR are specified in **table 5-1**.

5.1.2 Huber MBR

The Huber MBR system was operated in nitrification only mode as the system was designed with only aerobic and membrane tanks. **Figure 5-6** presents the MLSS concentrations in the aerobic tank of the Huber MBR system. The pilot system was seeded with sludge from an aeration tank of SBWRP. Once the system was seeded, the target MLSS concentration of 9–10 g/L for the Huber MBR system was achieved after about 1,100 hours of operation. Manual wasting was carried on to maintain the MLSS below 12.0 g/L as recommended by the manufacturer. This was done by manually opening a wasting valve on the aeration tank for a calculated period of time and at a known flow rate. **Figure 5-7** shows the SRT 7-d and wasting rate for Huber MBR pilot system. After about

2,000 hours of operation, a chemical cleaning was performed on the Huber MBR system, which required draining the membrane tank for soaking the membrane unit in chlorine solution as per manufacturer's recommended protocol. The loss of sludge in the membrane tank during chemical clean resulted in dilution of the MLSS concentration to about 8 g/L. Post cleaning, severe foaming was observed in the Huber MBR system, resulting in the need to be reseeded. After being reseeded, MLSS of the aeration tank was down to about 2 g/L. MLSS in the aeration tank of the system was back to 8 g/L at about 3,500 hours of operation. The Huber MBR pilot system was operated at an HRT of 8–21 hours during the study period. The DO concentration in the aerobic tank was maintained between 2–4 mg/L during the study period. This was done initially by providing continuous aeration, which resulted in slightly higher DO levels (greater than [>] 4 mg/L) than desired. In order to operate efficiently, after about 850 hours of operation, Huber recommended switching from continuous aeration to intermittent aeration to maintain the DO level between the desired level of 2–4 mg/L. **Figures 5-8** and **5-9** present the HRT and DO concentration for the Huber MBR system.

During most of the study period, the system was operated with a filtration cycle time of 540 seconds followed by a relaxation cycle time of 60 seconds. The scouring air was provided continuously at a flow rate of 30 scfm for the first 2,000 hours of operation irrespective of the flow rate. After 3,000 hours of operation, Huber recommended to reduce the scouring air to 18 scfm. **Figure 5-10** presents the membrane scouring air for the Huber MBR pilot system. The operating parameters for the system during the study are specified in **table 5-1.**

5.1.3 Kruger Neosep MBR

The Kruger Neosep MBR system was designed to operate in nitrification and denitrification mode. As shown in **figure 5-11**, the MLSS concentration in the aeration tank for Kruger Neosep MBR was maintained between 10–12 g/L during the entire study period. The system initially was seeded from the nearby MBR pilot system. The target concentration of 10–12 g/L was achieved after 200 hours of operation. The target MLSS concentration of 10–12 g/L was maintained by periodically manually wasting a calculated amount of sludge from the aeration tank. **Figure 5-12** shows the $SRT_{7\text{-}d}$ and wasting rate for the Kruger Neosep MBR system. During the study period, the system was operated at a total system HRT of about 5 hours including an anoxic HRT of about 1.5 hours. **Figure 5-13** shows the HRT for the Kruger Neosep MBR pilot system. The DO concentrations in the aerobic and anoxic tanks were maintained between 2–4 mg/L and <0.5 mg/L, respectively. **Figure 5-14** shows the DO concentrations for the Kruger Neosep MBR pilot system.

During the study period, the system was operated with a filtration cycle time of 540 seconds followed by relaxation period of 60 seconds. As shown in **figure 5-15**, membrane scouring air was provided continuously at 60 scfm for the first 2,100 hours. Following that, Kruger recommended reducing the membrane scouring air to 55 scfm. The operating parameters for the Kruger Neosep MBR system during the study are specified in **table 5-1**.

5.1.4 DynaLift MBR

The DynaLift MBR system was designed with anoxic and aerobic zones to operate in nitrification and denitrification mode. The system was initially seeded from a nearby MBR pilot system. **Figure 5-16** shows the MLSS concentration in the aeration tank of the DynaLift MBR system. As shown, the target MLSS concentration of 10–12 g/L was achieved after about 700 hours of operation. The MLSS concentration was maintained at desired level by automatic wasting as discussed in **section 4.3.4**. At 1,650 hours of operation, the air compressor used to operate the pneumatic valves of the pilot system failed, which resulted in turning off the filtration and influent pump. This caused the MLSS to drop to 7 g/L. During this downtime, the aeration blower and anoxic mixer were operated continuously to maintain the biology. Once the air compressor was replaced, the system was brought back into normal operation and reseeded from a nearby MBR pilot system to achieve the target MLSS of 10–12 g/L. At 2,300 hours of operation, the second air compressor failed, resulting in a downtime of few days. Following this, the system was partially drained and reseeded from nearby MBR pilot system to achieve the target MLSS concentration. As shown in **figure 5-18**, the system was operated at a total system HRT of 7–11 hours including an anoxic HRT of 3.5–4.5 hours. The DO concentrations for the DynaLift MBR pilot system are shown in **figure 5-19**. The aerobic DO concentration was maintained between 2–4 mg/L, whereas the anoxic DO concentration was maintained at less than 0.5 mg/L.

The DynaLift MBR system was operated with a filtration cycle time of 600 seconds followed by a permeate backpulse of 6 seconds at 52 gpm. During each backpulse, a vent valve on the top of the permeate piping was opened to air to remove any gas or air bubbles trapped during filtration. After every 11 filtration cycles, the membrane module was drained automatically before initiating a backwash. This was done to achieve an enhanced backwash on an empty membrane module. The drained MLSS was brought back to the anoxic tank and the entire procedure was completed in less than 25 seconds. The frequency of enhanced backwash varies from every 2 to 6 hours as per manufacturer recommendation. As shown in **figure 5-20**, the membrane scouring air was provided continuously at 6 scfm for first 2,400 hours, after which it was lowered to 5 scfm as per Parkson's recommendation. The operating parameters for the DynaLift MBR system are specified in **table 5-1**.

5.1.5 RO System

The RO pilot system was operated on effluent from two different MBR systems during the study period. Initially, the RO system was operated on effluent from Huber MBR for the first 140 hours. Following a membrane breach noticed in the

Huber MBR pilot, the operation of RO system was terminated temporarily. The pilot operation was resumed once Kruger MBR system was installed and effluent from that system was available to be used as a feed to the RO system. The RO system was then operated on Kruger MBR effluent for next 1,500 hours. During the entire study period, the target flux for the RO system was 12 gfd whereas the feed water recovery was 50%.

5.2 Membrane Performance

5.2.1 Puron MBR

Once the Puron MBR pilot was seeded with sludge, the pilot was operated at low flux for the first 500 hours till the target MLSS concentration was achieved. The TMP and flux data for the Puron MBR system are shown in **figure 5-21**. At 500 hours of operation, KMS recommended to change the membrane module, as the permeate turbidity was slightly higher than expected by KMS. Once the module was replaced with a new module, the system was operated at a target flux of 10 gfd between 500 and 900 hours of operation. Following that, a chemical clean was performed on the system; and a peaking experiment was conducted between operating hours of 910 and 1,055 hours to observe the membrane performance at peak flows. The results for the peaking experiment will be discussed further in **section 6** of the report. At 1,610 hours of operation, operating flux was increased to 24 gfd to observe the operational performance of the membrane at high-flux operation. Due to the limitation of the bioreactor volume and a concern about significant drop in HRT, this high-flux operation was conducted with 30–50% of the permeate recycle. This was done by pumping a portion of the permeate back to the membrane tank. The TMP increased from 1.9 to 3.8 psi during these 600 hours of operation at high flux. As a result, it was necessary to perform maintenance clean at run time of 2,300 hours. Following the maintenance clean, the TMP decreased to 2.3 psi, and operation at 24 gfd was continued. During this operating period, the TMP increased from 2.3 to 3.2 psi after 170 hours of operation; and maintenance clean was performed at 2,450 hours of operation. The system was then operated at 24 gfd for 300 hours, and a recovery clean was performed on the system at 2,750 hours.

After the recovery clean, the system was operated without permeate recycle at target flux of 15 gfd for about 165 hours during which the TMP increased from 1.3 to 1.6 psi resulting in a drop of specific flux from 11.5 to 9.0 gfd/psi. Following that, the system was operated at 11 gfd from 2,935 to 3,065 hours of operation during which the TMP increased from 1.0 psi to 1.6 psi. After performing maintenance clean, high-flux operation was continued to observe the fouling trend without permeate recycle. During the operation hours of 3,100 to 3,230, the system was operated at target flux of 24 gfd without permeate recycle, which resulted in an increase of TMP from 3.1 to 4.2 psi within 145 hours of operation. These results show that there was a significant difference in the fouling trend of the system when operating the pilot with and without permeate recycle at the same target flux. The low fouling rate during permeate recycle could be attributed to the nonbiodegradable organic matter filtered by the membrane during the first pass and is absent in the permeate recycle. Later, the pilot was decommissioned and shipped back to the manufacturer.

5.2.2 Huber MBR

Figure 5-22 presents the TMP and flux data for Huber MBR system. Once the Huber MBR pilot was seeded with sludge, the system was operated at a low flux for the first 700 hours of operation. This was done to avoid further membrane fouling while operating at low MLSS. Once the MLSS concentration reached 6 g/L, maintenance clean was performed on the unit; and the operating flux was increased gradually as the MLSS concentration in the aeration tank increased. The target MLSS concentration was achieved after about 1,000 hours of operation. It took slightly longer to achieve the target MLSS due to a relatively lower startup MLSS concentration. After 950 hours of operation, membrane air scouring blower failed and had to be repaired. After the repair was done, maintenance clean was performed; and the unit was brought back to normal operation. After the maintenance clean, a peaking experiment was conducted on the Huber MBR system during the 1,200 and 1,345 hours of operation. During this time period, the system operated at a sustained TMP of 1.5 psi. Results for the peaking experiments are discussed in detail in **section 6** of this report. Following the peaking experiment, maintenance clean was performed at 1,480 hours, and the system was operated at a target flux of 15 gfd from 1,520 to 1,870 hours of operation. During this period of 350 hours, the TMP of the system increased from 1.6 to 2.5 psi, resulting in a drop of specific flux from 9.6 to 5.9 gfd/psi. Even though the sludge wasting was initiated at 1,500 hours, the MLSS concentration was slightly higher than the target MLSS concentration. Some foaming also was observed in the aeration tank during this period. Several maintenance cleans were performed on the system between 1,870 and 2,070 hours of operation, but the specific flux could not be recovered. These maintenance cleans also resulted in severe foaming in both the aeration and membrane tank. This could be attributed to the chlorine (oxidant) used during the cleans.

To recover the specific flux, Huber recommended performing a chemical clean at 2,080 hours, which required wasting all the biomass in the membrane tank. As a result, the system was reseeded at about 2,350 hours. During this time period, a mechanical problem was observed in the bearing of the membrane module, which caused noncontinuous rotation of the membrane module. The project team also noticed an increase in the MBR effluent turbidity and increase in the operating pressure of the RO system during the same period. Following that, two membrane modules of the Huber VRM unit were found compromised. This is explained further in **section 5.2.5**. The RO system was operated on the Huber MBR effluent at that time. As a result, the Huber MBR unit was shutdown for repair at 2,250 hours of operation. As soon Huber Technology was notified about the problem, they responded promptly and sent a technician to fix the problem. Huber Technology reported never having this problem before on any of their installations. As shown in **figure 5-22**, this failure took a few weeks to repair and included changing two compromised membrane modules.

The Huber MBR system was brought back to normal operation at about 3,040 hours and was operated at a flux of 13.5 gfd between 3,040 and 3,180 hours. A maintenance clean was performed at 3,200 hours, and the flux was increased to 16 gfd. During the next 135 hours of operation at 16 gfd, the TMP increased from 1.3 to 2.7 psi. This could be attributed to the low MLSS levels in the aeration tank causing a relatively high F/M ratio in the reactor. The manufacturer-recommended MLSS range is between 10–12 g/L; and as seen during the operation hours of 1,000–1,700 hours, the system tends to perform well at MLSS concentration above 8,000 mg/L. A second run at 16 gfd was initiated at 3,355 hours of operation after performing a maintenance clean. As shown in figure 5-22, the TMP increased from 1.3 to 2.7 psi after 215 hours of operation, resulting in a drop in specific flux from 12.2 to 5.5 gfd/psi. Following this run, the pilot was decommissioned and shipped back to the manufacturer.

5.2.3 Kruger Neosep MBR

The Kruger MBR pilot system was seeded with sludge from a nearby MBR pilot system, which allowed achieving a target MLSS concentration in just 200 hours of operation. This was due to a higher seed MLSS concentration. **Figure 5-23** shows the TMP and flux data for the Kruger Neosep MBR. The system was operated at a target flux of 18 gfd throughout the study period. As shown, during the first 725 hours of operation, there was a small increase in TMP from 1.0 to 1.1 psi. A recovery clean was performed at 745 hours to begin a peaking experiment that lasted from 830–970 hours. Details of the peaking experiment are discussed in **section 6**. Following the peaking experiment, operation at target flux of 18 gfd was resumed. During the operational period of 970–2,160 hours, the TMP increased from 1.0 to 1.6 psi in 1,200 hours. The project team noticed an increase in the permeate turbidity during this time period, details of which are discussed further in **section 5.3.3**. As a result, Kruger recommended replacing the membrane module at 2,200 hours.

Once the membrane module was replaced, pilot operation was resumed at 2,280 hours at the same target flux of 18 gfd. The initial temperature corrected specific flux for the new membrane module was observed at 18.3 gfd/psi. After 340 hours of operation on the new module, the specific flux dropped from 18.3 to 11.1 gfd/psi. A recovery clean was performed at 2,620 hours and operation at 18 gfd was resumed. During the next 450 hours of operation, the TMP increased from 1.0 to 1.3 psi. The pilot testing was terminated at this point, and the pilot unit was returned to the manufacturer in mid August 2006.

5.2.4 DynaLift MBR

Once the DynaLift MBR pilot was configured and all components installed, the system was seeded with sludge from a nearby MBR pilot system. The TMP and flux data for the DynaLift MBR system are shown in **figure 5-24**. Once the target MLSS concentration of 10–12 g/L was reached after 500 hours of operation, the system was operated at a target flux of 30 gfd. A soak clean was performed at about 900 hours of operation to begin a peaking experiment with a clean membrane. The peaking experiment was conducted from 910–1,055 hours, details of which are discussed in **section 6**. Following the peaking experiment, operation at 30 gfd was resumed. During operating hours of 1,055–1,640, the TMP increased from 1.66 to 4.42 psi in 585 hours, resulting in a decrease in specific flux from 15.2 to 5.3 gfd/psi. As a result, a soak clean was performed at 1,640 hours as per Parkson's recommended cleaning procedure. Before the system could be restarted, the air compressor, used to control the pneumatic valves of the pilot system, failed and had to be replaced. This resulted in a downtime of about 300 hours.

Once the air compressor was replaced, a soak clean was performed, and operation at 30 gfd was resumed at 1,960 hours. While operating at 30 gfd, the TMP increased from 0.9 to 3.3 psi in 285 hours, resulting in the drop of specific flux from 26.7 to 5.8 gfd/psi. Following this drop in the specific flux, the project team decided to lower the operating flux to see if the system could recover without a soak clean. As the specific flux was gradually decreased from 30 to 20 gfd/psi keeping all other operating conditions same, the specific system flux recovered from 5.8 to 13.4 gfd/psi. But the fouling trend continued thereafter, and a soak clean was required at 2,295 hours of operation. At 2,300 hours of operation, the second air compressor failed, which resulted in a down time of few days. Once the air compressor was replaced, operation at 30 gfd was resumed. During operating hours of 2,465-2,750, the TMP increased from 0.9 to 3.4 psi. As a result, a soak clean was performed at 2750 hours. During the next run at 30 gfd, the TMP increased from 0.9 to 3.4 psi in 165 hours. Following this run, the pilot was decommissioned and returned to the manufacturer.

5.2.5 RO System

Once the RO pilot system arrived onsite, it was installed with 4040 HR RO membranes provided by KMS. Initially, the pilot was operated on Huber MBR effluent only as Puron MBR produced a relatively small volume of water due to a lower membrane area. The net operating pressure and flux data for the Koch 4040 HR RO membranes are shown in **figure 5-25**. During the entire study period, the RO membranes were operated at a target flux of 12 gfd and feed water recovery of 50%. During the initial run hours, the RO pilot operated very well at a specific flux of 0.11gfd/psi with a net operating pressure of 108 psi. After 140 hours of operation, the project team noticed a overnight decline in the specific flux, when the specific flux dropped to 0.08 gfd/psi. After proper investigation, the project team concluded that this rapid fouling of RO membranes was caused due to the presence of ferric chloride in the Huber MBR permeate, which was used as a feed to the RO unit. As part of a treatment process, 15-25 mg/L of ferric chloride is added to the raw wastewater at PLWWTP. Ferric chloride is usually removed by a MF/UF membrane. However, due to the mechanical problem with the Huber MBR unit, two membrane modules of the unit were compromised; and hence, ferric chloride passed into the permeate. As a result, the Huber unit was shutdown for repair. This resulted in temporary shutdown of the RO unit. In the meantime, a high pH clean was performed on the RO system, and the membranes were preserved in sodium metabisulfite solution.

Once the Kruger MBR pilot system was installed and running, the RO pilot system was brought back into operation. Once again, only single MBR permeate was used as a feed source to RO because the DynaLift MBR unit produced a relatively small volume of water due to a lower membrane area. As shown in **figure 5-25**, a high pH clean (alkaline clean) was not very effective in recovering the specific flux since the major foulant was ferric chloride. As a result, the project team decided to conduct a low pH clean (citric acid clean) on the RO membranes. As shown in **figure 5-25**, acid clean was very effective in removing ferric chloride, and the specific flux was recovered to 0.12 gfd/psi. The RO membranes then were operated for another 1,275 hours during which the specific flux dropped from 0.12 to 0.11 gfd/psi, indicating a relatively stable operation. The RO pilot operation was terminated in mid-June 2006.

5.3 Water Quality

5.3.1 Puron MBR

Water quality analysis were conducted on the Puron MBR permeate throughout the pilot run time. Table 5-2 presents the permeate water quality for the Puron MBR, details of which are discussed below in this section.

5.3.1.1 Particulate Removal

Figure 5-26 shows the influent and permeate turbidity concentrations for the Puron MBR system. The Puron MBR system achieved excellent particulate removal during the entire study period. The influent turbidity concentration ranged from 65–161 NTU with a median value of 112 NTU. The permeate turbidity concentration for Puron MBR ranged from 0.07–0.11 NTU with a median value of 0.09 NTU. At 500 hours of operation, KMS recommended to change the membrane module, since the permeate turbidity was slightly higher than expected by KMS. The project team did not notice any significant improvement in permeate turbidity concentration after replacing the membrane module.

5.3.1.2 Organics Removal

The Puron MBR system achieved excellent organics removal with permeate BOD5 concentration less than the detection limit of 2 mg/L for all the samples collected. The influent and permeate BOD5 concentrations for the Puron MBR are shown in figure 5-27. The median concentration for influent BOD5 was 161 mg/L and within the range of 97–277 mg/L for all the samples collected during the study period.

5.3.1.3 Inorganic Nitrogen Removal

Figure 5-28 shows the influent and permeate ammonia, nitrate and nitrite concentrations for Puron MBR system, which was operated in nitrification only mode during the study period. As shown, the influent ammonia-nitrogen concentration ranged from 17.6–32.5 mg/L-N with a median concentration of 23.2 mg/L-N, whereas the permeate ammonia-nitrogen concentration was 0.3 mg/L or less for most of the samples collected during the study period, indicating complete nitrification. As the system was operated in nitrification-only mode, the median nitrate-nitrogen concentration for the MBR permeate was 29.3 mg/L-N and ranged between 14.8–40.5 mg/L-N as expected. The total inorganic nitrogen (TIN) concentration in the MBR influent ranged from 18.4–33.0 mg/L-N with a median concentration of 24.0 mg/L-N. The TIN concentration in the MBR permeate was calculated at a median concentration of 31.1 mg/L-N and ranged between 16.5–42.3 mg/L-N.

5.3.1.4 Microbial Rejection

Figure 5-29 shows the microbial concentrations in the influent and permeate of the Puron MBR system. The Puron MBR system achieved more than 5-log removal of total coliforms and fecal coliforms and more than 3-log removal of inherent coliphage. The median concentration for total coliforms and fecal coliforms in MBR influent was 6.6E+07 and 5.4E+06 CFU/100 mL, respectively. The median concentration for inherent coliphage in the MBR influent was 2.1E+04 PFU/100 mL. The fecal coliform and inherent coliphage levels in MBR permeate were found below the detection limit for most of the samples collected during the normal operation.

5.3.2 Huber MBR

Table 5-3 summarizes the permeate water quality for Huber MBR, details of which are discussed below in this section.

5.3.2.1 Particulate Removal

The influent turbidity concentration during the study period ranged between 65–161 NTU with a median concentration of 112 NTU. As shown in figure 5-30, the Huber MBR system achieved excellent particulate removal with permeate turbidity values of <0.1 NTU during normal operation with median concentration of 0.05 NTU. Due to a mechanical problem at about 2,000 hours, two membrane modules of the system were compromised; and so the permeate turbidity values were measured slightly higher than usual (0.2 NTU compared to 0.05 NTU). Once the mechanical problem was resolved and the damaged membrane modules were replaced with new ones, permeate turbidity values were back to normal. As shown, the permeate turbidity values were measured at <0.1 NTU after 2,900 hours of operation.

5.3.2.2 Organics Removal

The influent and permeate BOD5 concentrations for the Huber MBR system are shown in figure 5-31. The median concentration for influent BOD5 was 161 mg/L and within the range of 97–277 mg/L for all the samples collected during the study period. The BOD5 concentrations for Huber MBR permeate were less than the detection limit of 2 mg/L for all the samples collected, indicating more than 98% BOD5 removal during the study period.

5.3.2.3 Total Inorganic Nitrogen Removal

Figure 5-32 presents the inorganic nitrogen removal achieved by the Huber MBR system. The influent ammonia concentration ranged between 17.6–32.5 mg/L-N with a median concentration of 23.2 mg/L-N during the entire study period. The Huber MBR pilot was designed to operate in nitrification only mode. The system achieved complete nitrification during the pilot testing period with permeate ammonia concentrations close to the detection limit of 0.2 mg/L-N for most of the samples collected during the testing. After about 800 hours of operation, Huber recommended to switch the air blower for the aeration tank from continuous mode to intermittent mode to operate the system more efficiently by reducing the air consumption. Accordingly, the air blower was operated intermittently to maintain the DO level in the aeration tank between 1 and 4 mg/L. Nitrate concentrations in the permeate were measured at a median value of 15.2 mg/L-N which was expected since the system was operated in nitrification only mode. The TIN concentration in the influent and permeate was calculated at median values of 24.0 and 16.7 mg/L-N, respectively.

5.3.2.4 Microbial Rejection

The microbial concentrations for the Huber MBR influent and permeate are shown in figure 5-33. The Huber MBR system achieved more than 6-log removal of total coliforms and more than 5-log removal of fecal coliforms. The median concentration for total coliforms and fecal coliforms in MBR influent was measured at 6.6E+07 and 5.4E+06 CFU/100 mL, respectively. The Huber MBR system also achieved more than 3-log removal of inherent coliphage. The median concentration for inherent coliphage in the MBR influent was measured at 2.1E+04 PFU/100 mL. The fecal coliform and inherent coliphage levels in the MBR permeate were found below the detection limit for all the samples collected during the normal operation.

5.3.3 Kruger Neosep MBR

Results obtained from the water quality analysis conducted on the Kruger Neosep MBR are summarized in table 5-4 and discussed in detail in the following sections.

5.3.3.1 Particulate Removal

Figure 5-34 shows the influent and permeate turbidity concentrations for the Kruger Neosep MBR system. The influent turbidity concentration ranged from

65–161 NTU with a median value of 112 NTU. As shown, the Kruger Neosep MBR system achieved excellent particulate removal for first 900 hours of operation with permeate turbidity concentrations of <0.1 NTU, after which a spike in permeate turbidity was observed. Following that, permeate piping was cleaned; and the turbidity values stayed low for next few days. But the project team started noticing a gradual increase in the permeate turbidity after 1,400 hours of operation. Once Kruger was notified, it responded promptly and drained the membrane tank to determine the problem. Out of 100 membrane plates in the module, 4 membrane plates were found to be compromised and were plugged to eliminate passage of particulate matter in the permeate. Following that, the system achieved excellent particulate removal, but Kruger recommended replacing the entire membrane module. At 2,200 hours of operation, the membrane module was replaced with a new one, and permeate turbidity concentrations were <0.1 NTU as expected for the rest of the study period. The median concentration for the permeate turbidity was measured at 0.06 NTU during the study period.

5.3.3.2 Organics Removal

The Kruger Neosep MBR system achieved excellent organics removal with permeate BOD5 concentration less than the detection limit of 2 mg/L for all the samples collected. The influent and permeate BOD5 concentrations for the Kruger Neosep MBR are shown in figure 5-35. The median concentration for influent BOD5 was 161 mg/L and within the range of 97–277 mg/L for all the samples collected during the study period.

5.3.3.3 Total Inorganic Nitrogen Removal

Figure 5-36 presents the inorganic nitrogen removal achieved by Kruger Neosep MBR system. The influent ammonia concentration ranged between 17.6–32.5 mg/L-N with a median concentration of 23.2 mg/L-N during the entire study period. The pilot was designed to operate in nitrification and denitrification mode. The system achieved complete nitrification during the pilot testing period with permeate ammonia concentrations close to the detection limit of 0.2 mg/L-N for most of the samples collected during the testing. Nitrate concentrations in permeate were measured at a median value of 9.8 mg/L-N, indicating partial denitrification. The TIN concentration in the influent and permeate were calculated at median values of 24.0 and 16.7 mg/L-N, respectively.

5.3.3.4 Microbial Rejection

Figure 5-37 shows the microbial concentrations in the influent and permeate of the Kruger Neosep MBR system. The system achieved more than 6-log removal of total coliforms and more than 5-log removal of fecal coliforms. The median concentration for total coliforms and fecal coliforms in MBR influent was 6.6E+07 and 5.4E+06 CFU/100 mL, respectively. The median concentration for inherent coliphage in the MBR influent was 2.1E+04 PFU/100 mL. The system also achieved more than 3-log removal of inherent coliphage. The fecal coliform and inherent coliphage concentrations in permeate were measured below the detection limit for most of the samples collected during normal operation.

5.3.4 DynaLift MBR

Table 5-4 summarizes the permeate water quality for DynaLift MBR, details of which are discussed below in this section.

5.3.4.1 Particulate Removal

The influent turbidity concentration during the study period ranged between 65–161 NTU with a median concentration of 112 NTU. As shown in figure 5-38, the DynaLift MBR system achieved excellent particulate removal with permeate turbidity concentrations of <0.1 NTU for all the samples collected during the study period. The median permeate turbidity concentration was measured at 0.04 NTU.

5.3.4.2 Organics Removal

The DynaLift MBR system achieved excellent organics removal with permeate BOD5 concentration less than the detection limit of 2 mg/L for all the samples collected. The influent and permeate BOD5 concentrations for the DynaLift MBR system are shown in figure 5-39. The median concentration for influent BOD5 was 161 mg/L and within the range of 97–277 mg/L for all the samples collected during the study period.

5.3.4.3 Inorganic Nitrogen Removal

Figure 5-40 presents the inorganic nitrogen removal achieved by the DynaLift MBR system. The influent ammonia concentration ranged between 17.6–32.5 mg/L-N with a median concentration of 23.2 mg/L-N during the entire study period. The pilot was designed to operate in nitrification and denitrification mode. The system achieved complete nitrification during the pilot testing period with permeate ammonia concentrations close to the detection limit of 0.2 mg/L-N for most of the samples collected during the testing. Nitrate concentrations in permeate were measured at a median value of 4.2 mg/L-N indicating partial denitrification. The TIN concentration in the influent and permeate was calculated at median values of 24.0 and 6.0 mg/L-N, respectively.

5.3.4.4 Microbial Rejection

The microbial concentrations for the DynaLift MBR influent and permeate are shown in figure 5-41. The system achieved more than 6-log removal of total coliforms and more than 5-log removal of fecal coliforms. The median concentration for total coliforms and fecal coliforms in MBR influent was measured at 6.6E+07 CFU/100 mL and 5.4E+06 CFU/100 mL, respectively. The system also achieved more than 3-log removal of inherent coliphage. The median concentration for inherent coliphage in the MBR influent was measured at 2.1E+04 PFU/100 mL. The fecal coliform and inherent coliphage levels in the

DynaLift MBR permeate were found below the detection limit for most of the samples collected during the normal operation.

5.3.5 RO System

Figure 5-42 shows the feed and permeate conductivity concentrations for Koch 4040 HR membrane. The RO membrane achieved more than 98% rejection of conductivity with median permeate conductivity concentration of 32 μS. The median feed conductivity concentration was measured at 1,720 μS during the study period.

6. Peaking Study

6.1 Background

One of the challenges for MBRs is to handle wet weather flows, whether it is diurnal or seasonal. Irrespective of the influent wastewater quality during peak flows, wastewater has to pass through the membrane to be considered treated water. Diurnal flow variations are a concern for many wastewater treatment plants, especially when it is a dead-end plant. One option to handle the peak flows is to provide an equalization basin upstream of MBR, but installation of large tanks would defeat one of the key advantages of MBR, which is a small footprint design. As a result, to handle these peak flows, MBRs usually are designed with a peaking factor (peak flow to average flow ratio). These peaking factors vary from plant to plant but are usually around 2 to 3 (Chapman et al., 2006). Very little published literature has been available about the membrane performance and the change in the operating parameters during the peak flow operation.

To assess the membrane performance during peak flows for these new MBR systems, a peaking study was conducted on each MBR pilot system for 6 consecutive days. The membranes were cleaned before each peaking study as per the cleaning protocol recommended by the manufacturer (appendix B). During this 6-day period, each MBR system was operated at a peak flow for a 2-hour period, twice a day, to assess the fouling trend of the membranes and to see if the operating pressures stayed below the manufacturer's recommendation. During the peaking study, each MBR pilot was operated at average and peak flows as recommended by the manufacturer. The terms Fmin, Favg, and Fmax, used in section 6.2, indicate the minimum flux, average flux, and maximum flux operation for each system. For the Puron MBR, average flux operation Favg was referred to as optimum flux operation Fopt.

6.2 Operating Parameters During Peaking Study

6.2.1 Puron MBR

As discussed in section 5.1.1, the Puron MBR system was designed to operate in three different modes, depending on the level in the aeration tank. Manufacturer recommended operating parameters for the system during the peaking study are specified in table 6-1. As shown, the scouring air and recirculation flow rate were increased when switching from average flux to peak flux operation. During the peaking study, the system was operated with permeate backwash for 15 seconds after each filtration cycle. As shown in table 6-1, the backwash flow rates, filtration cycle time, and scouring air requirements varied based on the operating mode. During the peaking experiment, the system was operated in maximum-flux

(Fmax) mode for 4 hours a day for 6 consecutive days by increasing the feed flow to the system and, thereby, increasing the tank level. For the rest of the day, the system was operated in Fmin and Fopt. The daily peaking schedule for the Puron MBR is shown in table 6-2. The 24-hour weighted average flux for the Puron MBR during the peaking study was 13.8 gfd. The formula to calculate 24-hour weighted average flux is discussed in section 4.6.

6.2.2 Huber MBR

During the peaking study, the system was operated with a filtration cycle time of 240 seconds followed by a relaxation period of 60 seconds. The manufacturer-recommended operating parameters for the Huber MBR during the peaking study are specified in table 6-3. As shown, the recirculation flow rate and the scouring air were not increased while switching from average flux to peak flux operation. The daily peaking schedule for the system for a 6-day period is specified in table 6-4. The 24-hour weighted average flux for the Huber MBR system during the peaking study was 17.4 gfd.

6.2.3 Kruger Neosep MBR

The manufacturer-recommended operating parameters for the Kruger Neosep MBR system during the peaking study are specified in table 6-5. During the peaking study, the system was operated with a filtration cycle time of 540 seconds followed by a relaxation period of 60 seconds. The scouring air was kept constant, whereas the recirculation flow rate was increased when switching from average flux to peak flux operation. The daily peaking schedule for the system is specified in table 6-6. The 24-hour weighted average flux for the Kruger Neosep MBR during the peaking study was 20.7 gfd.

6.2.4 DynaLift MBR

During the peaking study, the DynaLift MBR system was operated with a filtration cycle time of 600 seconds followed by a permeate backpulse of 6 seconds at 52 gpm. The manufacturer-recommended operating parameters for the system during peaking study are specified in table 6-7. As shown, the scouring air was kept constant, whereas the recirculation flow rate was increased when switching from average flux to peak flux operation. The daily peaking schedule for the system is shown in table 6-8. The 24-hour weighted average flux for DynaLift MBR during the peaking study was 32.5 gfd.

6.3 Membrane Performance During Peaking Study

6.3.1 Puron MBR

During the 6-day peaking study, the temperature-corrected specific flux of the Puron MBR system dropped from 13.7 to 13.3 gfd/psi, indicating a stable operation. As shown in figure 6-1, as the flow was increased to achieve the peak flux, the temperature corrected specific flux dropped from 13.7 gfd/psi at average flux to 8.8 gfd/psi at peak flux. This temporary drop in the specific flux during peak flux operation could be attributed to the operation beyond the critical flux, the point above which TMP is no longer proportionate to the flux. Once the operation at average flux was resumed, the specific flux was recovered back to the normal values. A similar trend was observed for all submerged MBR systems evaluated during the study.

6.3.2 Huber MBR

The membrane performance data for the Huber MBR is shown in figure 6-2. As shown, the temperature-corrected specific flux at average flux stayed steady at 10.0 gfd/psi during the 6-day peaking study, indicating a stable operation. As the pilot operation was switched from average flux to peak flux, the temperature-corrected specific flux dropped from 10.0 to 7.3 gfd/psi, which could be attributed to operation beyond critical flux as explained in section 6.3.1.

6.3.3 Kruger Neosep MBR

As shown in figure 6-3, the temperature corrected specific flux for the Kruger Neosep MBR system dropped from 15.7 to 14.2 gfd/psi during the 6-day peaking study, indicating a stable operation. When switching from average flux operation to peak flux operation, the temperature-corrected specific flux dropped from 15.7 to 12.0 gfd/psi. This could be attributed to operation beyond critical flux as seen with other submerged MBR pilot units.

6.3.4 DynaLift MBR

As shown in figure 6-4, the temperature-corrected specific flux for the system at average flux operation dropped from 17.2 to 15.5 gfd/psi during the 6-day peaking study. When switching from average flux to peak flux operation, the temperature-corrected specific flux stayed steady at 17.2 gfd/psi. Unlike submerged MBRs, the temperature corrected specific flux of the DynaLift (external) MBR system did not drop significantly when switching from average flux to peak flux operation. This could be attributed to the high recirculation flow rate and better turbulence available in external MBRs. During the study, the recirculation flow rate for the DynaLift MBR was 10–12 times the permeate flow rate compared to that of 3–5 times in submerged MBRs (Puron, Huber, and Kruger Neosep).

7. Performance Comparison of MBR Systems

7.1 MBR Pilot Operating Experience

7.1.1 Puron MBR

The Puron MBR pilot system was fully automated and required very little operator attention. The sludge wasting also was done automatically. Once the online TSS sensor was calibrated correctly, the MLSS levels in the aeration tanks could be maintained very well within a desired range. The feed line to the pilot was a 1-inch pipe which got clogged a few times. As a result, the feed pump had to be stopped, and the line had to be cleaned manually to get the desired flow rate. The feed pump was designed for average flow conditions. As a result, an external submersible pump had to be used to maintain the desired feed flow to the pilot during the peaking study. The biology air blower was also designed for average flow conditions and resulted in a low DO level in the aeration tank during peaking study, even when operating at 100% capacity.

7.1.2 Huber MBR

The Huber MBR pilot system was fully automated, and each of the pilot components could be operated either in manual or automatic mode via a very simple touch screen. The pilot system required operator attention for sludge wasting since the sludge wasting had to be done manually. Since there was no flowmeter on the sludge wasting line, the sludge volume had to be measured manually. The recirculation pump, designed to transfer sludge from the aeration tank to the membrane tank, was controlled via time setpoint instead of running continuously. The recirculation pump would start after an operator-desired drawdown in the membrane tank occurred and run for an operator-desired time period. The operator had to be careful while entering this setpoint at different permeate flow rates.

7.1.3 Kruger Neosep MBR

The Kruger Neosep MBR pilot system was fully automated but required operator attention for sludge wasting. Though the sludge wasting had to be done manually, Kruger provided a calibrated tank to calculate the volume of sludge wasted everyday. The feed pump to the pilot system lost prime a few times due to a faulty check valve and had to be manually primed. Kruger designed the MBR pilot system with telescoping valves on the aeration and membrane tank to allow wasting desired volume of sludge from either the aeration or membrane tank. These telescopic valves were very helpful in removing foam from the aeration tank since they allowed wasting sludge from the top of the tank.

7.1.4 DynaLift MBR

The DynaLift MBR pilot system was fully automated but required operator attention for sludge wasting. The online TSS sensor for the aeration tank was not functioning correctly; as a result, the operator had to decide the set points for sludge wasting based on the lab results. Also, the flowmeter on the sludge wasting line did not function well; so the sludge wasting volume had to be calculated manually. The air compressor, used to operate the pneumatic valves on the system, failed twice during the study period and resulted in a downtime for a few days.

7.2 Bioreactor Design and Performance

The target MLSS concentration for all four pilot systems was between 10–12 g/L. The median $SRT_{7\text{-}d}$ for MBR pilots ranged between 13–33 days. The median $SRT_{7\text{-}d}$ for the Puron and Huber MBR were calculated at 13 and 15 days, respectively, whereas those for the Kruger Neosep MBR and DynaLift MBR were calculated at 20 and 33 days, respectively. The HRT for Puron and Kruger Neosep MBR systems ranged between 4–11 and 5–7 hours, respectively, whereas that for the DynaLift and Huber MBR systems ranged slightly higher at 7–11 and 8–21 hours, respectively.

Figure 7-1 presents the F/M ratio for all four MBR systems. This ratio was calculated using the influent BOD5 concentration and VSS concentration in the aeration tank of the pilot units. The formula to calculate F/M ratio is discussed in section 4.6. If the MLSS concentration and influent BOD5 concentration for each MBR pilot system were the same, then the pilot designed with higher HRT will have a relatively lower F/M ratio. The F/M ratio for MBR pilot systems ranged between 0.05–0.09 g BOD/g VSS.d, which is within the desired range of 0.05–0.1 g/g.d. As shown in figure 7-1, the F/M ratio for the DynaLift MBR pilot was the lowest at 0.05, indicating a relatively higher HRT compared to other systems. The median F/M ratio for the Huber MBR was highest among all four pilots at 0.09, even though the system HRT was also highest among all four pilots. This occurred due to operation of the pilot at low MLSS levels for a longer time period during the startup and after reseeding. Due to a relatively larger bioreactor volume of the Huber MBR pilot, the seed sludge was diluted after each seeding, resulting in a lower startup MLSS concentration and relatively longer time to achieve the target MLSS concentration.

7.3 Membrane Performance

Figure 7-2 shows the measured median net flux and average run time for each MBR pilot system during the pilot study. The median net flux for submerged MBR systems ranged between 13.3–15.9 gfd, whereas that for the external MBR system was measured at 26.9 gfd. As shown in figure 7-2, the DynaLift MBR pilot system, which is an external MBR system, had the highest median net flux at 26.9 gfd during the pilot study, whereas the Puron MBR pilot system had the lowest median net flux at 13.3 gfd. The median net flux for the Huber and Kruger Neosep MBR pilot system was measured at 14.7 and 15.9 gfd, respectively.

Figure 7-3 presents the measured scouring air required per unit membrane area for each MBR pilot system. The scouring air required for the MBR pilot systems ranged between 0.019–0.040 scfm/ft^2. As shown in figure 7-3, the Kruger Neosep MBR pilot system had the highest scouring air requirement per unit membrane area at 0.040 scfm/ft^2, whereas the Puron and DynaLift MBR pilot systems had the lowest scouring air requirement per unit membrane area at 0.019 scfm/ft^2. The Puron MBR system uses intermittent aeration (e.g., 10 seconds on/10 seconds off at average flux operation) for membrane scouring, which resulted in the lowest scouring air requirement. The DynaLift MBR system, which is an external crossflow MBR, has a relatively higher recirculation flow requirement (compared to submerged MBRs) to maintain a better crossflow velocity and relies less on scouring air, thereby resulting in the lowest scouring air requirement. The scouring air for the Huber MBR pilot system was measured at 0.026 scfm/ft^2.

Operation at a higher net flux results in lower membrane area requirements, thereby resulting in a lower capital cost for membranes. However, one should also consider the average run time between maintenance cleans when comparing net flux for MBR systems. Shorter run time requires more frequent maintenance cleans, thereby resulting in a higher operating cost. Another factor that impacts the operating cost is the scouring air required per unit membrane area. By measuring median net flux and scouring air per unit membrane area, one can calculate the scouring air required to produce a certain volume of water in a day (as explained in section 4.6). By comparing these numbers, one can get a good estimate of capital and operating cost for each MBR system.

Based on the measured median net flux and scouring air requirements for the pilot systems during the pilot study, estimates were made for membrane area and scouring air requirements for a 1-MGD plant. The results from these calculations are presented in table 7-1. Though these results were based on the actual pilot study, it is highly recommended to operate the pilots for a longer period (1 year or more) at a steady-state before drawing any strong conclusions. As shown in table 7-1, the estimated membrane area requirement for 1 MGD ranged between 37,217–75,164 ft^2, whereas the estimated scouring air required for a 1-MGD plant ranged between 714–2,503 scfm.

7.4 MBR Effluent Water Quality

7.4.1 Particulate Removal

Figure 7-4 shows the probability plot for MBR influent and permeate turbidity for all four MBR systems. The median turbidity for MBR influent was measured at 112 NTU. As shown in the figure, all four MBR systems achieved permeate turbidity of <0.2 NTU for most of the study period. The permeate turbidity concentrations for the Huber and Kruger Neosep MBR systems were slightly higher than expected for some of the sampling period due to the membrane breach that occurred in these systems. The median permeate turbidity measured for the Puron, Huber, Kruger Neosep, and DynaLift MBR systems were 0.09, 0.05, 0.06, and 0.04, respectively.

7.4.2 Organics Removal

Figure 7-5 shows the probability plot for MBR influent and permeate BOD5 concentrations for all four MBR systems. As shown in the figure, the median concentration for influent BOD5 was measured at 161 mg/L. All four MBR systems achieved excellent organics removal with permeate BOD5 concentration of <2 mg/L for 100% of the time.

7.4.3 Inorganic Nitrogen Removal

Figure 7-6 shows the probability plot for MBR influent and permeate ammonia-nitrogen concentrations for all four MBR systems. The median concentration for ammonia-nitrogen in the influent was measured at 23.3 mg/L-N. As shown, all four MBR systems achieved permeate ammonia concentration of less than 0.2 mg/L-N for most of the study period, indicating complete nitrification. Figure 7-7 shows the probability plot for MBR influent and permeate TIN concentrations for all four MBR systems. As shown, the Kruger Neosep and DynaLift MBR systems achieved better TIN removal since both systems were designed for nitrification and denitrification and were able to achieve significant nitrate removal. The median TIN concentrations in the permeate for the Puron, Huber, Kruger Neosep and DynaLift MBR pilot systems were measured at 31.1, 16.7, 11.7, and 6.0 mg/L-N, respectively.

7.4.4 Microbial Removal

Figure 7-8 shows the probability plot for MBR influent and permeate concentrations of total coliforms for all four MBR systems. As shown, the median concentration for total coliforms in the influent was measured at 6.6E+07 CFU/100 mL. The median concentration of total coliforms in permeate for the Puron, Huber, Kruger Neosep and DynaLift MBR systems was measured at 100, <10, <10, and 20 CFU/100 mL, respectively. Figure 7-9 presents the probability plot of total coliform removal by all four MBR systems. The median values for log-removal of total coliforms by the Puron, Huber, Kruger Neosep, and DynaLift MBR systems were measured at 5.6, 6.2, 6.8, and 6.6 log, respectively.

Figure 7-10 presents the probability plot for the MBR influent and permeate concentrations of fecal coliforms for all four MBR systems. As shown in the figure, the median influent fecal coliform concentration was measured at 5.4E+06 CFU/100 mL. The median concentration of fecal coliform in

MBR permeate was measured at <10 CFU/100 mL for all MBR systems. Figure 7-11 shows the probability plot for log removal of fecal coliform by each MBR system. As shown in figure 7-11, the median log removal values for the Puron, Huber, Kruger Neosep, and DynaLift MBR systems were measured at 5.4, 5.5, 5.8, and 5.9 log, respectively.

Figure 7-12 presents the probability plot of coliphage concentrations for MBR influent and permeate for all four systems. The median influent concentration of coliphage was measured at 2.1E+04 PFU/100 mL, respectively. The median permeate concentration for coliphage was measured at <10 PFU/100 mL for all MBR systems. Figure 7-13 shows the log removal of coliphage by each MBR system. As shown in the figure, the Puron, Huber, Kruger Neosep, and DynaLift MBR pilot system achieved 3.4-, 3.4-, 3.2-, and 3.2-log removal of coliphage, respectively.

8. Title 22 Approval of MBR Systems

8.1 Background

One of the key objectives of this study was to assess the water quality produced by these new MBR systems to see if it met the CDPH Title 22 water recycling criteria. Per CDPH regulations for Title 22 filtered wastewater, turbidity for membrane-filtered wastewater should not exceed 0.2 NTU for more than 5 percent of the time within a 24-hour period and should not exceed 0.5 NTU at any time (California Department of Public Health, 2006). In the past, the project team has worked with CDPH to establish criteria for MBR systems for meeting Title 22 approval (Adham, et al., 2001a, b).

As part of the current Bureau of Reclamation study, the project team has completed Title 22 testing of MBR systems provided by Koch Membrane Systems (KMS), Huber Technology, Kruger Inc., and Parkson Corporation. Separate reports summarizing test results from each MBR system were submitted to CDPH for approval in March–September 2006 (DeCarolis et al., 2006a, b, c, and d). The procedure and results from the Title 22 testing of these new MBR systems are discussed in following sections.

8.2 Title 22 Test Procedure

To assess the capability of these new MBR systems to meet Title 22 water recycling criteria, a peaking study was conducted on all four MBR systems as per manufacturer-recommended operating parameters. The details about the peaking study are discussed in section 6 of this report. The primary objectives of the peaking study were to assess the permeate turbidity at average and peak flux operation and to assess the virus rejection capability of the membrane at two different membrane conditions.

To accomplish these objectives, permeate turbidity of each MBR system was continuously monitored at every minute for 6 consecutive days during the peaking study while operating the system at average and peak fluxes. Also, two virus challenge experiments were conducted on each MBR system while operating at peak flux:

- At the beginning of the peaking study on cleaned membrane
- On the last day of the peaking study.

Results from the Title 22 testing of each MBR system are discussed in the following section.

8.3 Results and Discussion

Table 8-1 summarizes the results obtained from Title 22 testing of each MBR system. It shows the 50th percentile removal of MS-2 phage by each system, which was calculated based on the results obtained from two virus challenge experiments on each system as discussed in a previous section. It also shows the 95th-percentile level of permeate turbidity measured during the entire 6-day peaking study.

As shown in table 8-1, all four MBR systems were able to produce effluent with turbidity of less than 0.2 NTU for 100% of the time and to meet the CDPH turbidity requirements for recycled water. The virus rejection capability of each MBR system varied depending on the nominal and absolute pore size of the membrane and the backwash/relaxation mechanism used by each MBR system. Even though the nominal pore size of all four membranes of these MBR systems fell within the ultrafiltration range (<0.1 µm), a significant difference in the virus rejection capability of these systems was observed during the Title 22 testing.

As per the information obtained from the manufacturers, the nominal pore size of the membrane used by Puron, Huber, Kruger and DynaLift MBR systems are 0.05, 0.04, 0.08, and 0.03 µm, respectively. The absolute pore size for the Huber and DynaLift MBR systems are 0.09 and 0.05 µm, respectively. The project team was not able to obtain the absolute pore sizes for the Puron and Kruger MBR systems. Of the four MBR systems evaluated, the Puron and DynaLift MBR systems used backwash at the end of each filtration cycle, whereas Huber and Kruger, with the flat-sheet membranes, used relaxation at the end of each filtration cycle.

As shown in table 8-1, the Puron MBR, which uses a membrane with a nominal pore size of 0.05 µm and uses backwash at the end of each filtration cycle, got the lowest virus removal (1.0-log) at 50th percentile, whereas the DynaLift MBR, which uses a membrane with nominal pore size of 0.03 µm and also uses backwash, achieved the highest virus removal (4.0-log). On the other hand, the Kruger and Huber MBR systems were able to achieve 3.0- and 4.0-log removal of virus, respectively, at 50th percentile. Both of these systems use relaxation at the end of the filtration cycle and have a nominal pore size in the ultrafiltration range.

It should be noted that the nominal pore sizes of all membranes were obtained from the individual manufacturers and not measured as part of this study.

Based on the results obtained from the Title 22 testing of these MBR systems, all four MBR systems received conditional approval from CDPH in 2006. The approval letters for each MBR system from CDPH are attached in appendix E.

9. Cost Analysis

9.1 Background

The purpose of this cost analysis was to perform budgetary cost estimates of the newly developed MBR systems tested during this study, which will soon be offered in the United States municipal wastewater treatment market. Each system offers unique design features, which may reduce capital and/or O&M costs. It was also intended to compare the current MBR cost estimates to historical cost estimates (2000–2003) to gain some insight on the overall trend of MBR costs in the municipal wastewater treatment market. Due to the increasing number and size of MBR facilities in the United States, it is important for industry to have current cost estimates to allow for proper planning.

9.2 Costing Approach

Cost analysis were performed to estimate the capital and operational costs of full-scale MBR water reclamation systems for treatment capacities of 1 and 5 MGD (4,000–20,000 cubic meters per day [m^3/day]). The analysis was based on specific MBR design criteria established previously by the project team (Adham et al., 2004). Costs were determined for complete MBR wastewater reclamation systems consisting of headworks, process basins, membrane component, mechanical equipment, blower and pump building, chlorination system, and effluent storage. All costs except those related to the membrane component of the MBR systems were derived from previous estimates (Adham et al., 2004) and updated using the current Engineering News Record Construction Cost Index (ENRCCI) and Chemical Engineering Plant Cost Index (CEPCI). Costs associated with the membrane component of the MBR systems were based on budgetary costs estimates provided by suppliers of the newly developed MBR systems including Koch Membrane Systems, Huber Technologies Inc., Kruger Inc., and Parkson Corporation. To get comparable quotes from all suppliers, a memo was created and given to each supplier, which provided specific information related to the cost request. Appendix F includes specific information related to the cost updates along with an example of the cost request memo sent to each supplier.

9.3 Design Criteria

The cost estimates were based on the following raw wastewater quality and design criteria established by the project team.

BOD5	290 mg/L
COD	700 mg/L

TSS	320 mg/L
VSS	260 mg/L
NH_3-N	30 mg/L
TKN	60 mg/L
TP	2 mg/L
TDS	1,200 mg/L
Alkalinity	245 mg/L
Temperature	20 °C

The MBR systems were designed using the following criteria:

Flux, instantaneous	15–19 gfd at 25 °C (submerged MBR systems) 30 gfd at 25 °C (external MBR systems)
MLSS	8,000 mg/L
F/M	0.13 day^{-1}
HRT	6 hours
SRT	10 days

The flux values used in the costs assessments were based on values demonstrated during the pilot testing from each MBR supplier.

Furthermore, all installations were designed to meet the following effluent water quality:

Complete nitrification (i.e., NH_4-N<1.0 mg/L)

Denitrification (i.e., NO_3-N<10 mg/L)

Biochemical oxygen demand (BOD5) < 2.0 mg/L

Biological phosphorus removal (i.e., total phosphorus-P <0.2 mg/L)

For these estimates, all systems were assumed to be sewer mining or scalping facilities built on a clean plot of land and designed to operate on raw municipal wastewater.

9.3.1 Capital Costs

Table 9-1 provides capital cost estimates for the various MBR systems designed for 1- and 5-MGD capacities. The table includes total capital costs ($K) and amortized capital costs (thousand dollars per year [$K/year]) assuming a 5% interest rate over a 30-year period. As shown, the total capital cost estimate for the 1.0-MGD installations ranged from $7,990– $9,850, while the amortized cost ($K/yr) ranged from $520–$641. The range in capital costs directly reflects the range of membrane costs acquired from the four participating MBR suppliers.

It should be noted that all factors (%) used to develop these cost estimates, including electrical (15%), mechanical/plumbing/heating, ventilation, and air conditioning (13%), sitework (9%), contractor overhead and profit (15%), contingency (15%), engineering/legal/administration (15%), and equipment installation (25%), represent typical values based on the project teams experience only and can be adjusted based on local conditions and individual experience.

The headworks for all installations included bar screening (6 mm) and vortex grit removal; costs associated with lift pumps for raw sewage and odor control were not included in the estimate. All capital costs associated with the headworks were taken from previous budgetary costs prepared by MWH (Adham et al., 2004) and adjusted using ENRCCI 20 city average.

Basin costs include concrete and ancillary equipment associated with the aerobic/membrane, anoxic, and anaerobic components of the MBR system. In addition, the costs include basin excavation, structural fill, back fill, and waste dirt to haul off site. All basin costs, with the exception of the DynaLift MBR systems, were based on previous estimates prepared by MWH and updated using ENRCCI 20 City average. Because the DynaLift MBR utilizes external membranes, the basin costs previously estimated by the project team were not applicable. As a result, the costs for the basins associated with this system were based on information provide by Parkson Corporation.

The capital costs of the MBR systems also included a 5-ton bridge crane, which would be used to lift the membranes during installation and periodic inspection, if necessary. This cost estimate was based on previous estimates and updated to 2006 using the CEPCI.

Mechanical costs shown include fine screening, mixers, aeration equipment, and recirculation pumps and piping. Original costs of fine screening provided by Waste Tech Inc (Libertyville, Illinois) were based on Roto-Sieve (RS) perforated drum screens and included costs of both duty and standby screens. All mechanical costs were updated to 2006 using CEPCI. A factor of 25% was included in the mechanical cost to account for equipment installation.

Membrane system costs, including membranes, pumps, blowers, and miscellaneous equipment, were developed from budgetary cost proposals provided by the participating suppliers. A factor of 25% was added to the capital equipment costs provided by each manufacturer to account for equipment installation. Each supplier was requested to provide membrane costs to include a 5-year nonprorated warranty. In addition, the suppliers were requested that the costs include adequate membranes to produce the desired capacities at flux rates demonstrated during pilot testing. The values of instantaneous flux during pilot testing ranged from 14.7–18.5 gfd for the submerged MBR systems and 30 gfd for the external MBR system. Net flux differs from instantaneous flux as it accounts for downtime due to relaxation/backwashing, product water used backwashing/maintenance cleans. In general, such losses amount to about 10% of daily production. Each supplier was requested to account for these losses when estimating membrane costs.

Blower and pump building costs shown are based on two-story building and include all capital costs associated with process blowers, blower piping and valving, and blower instrumentation. Building costs were updated to 2006 ENRCCI; all other costs were updated to CEPCI. A factor of 25% was added to the cost to account for equipment installation.

9.3.2 Operation and Maintenance Costs

Table 9-2 provides the estimated annual and total O&M costs (5% interest rate over a 30-year period) for all MBR installations considered. As shown, key O&M costs included labor, equipment repair and replacement parts, chemicals (membrane cleaning and disinfection), membrane replacement, and electricity. Details on assumptions used to estimate these O&M costs are provided elsewhere (Adham et al., 2004). Membrane replacement costs were provided by the participating suppliers and are based on an 8-year membrane life. All other unit cost assumptions are provided in appendix F. As provided in table 9-2, the annually O&M cost ($K/yr) for the 1-MGD ranged from $218–$302. The range in values is reflective of differences in membrane replacement costs ($K/yr) provided by the participating MBR suppliers, which ranged from $40–$106.

Figure 9-1 provides a visual representation of the percent contribution each O&M component has on the total annual associated with a 1-MGD MBR system. These costs were based on average membrane replacement costs provided by the participating suppliers. As shown, the two largest components of the O&M cost includes membrane replacement (28%) and energy (34%). The two main energy demands of the MBR system include that required by air blowers to provide process air and scour the membranes. Judd et al., 2006, reported that these demands make up 35 and 38%, respectively, of the total energy demand associated with a 1.5-MGD MBR system.

9.3.3 Total Costs and Economy of Scale

Table 9-3 provides a summary of the capital and O&M cost estimates for complete MBR systems based on 1 and 5 MGD capacities. The total capital costs and estimated O&M costs were assumed to provide present worth values of each installation. The present worth values shown are based on a 5% interest rate over a 30-year period. As shown, the present worth ($K) for the 1- and 5-MGD capacity system was estimated between $11,260–$14,429 and $47,064–$58,954, respectively. Table 9-4 provides total costs (dollars per 1,000 gallons [$/1,000 gal]) for each capacity. These costs were derived from the amortized capital cost and the annual O&M cost associated with each capacity. The table shows that the total cost ($/1,000 gal) for the 1-MGD capacity ranged from $2.02–$2.58.

An economy of scale analysis of the costs associated with the MBR process components (excluding membrane costs) and the membrane system only was conducted for 1- and 5-MGD capacities. As shown in figure 9-2, the total costs ($K/MGD) (based on the average values of the four systems analyzed) associated with these two capacities was determined to be $12,844 and $10,602, respectively. The figure shows an economy of scale exists for both the MBR process components (16.5%) and the membrane system only component (23.6%). The former would be expected as the cost of construction and raw material decreases with size and bulk quantity.

9.4 MBR Cost Trends

9.4.1 Complete MBR System Costs

The capital cost estimates of the newly developed MBR systems were compared with previous cost estimates for 1-MGD MBR systems made by the project team in 2000 and 2003. The estimates of the membrane systems were obtained from original budget proposals provided by Zenon and Kubota in the given years (Adham et al., 2000 and 2004) and budget proposals received from the suppliers of the newly developed MBR systems in 2006. All previous budgetary cost estimates of the membrane systems were adjusted to current dollars using the consumer price index (CPI) published by the U.S. Department of Labor (Bureau of Labor Statistics Data, 2006). Membrane system costs include costs associated with the membranes, pumps, blowers, and miscellaneous equipment along with installation. Capital costs for all other MBR process components (i.e., headworks, process basins, blower/pump building, chlorine dosing system, and effluent storage) were based on original estimates (Adham et al., 2004) and adjusted using ENRCCI and CEPCI for the desired years. As shown in figure 9-3, there has been a steady increase (approximately 24%) in costs associated with MBR process components (excluding membrane system) between 2000–2006. Interestingly, as shown in figure 9-4, the opposite trend was observed for membrane system costs, which actually have decreased by approximately 33% over the same time period. The rise in nonmembrane costs associated with the MBR system is due to the increased cost of concrete and other raw materials used for plant construction. The drop in membrane system costs may be attributed to advancements in manufacturing and increased competition in the market place. These trends have resulted in the overall total cost for 1-MGD MBR systems to be fairly level (i.e., <10% increase) between 2000 and 2006.

10. References

Adham, S. and P. Gagliardo, 1998. *Membrane Bioreactors for Water Repurification – Phase I*. Desalination Research and Development Program Report No. 34, Project No. 1425-97-FC-81-30006. U.S. Department of Interior, Bureau of Reclamation.

Adham, S., R. Merlo, and P. Gagliardo, 2000. *Membrane Bioreactors for Water Reclamation – Phase II*, Desalination Research and Development Program Report No. 60, Project No. 98-FC-81-0031. U.S. Department of Interior, Bureau of Reclamation.

Adham, S. and S. Trussell, 2001. *Membrane Bioreactors: Feasibility and Use in Water Reclamation*, Final Report Project # 98-CTS-5. Water Environment Research Foundation.

Adham, S., D. Askenaizer, R. Trussell, and P. Gagliardo, 2001a. *Assessing the Ability of the Zenon Zenogem® Membrane Bioreactor to Meet Existing Water Reuse Criteria*, Final Report. National Water Research Institute.

Adham, S., D. Askenaizer, R. Trussell, and P. Gagliardo, 2001b. *Assessing the Ability of the Mitsubishi Sterapore Membrane Bioreactor to Meet Existing Water Reuse Criteria*, Final Report. National Water Research Institute.

Adham, S. and J. DeCarolis, 2004. *Optimization of Various MBR Systems for Water Reclamation – Phase 3*. Final Report, Project No. 01-FC-81-0736. U.S. Department of Interior, Bureau of Reclamation.

Bureau of Labor Statistics, 2006. Consumer Price Index: Area = Los Angeles-Riverside-Orange County, California, Item = All Items, Base Period = 1982-84. Published by the U.S. Department of Labor at: www.bls.gov.

California Department of Public Health, 2006. *Treatment Technology Report for Recycled Water*. Department of Public Health, State of California Division of Drinking Water and Environmental Management.

Chapman, S., G. Leslie, and I. Law, 2006. *Membrane Bioreactors for Municipal Wastewater Treatment – An Australian Perspective* at www.membrane.unsw.edu.au.

City of San Diego, 2005. *2005 Annual Reports and Summary, Point Loma Wastewater Treatment Plant and Point Loma Ocean Outfall.*

DeCarolis, J., Z. Hirani, and S. Adham, 2006a. *Assessing the Ability of the PURON™ Membrane Bioreactor to Meet Existing Water Reuse Criteria*, Final Report. California Department of Public Health.

DeCarolis, J., Z. Hirani, and S. Adham, 2006b. *Assessing the Ability of the Huber Vacuum Rotation Membrane VRM® Bioreactor and MembraneClearBox® to Meet Existing Water Reuse Criteria*, Final Report. California Department of Public Health.

DeCarolis, J., Z. Hirani, and S. Adham, 2006c. *Assessing the Ability of the Kruger Neosep™ Membrane Bioreactor to Meet Existing Water Reuse Criteria*, Final Report. California Department of Public Health.

DeCarolis, J., Z. Hirani, and S. Adham, 2006d. *Assessing the Ability of the DynaLift™ Membrane Bioreactor to Meet Existing Water Reuse Criteria*, Final Report. California Department of Public Health.

Frost and Sullivan, 2004. *U.S. and Canada Membrane Bioreactor Markets, Report # A658-15* at www.frost.com

Judd, S., 2006. *The MBR Book: Principles and Applications for Water and Wastewater Treatment*. Published by Elsevier LTD, pp. 178-179.

Montgomery Watson Harza, 2004. *Application of Membrane Bioreactors followed by Desalting Reverse Osmosis Membranes for the Treatment of Primary Wastewater for Water Reuse*, Final Report, Desalination Research and Innovation Partnership (DRIP) Project. City of San Diego.

Morgan, C., L.E. LeBrun, R. van't Oever, 2006. *Innovative Application of Two-Phase Flow Yields Low Energy Side-stream Membrane Bioreactor Process.* Paper Presented at the WEF Annual Technical Exhibition and Conference, WEFTEC' 06.

Van der Roest, H.F., D.P. Lawrence, and A.G.N. van Bentem, A.G.N., 2002. *Membrane Bioreactors for Municipal Wastewater Treatment,* STOWA Report. IWA Publishing.

Appendix A

Tables and Figures

List of Tables

List of Figures

List of Figures (continued)

Figure *Page*

List of Figures (continued)

Table 4-1. MBR Influent Wastewater Quality during Bureau of Reclamation Study

Parameter	Units	No. of Analysis	Median	Minimum	Maximum
BOD	mg/L	124	161	97	277
COD	mg/L	5	371	344	412
TOC	mg/L	4	62	47	93
Ammonia-N	mg/L-N	67	23.2	17.6	32.5
Nitrate-N	mg/L-N	64	0.226	0.226	0.452
Nitrite-N	mg/L-N	64	0.304	0.152	0.89
TSS	mg/L	182	185	123	367
VSS	mg/L	123	139	86	290
pH	-	107	7.1	6.3	7.7
Turbidity	NTU	107	112	65	161
Total Coliform	CFU/100 mL	21	6.6E+07	1.0E+05	1.5E+08
Fecal Coliform	CFU/100 mL	21	5.4E+06	2.8E+04	1.3E+07
Total Coliphage	PFU/100 mL	19	2.1E+04	2.0E+03	6.4E+04

Table 4-2. Specifications for the MBR Membranes

Parameter	Puron	Huber	Kruger	DynaLift
Commercial Designation	L1	NADIR-P150F	Neosep K100	DynaLift 38 PRV
Shape	Hollow-fiber	Flat-Sheet	Flat-Sheet	Tubular
Nominal Pore Size (µm)	0.05	0.038	0.08	0.03
Absolute Pore Size (µm)	-	0.09	-	0.05
Inner Diameter of Tubes (mm)	N/A	N/A	N/A	5.2
Membrane Material	PES	PES	PVDF/PET	PVDF
Active Membrane Area (ft^2)	323	1,162	1,506	312
Typical Design Flux (gfd)	11.8 - 20.6	18	17	20 - 45
Maximum Backwash Pressure (psi)	14.7	2.0	1.4	14.5
Trans-Membrane Pressure Range (psi)	1.5 - 3.7	0.7 - 6.5	0.5 - 4	1.0 - 5.0
Maximum Temperature (ºC)	40	95	40	40
pH Range	3 -12	1 - 14	2 - 10	2 - 10

As per information provided by manufacturers

Table 4-3. Specifications for the RO Membranes

Parameter	Koch
Commercial Designation	4040-HR
Membrane Construction	Thin Film Composite (TFC)
Membrane Rejection Layer	Polyamide
Spiral Wound Configuration	
Element length	40 in. (101.6 cm)
Element diameter	3.9 in. (9.91 cm)
Membrane Area	85 ft^2 (7.8 m^2)
Operating pH range	4 - 11
Maximum Feed Turbidity	1 NTU
Maximum Operating Pressure	600 psi (4,140 kPa)
Maximum Operating Temperature	113 deg F (45 deg C)
Maximum Continous Free Chlorine	< 0.1 mg/L
Performance Specifications @ Manufacturers Test Conditions:	
Feed Water Pressure	225 psi (1,550 kPa)
Feed Water Recovery	0.15
Temperature	77 deg F (25 deg C)
Permeate Flow	2,300 gpd (8.7 m^3/d)
Feed TDS	700 mg/L
Salt Rejection	99.4 %

Table 4-4. Specifications for the Roto-Sieve Screen

	Roto-Sieve Screen
Model	4024-40
Configuration	Rotating Perforated Drum Screen
Perforations (mm)	0.8
Maximum Capacity (gpm)	475
Inner Diameter of Tubes (mm)	N/A
Length x Width x Height (m x m x m)	1.81 x 0.88 x 1.3
Drum Rotation (rpm)	14
Spray Water Consumption (gpm)	7.1
Drum Inclination, standard (deg)	6
Drive Motor - Rated Power (kW)	0.37
Drive Motor - Rated Current (230 / 400 V)	1.91 / 1.10

Table 4-5. Analytical Methods / Detection Limits for Measured Water Quality Parameters

Parameter	Units	Method	Detection Limit
TSS/VSS	mg/L	SM 2540D/E	1.6
BOD5	mg/L	SM 5210B	2
COD	mg/L	SM 5220D / EPA 410.4	22/5
TOC	mg/L	EPA 415.1	0.5
Ammonia-N	mg/L-N	SM 4500 B&E	0.2
Nitrate-N	mg/L-N	EPA 300	0.011
Nitrite-N	mg/L-N	EPA 300	0.009
Ortho-Phosphate-P	mg/L-P	Hach 8048	0.02
Total Coliform	CFU/100 mL	SM 9222 B	10
Fecal Coliform	CFU/100 mL	SM 9222 D	10
Total Coliphage	PFU/100 mL	SM 9224 F	10

Table 5-1. Operating Parameters for MBR Pilot Systems

Parameter	Puron	Huber	Kruger	DynaLift
HRT (hours)	4 -11	8 - 21	5 - 7	7 -11
Median SRT $_{7\text{-d}}$ (days)	13	15	20	33
MLSS (g/L)	9 - 12	8 - 14	9 - 12	8 - 12
Flux (gfd)	10 - 24	13 - 17	17 - 19	19 - 31
Filtration Cycle (seconds)	360	540	540	600
Backpulse or Relaxation	Backpulse	Relax	Relax	Backpulse
Backpulse/Relaxation Time (seconds)	20	60	60	6
Backpulse Flux (gfd)	13 - 25	-	-	210 - 250

Table 5-2. Puron™ MBR Permeate Water Quality

Parameter	Units	No. of Analysis	Median	Minimum	Maximum
BOD	mg/L	59	<2	<2	<2
COD	mg/L	5	74	22	132
TOC	mg/L	3	5.4	5.2	5.4
Ammonia-N	mg/L-N	27	0.3	<0.2	0.6
Nitrate-N	mg/L-N	32	29.3	14.8	40.5
Nitrite-N	mg/L-N	31	<1.52	<1.52	1.52
Turbidity	NTU	58	0.09	0.07	0.11
Total Coliform	CFU/100 mL	9	100	30	200
Fecal Coliform	CFU/100 mL	8	<10	<10	10
Total Coliphage	PFU/100 mL	9	<10	<10	20

Table 5-3. Huber® MBR Permeate Water Quality

Parameter	Units	No. of Analysis	Median	Minimum	Maximum
BOD	mg/L	65	<2	<2	<2
COD	mg/L	1	78	78	78
TOC	mg/L	3	8.5	6.3	8.6
Ammonia-N	mg/L-N	23	0.3	<0.2	2.2
Nitrate-N	mg/L-N	28	15.2	0.5	37.2
Nitrite-N	mg/L-N	27	<1.52	<1.52	<1.52
Turbidity	NTU	185	0.05	0.04	0.18
Total Coliform	CFU/100 mL	9	<10	<10	160
Fecal Coliform	CFU/100 mL	8	<10	<10	20
Total Coliphage	PFU/100 mL	9	<10	<10	20

Table 5-4. Kruger Neosep™ MBR Permeate Water Quality

Parameter	Units	No. of Analysis	Median	Minimum	Maximum
BOD	mg/L	35	<2	<2	<2
Ammonia-N	mg/L-N	33	<0.2	<0.2	0.3
Nitrate-N	mg/L-N	27	9.8	5	23.9
Nitrite-N	mg/L-N	27	<1.52	<1.52	1.61
Turbidity	NTU	193	0.06	0.04	0.42
Total Coliform	CFU/100 mL	10	<10	<10	220
Fecal Coliform	CFU/100 mL	12	<10	<10	450
Total Coliphage	PFU/100 mL	11	<10	<10	12

Table 5-5. DynaLift™ MBR Permeate Water Quality

Parameter	Units	No. of Analysis	Median	Minimum	Maximum
BOD	mg/L	23	<2	<2	<2
Ammonia-N	mg/L-N	20	0.3	<0.2	1.7
Nitrate-N	mg/L-N	14	4.2	0.5	16.4
Nitrite-N	mg/L-N	14	<1.52	<1.52	<1.52
Turbidity	NTU	159	0.04	0.03	0.06
Total Coliform	CFU/100 mL	10	20	<10	100
Fecal Coliform	CFU/100 mL	11	<10	<10	80
Total Coliphage	PFU/100 mL	10	<10	<10	<10

Table 6-1. Operating Parameters for Puron™ MBR During Peaking Study

Mode	Flux	Filtration Cycle Time	Backwash Time	Backwash Flux	Scouring Air	Scouring Air Blower	Recirculation Ratio
	(gfd)	(seconds)	(seconds)	(gfd)	(scfm)	(On/Off)	
F_{max}	35	360	15	24	6.5	10 sec/10 sec	3
F_{opt}	11	360	15	18	6	10 sec/20 sec	4
F_{min}	5	480	15	13	4	10 sec/30 sec	8

Table 6-2. Daily Peaking Schedule for Puron™ MBR

Time Range	Peaking Factor	Flux (gfd)
00:00 - 08:30	1.0 Q	11.2
08:30 - 10:30	3.2 Q	35.7
10:30 - 13:30	0.5 Q	5.4
13:30 - 15:30	3.2 Q	35.7
15:30 - 18:30	0.5 Q	5.4
18:30 - 23:59	1.0 Q	11.2

Q = Average Permeate Flow as recommended by the manufacturer

Table 6-3. Operating Parameters for Huber® MBR During Peaking Study

Mode	Flux	Filtration Cycle Time	Relaxation Time	Scouring Air	Scouring Air Blower	Recirculation Ratio
	(gfd)	(seconds)	(seconds)	(scfm)	(On/Off)	
F_{max}	33	240	60	28	Continous	2
F_{avg}	15	240	60	28	Continous	4
F_{min}	12	240	60	28	Continous	5

Table 6-4. Daily Peaking Schedule for Huber® MBR

Time Range	Peaking Factor	Flux (gfd)
00:00 - 08:30	0.9 Q	15.3
08:30 - 10:30	1.9 Q	33.0
10:30 - 13:30	0.7 Q	12.0
13:30 - 15:30	1.9 Q	33.0
15:30 - 18:30	0.7 Q	12.0
18:30 - 23:59	0.9 Q	15.3

Q = Average Permeate Flow as recommended by the manufacturer

Table 6-5. Operating Parameters for Kruger Neosep™ MBR During Peaking Study

Mode	Flux	Filtration Cycle Time	Relaxation Time	Scouring Air	Scouring Air Blower	Recirculation Ratio
	(gfd)	(seconds)	(seconds)	(scfm)	(On/Off)	
F_{max}	35	540	60	55	Continous	4
F_{avg}	18	540	60	55	Continous	5

Table 6-6. Daily Peaking Schedule for Kruger Neosep™ MBR

Time Range	Peaking Factor	Flux (gfd)
00:00 - 08:30	1.0 Q	17.7
08:30 - 10:30	2.0 Q	35.4
10:30 - 13:30	1.0 Q	17.7
13:30 - 15:30	2.0 Q	35.4
15:30 - 23:59	1.0 Q	17.7

Q = Average Permeate Flow as recommended by the manufacturer

Table 6-7. Operating Parameters for DynaLift™ MBR During Peaking Study

Mode	Flux	Filtration Cycle Time	Backwash Time	Backwash Flux	Scouring Air	Scouring Air Blower	Recirculation Ratio
	(gfd)	(seconds)	(seconds)	(gfd)	(scfm)	(On/Off)	
F_{max}	45	600	6	240	6	Continous	10
F_{avg}	30	600	6	240	6	Continous	11

Table 6-8. Daily Peaking Schedule for DynaLift™ MBR

Time Range	Peaking Factor	Flux (gfd)
00:00 - 08:30	1.0 Q	30.0
08:30 - 10:30	1.5 Q	45.0
10:30 - 13:30	1.0 Q	30.0
13:30 - 15:30	1.5 Q	45.0
15:30 - 23:59	1.0 Q	30.0

Q = Average Permeate Flow as recommended by the manufacturer

Table 7-1. Comparison of Net Flux and Scouring Air Requirements for MBR Pilot Systems

	Measured Median Net Flux	Estimated Membrane Area for 1-MGD	Measured Scouring Air required per sq. ft. of Membrane	Estimated Scouring Air for 1-MGD
	(gfd)	(ft^2)	($scfm/ft^2$)	(scfm)
Puron*	13.3	75,164	0.019	895
Huber	14.7	67,880	0.026	1,712
Kruger	15.9	62,813	0.040	2,503
DynaLift	26.9	37,217	0.019	714

* For Puron MBR, median net flux was calculated including runs with permeate recycle

Table 8-1. Results from Title 22 Testing of MBR Pilot Systems

	Approved Peak Flux (gfd)	50th Percentile Removal of MS-2 Phage (Virus) (log)	95th Percentile Permeate Turbidity (NTU)
Puron	35	1.0	<0.1
Huber	33	4.0	<0.05
Kruger	35	3.0	<0.05
DynaLift	45	4.0	<0.05

Table 9-1. Capital Cost for Newly Developed MBR Systems

Item	Capital Costs, $K	
	1.0 MGD	**5.0 MGD**
Headworks	$516	$2,064
Basins	$503	$2,346
5-ton bridge crane	$56	$69
[1]**Membrane System**	$1,419-$2,330	$5,803-$7,750
Mechanical	$480	$2,766
Blower and Pump building	$274	$962
Chlorine Dosing System	$248	$1,242
Subtotal	$3,441-$4,352	$15,183-$17,130
Electrical, 15%	$525-$661	$2,222-$2,700
Mechanical/ Plumbing/HVAC, 13%	$455-$573	$1,926-$2,340
Sitework, 9%	$315-$397	$1,333-$1,620
Subtotal	$4,791-$6,039	$20,295-$24,659
Contractor Overhead and Profit, 15%	$719-$906	$3,044-$3,699
Subtotal-Construction Cost	$5,509-$6,945	$23,339-$28,357
Land	$825	$1,925
Contingency, 15%	$826-$1,042	$3,501-$4,254
Engineering/Legal/Administration, 15%	$826-$1,042	$3,501-$4,254
Total Capital Cost, $	$7,990-$9,850	$32,270-$38,790
Interest Rate	5%	5%
Number of Years	30	30
P/A Factor	15.37	15.37
Amortized Capital Cost, $/yr	$520-$641	$2,099-$2,523

[1] Costs based on proposals received from MBR vendors in July/August 2006. Please note that the capital costs received from MBR vendors were increased by 25% to account for installation.

Table 9-2. O&M Cost for Newly Developed MBR Systems

Item	O & M Costs, $K/yr	
	1.0 MGD	5.0 MGD
Electrical power for process/miscellaneous	$88	$438
Equipment repairs/lubricants/replacement	$38-$57	$159-$223
Chemical Cleaning	$9	$46
Chemical Cost for Disinfection	$5	$26
Diffuser Replacement	$3	$14
[1, 2] Membrane Replacement	$40-$106	$193-$478
Labor	$35	$98
Total O&M Costs in First Year, $	$218-$302	$974-$1,323
Interest rate	5%	5%
Number of Years	30	30
P/A Factor	15.37	15.37
Total Estimated O&M Costs, $	**$3,350-$4,649**	**$14,974-$20,344**

[1] Membrane Replacement cost estimates based on 8-yr life; annual costs shown would fund account annually.
[2] Costs based on proposals received from MBR vendors in July/August 2006.

Table 9-3. Summary of Capital and O&M Cost for Newly Developed MBR Systems

Capacity (MGD)	Capital Costs, $K	Total O&M Costs, $K	Present Worth Value, $K
1	$7,990-$9,850	$3,350-$4,649	$11,260-$14,429
5	$32,270-$38,790	$14,974-$20,344	$47,064-$58,954

Table 9-4. Summary of Costs, $/kgal for Newly Developed MBR Systems

Capacity (MGD)	Amortized Capital Costs, $K/yr	O&M Costs, $K/yr	Total Cost, $K/yr	Total Cost, $/1000 gal
1	$520-$641	$218-$302	$738-$943	$2.02-$2.58
5	$2,099-$2,523	$974-$1,323	$3,073-$3,846	$1.68-$2.11

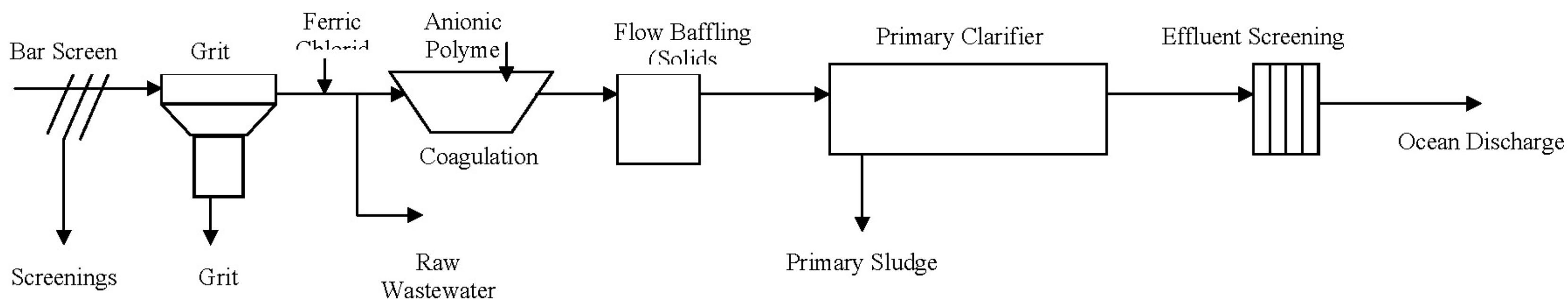


Figure 4-1. Schematic of the Point Loma Wastewater Treatment Plant.

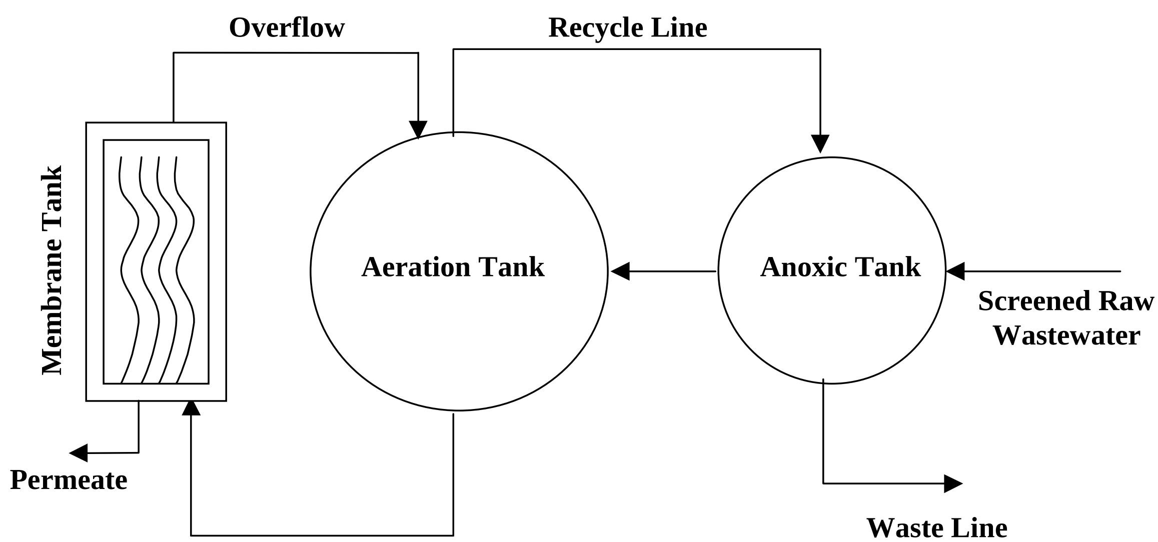


Figure 4-2. Schematic of the Puron™ MBR Pilot System.

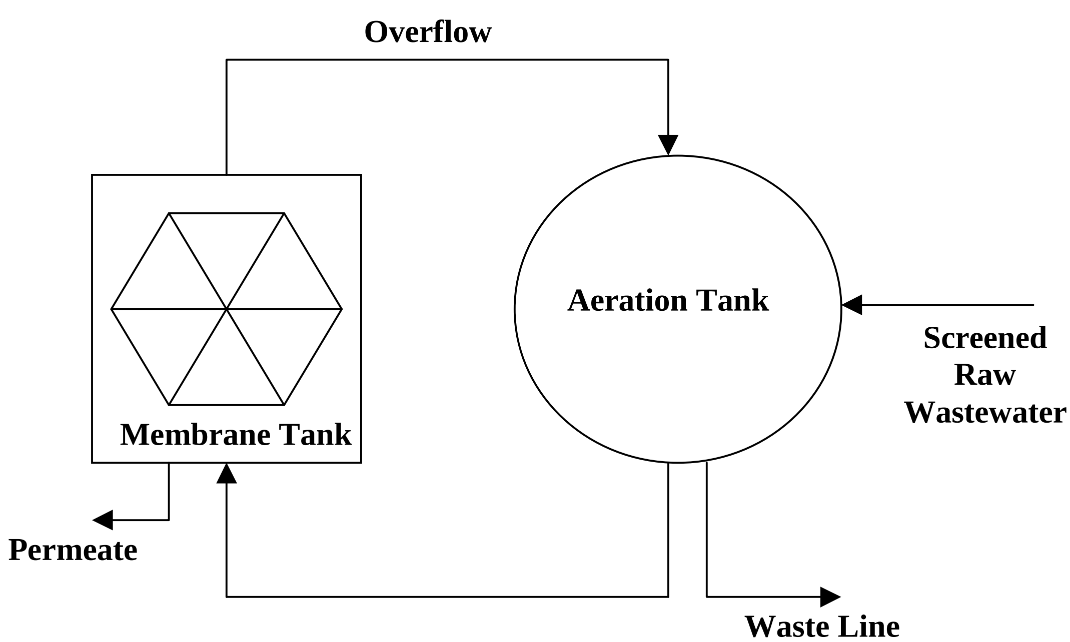


Figure 4-3. Schematic of the Huber® MBR Pilot System.

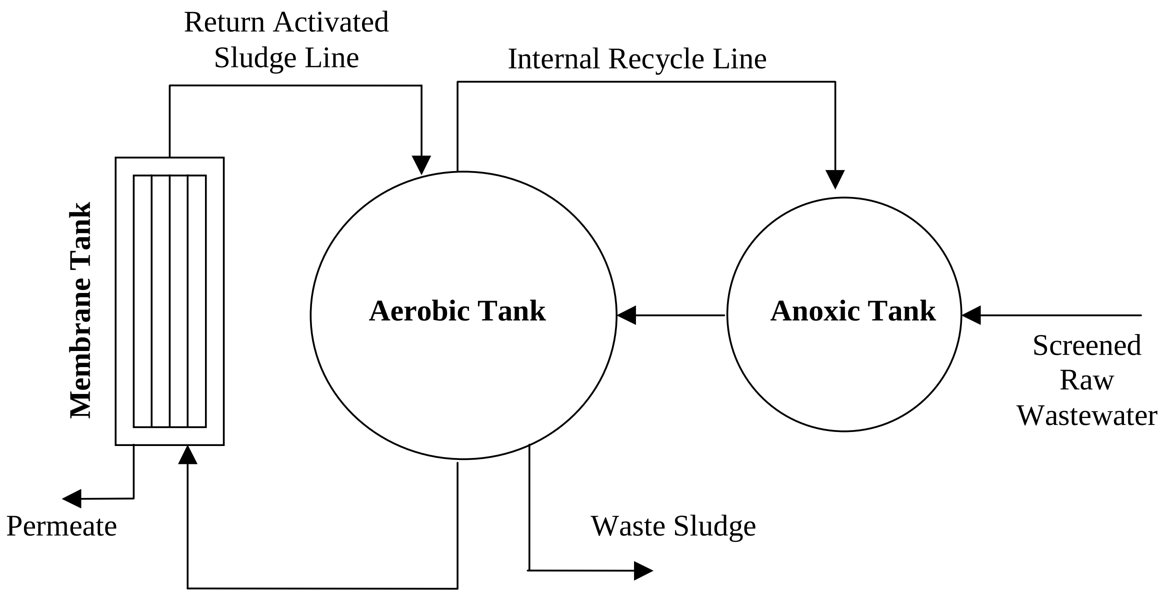


Figure 4-4. Schematic of the Kruger Neosep™ MBR Pilot System.

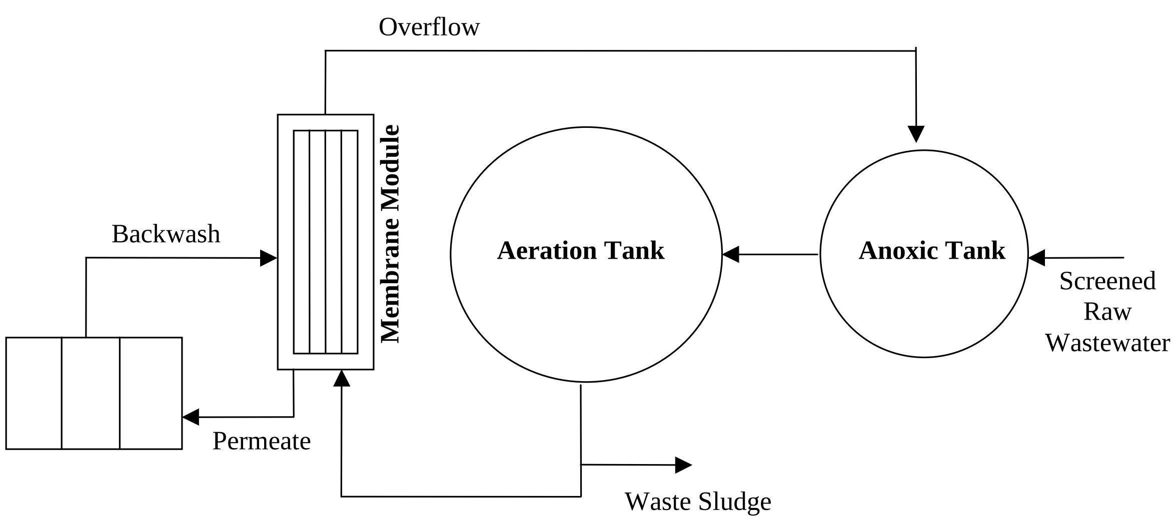


Figure 4-5. Schematic of the DynaLift™ MBR Pilot System.

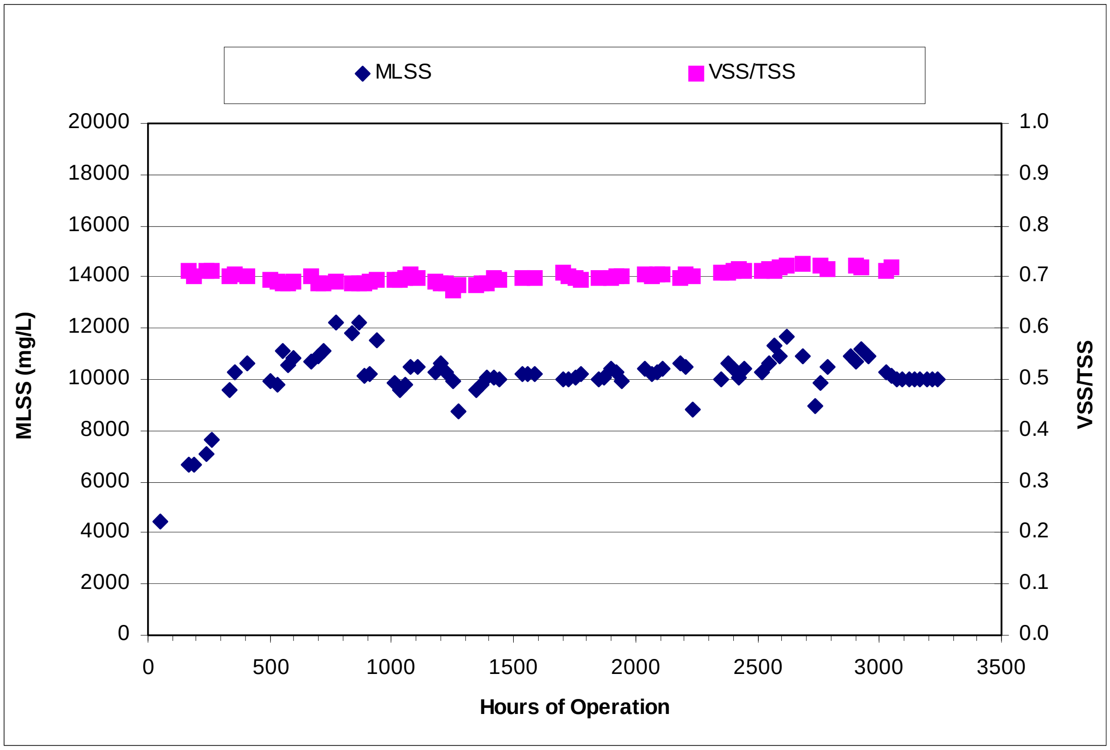


Figure 5-1. MLSS Concentrations in the Puron™ MBR.

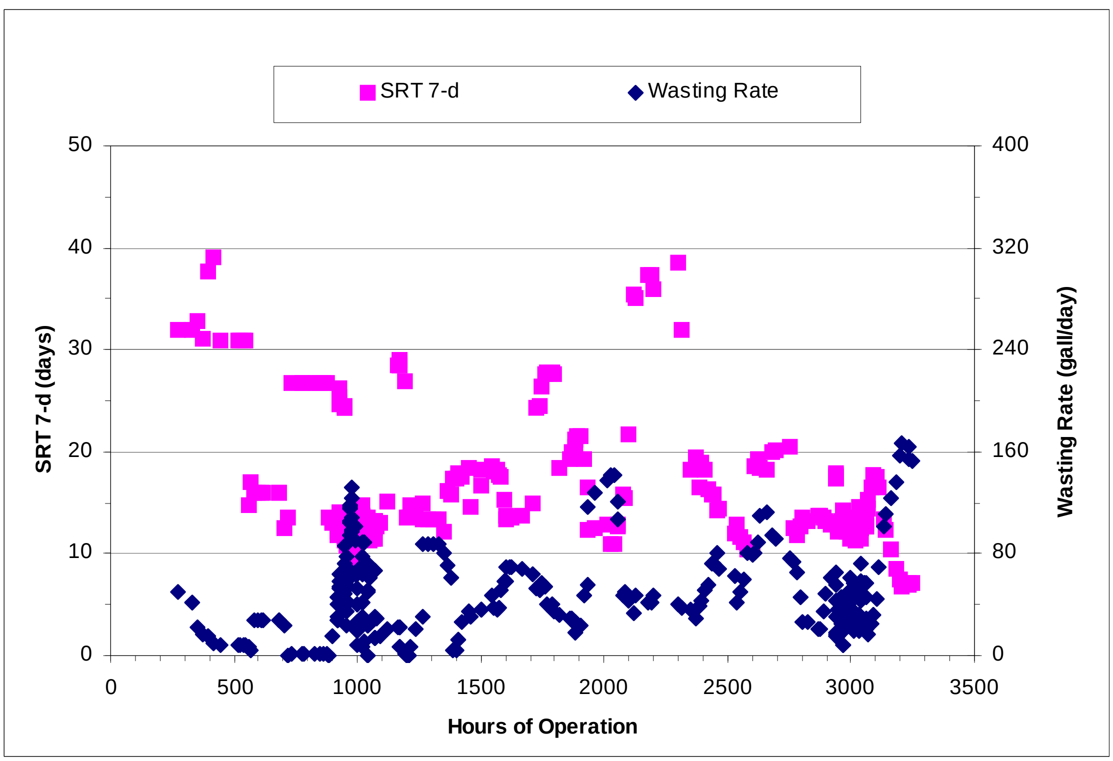


Figure 5-2. $SRT_{7\text{-}d}$ and Wasting Rate for the Puron™ MBR.

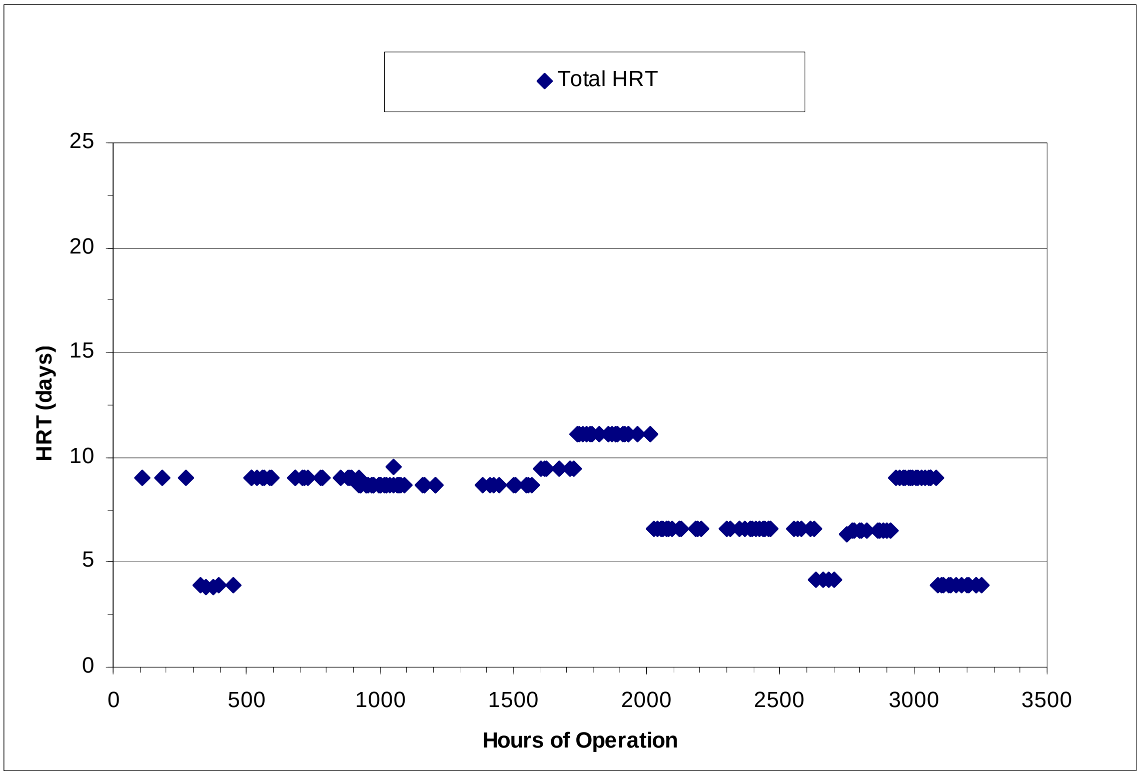


Figure 5-3. HRT for the Puron™ MBR.

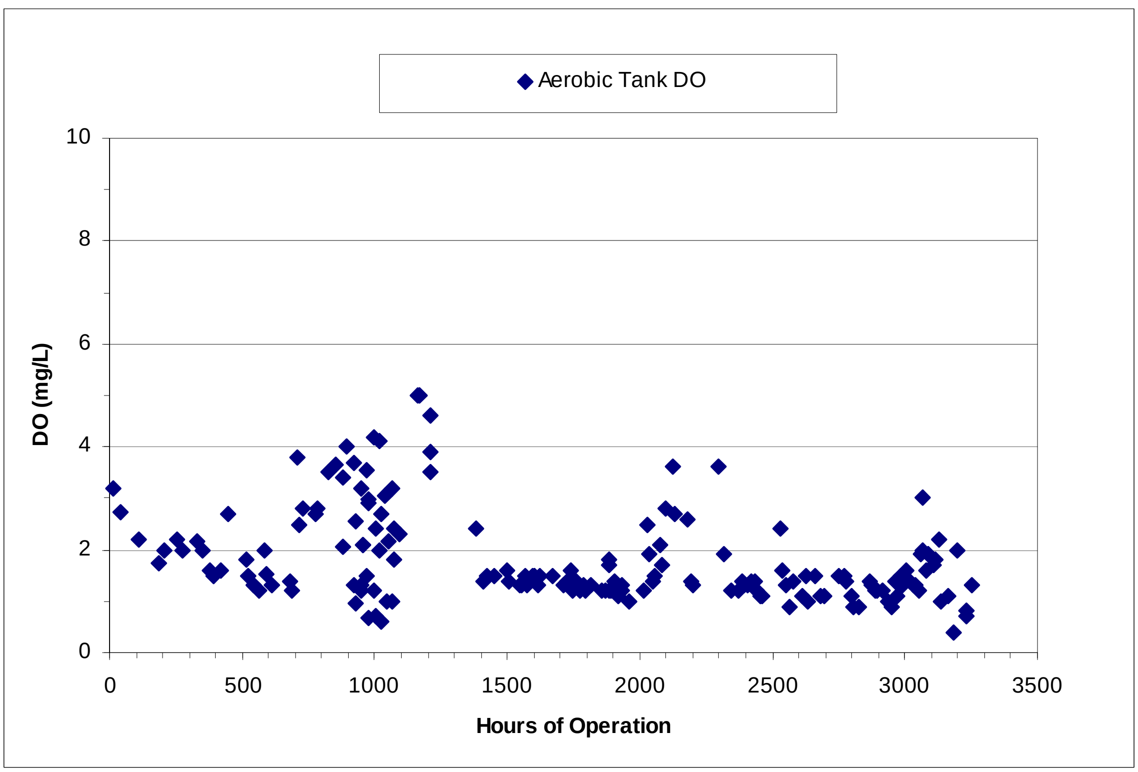


Figure 5-4. DO Concentrations for the Puron™ MBR.

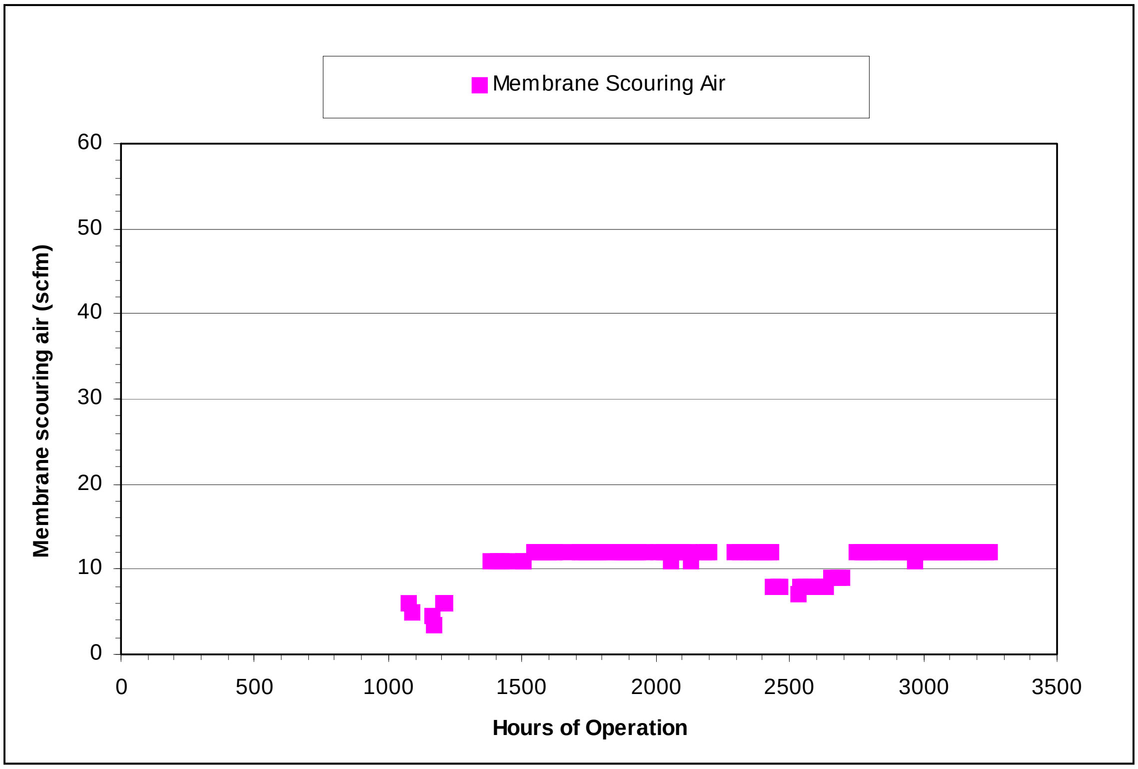


Figure 5-5. Membrane Scouring Air for the Puron™ MBR.

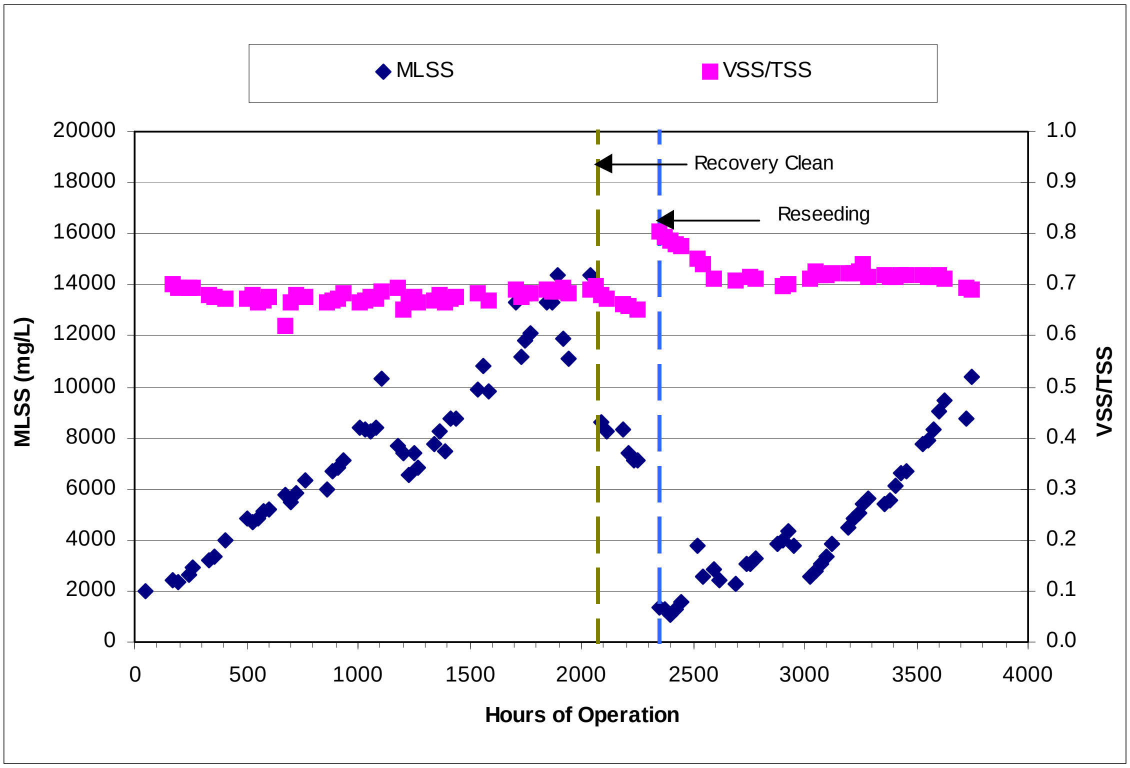


Figure 5-6. MLSS Concentrations in the Huber® MBR.

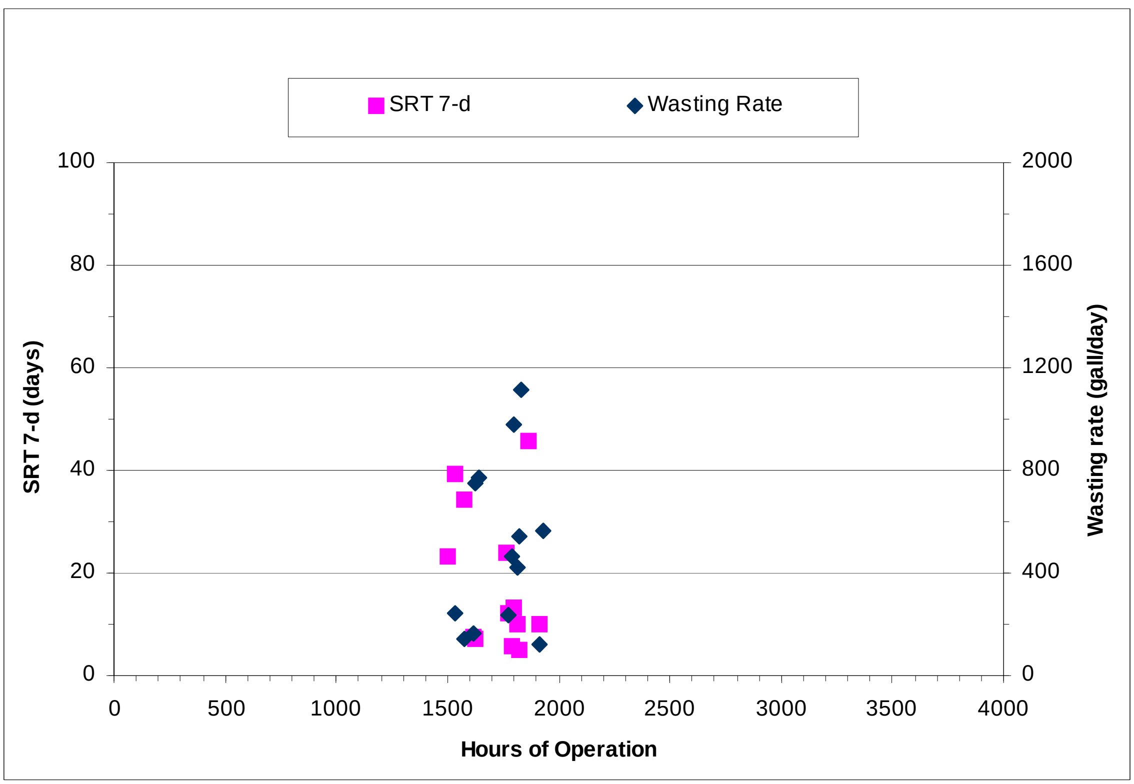


Figure 5-7. $SRT_{7\text{-}d}$ and Wasting Rate for the Huber® MBR.

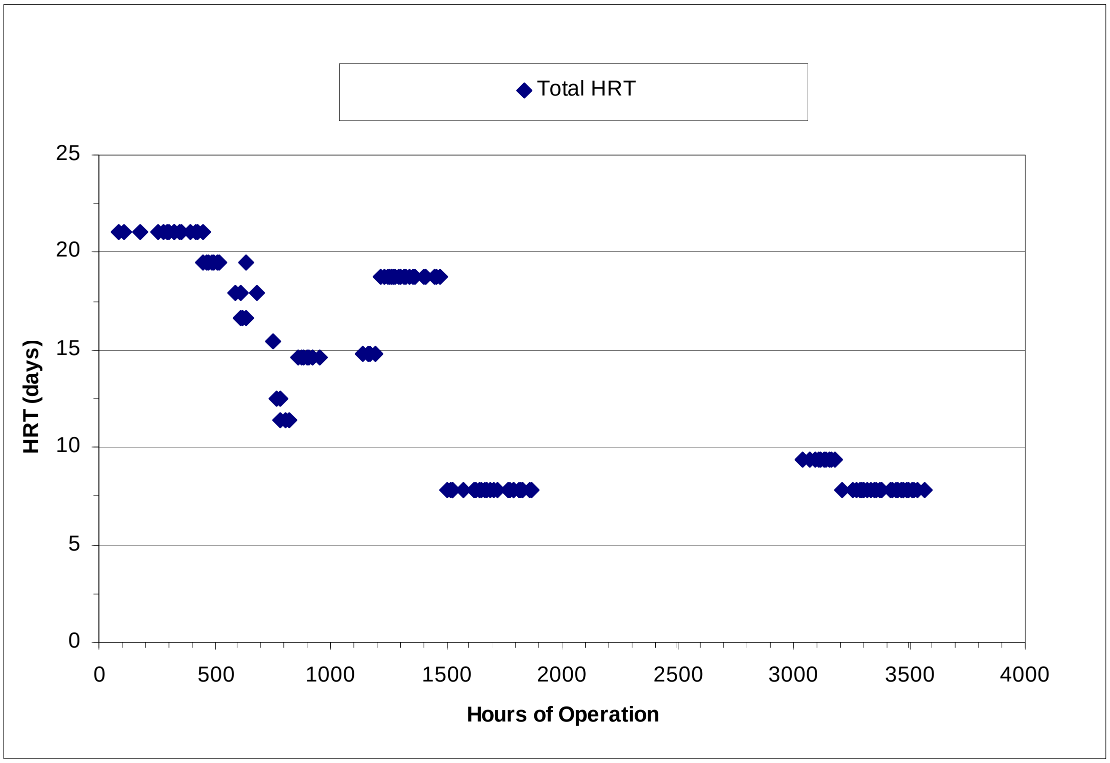


Figure 5-8. HRT for the Huber® MBR.

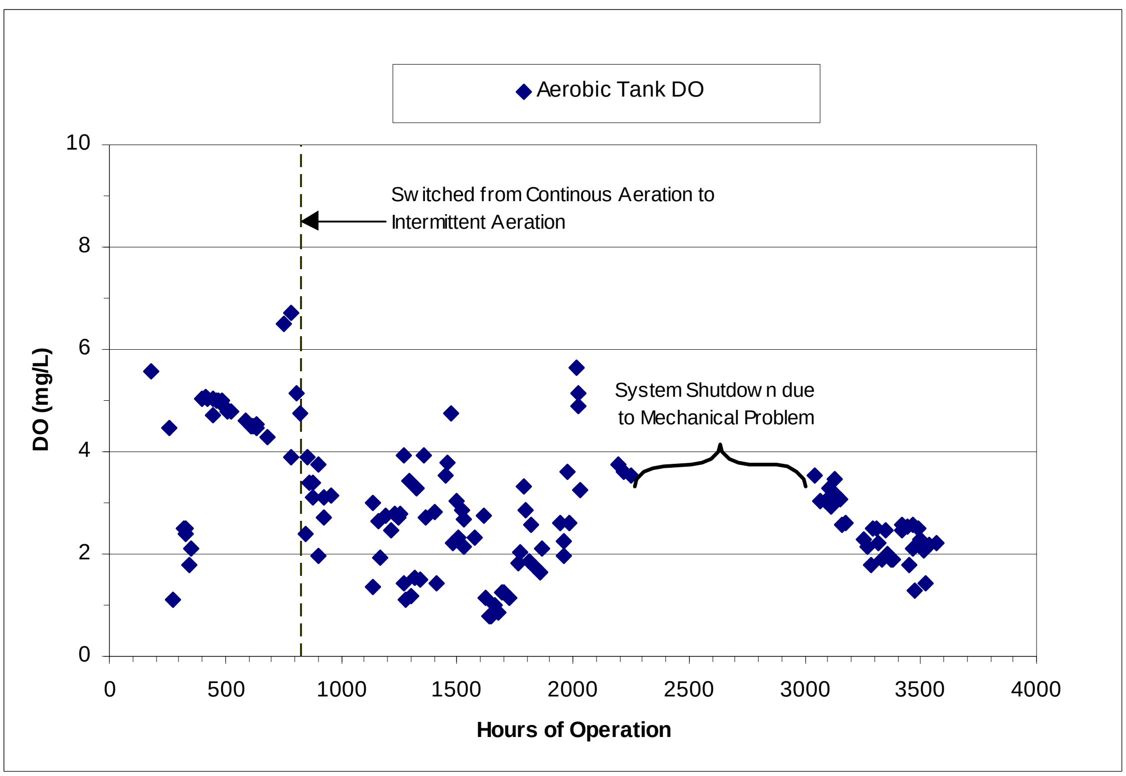


Figure 5-9. DO Concentrations for the Huber® MBR.

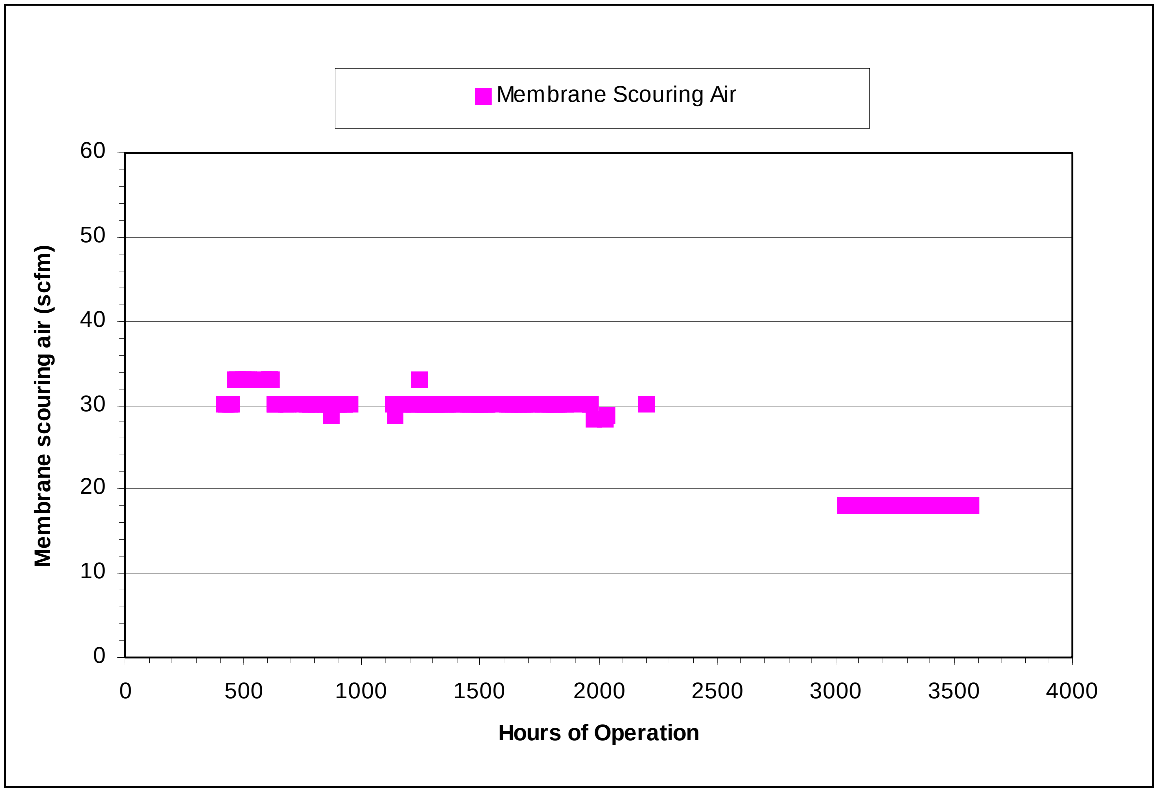


Figure 5-10. Membrane Scouring Air for the Huber® MBR.

Figure 5-11. MLSS Concentrations in the Kruger Neosep™ MBR.

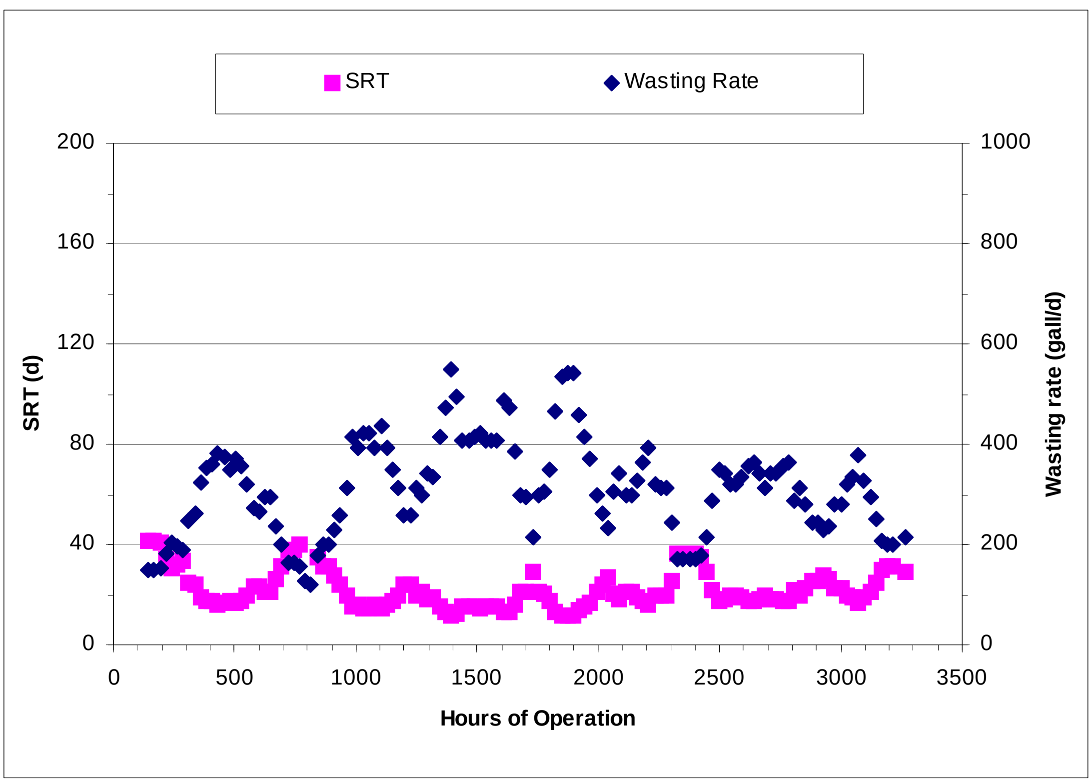


Figure 5-12. $SRT_{7\text{-}d}$ and Wasting Rate for the Kruger Neosep™ MBR.

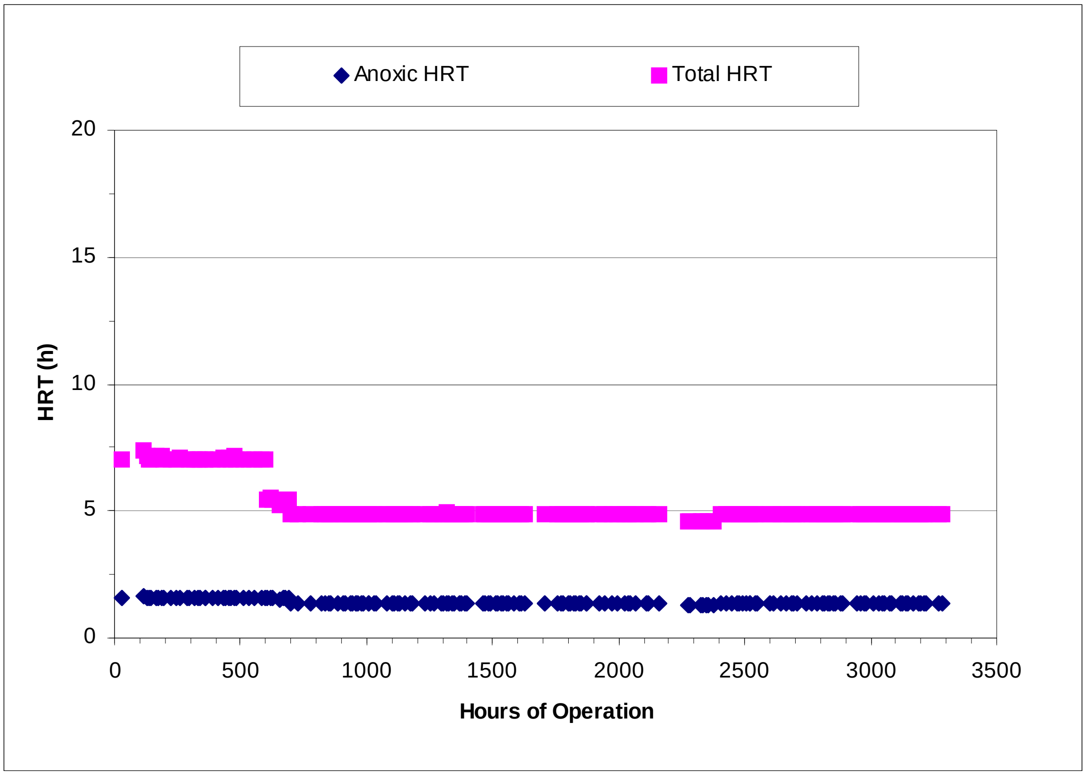


Figure 5-13. HRT for the Kruger Neosep™ MBR.

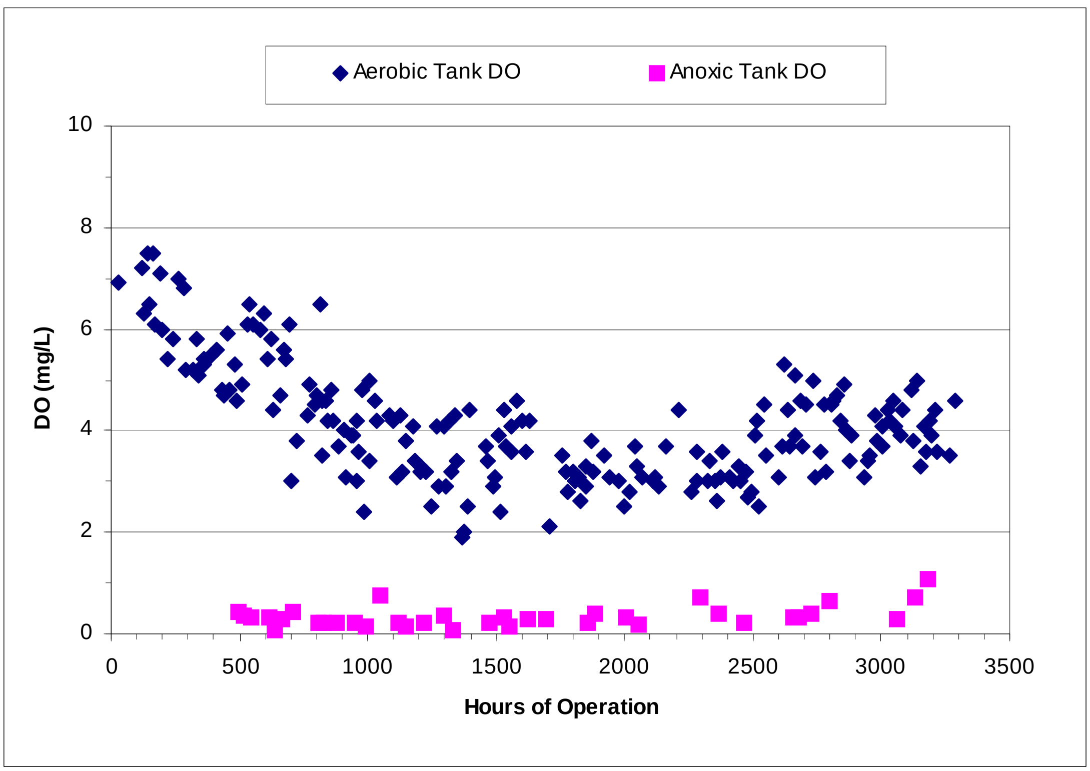


Figure 5-14. DO Concentrations for the Kruger Neosep™ MBR.

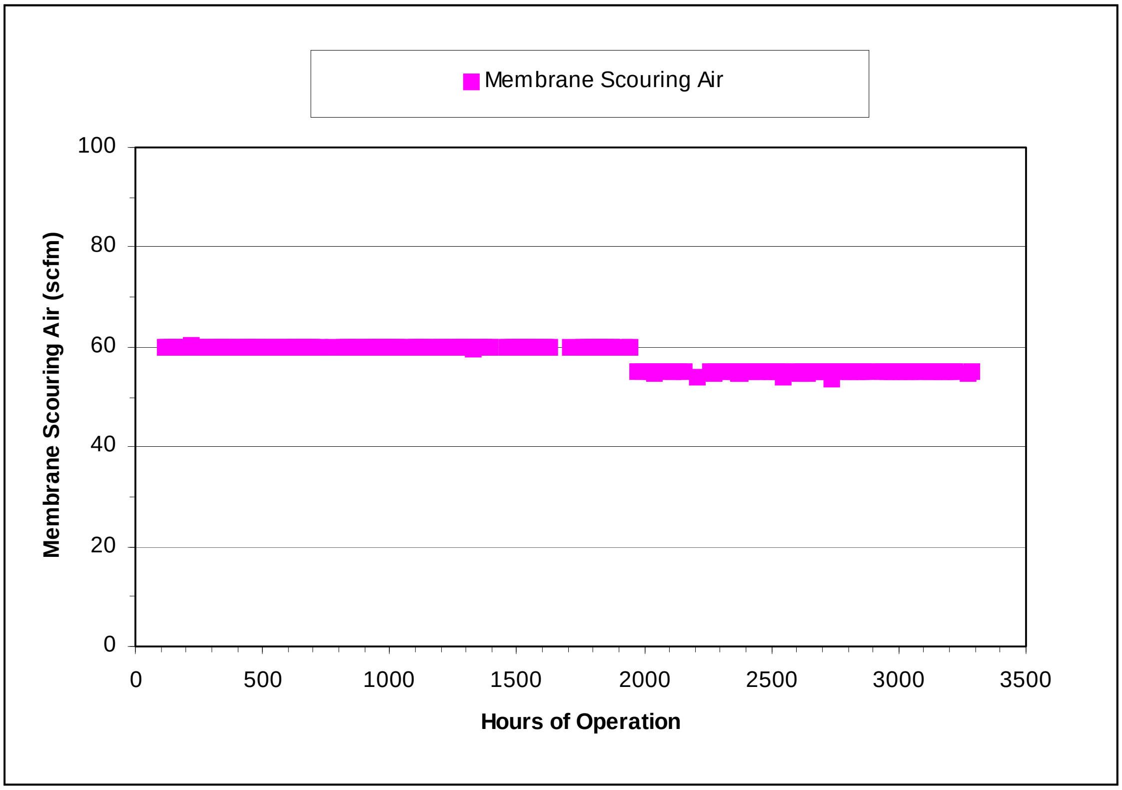


Figure 5-15. Membrane Scouring Air for the Kruger Neosep™ MBR.

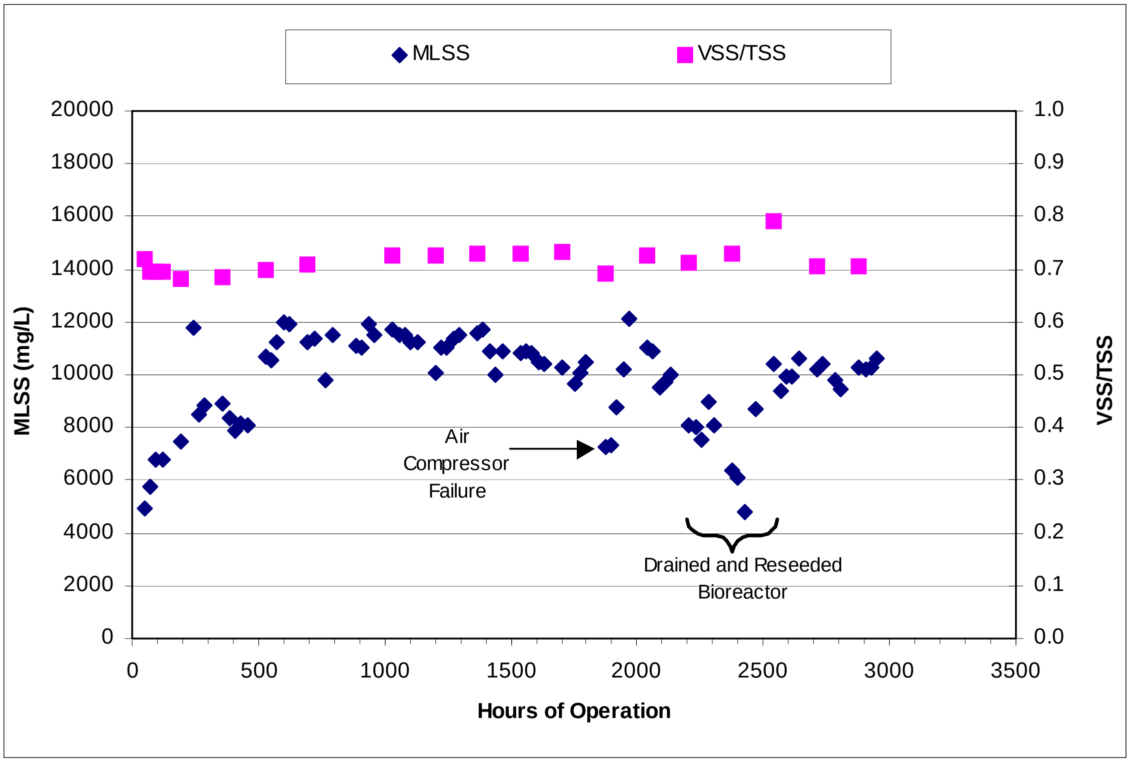


Figure 5-16. MLSS Concentrations in the DynaLift™ MBR.

Figure 5-17. SRT$_{7\text{-}d}$ and Wasting Rate for the DynaLift™ MBR.

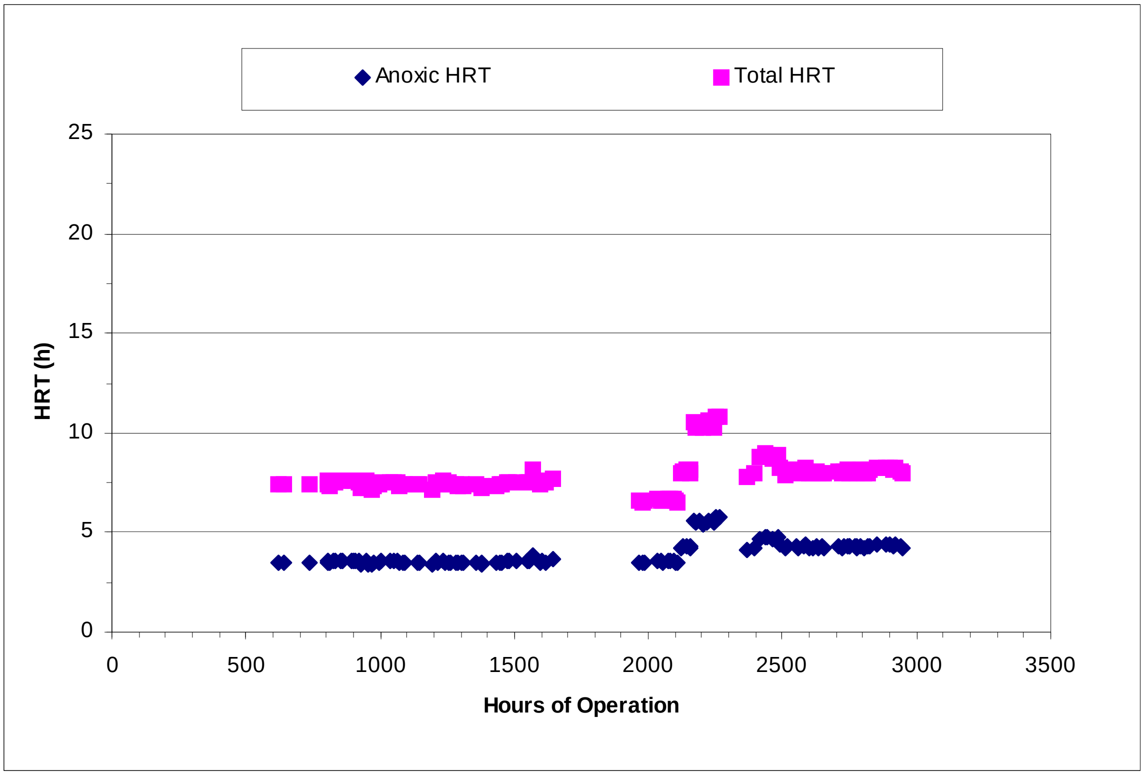


Figure 5-18. HRT for the DynaLift™ MBR.

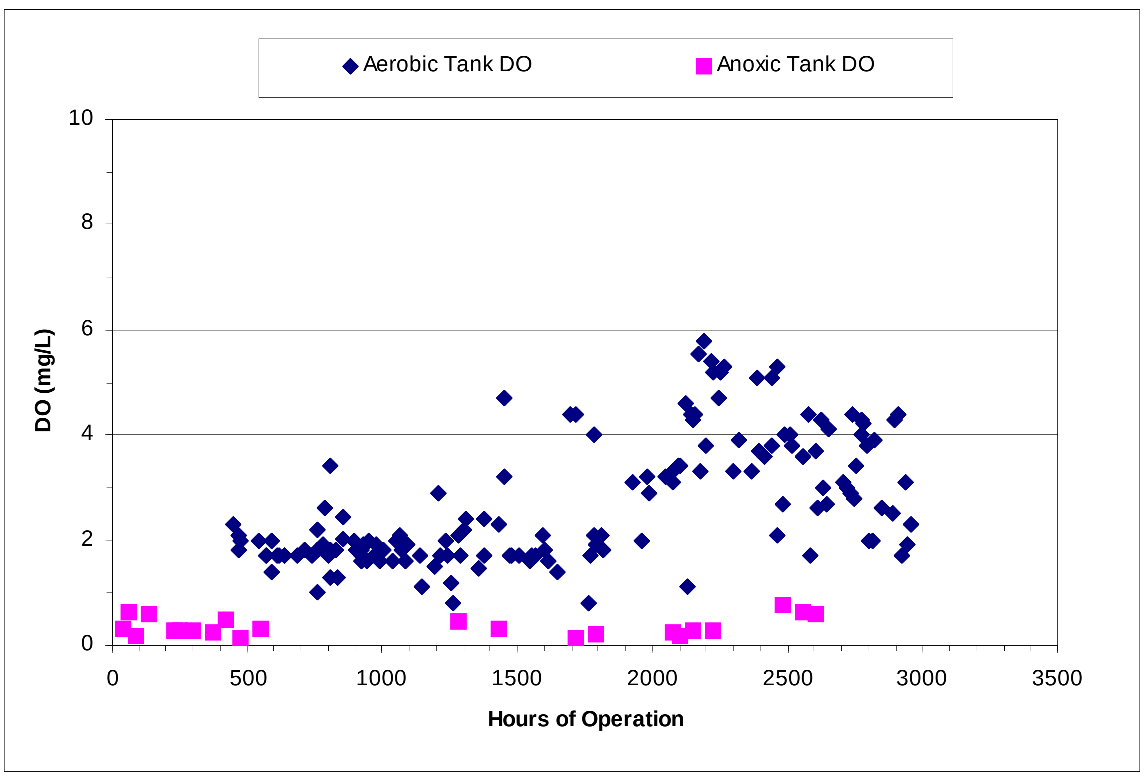


Figure 5-19. DO Concentrations for the DynaLift™ MBR.

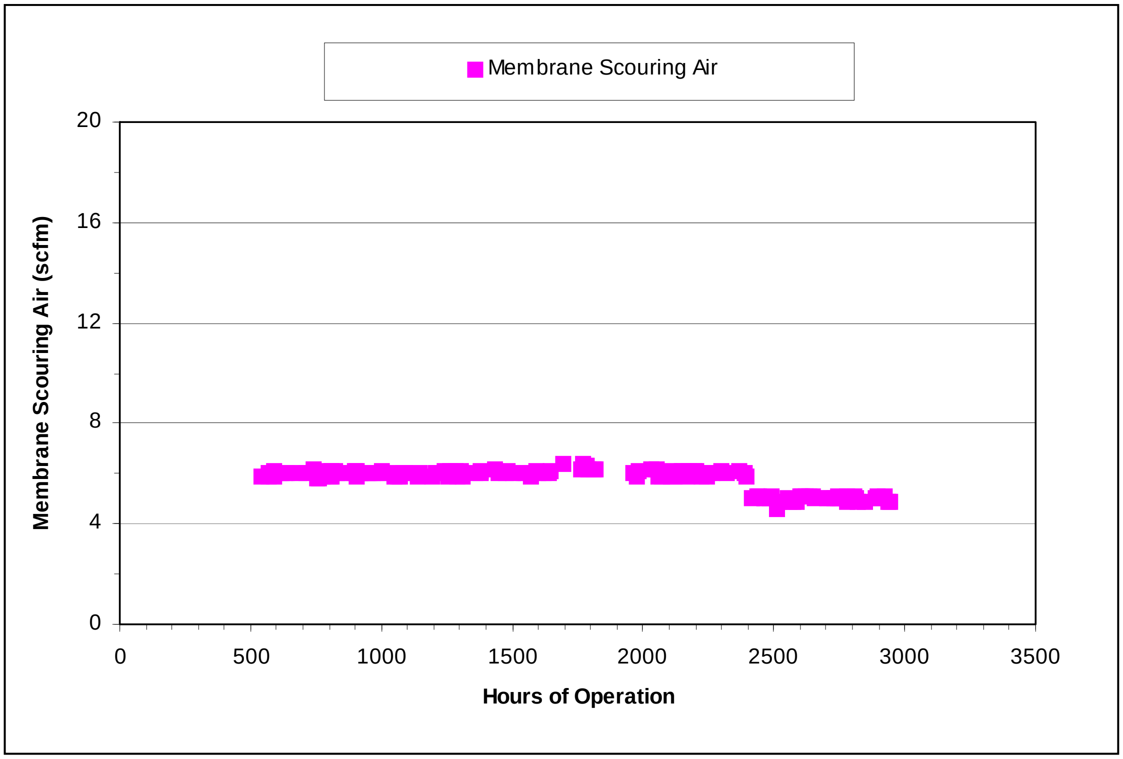


Figure 5-20. Membrane Scouring Air for the DynaLift™ MBR.

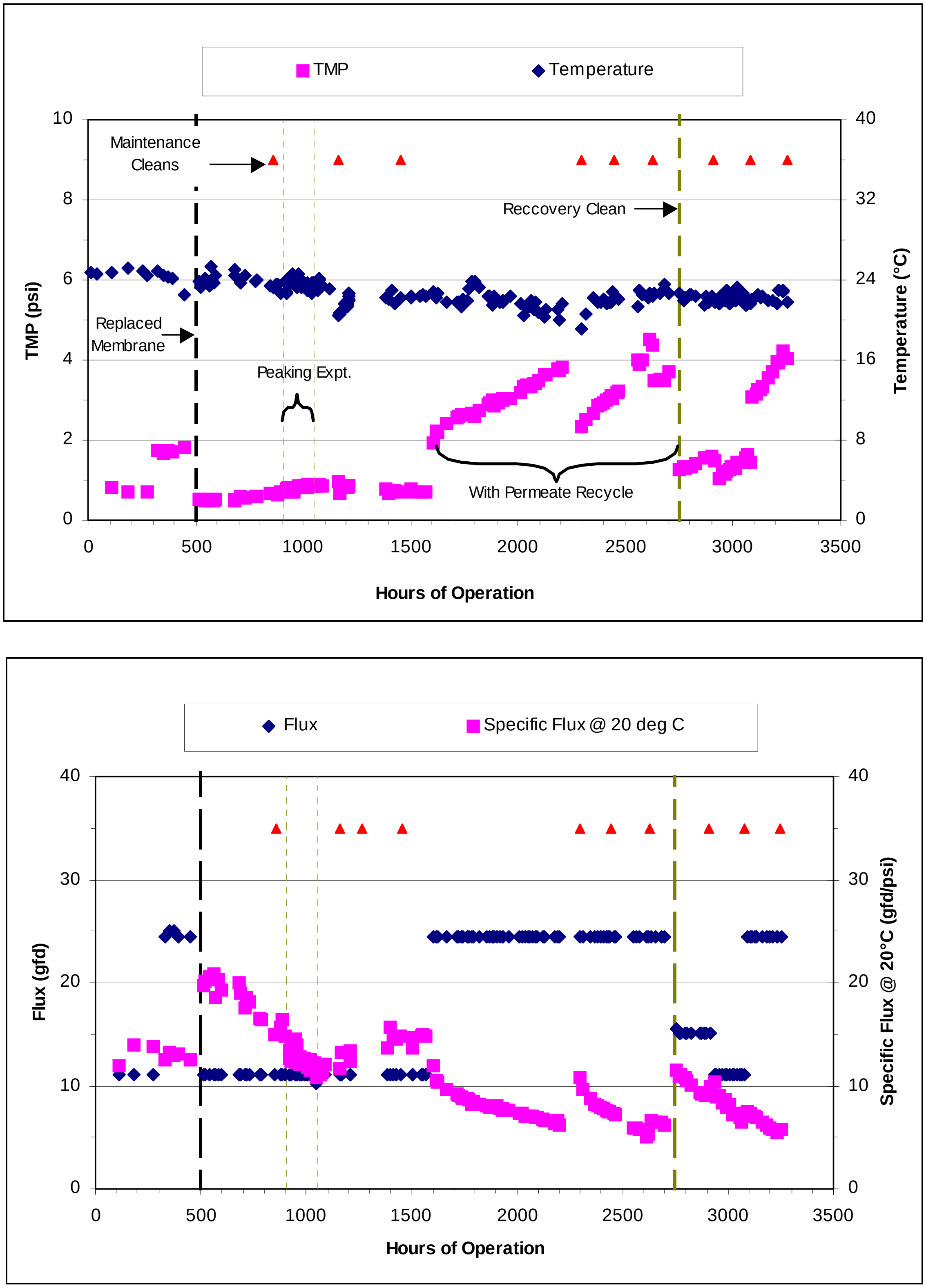


Figure 5-21. Membrane Performance of the Puron™ MBR.

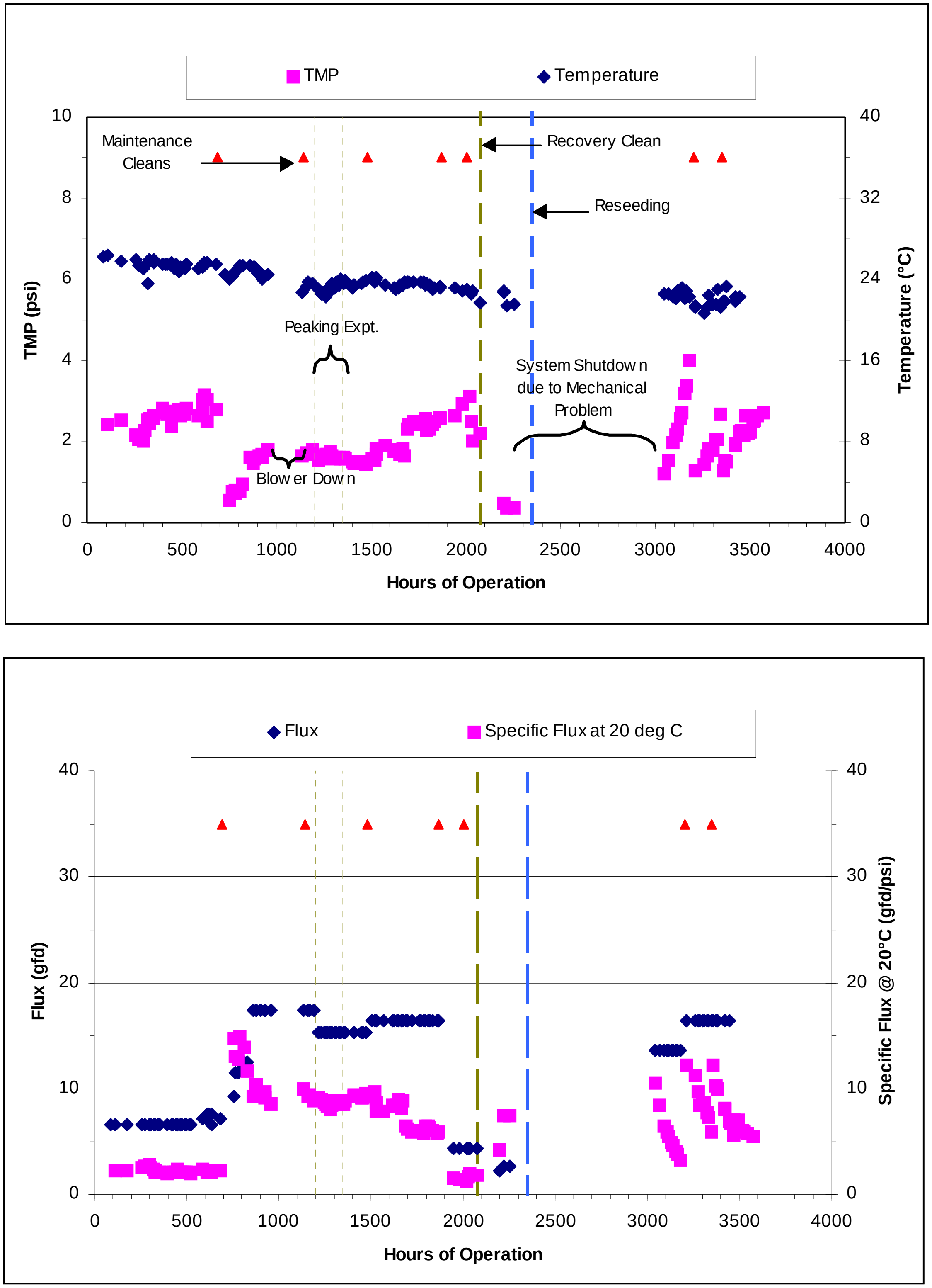


Figure 5-22. Membrane Performance of the Huber® MBR.

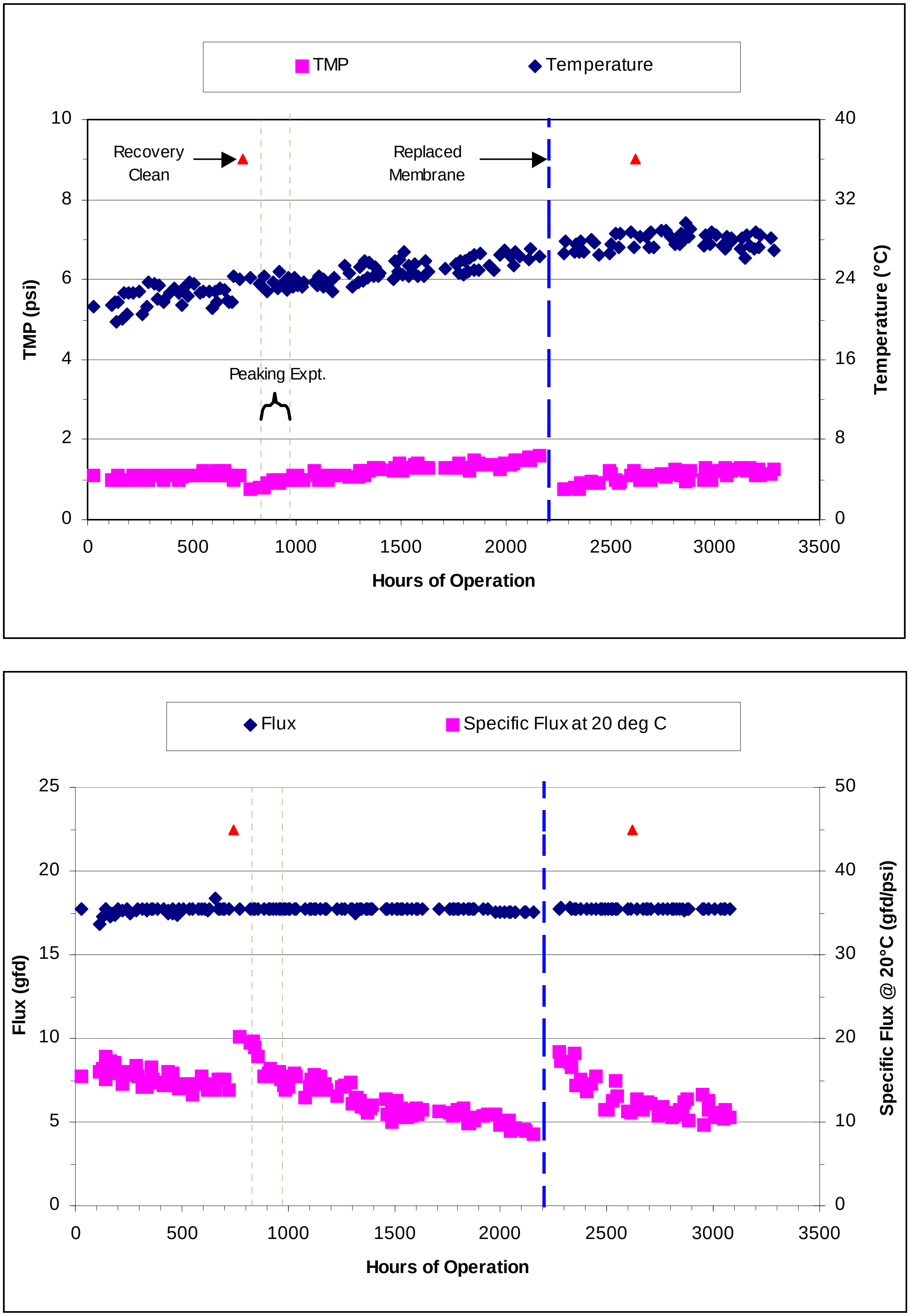


Figure 5-23. Membrane Performance of the Kruger Neosep™ MBR.

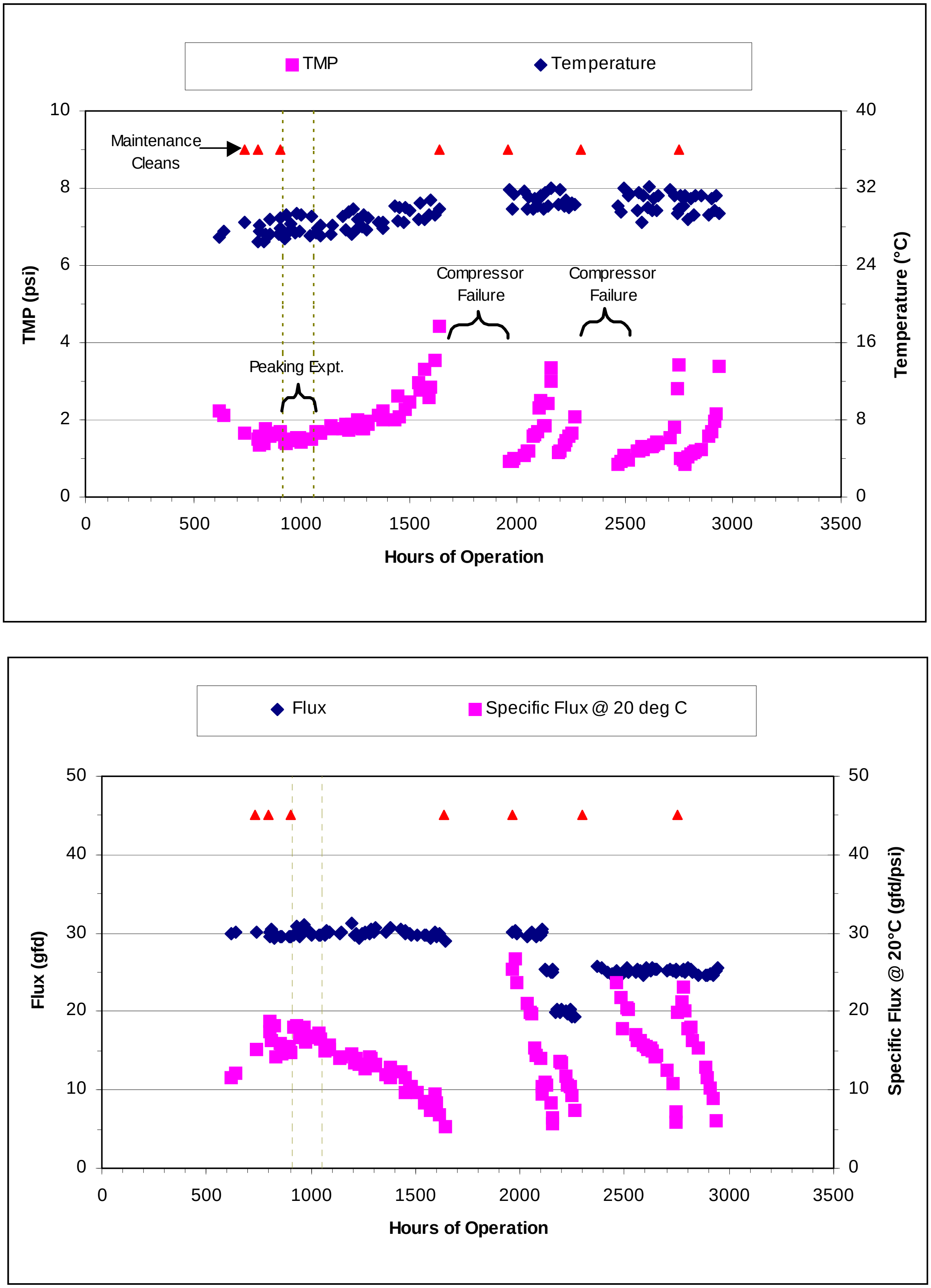
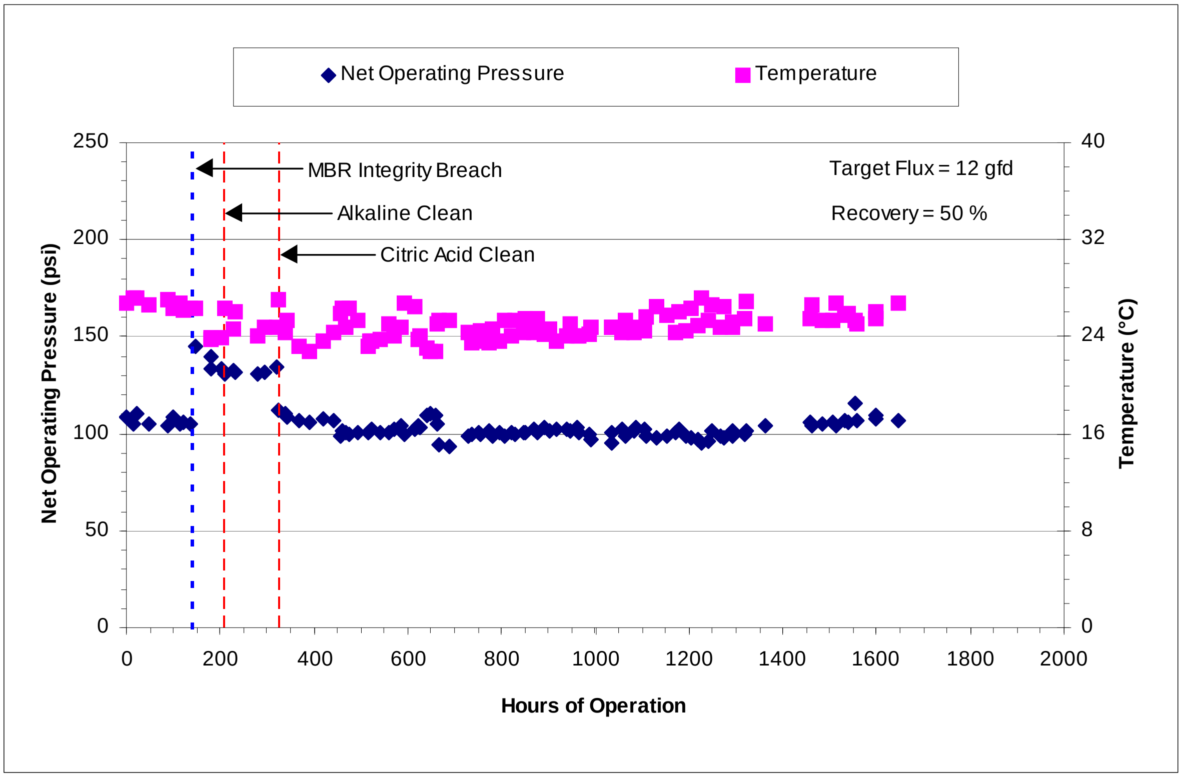


Figure 5-24. Membrane Performance of the DynaLift™ MBR.



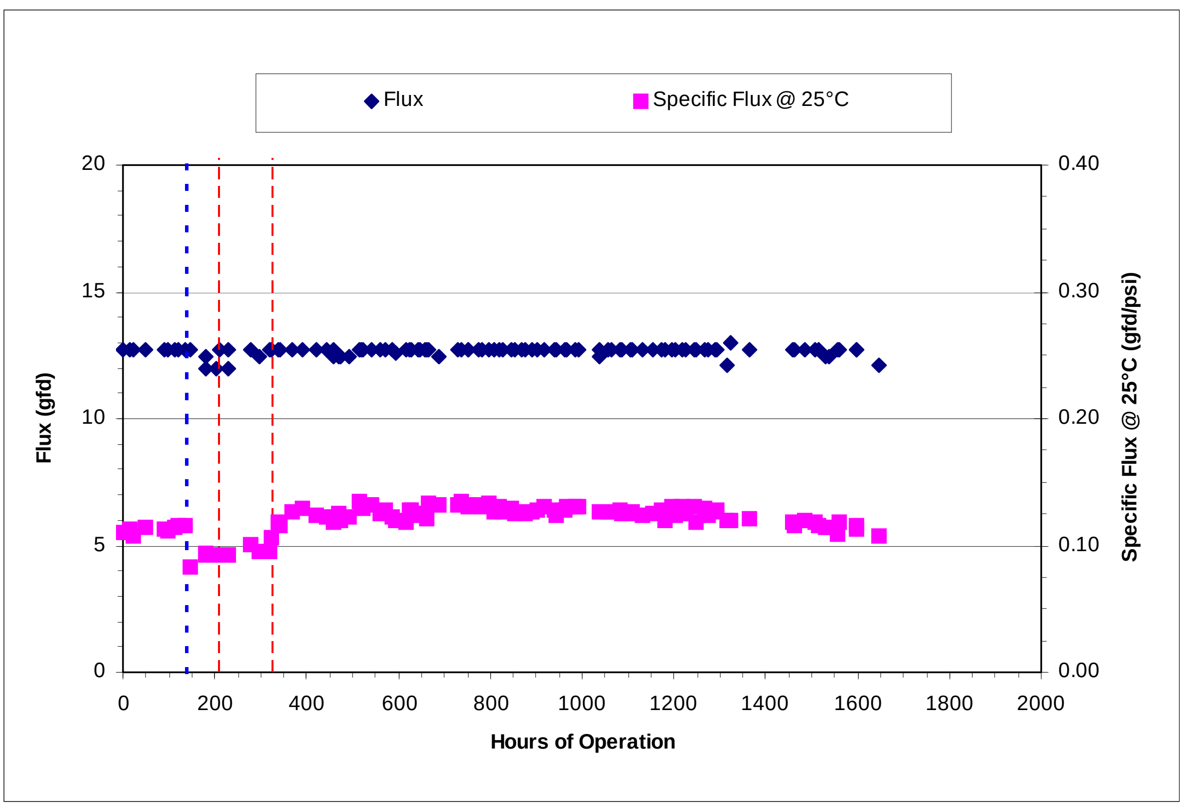


Figure 5-25. Membrane Performance of the Koch 4040 HR RO Membrane.

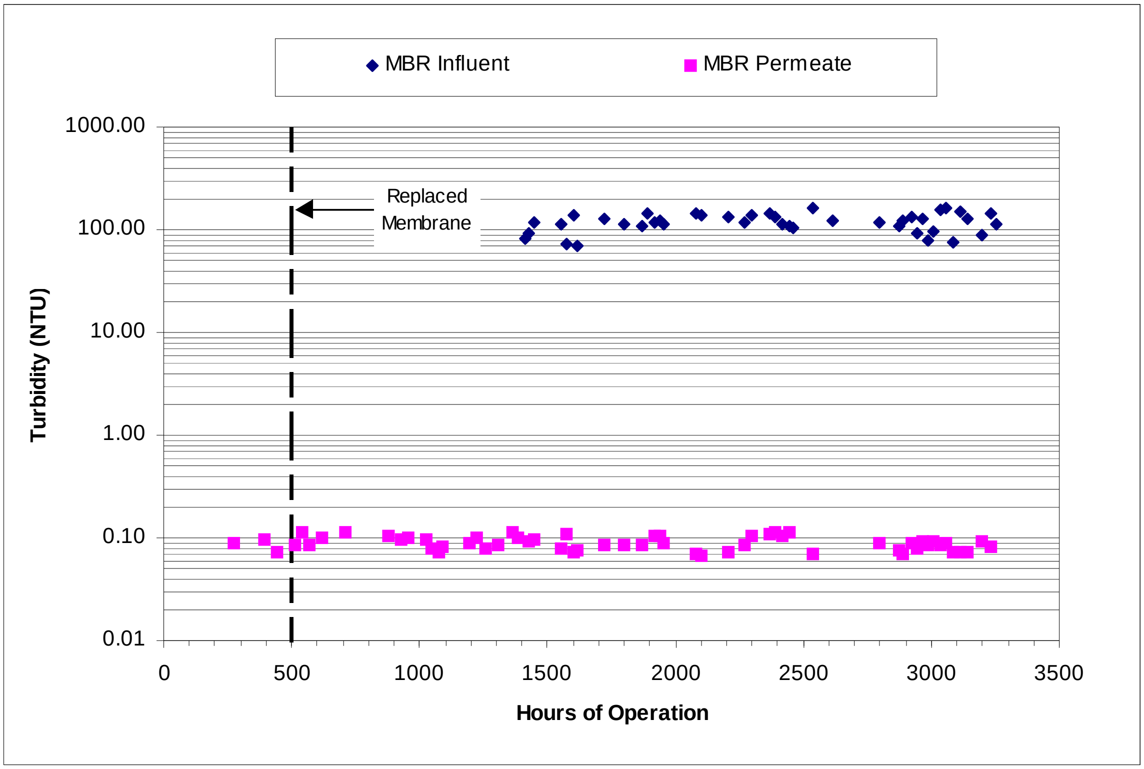


Figure 5-26. Particulate Removal by Puron™ MBR.

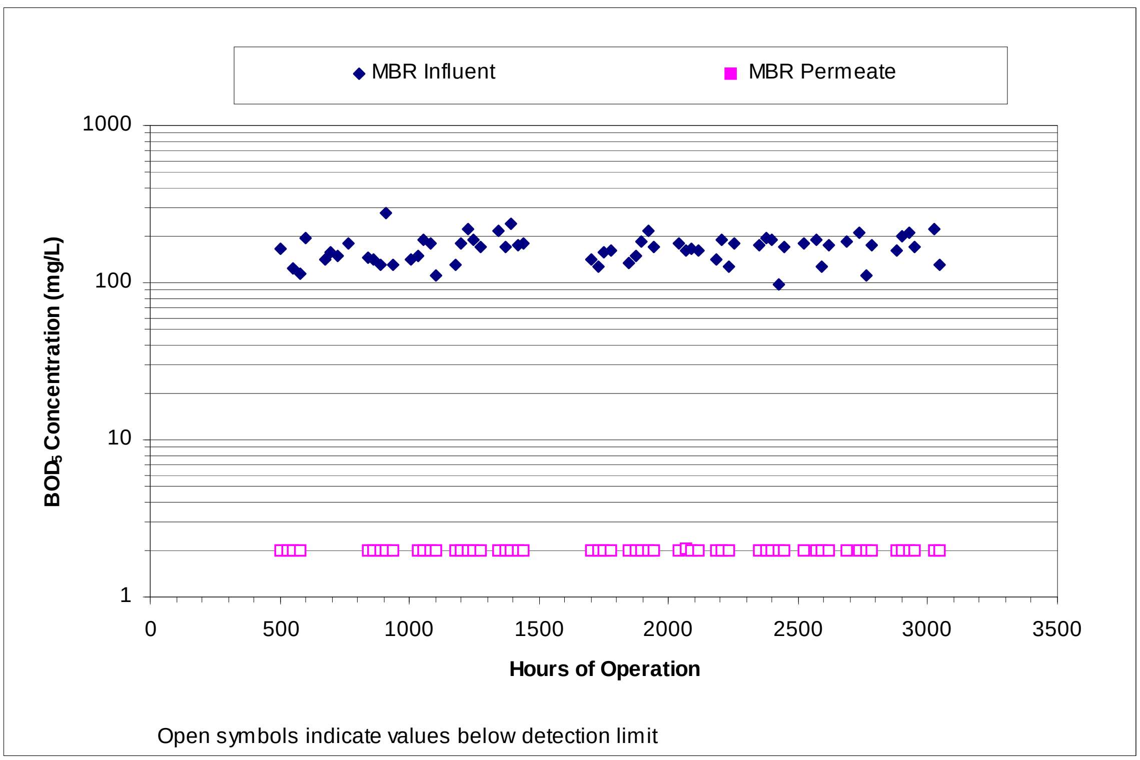


Figure 5-27. Organics Removal by Puron™ MBR.

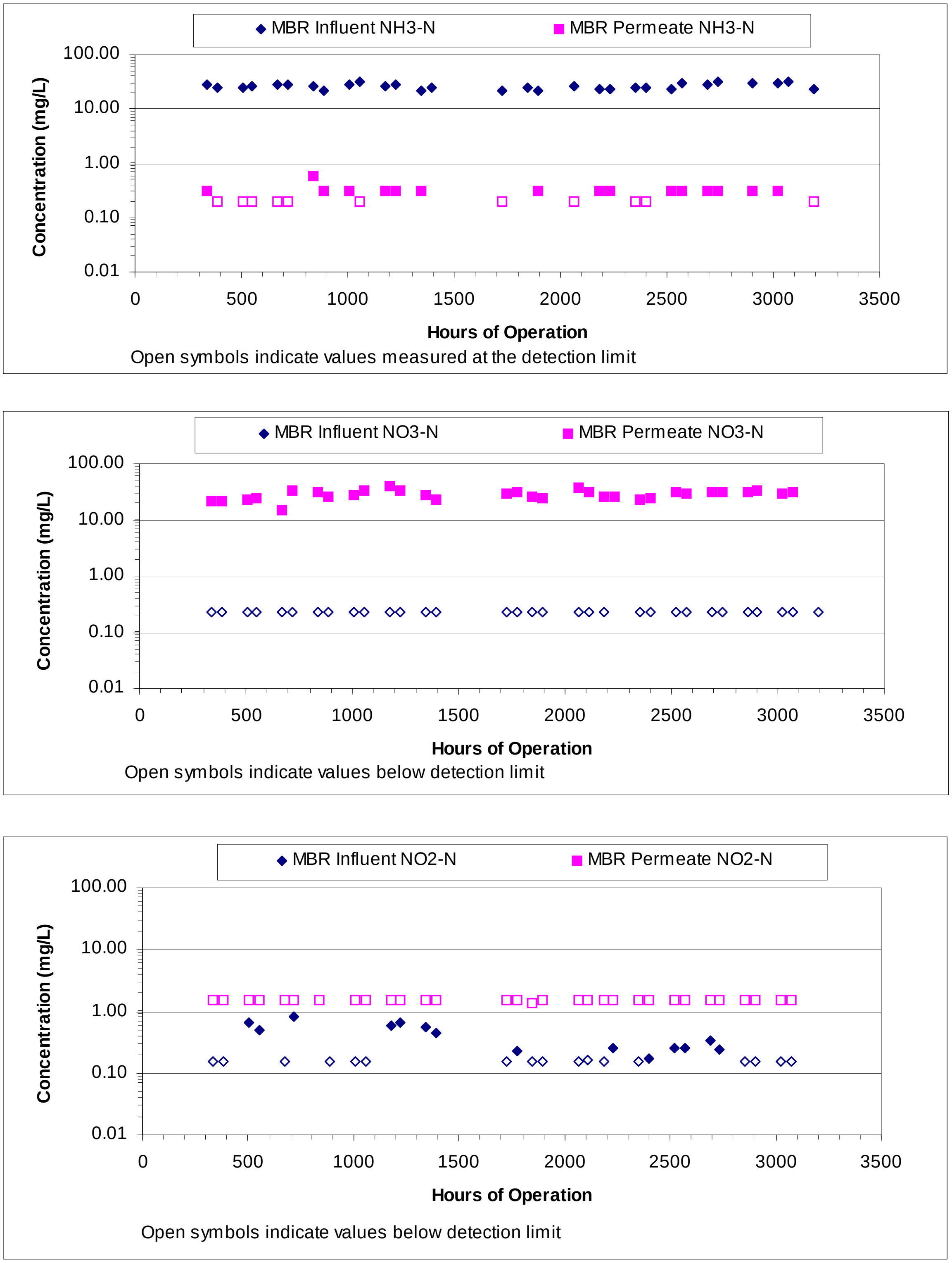


Figure 5-28. Inorganic Nitrogen Removal by Puron™ MBR.

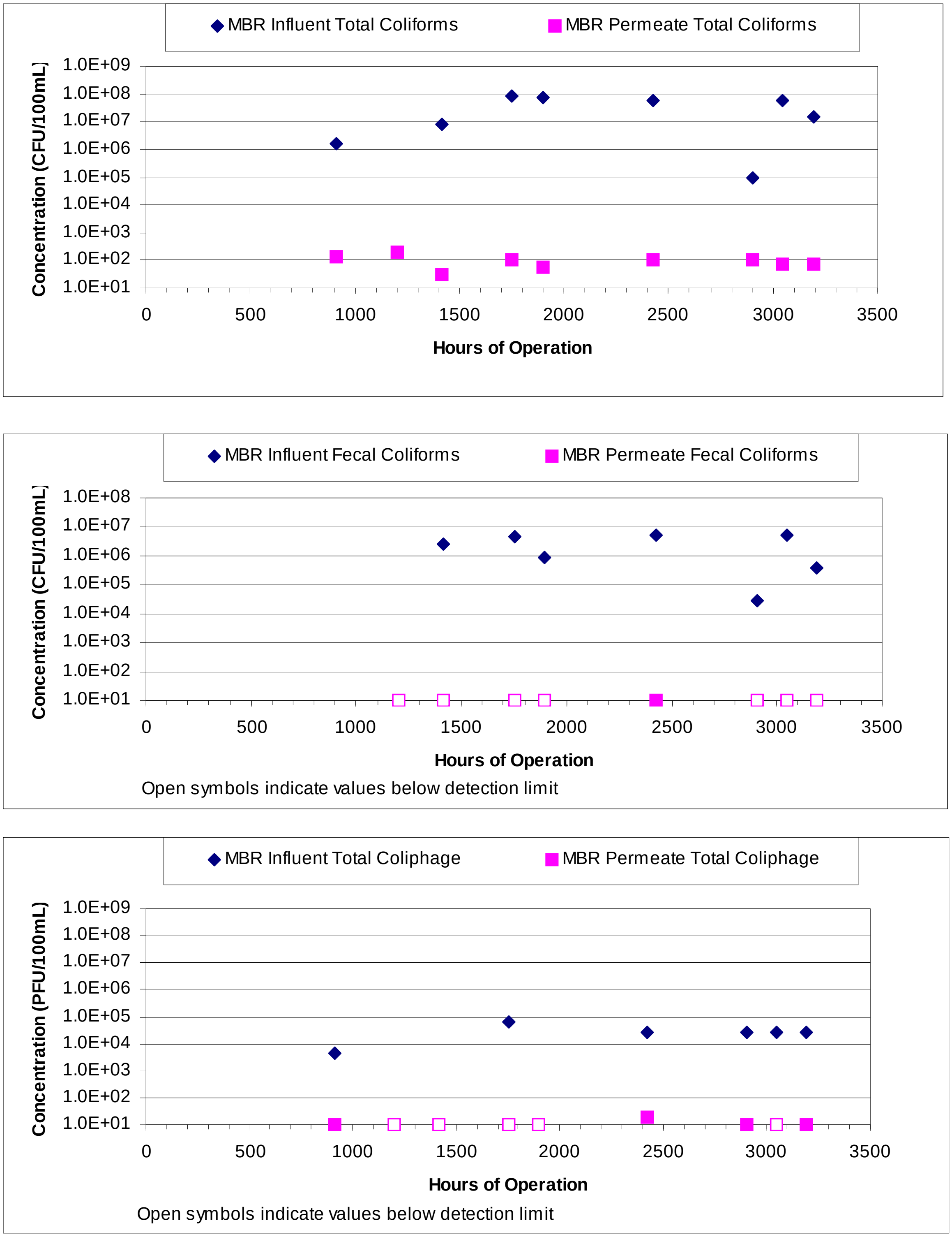


Figure 5-29. Microbial Rejection by Puron™ MBR.

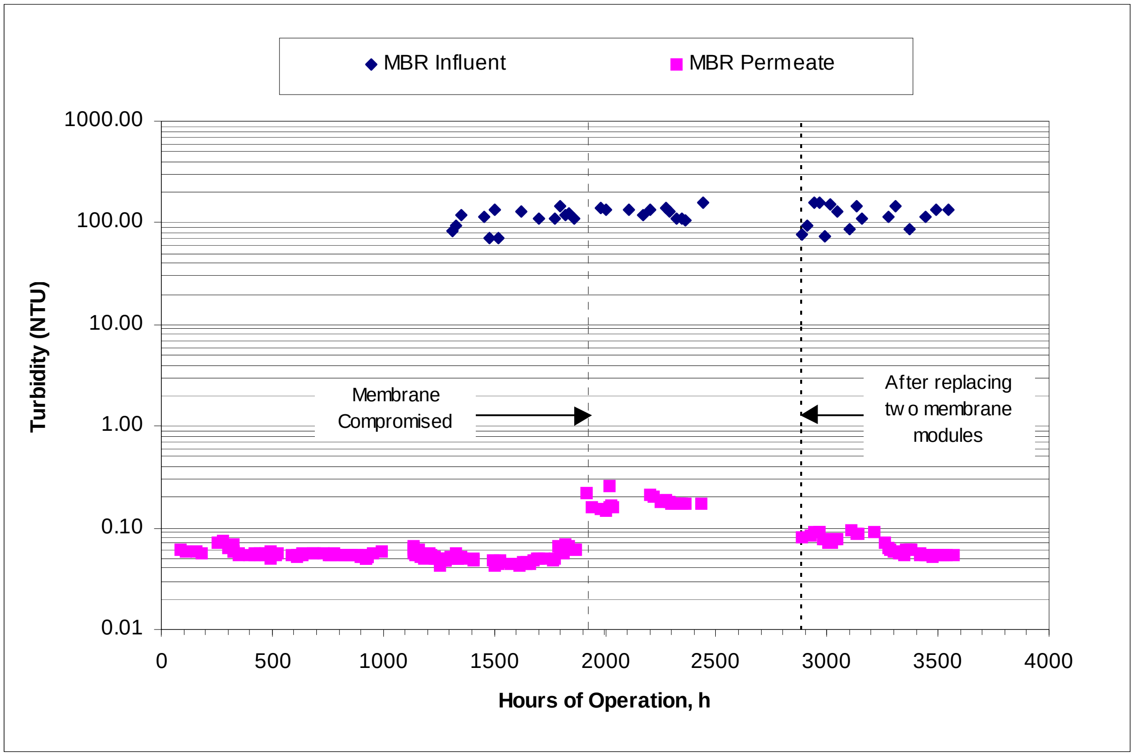


Figure 5-30. Particulate Removal by Huber® MBR.

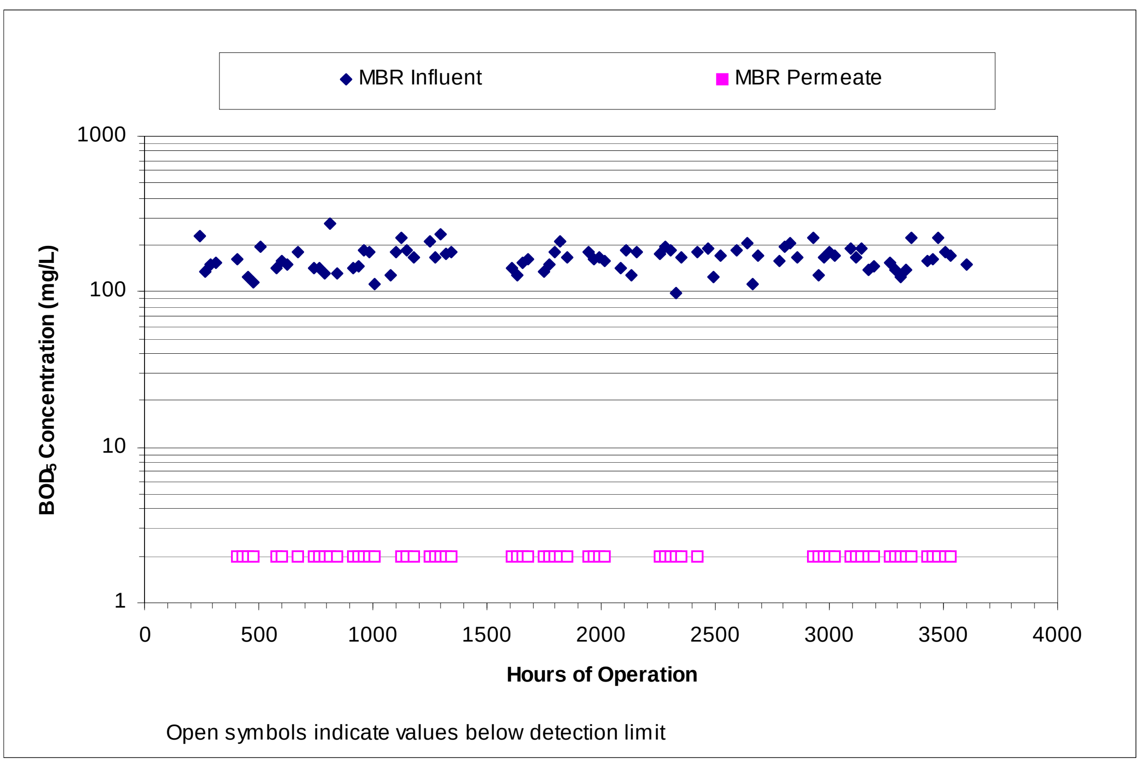


Figure 5-31. Organics Removal by Huber® MBR.

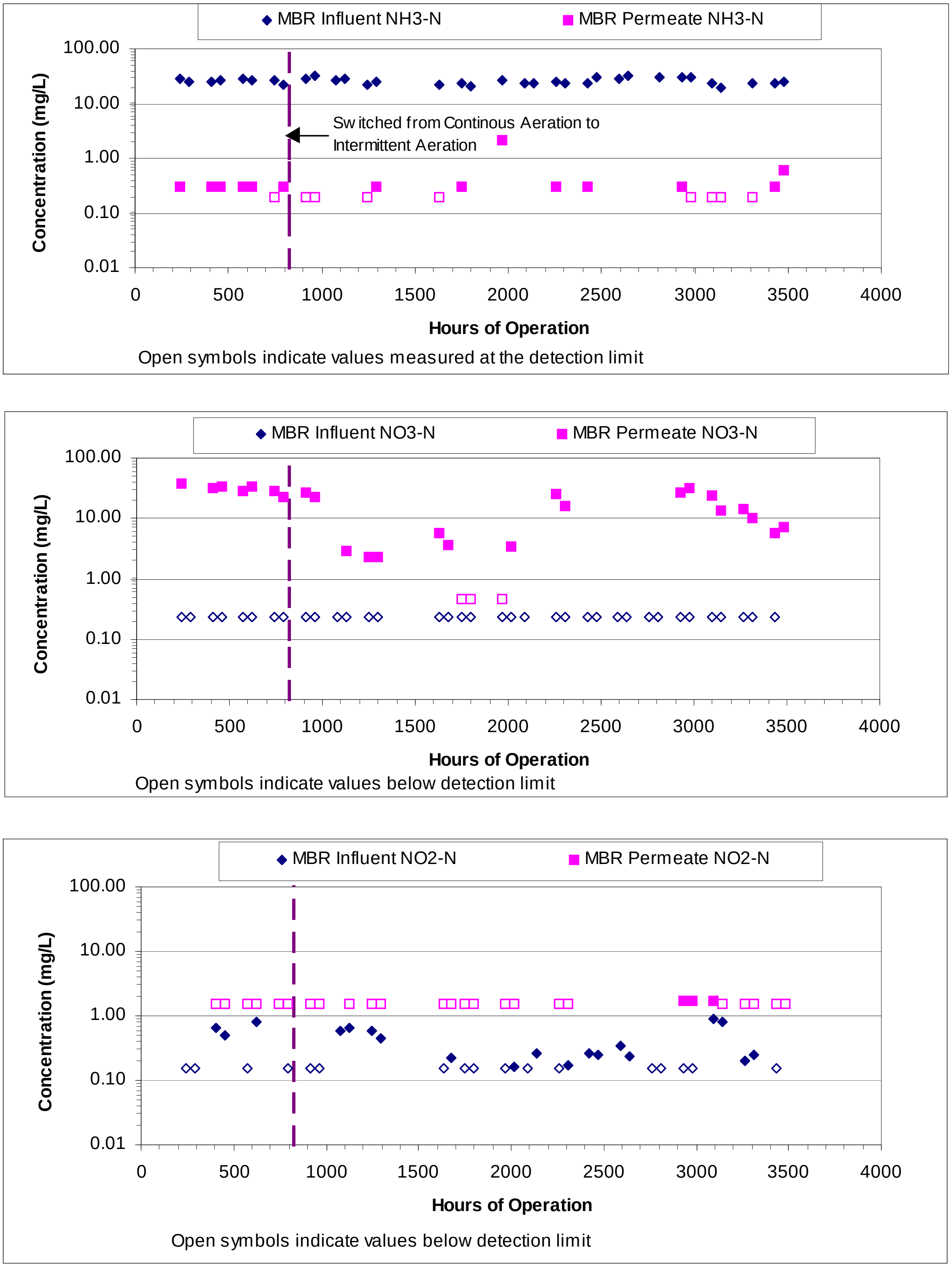
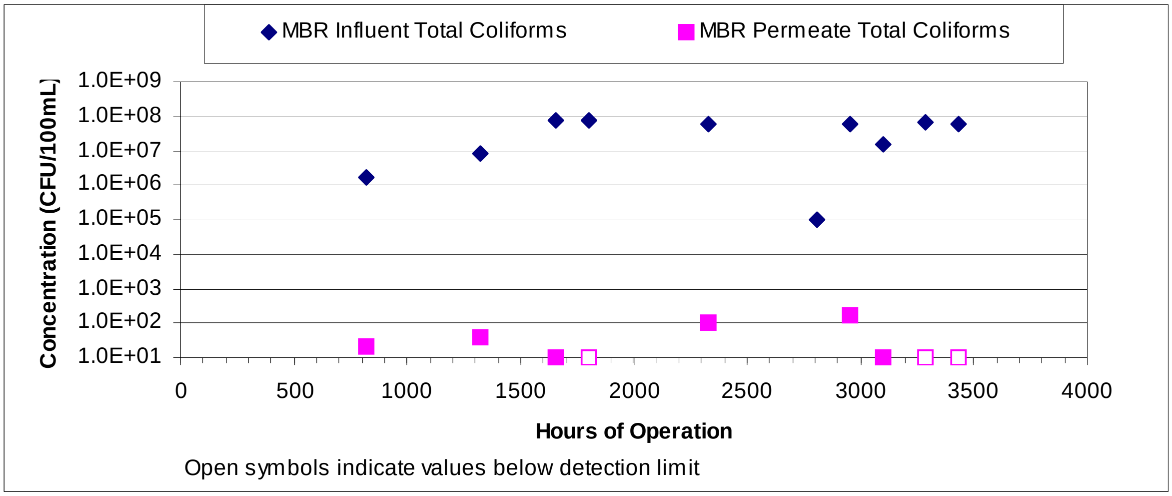
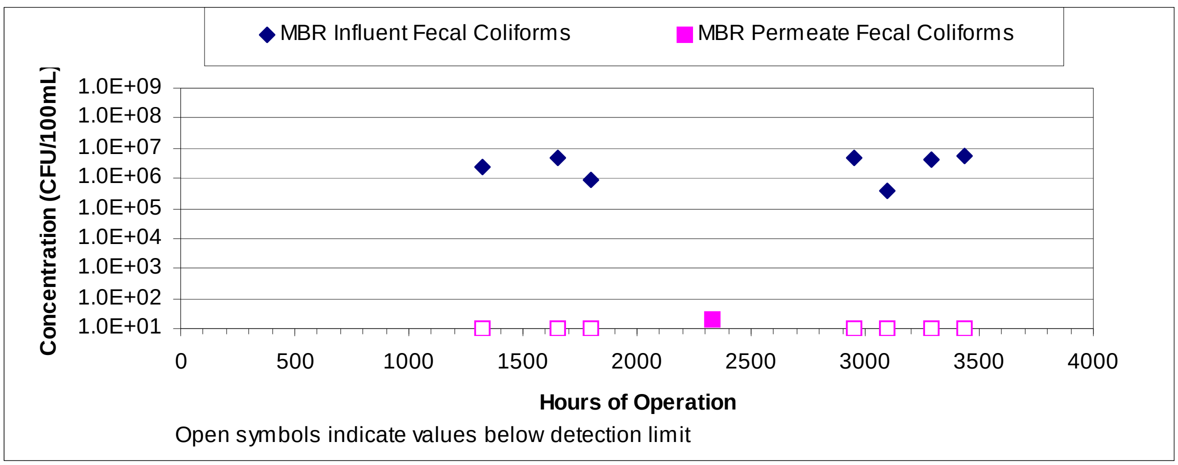


Figure 5-32. Inorganic Nitrogen Removal by Huber® MBR.





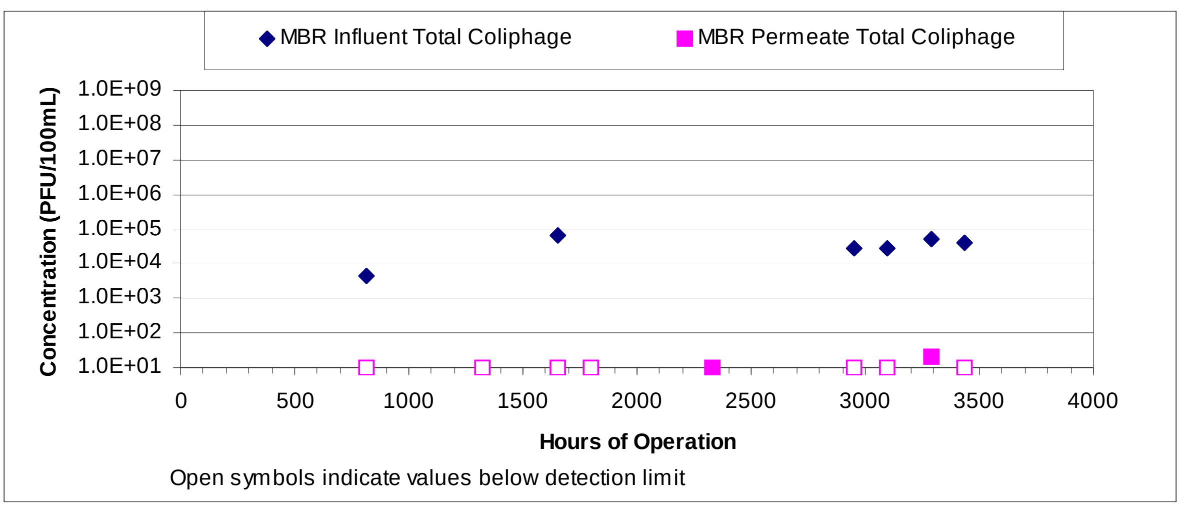


Figure 5-33. Microbial Rejection by Huber® MBR.

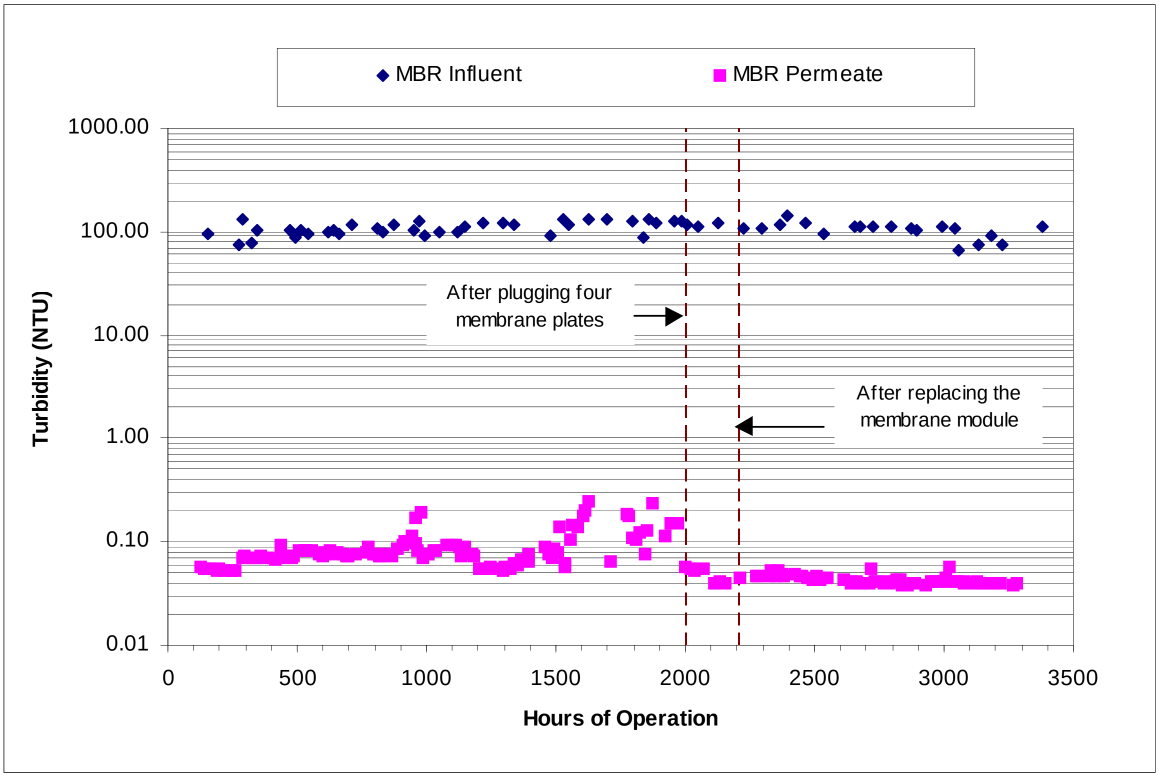


Figure 5-34. Particulate Removal by Kruger Neosep™ MBR.

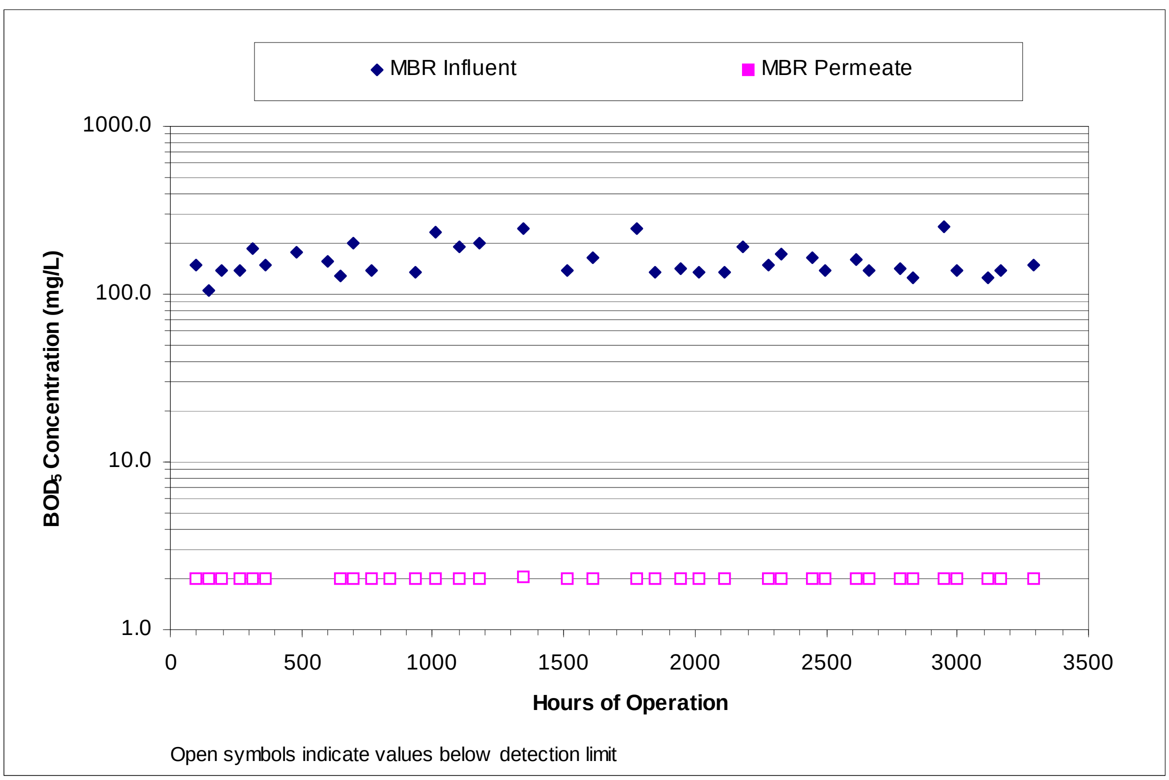


Figure 5-35. Organics Removal by Kruger Neosep™ MBR.

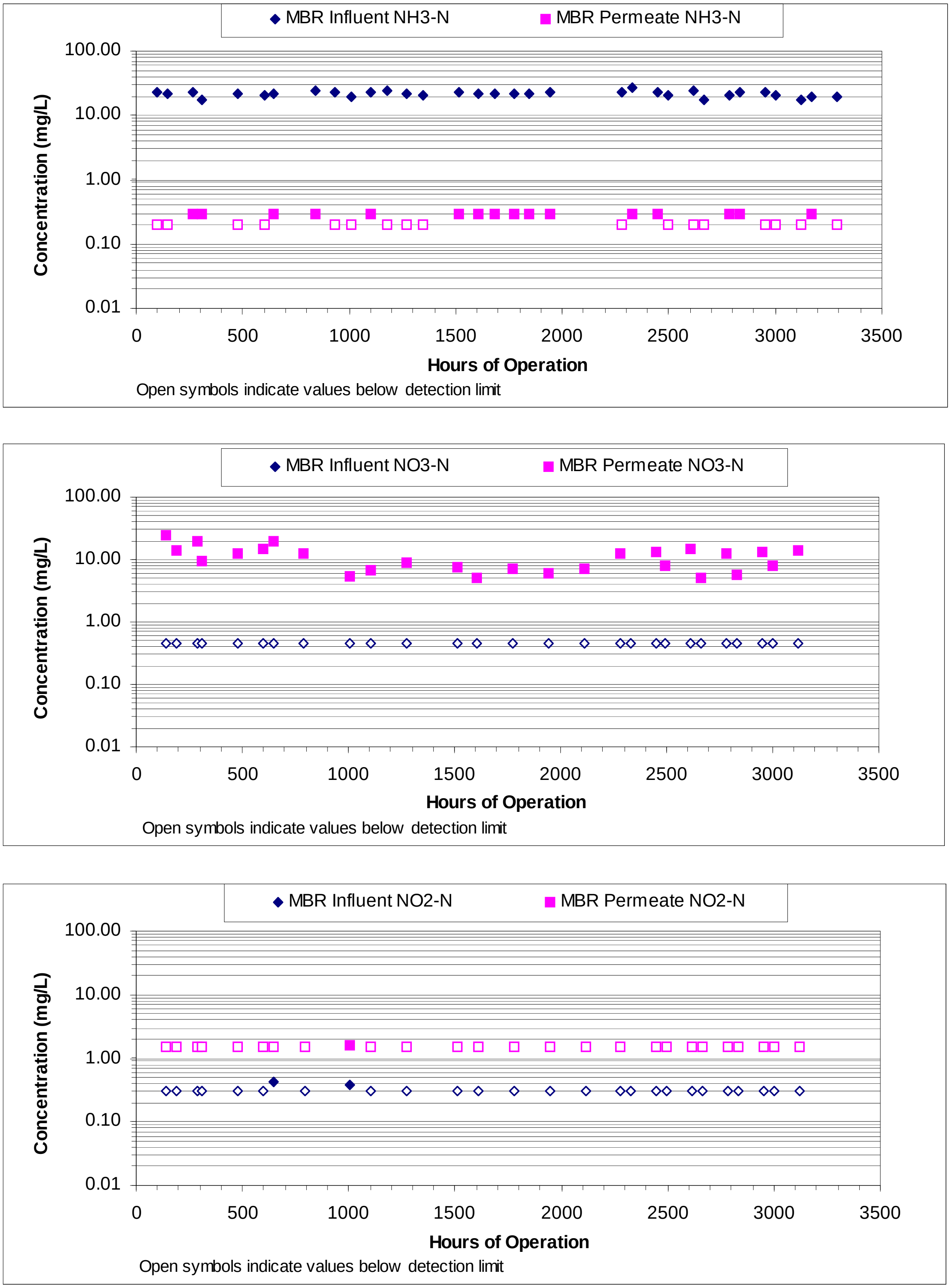
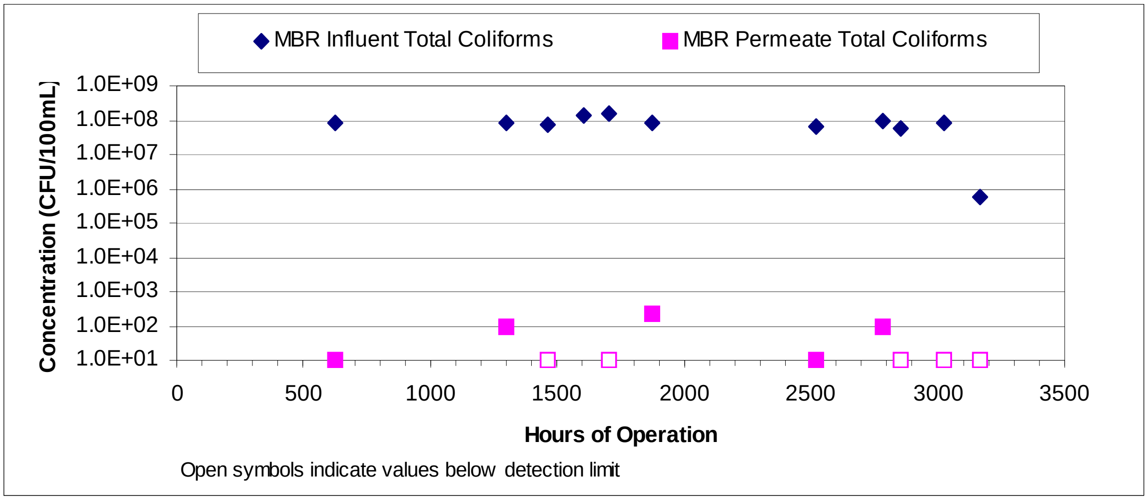
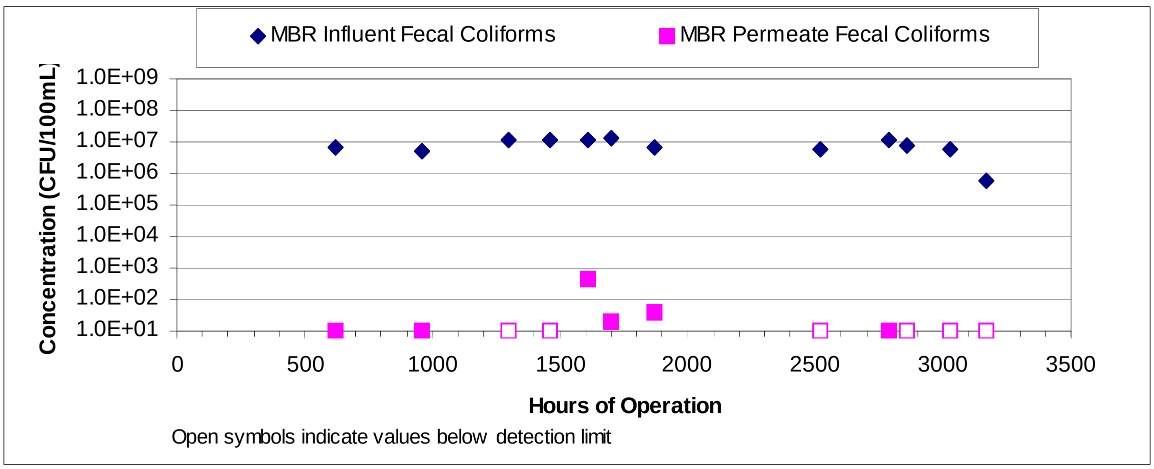


Figure 5-36. Inorganic Nitrogen Removal by Kruger Neosep™ MBR.





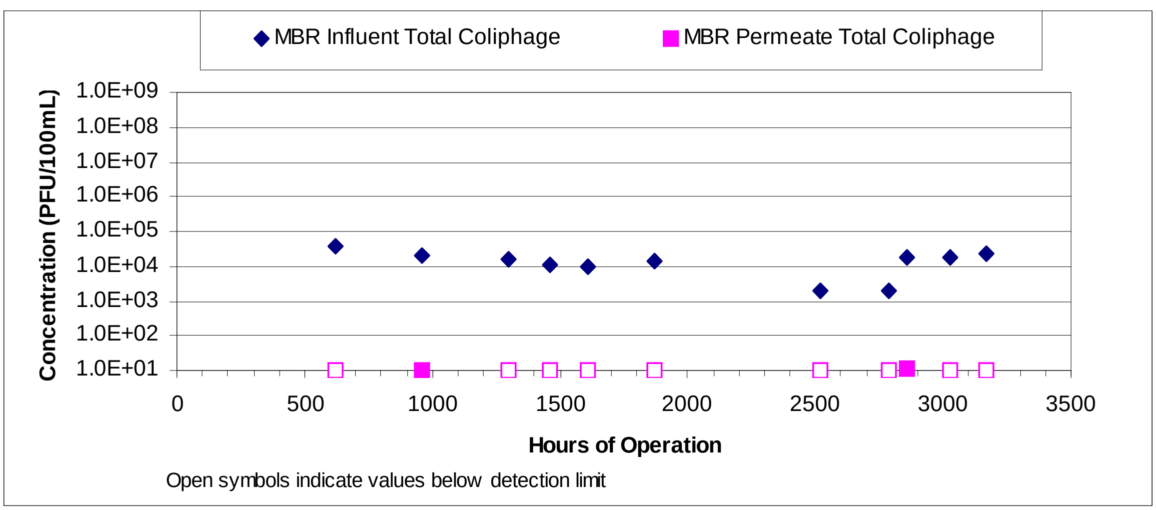


Figure 5-37. Microbial Rejection by Kruger Neosep™ MBR.

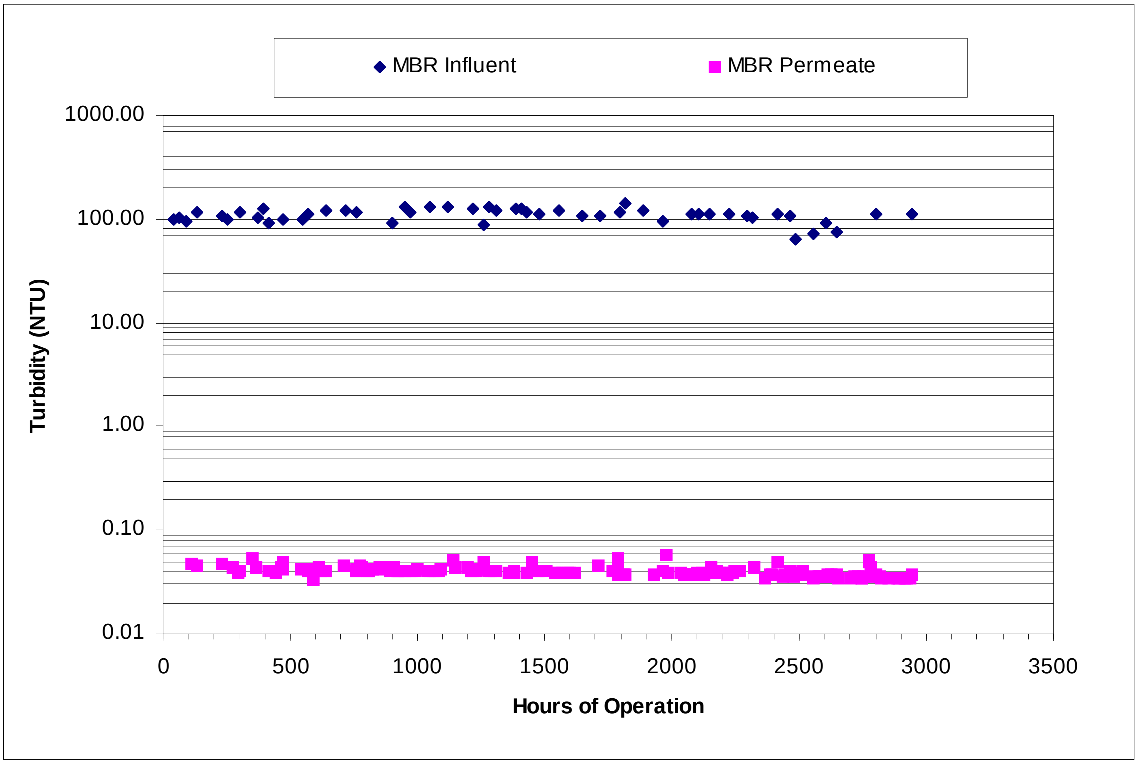


Figure 5-38. Particulate Removal by DynaLift™ MBR.

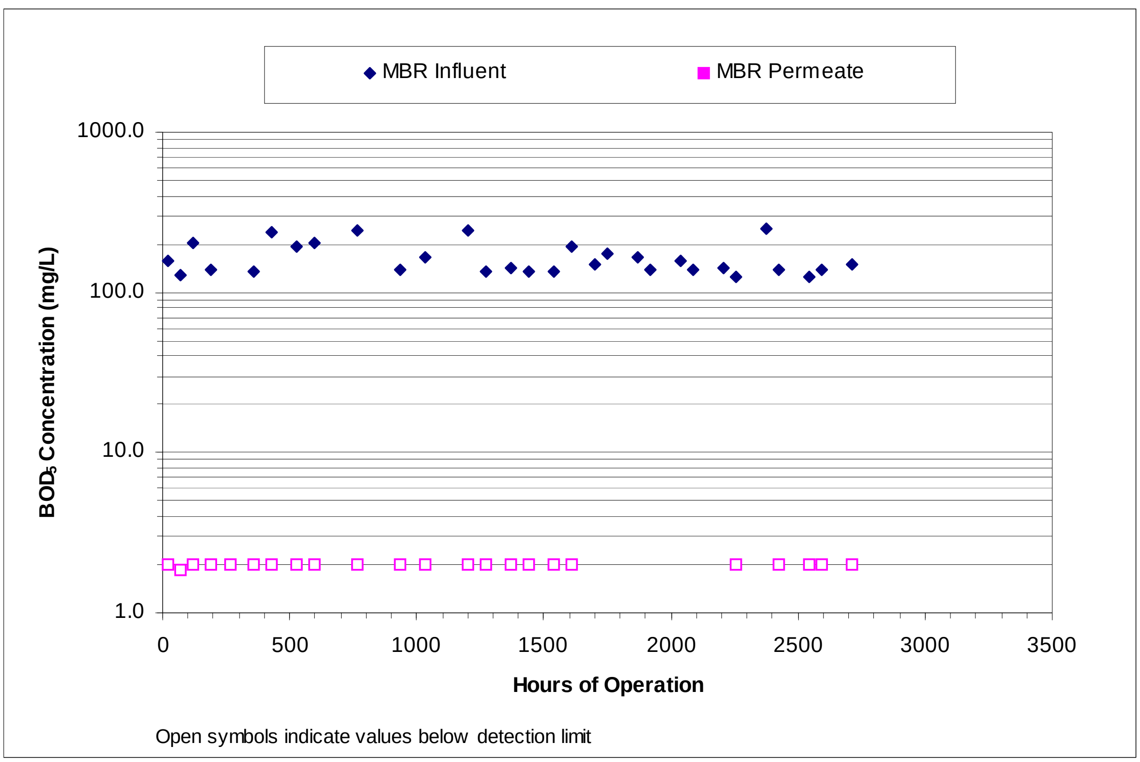


Figure 5-39. Organics Removal by DynaLift™ MBR.

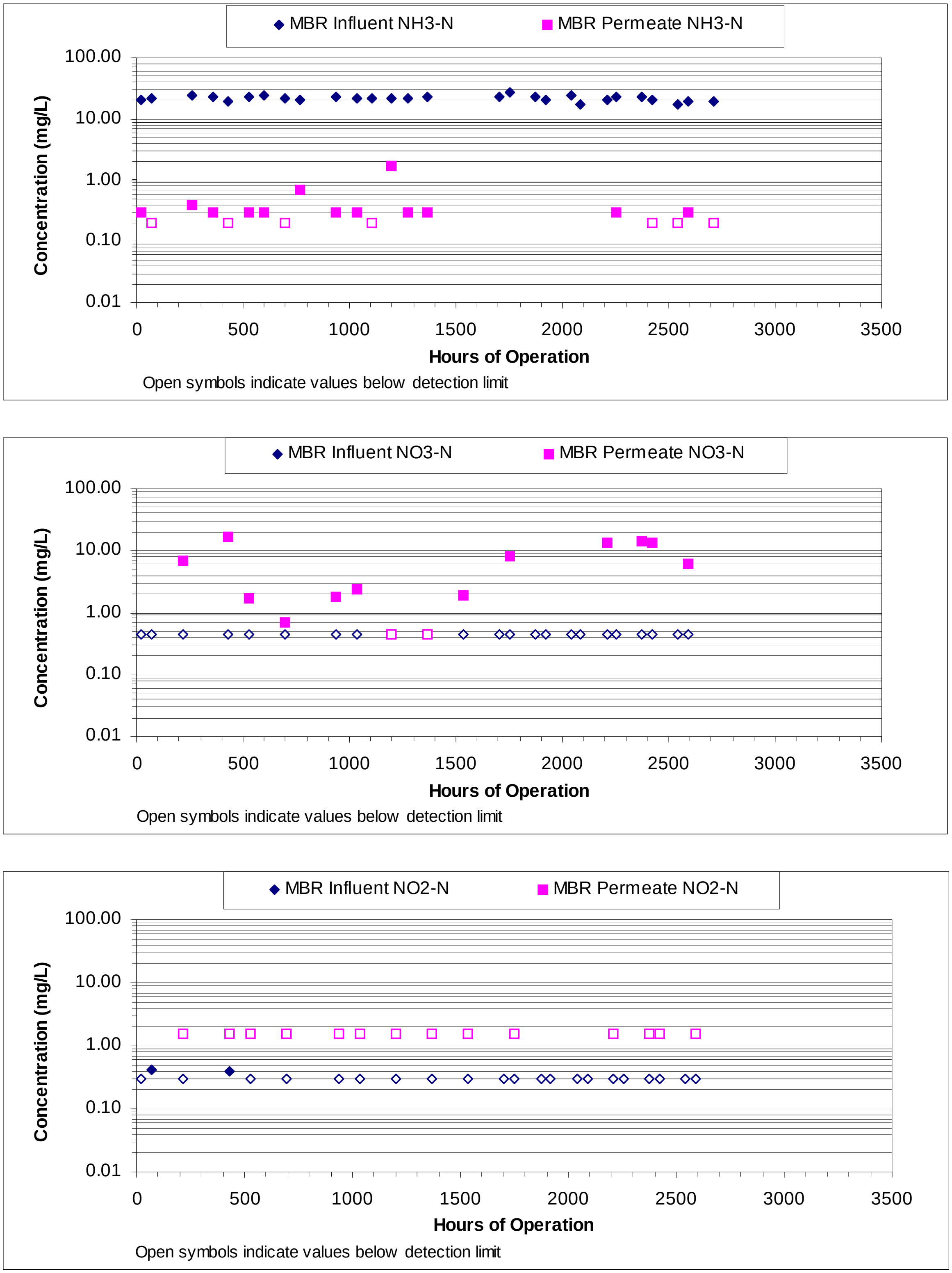


Figure 5-40. Inorganic Nitrogen Removal by DynaLift™ MBR.

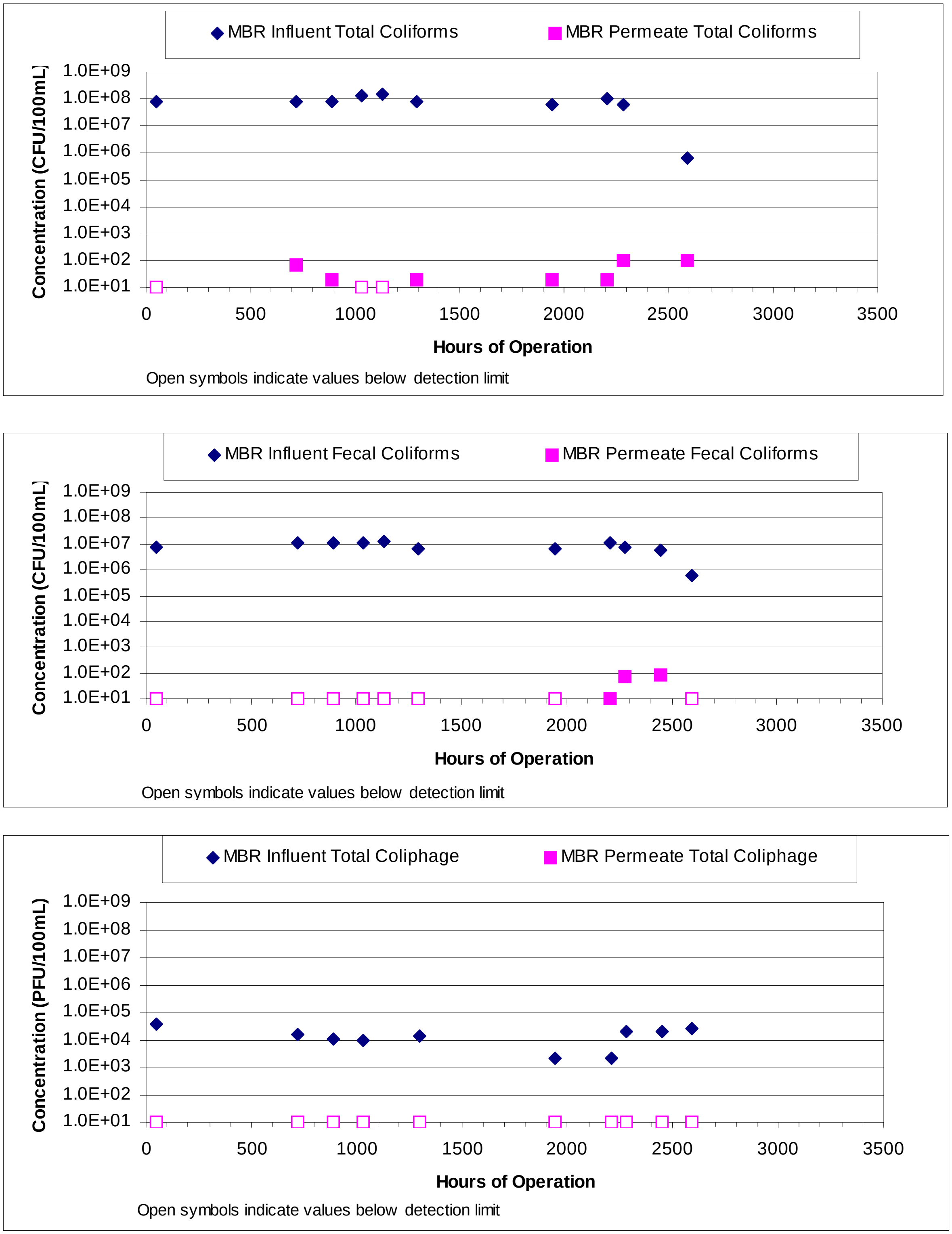


Figure 5-41. Microbial Rejection by DynaLift™ MBR.

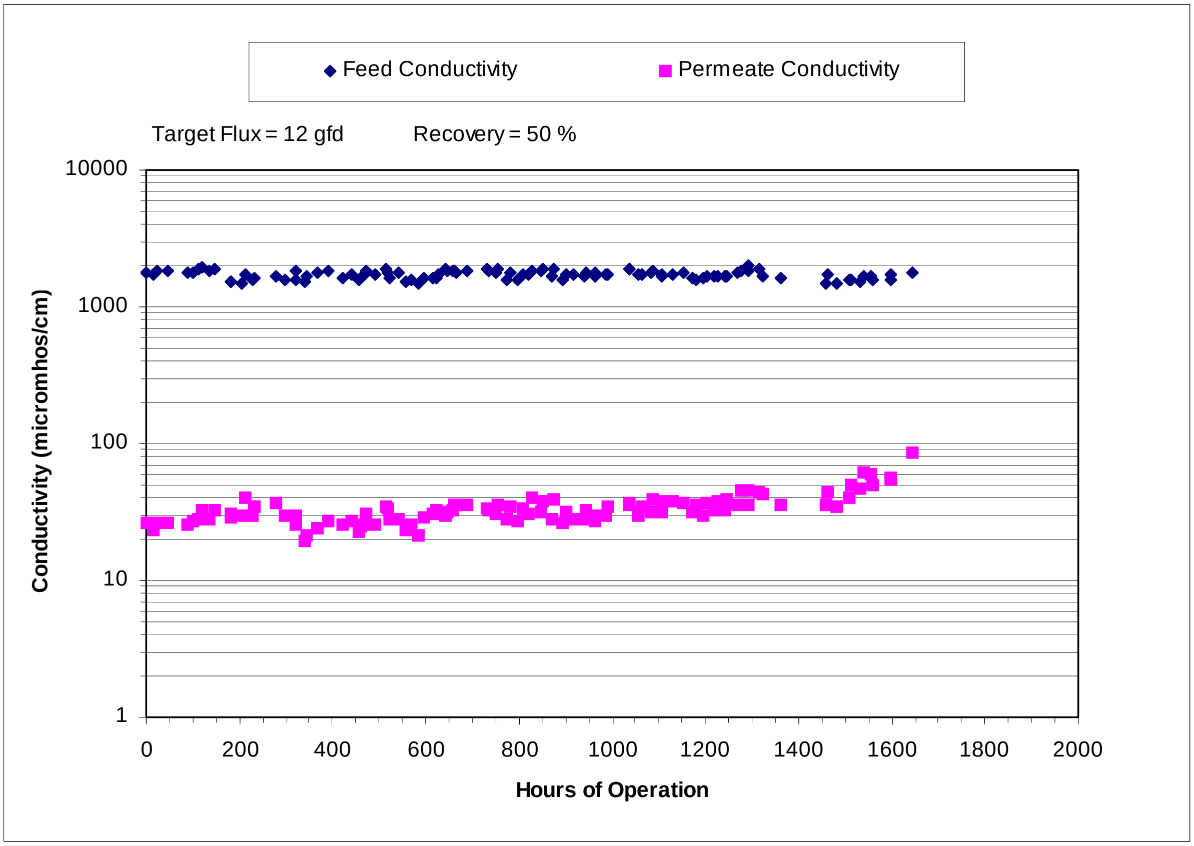
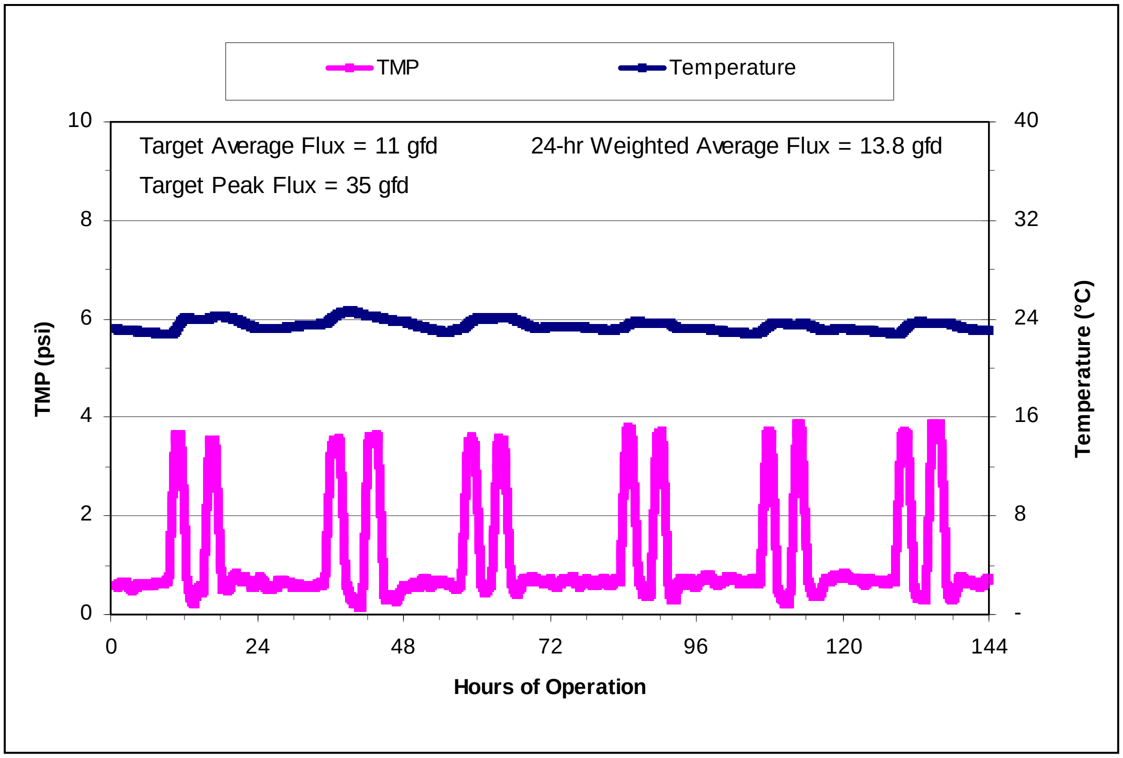


Figure 5-42. Conductivity Rejection by Koch 4040 HR RO Membrane.



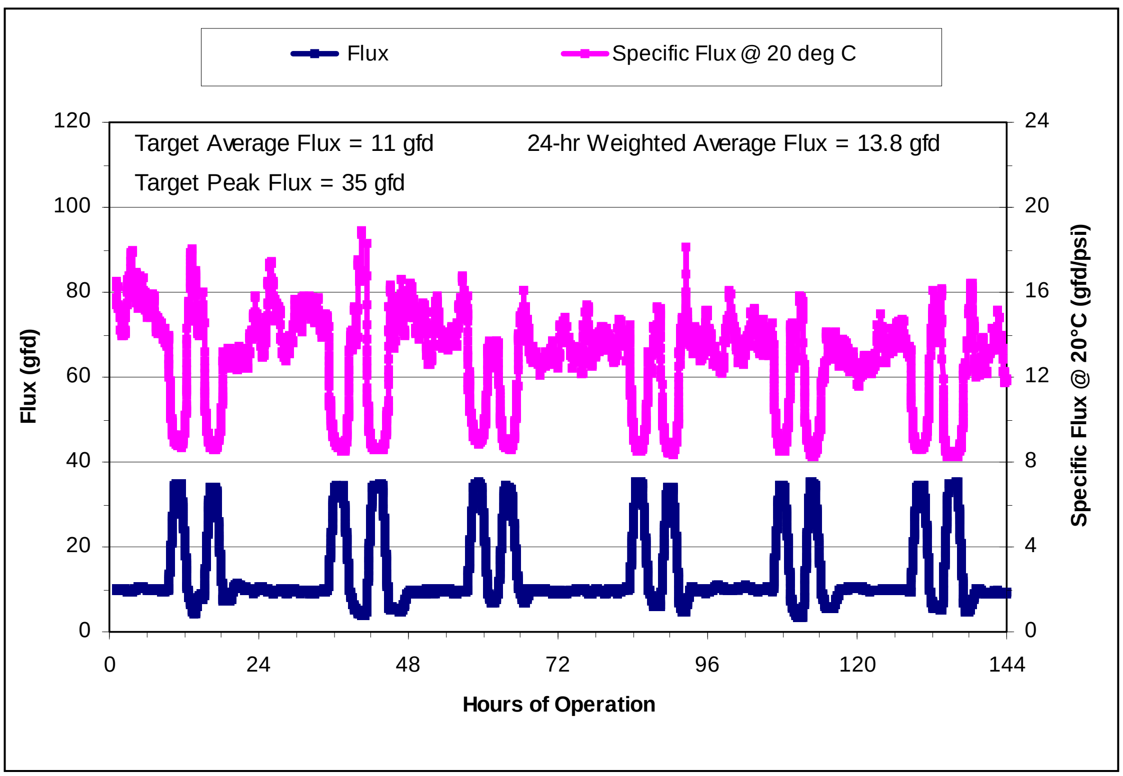
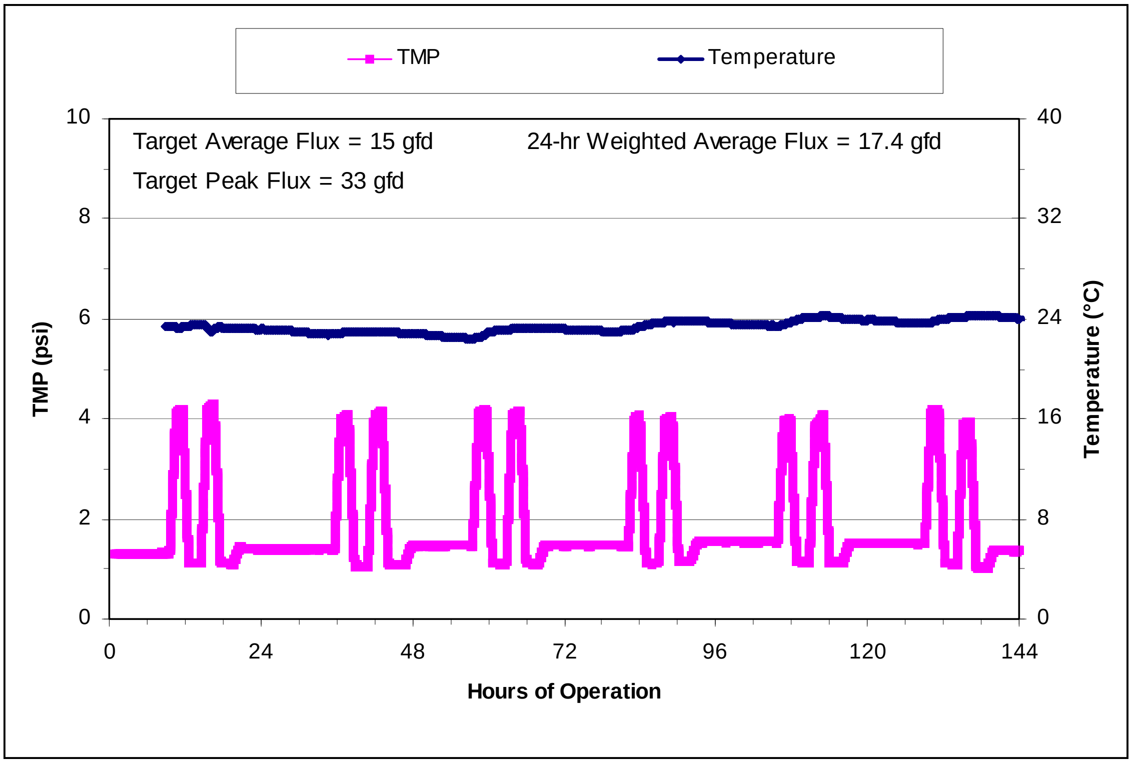


Figure 6-1. Membrane Performance of Puron™ MBR During Peaking Study.



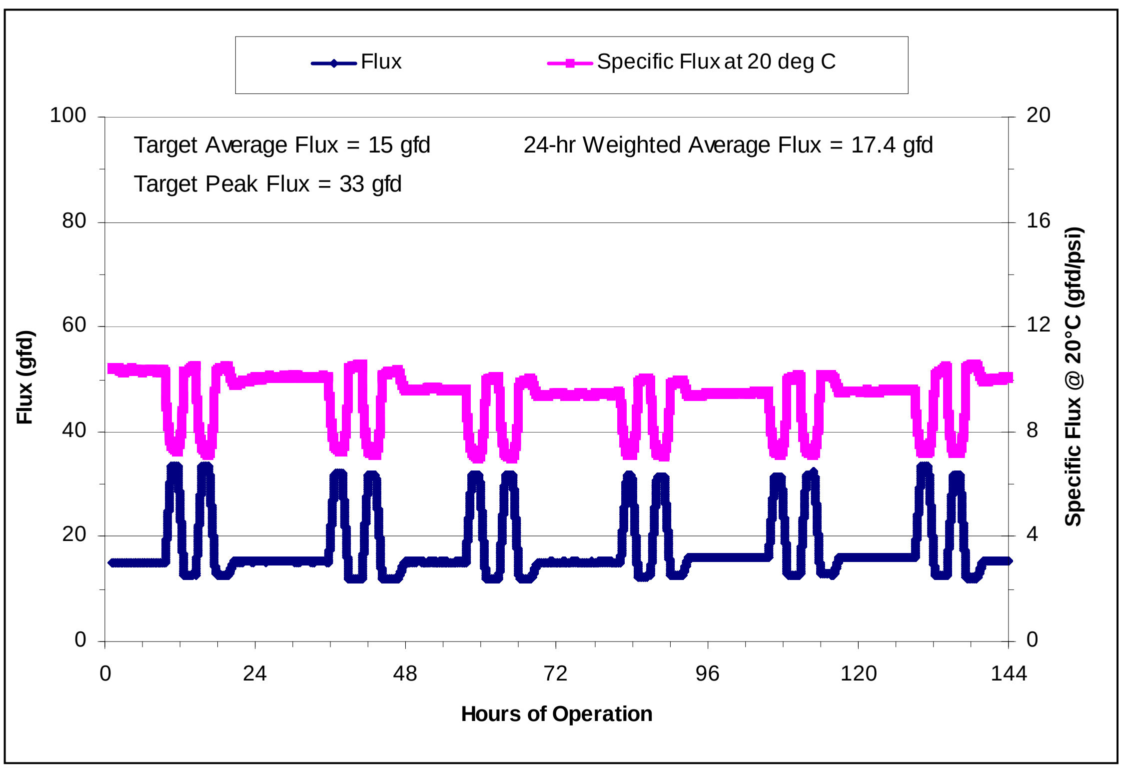
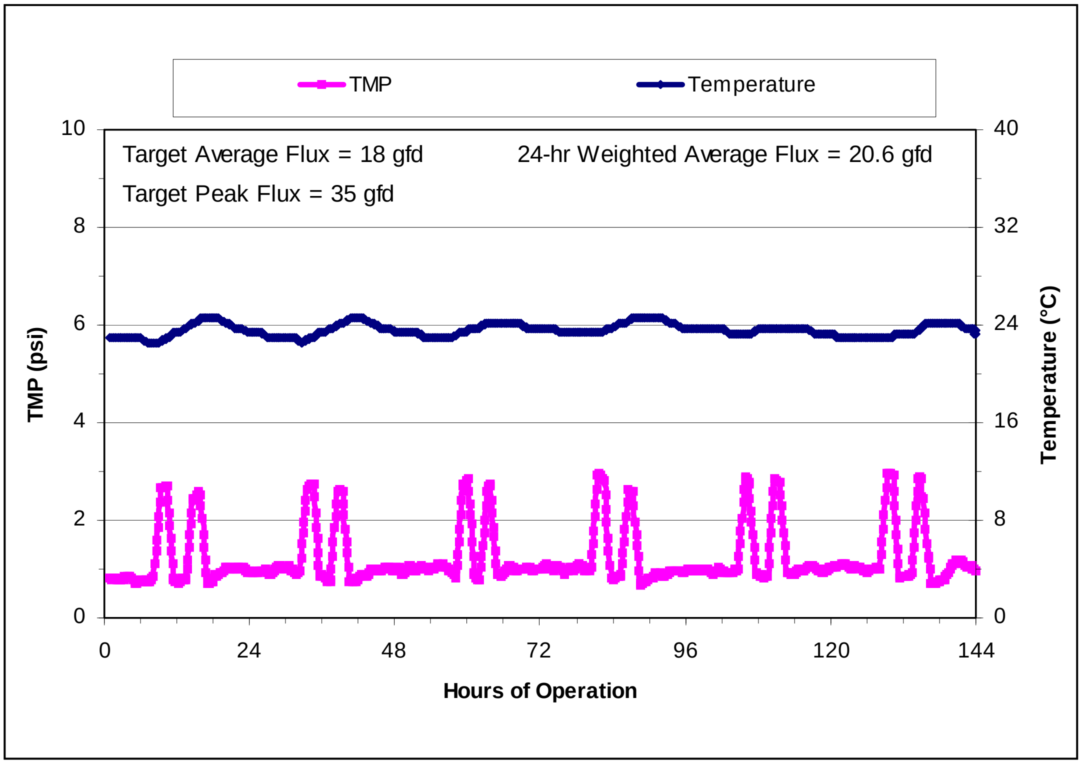


Figure 6-2. Membrane Performance of Huber® MBR During Peaking Study.



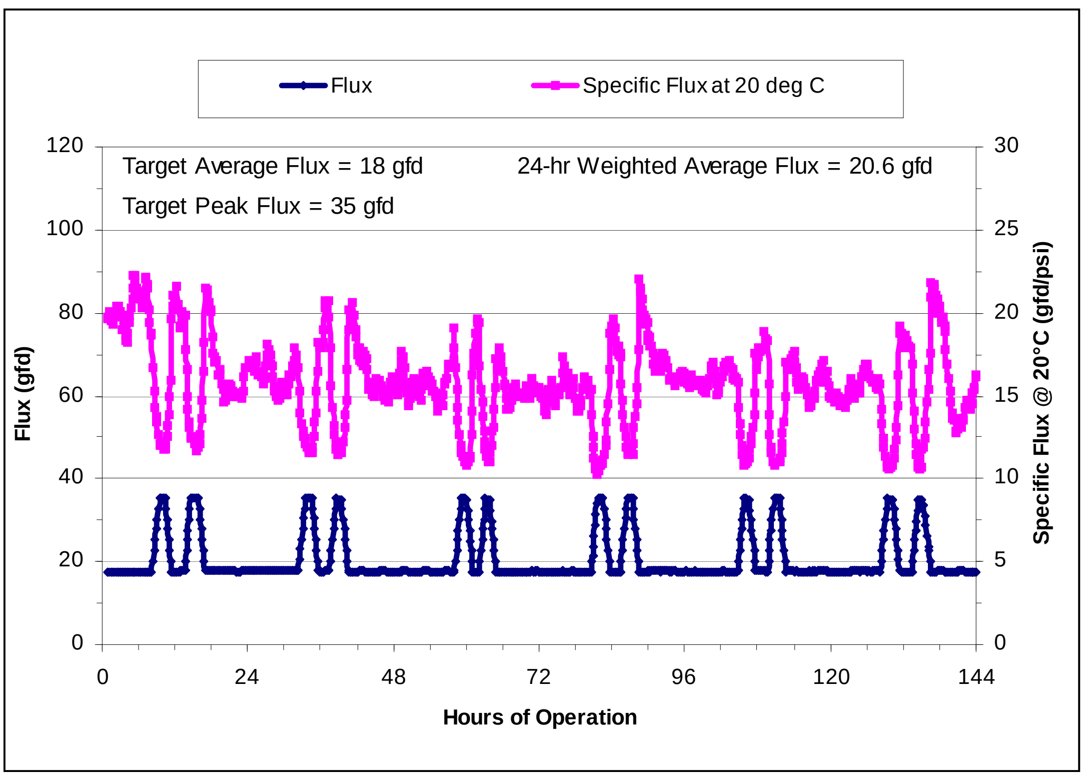
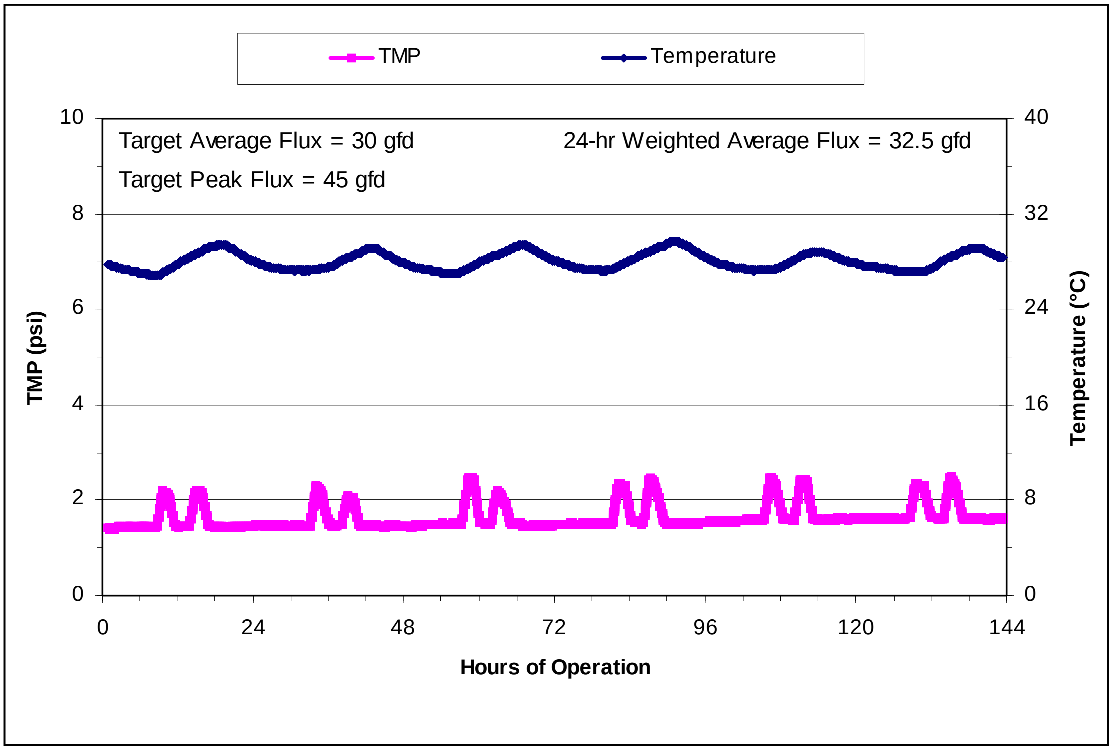


Figure 6-3. Membrane Performance of Kruger Neosep™ MBR During Peaking Study.



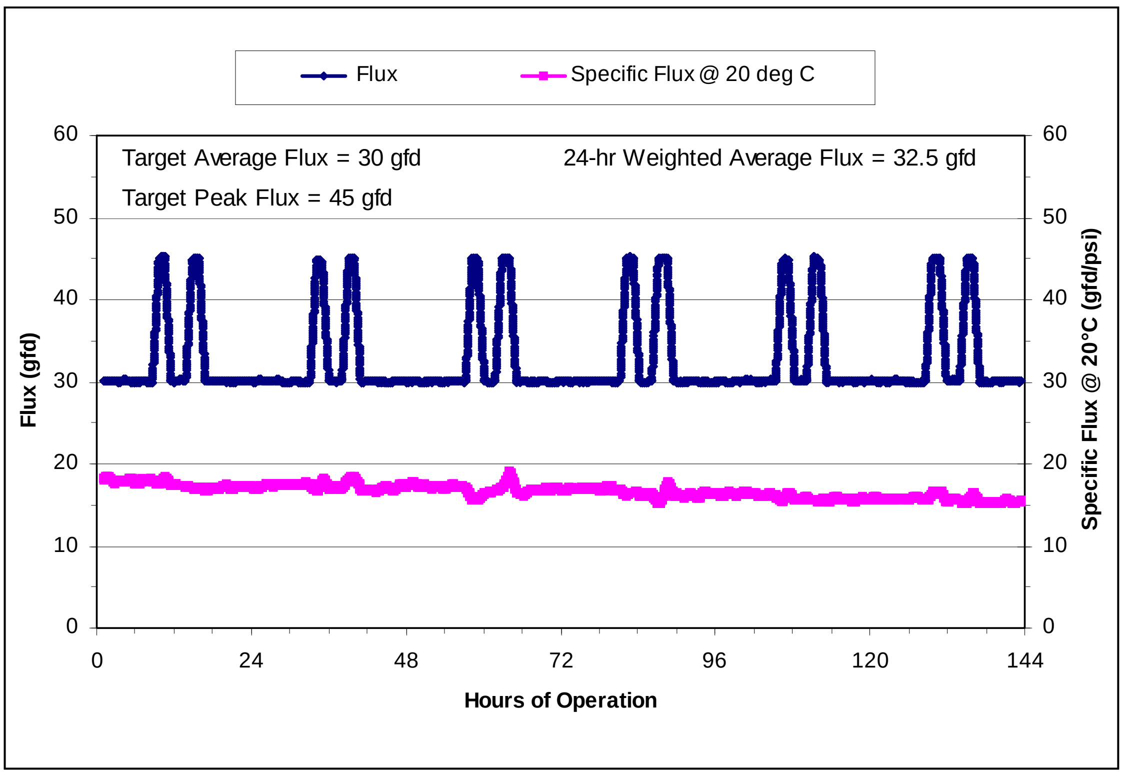


Figure 6-4. Membrane Performance of DynaLift™ MBR During Peaking Study.

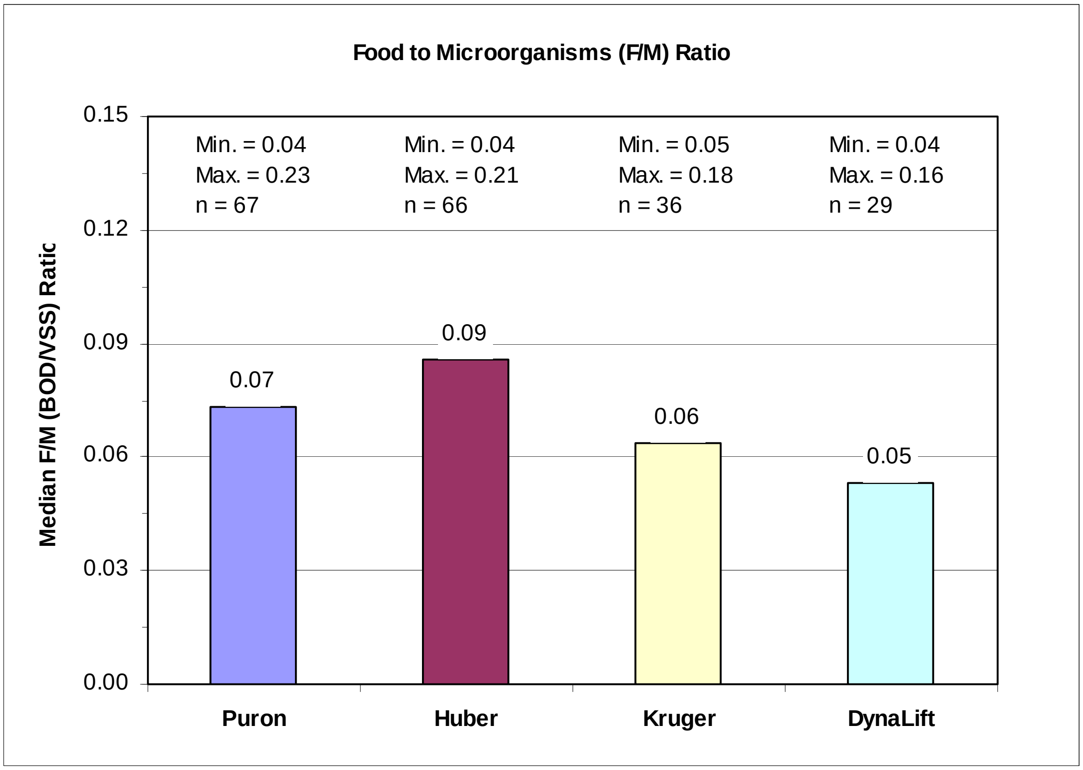


Figure 7-1. Food to Microorganism (F/M) Ratios for MBR Systems.

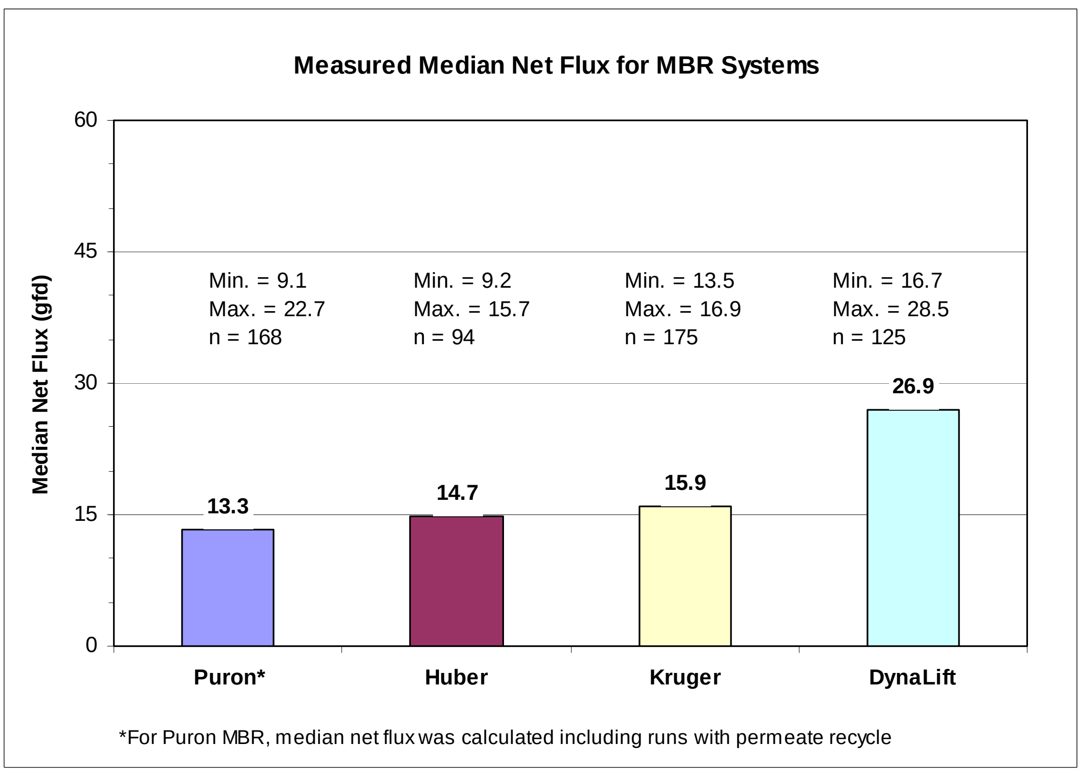


Figure 7-2. Measured Median Net Flux for MBR Systems.

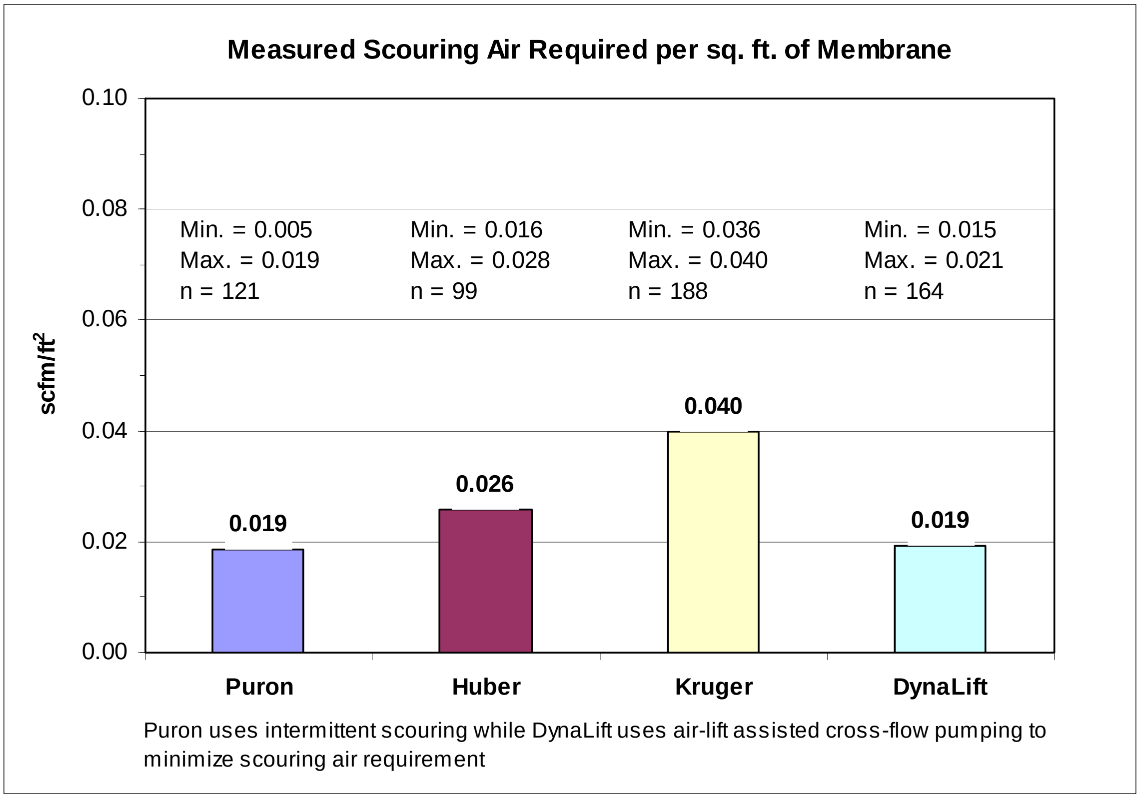


Figure 7-3. Measured Scouring Air Required per sq. ft. of Membrane for MBR Systems.

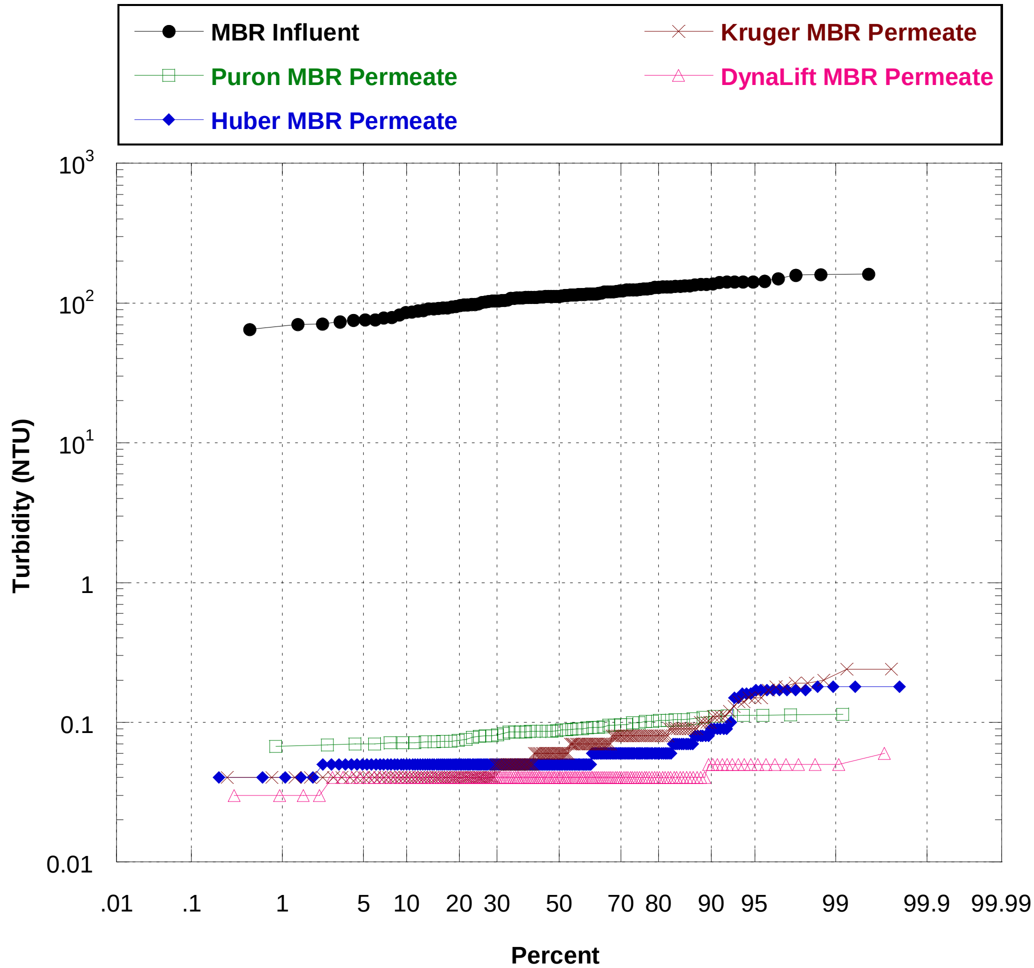


Figure 7-4. Probability Plot of Particulate Removal by MBR Systems.

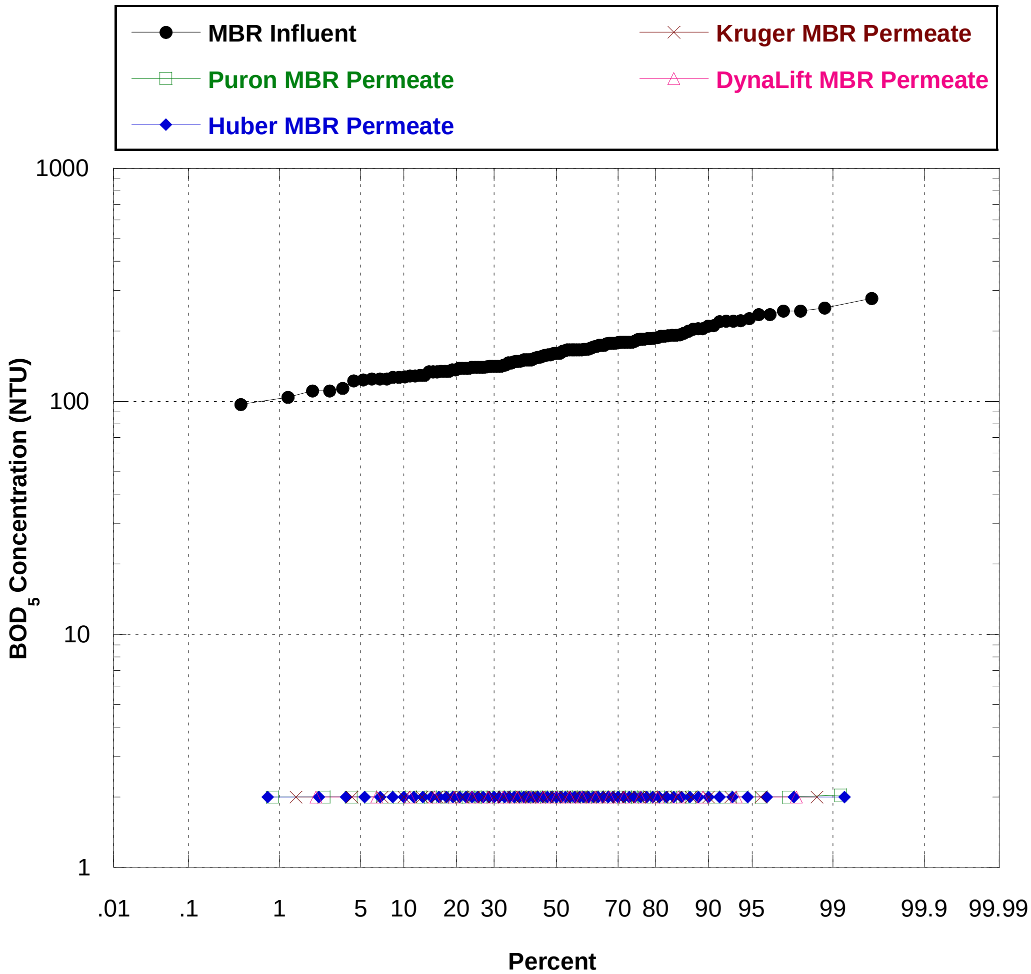


Figure 7-5. Probability Plot of Organics Removal by MBR Systems.

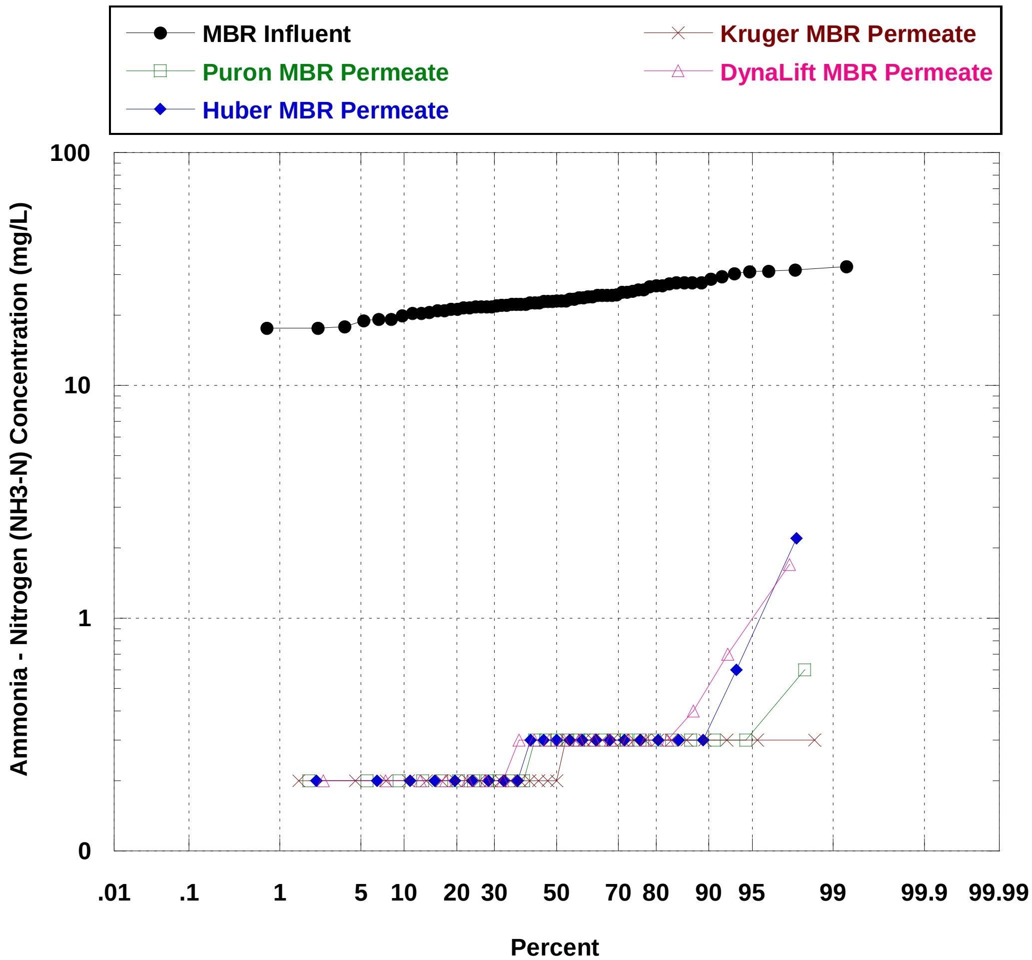


Figure 7-6. Probability Plot of Ammonia-Nitrogen Removal by MBR Systems.

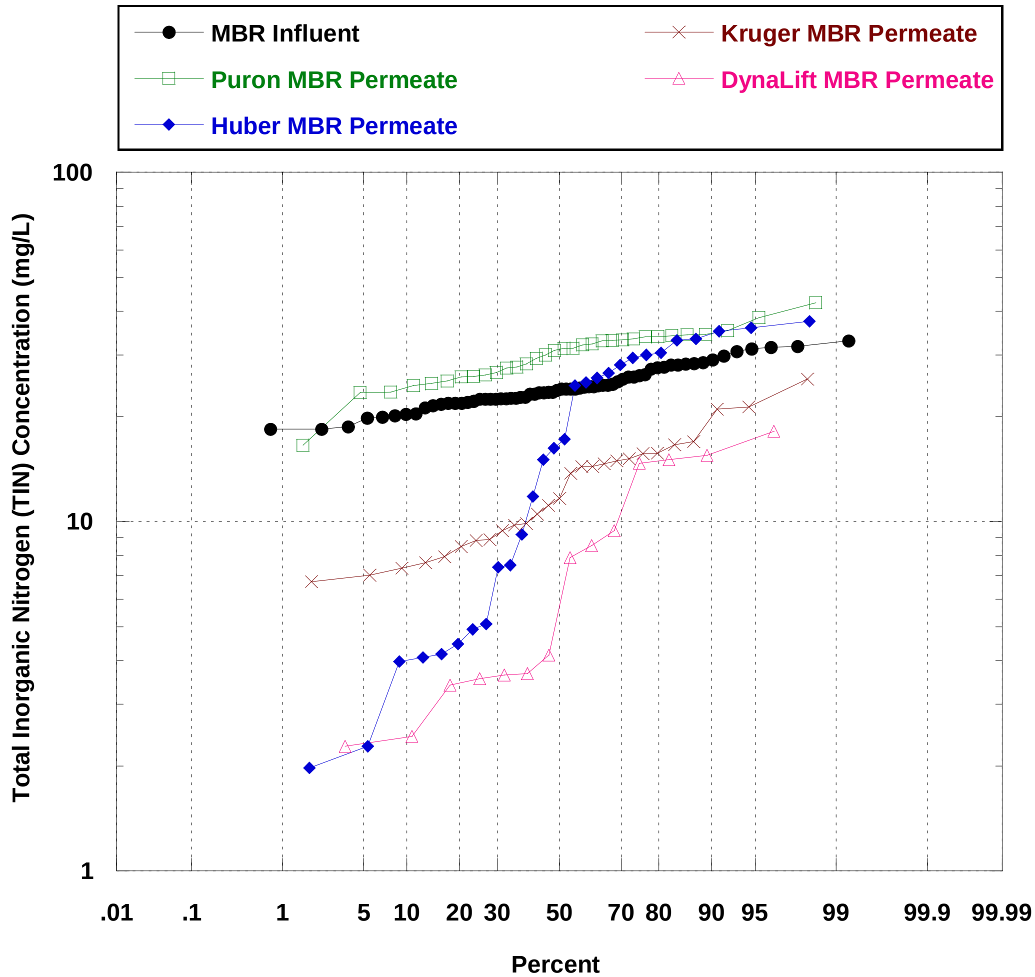


Figure 7-7. Probability Plot of Total Inorganic Nitrogen Removal by MBR Systems.

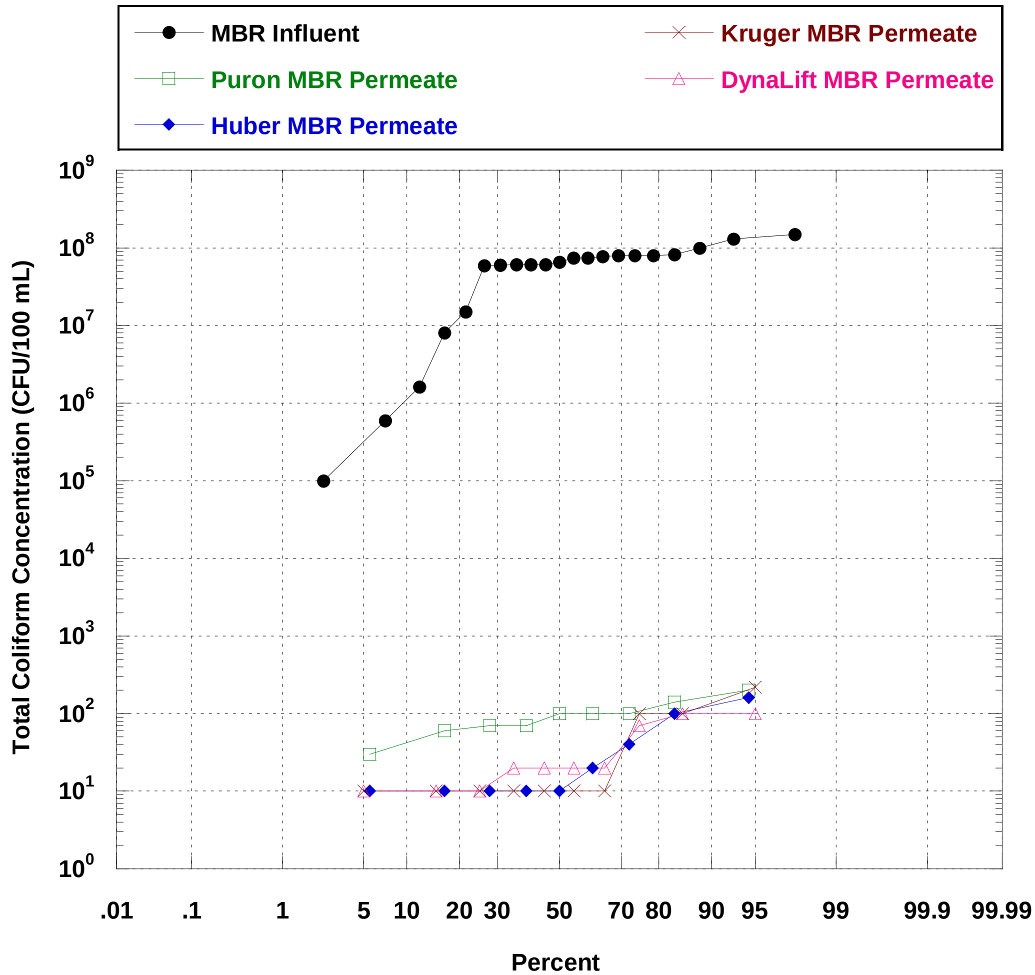


Figure 7-8. Probability Plot of Total Coliform Concentrations for MBR Systems.

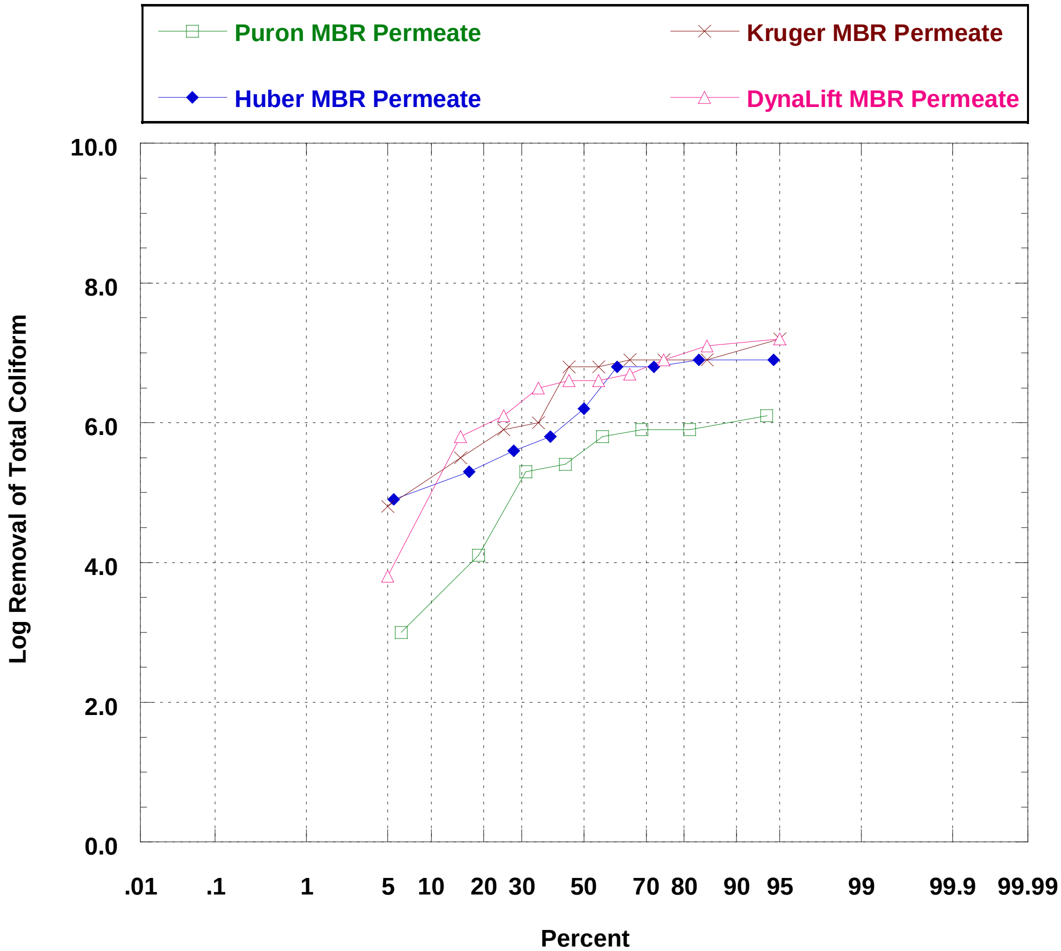


Figure 7-9. Probability Plot of Log Removal of Total Coliforms by MBR Systems.

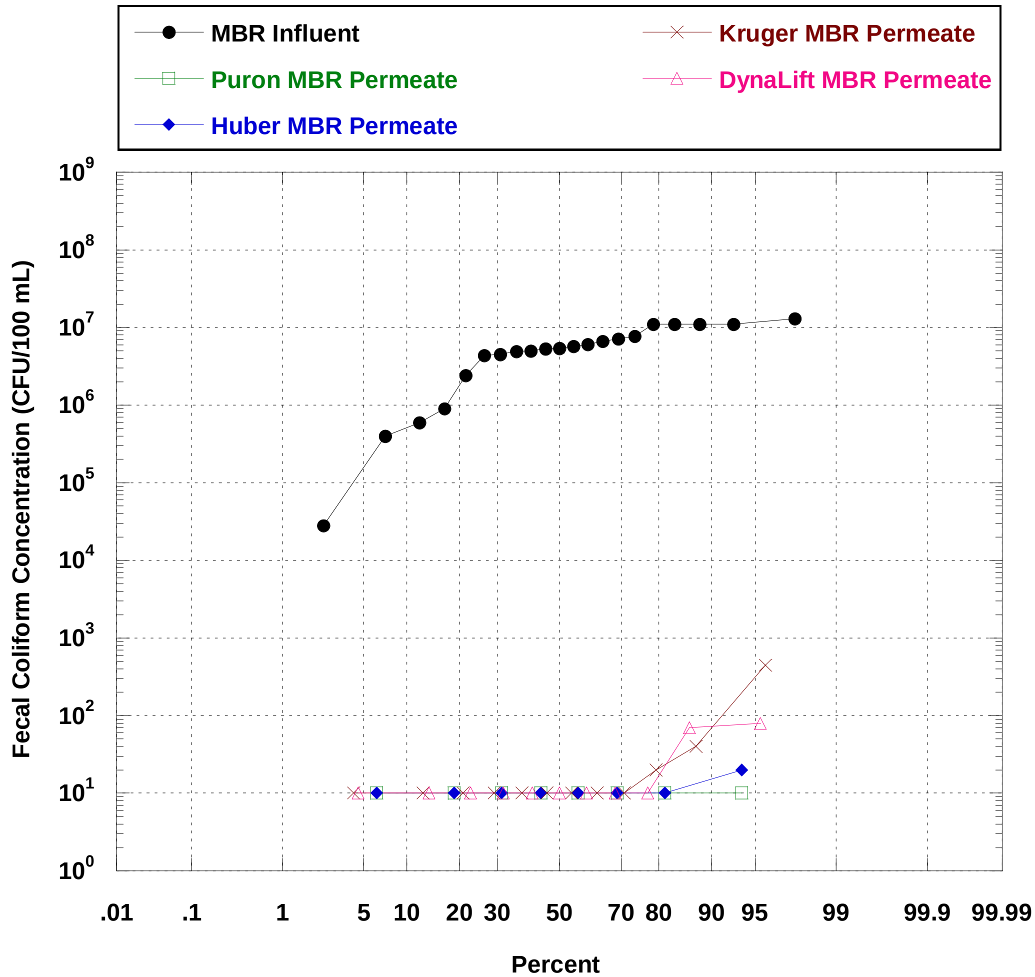


Figure 7-10. Probability Plot of Fecal Coliform Concentrations for MBR Systems.

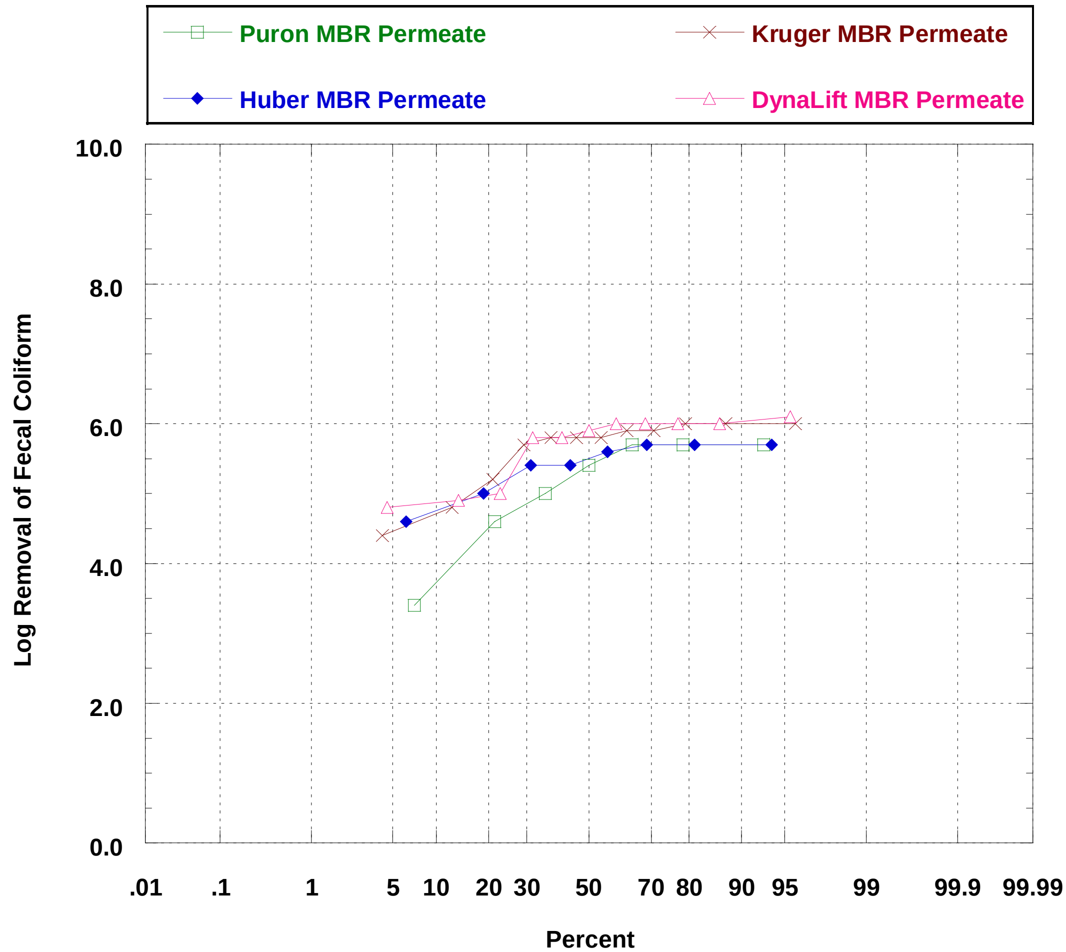


Figure 7-11. Probability Plot of Log Removal of Fecal Coliform by MBR Systems.

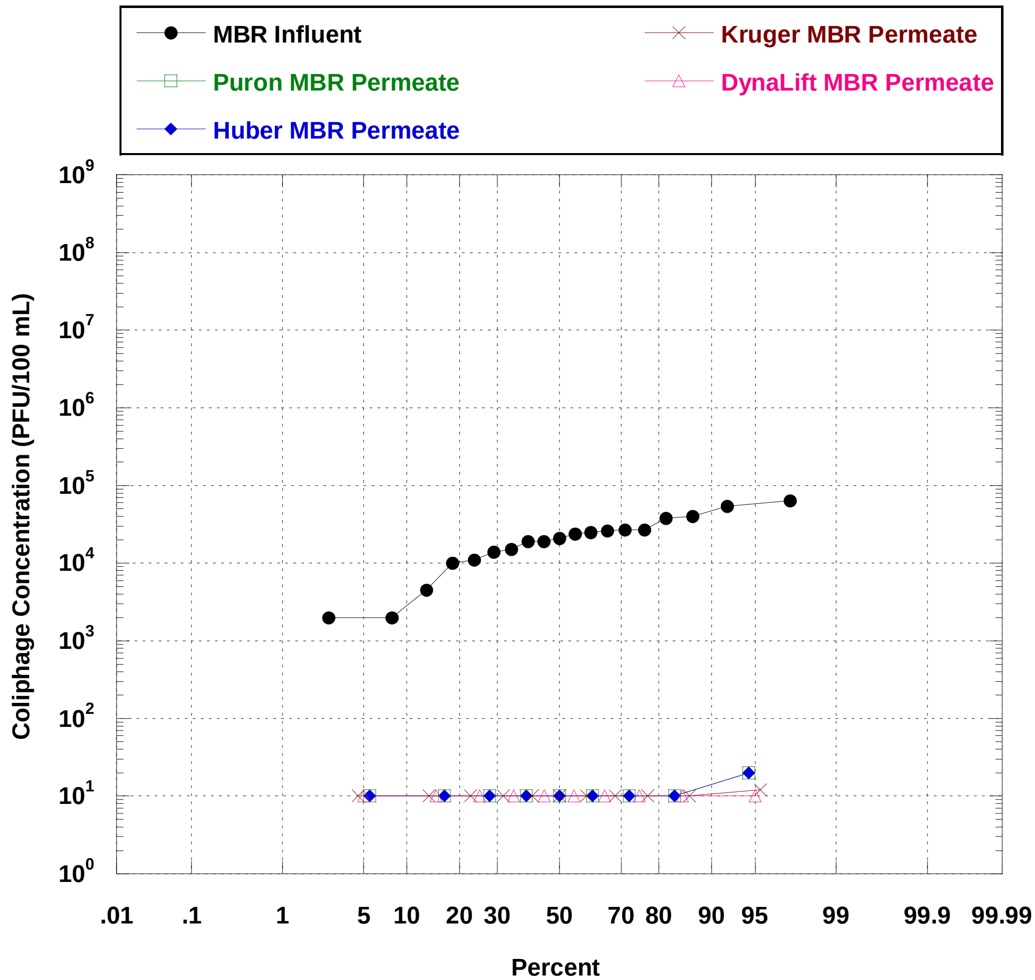


Figure 7-12. Probability Plot of Coliphage Concentrations for MBR Systems.

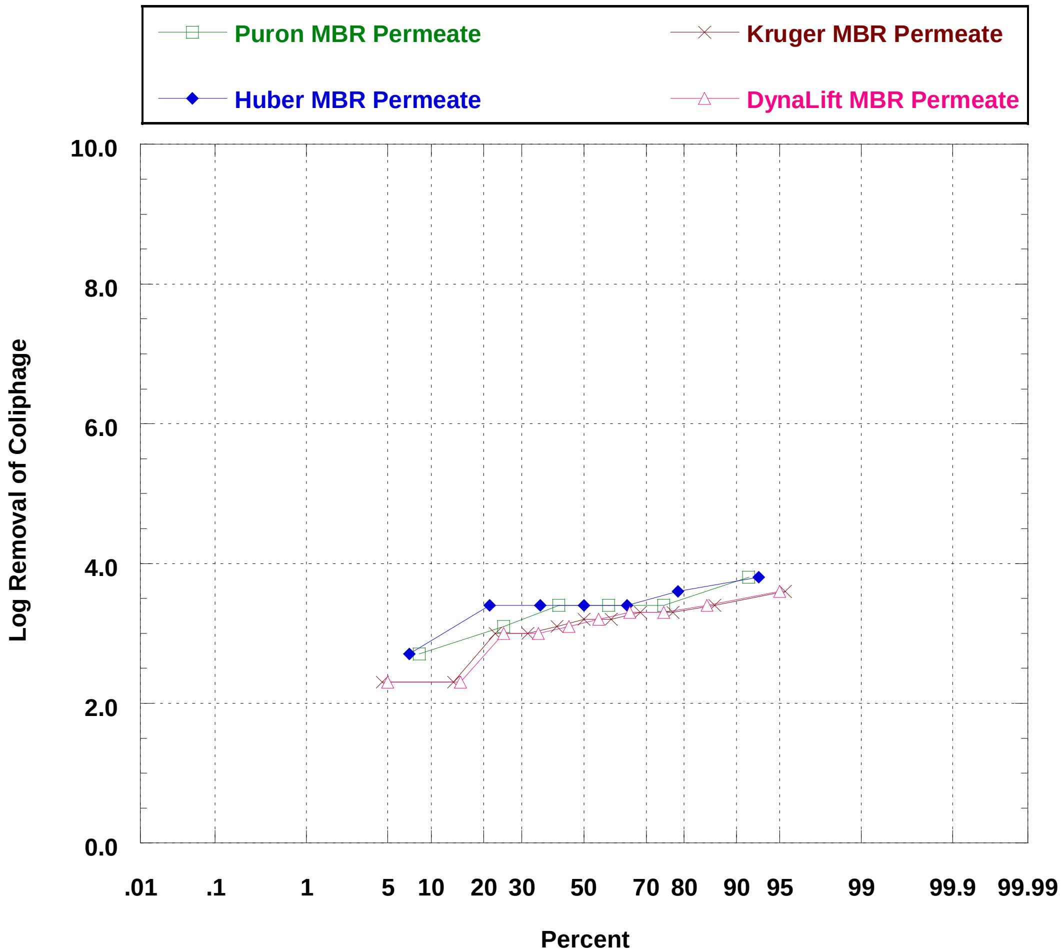


Figure 7-13. Probability Plot of Log Removal of Coliphage by MBR Systems.

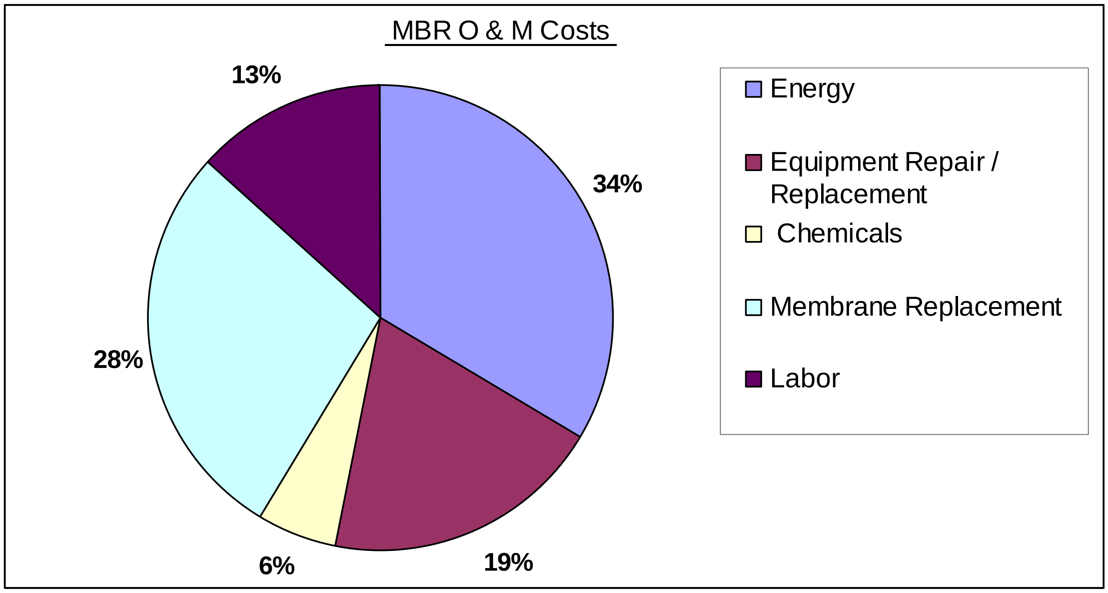


Figure 9-1. Breakdown for O&M Costs for 1-MGD MBR System.

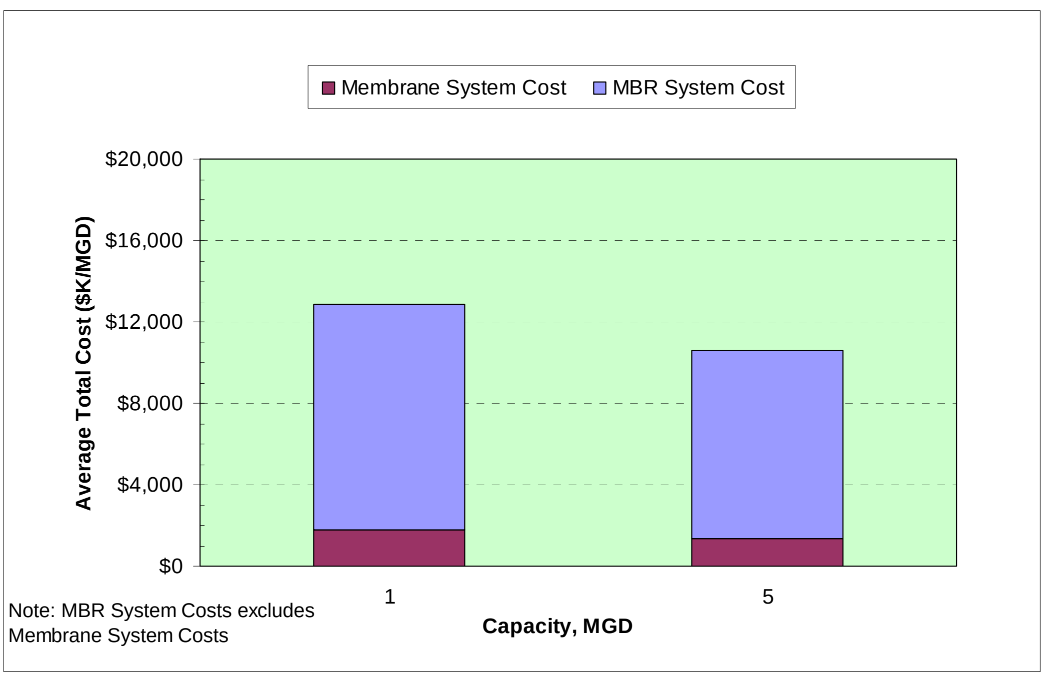


Figure 9-2. Economy of Scale: 1 & 5-MGD Capacity MBR Systems.

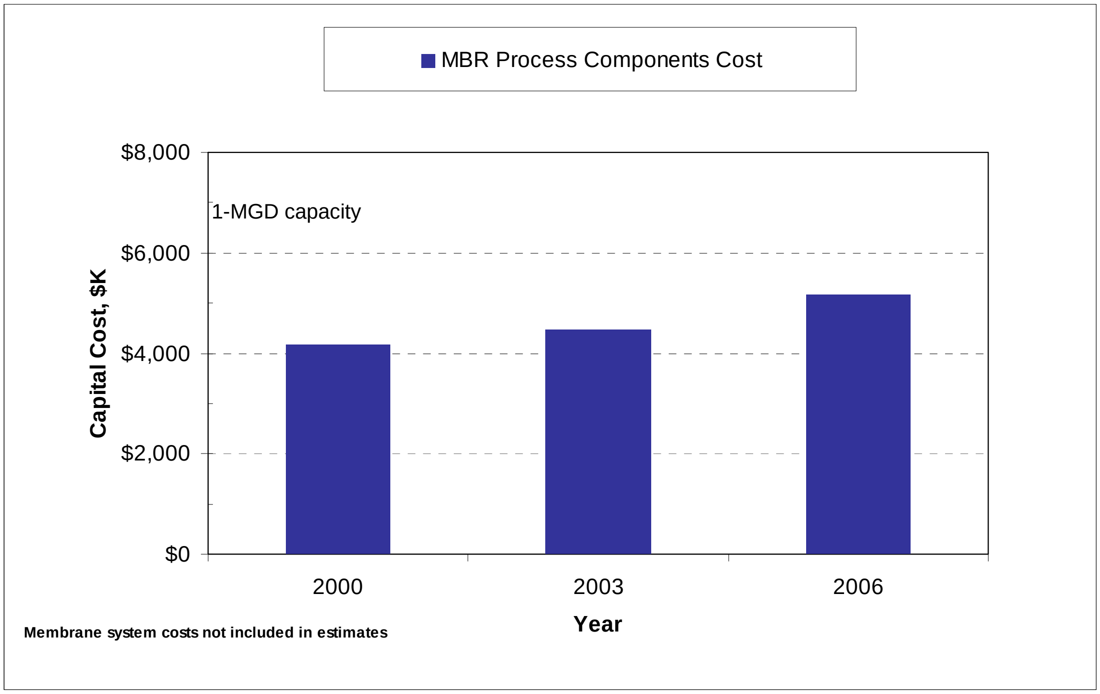


Figure 9-3. Capital Cost Estimates of 1-MGD MBR Process Components (2000-2006).

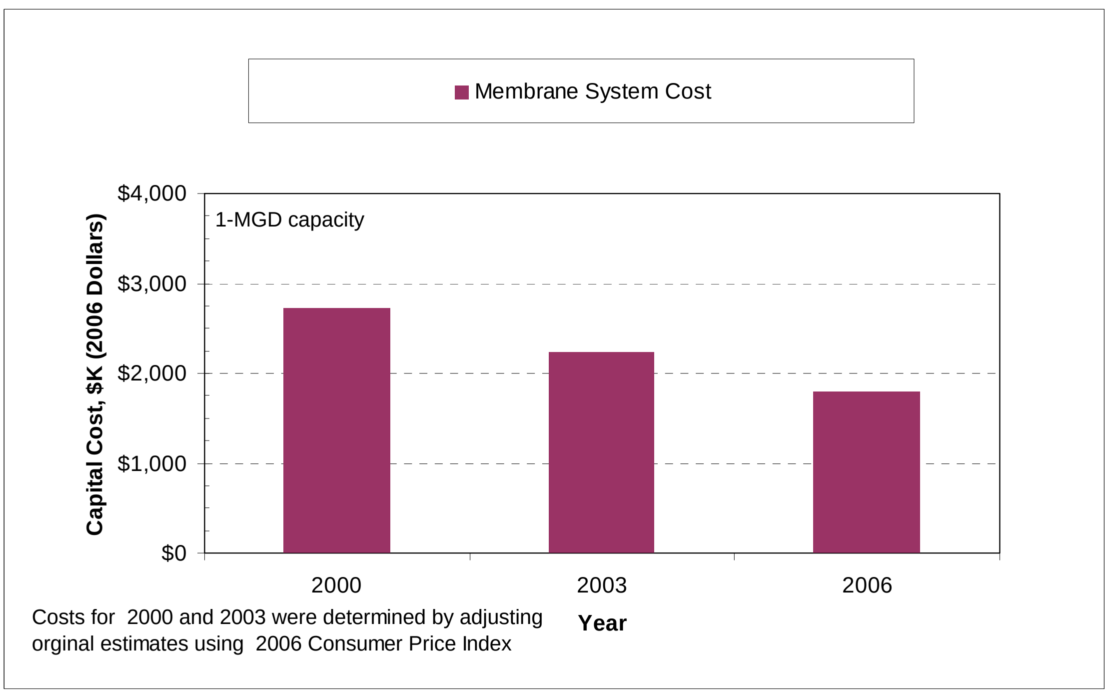


Figure 9-4. Capital Cost Estimates of 1-MGD MBR Membrane Systems.

Appendix B

Membrane Cleaning Procedures

Puron MBR Maintenance Cleaning Protocol (Specific to the Pilot Unit)

Step 1: Chlorine Clean

1. Prepare 25 Liters of 0.4 % (W/W) of Sodium Hypochlorite solution in the chlorine chemical tank
2. Set the chlorine pump speed to 380 ml/min.
3. Set the following parameters on the "UF BF/Clean" Screen:
   Pre Chlor Dose Time = 100 seconds
   Max. Clean BF Time = 40 seconds
   Min. Clean BF Time = 1800 seconds
   Clean Soak Time = 300 seconds
   Clean Purge Time = 60 seconds
4. Set permeate backpulse flow-rate to 0.8 gpm.
5. Initiate Clean from the PLC
6. After cleaning is complete, bring the system back to operation.

Step 2: Citric Acid Clean (Should be followed by Chlorine Clean)

7. Prepare Citric Acid Solution by adding 50 g of 100% Citric Acid to 25 L of citric acid chemical tank.
8. Set the citric acid pump speed to 380 ml/min.
9. Set the following parameters on the "UF BF/Clean" Screen:
   Pre Chlor Dose Time = 100 seconds
   Max. Clean BF Time = 40 seconds
   Min. Clean BF Time = 1800 seconds
   Clean Soak Time = 300 seconds
   Clean Purge Time = 60 seconds
10. Set permeate backpulse flow-rate to 0.8 gpm.
11. Initiate Clean from the PLC
12. After cleaning is complete, bring the system back to operation.

Puron MBR Recovery Cleaning Protocol (Specific to the Pilot Unit)

This cleaning takes place in the membrane tank by completely submerging the membrane in the cleaning solution.

Step 1: Chlorine Clean

1. Drain the membrane tank by pumping sludge from the membrane tank to the aeration tank.
2. Soak the membrane in 1000 mg/L of Sodium Hypochlorite solution. Sodium Hydroxide is used to adjust pH. Cleaning temperature is preferably 86-104°F (30-40°C).

Step 2: Citric Acid Clean (Should be followed by Chlorine Clean)

3. Flush the membrane tank with water few times after chlorine soak.
4. Soak the membrane in 2500 mg/L of Citric Acid to achieve a pH of 2.5-3. Cleaning temperature is preferably 86-104°F (30-40°C).

Huber MBR Maintenance Cleaning Protocol (Specific to the Pilot Unit)

1. Turn the system in manual operation mode, which will turn off all the equipment on the pilot unit.
2. Once the solids in the membrane tank settle down, drain the supernatant from top of the membrane tank so that the membrane tank level is at 1.5 m.
3. Turn on the membrane air scouring blower, membrane module drive and aeration blower.
4. Rinse the membrane module with tap-water so that the debris and fibrous material trapped between the membrane plates are removed.
5. Prepare 2000-ppm sodium hypochlorite solution in a 50-gallon container.
6. Connect a small submersible pump to the cleaning valve at the bottom of the pilot unit.
7. Pump the sodium hypochlorite solution very slowly through the cleaning valve so that the pressure measured by the pressure probe of the membrane filtration does not exceed 20 mbar. Allow about one

hour time period to pump the 50-gallon solution through the membrane. Cleaning temperature is preferably 30-50°C.

8. Keep the membrane module soaked in the chlorine solution for two hours before bringing the unit back in operation.
9. If specific flux is not recovered with chlorine clean, then a 2000-ppm citric acid clean should be performed immediately after performing chlorine clean.

Huber MBR Recovery Cleaning Protocol (Specific to the Pilot Unit)

This cleaning takes place in the membrane tank by completely submerging the membrane in the cleaning solution.

Step 1: Chlorine Clean

1. Turn the system in manual operation mode, which will turn off all the equipment on the pilot unit.
2. Once the solids in the membrane tank settle down, drain the supernatant from top of the membrane tank and transfer the solids into the aeration tank.
3. Turn on the membrane air scouring blower, membrane module drive and aeration blower.
4. Rinse the membrane tank and the membrane module with tap-water.
5. Fill the membrane tank with 200-ppm sodium hypochlorite solution. Soak time depends on the extent of fouling and the membrane condition. Cleaning temperature is preferably 30-50°C.
6. Drain the membrane tank and rinse the membrane tank and the membrane module with tap-water several times.

Step 2: Citric Acid Clean (Should be followed by Chlorine Clean if required)

7. Fill the membrane tank with 200-ppm citric acid and let the membrane module soak in the cleaning solution for the desired period of soak time. Cleaning temperature is preferably 30-50°C.

8. Drain the cleaning solution and rinse the membrane tank and the membrane module with tap-water several times before bringing the unit back to normal operation.

Kruger Neosep MBR Recovery Cleaning Protocol (Specific to the Pilot Unit)

Step 1: Chlorine Clean

1. Make sure that the chemical injection valve is closed
2. Feed the chemical tank with 500 L of 500 mg/L of chlorine solution
3. Stop filtration and close the permeate discharge valve
4. Raise the water level in the membrane tank to 138 inches
5. Keep the internal recycle pump and RAS pump in automatic mode
6. Slowly open the chemical injection valve to inject chemicals
7. After injection is complete, soak the membrane module for about 2 hours
8. Close the chemical injection valve
9. Restart the filtration
10. For first few minutes of filtration, send the permeate to the drain to purge the chemicals from the permeate line

Step 2: Citric Acid Clean (Should be followed by Chlorine Clean)

11. Prepare 1.5 % wt solution of Citric Acid in the 500 L chemical tank
12. Make sure that the chemical injection valve is closed
13. Stop filtration and close the permeate discharge valve
14. Raise the water level in the membrane tank to 138 inches
15. Keep the internal recycle and RAS pump in automatic mode
16. Slowly open the chemical injection valve to inject chemicals
17. After injection is complete, soak the membrane for 1 to 2 hours depending on the membrane fouling condition
18. Close the chemical injection valve
19. Restart the filtration

20. For first few minutes of filtration, send the permeate to the drain to purge the chemicals from the permeate line

DynaLift MBR Recovery Cleaning Protocol (Procedure Specific to the Pilot Unit)

Chlorine & Citric Acid Clean

1. Turn off the system by turning off the system run and filtration run switches on the main screen of the HMI panel.
2. Put the aeration blower in Hand mode. This will keep the sludge mixed in the aeration tank during cleaning.
3. Make sure all three cleaning tanks are full of permeate and the valves interconnecting the tanks are closed.
4. Remove the hose from the drain tank to the anoxic tank and put it to sewer. This will remove all cleaning chemicals to sewer instead of putting them in the bioreactor.
5. Close the valve on the discharge of permeate to the turbidimeter. This will prevent cleaning fluids from passing to the turbidimeter.
6. Mix 200 ppm of NaOCl in the cleaning tank closest to the membrane module. Based on the tank volume of 45 gallons, approximately 400 mL of 10% NaOCl will be required.
7. Mix about 10 lbs of anhydrous citric acid in the third 45-gallon cleaning tank (furthest away from the module).
8. Check the setpoints for cleaning in the lower right corner of the screen.
    a. Fill Time – 20 seconds
    b. NaOCl Soak Time 1 – 20 minutes
    c. NaOCl Soak Time 2 – 30 minutes
    d. Citric Soak Time – 40 minutes (if citric acid clean is not required, then use 1 minute)

9. Push the Soak Clean button on the screen. The system will automatically perform the cleaning. It will take about 60 minutes without citric acid and 100 minutes with citric acid.
10. After the cleaning is over, reconnect the hose from the drain back to the anoxic tank.
11. Start the system in accordance with the start-up procedures.
12. Open the valve from permeate to the turbidimeter after about 30 minutes of operation.

Appendix C

QA/QC MEMORANDUM

M E M O R A N D U M

MWH
MONTGOMERY WATSON HARZA

To:	**James DeCarolis, Ph.D.**	**Date:**	10/01/2005
From:	**Zakir Hirani**	**Reference:**	
Subject:	**Evaluation of Newly Developed MBR Systems for Water Reclamation: QA/QC Protocol**		

Pilot testing for the Bureau of Reclamation project entitled "Evaluation of Newly Developed MBR Systems for Water Reclamation" begun in October of 2005 at the Point Loma Waste Water Treatment Plant (PLWWTP) in San Diego, California. To ensure the accuracy and integrity of the data collected, a number of quality assurance and quality control procedures were followed throughout the experiment. This Technical Memorandum (TM) summarizes these procedures for the on-site instrument verification and water quality analysis performed by the project team, including:

- On-line Turbidimeters
- On-line Conductivity Meter
- On-line Dissolved Oxygen (DO) Meters
- System Thermometers
- Membrane System Pressure Gauges
- System Rotameters
- Membrane System Run-hour Clock
- Chemical Feed Pumping Rate
- Portable DO/Temperature Meter
- Portable pH Meter
- Desktop Turbidimeter

The sampling protocol for off-site water quality analysis is also described herein. All off-site water quality analysis were analyzed at one of the following locations: These labs consisted of: City of San Diego's Point Loma WWTP Laboratory, Industrial Waste Laboratory at Alvarado and Marine Microbiology Laboratory as well as Calscience Environmental Laboratory located in Garden Grove, CA. All labs have the State of California Department of Health Services (DHS) Environmental Laboratory Accredited Programs (ELAP) and follow the associated QA/QC requirements.

Lastly, this TM provides the QA/QC procedures followed to ensure accurate data management and data analyses of all water quality and operational data collected during this study.

ON-LINE TURBIDIMETERS

Permeate turbidity for all four MBR systems was measured by using Hach's 1720C online low-range turbidimeter. Readings on the turbdimeter were recorded manually twice a day for each system. In addition to that, a data-logger was used to record turbidity every minute from these turbidimeters. The turbidimeters were periodically cleaned and calibrated as per the instructions provided in Hach's manual.

ON-LINE CONDUCTIVITY METER

Feed and permeate conductivity was measured continously via two separate online conductivity meters installed on the RO skid. Readings from these meters were recorded manually twice a day. These meters were calibrated at the beginning of the test period using standard solutions. In addition, daily comparisons were performed between the on-line conductivity readings and on-site lab results. Both online conductivity meters were calibrated using two standard solutions: 23 μS and 1500 μS.

ON-LINE DISSOLVED OXYGEN (DO) METER

DO meters equipped on the MBR systems were calibrated using the manufacturers protocol at the beginning of the study. To ensure accuracy, values were compared throughout the study to those measured by the hand held DO meter.

MEMBRANE SYSTEM THERMOMETERS

The thermometers installed on the systems were verified at a normal operating temperature (25-30°C) using an NIST thermometer at the beginning of the study. The thermometers used to monitor the temperature of the MBRs and RO feed water were all within 5% error.

MEMBRANE SYSTEM PRESSURE GAUGES

Pressure and vacuum gauges supplied with the membrane systems tested were verified against new certified pressure and vacuum gauges. The certified pressure and vacuum gauges were manufactured by Ashcroft and have an accuracy of 0.25% over their range (0-30 psi pressure, 0-30 in Hg vacuum). Where possible, system gauges were removed and tested over the expected range of operating pressures against the verification gauge, using a portable hand pump.

MEMBRANE SYSTEM ROTAMETERS

The digital flow-meters and rotameters on MBR systems and RO system were verified volumetrically by bucket tests using calibrated containers or graduated cylinders and a stopwatch. The measured flow rate was compared with flows indicated on the rotameters or digital meters. Measured and indicated flow rates were within 5% error. Membrane system air flow rotameters were factory calibrated prior to the study. [*Please note: there exists no practical method of volumetrically verifying the air flow rates during the pilot study*.]

MEMBRANE SYSTEM RUN HOUR CLOCK

All system run hour clocks used during this study were checked at the beginning of the study for accuracy using a stop watch.

CHEMICAL FEED PUMPING RATE

The LMI pumps used for chemical injection were calibrated at the beginning of the study and continually checked for accuracy. The flow-rates were verified using a graduated cylinder and a stopwatch.

PORTABLE DISSOLVED OXYGEN/TEMPERATURE METER

A hand-held YSI Model 550A dissolved oxygen meter was used to measure DO in the aerobic and anoxic tank of the MBR systems. The DO meter was factory calibrated prior to the study, and was re-calibrated once every two weeks according to manufacturer's directions

PORTABLE pH METER

A handheld Hach sensION1 pH meter was used to measure the pH of the MBR influent, aeration tanks, RO feed and RO permeate. The meter was calibrated once every two weeks using a 3 point calibration with buffers 4, 7, and 10. The calibration was confirmed daily using a Laboratory check standard.

DESKTOP TURBIDIMETER

A Hach 2100N desktop turbidimeter was used to perform onsite turbidity analyses of feed and permeate samples. Readings for permeate samples were recorded in non-ratio operating mode whereas that for feed samples were recorded using ratio mode. Weekly primary calibration and daily secondary calibrations were performed on desktop turbidimeter to ensure accuracy of the readings.

WATER QUALITY SAMPLING PROTOCOL

All sample lines were properly sterilized (for microbial samples) and flushed for a minimum of one minute prior to sampling. Sample containers were obtained from the labs performing the analyses and all preservation chemicals were added to the bottles by the lab prior to sampling, when required. Filtering or any other required preparatory steps were also be performed by the respective lab performing the analysis. Samples were delivered to the off-site labs either on the same day or next day morning. Standard shipping and packing procedures were followed, including isolating samples and storage of samples in a cooler packed with plastic bubble wrap to prevent breaking of glass sample bottles. Ice packs were added to the coolers containing samples requiring storage at 4 degrees C. The samples were delivered and analyzed within the allotted holding time for each measured parameter.

A chain of custody was filled out on-site by the person performing the sampling and given to the courier when the samples were picked up for delivery. Upon receipt, a representative from the lab signed the Chain of Custody and the samples were released to their custody. A copy of the signed Chain of Custody was then sent back to the sampler and was kept on file at the pilot site.

DATA MANAGEMENT/ANALYSES

All water quality data collected on-site was merged with data obtained from offsite laboratories throughout the study. Operational data was recorded on raw data sheets and routinely inputted into a database. The water quality and operational databases were combined to create a comprehensive database, which was used for data analysis, retrieval, reporting and graphics. All data inputted to the database was checked and verified by the onsite engineer. Lastly, data files were periodically sent to TAC members during the study for analysis.

Appendix D

Photographs of Pilot Equipment

Photograph of the Puron MBR Pilot System

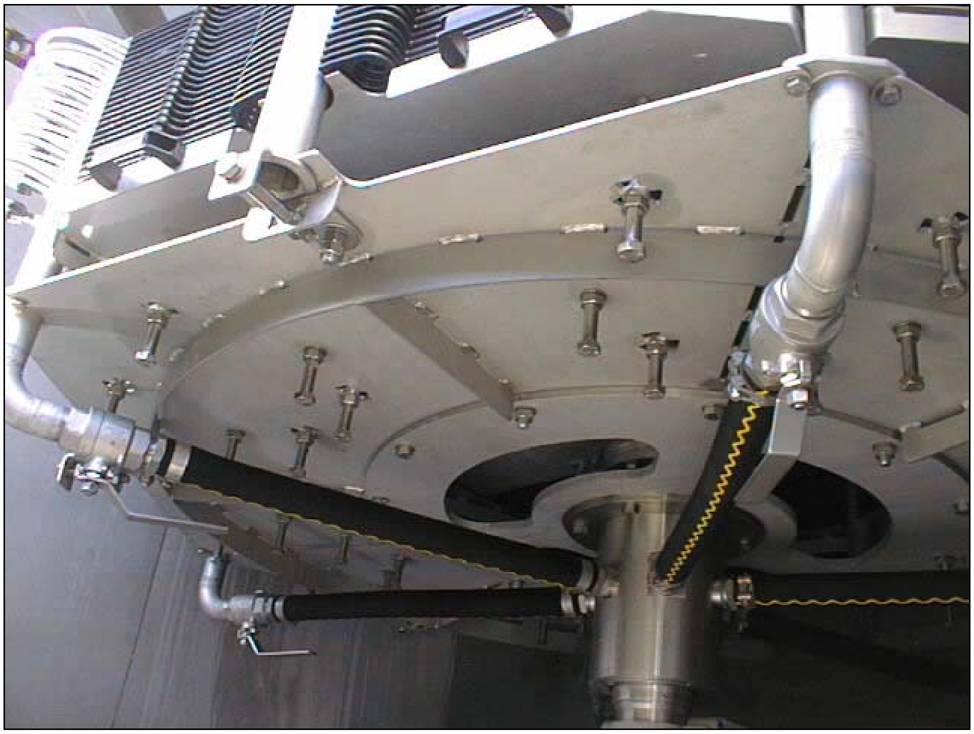
Photograph of the Puron MBR Membrane Module

Permeate and Chemical Clean Tanks for Puron MBR Pilot System

Top View of the Aerobic Tank and Mixer for Puron MBR Pilot System

Photograph of the Huber MBR Pilot System

Photograph of the Huber MBR Membrane Module



Side View of the Huber VRM Membrane Module

Top View of the Aeration Tank of Huber MBR Pilot System

Photograph of the Kruger Neosep MBR Pilot System

Photograph of the Kruger Neosep MBR Membrane Module

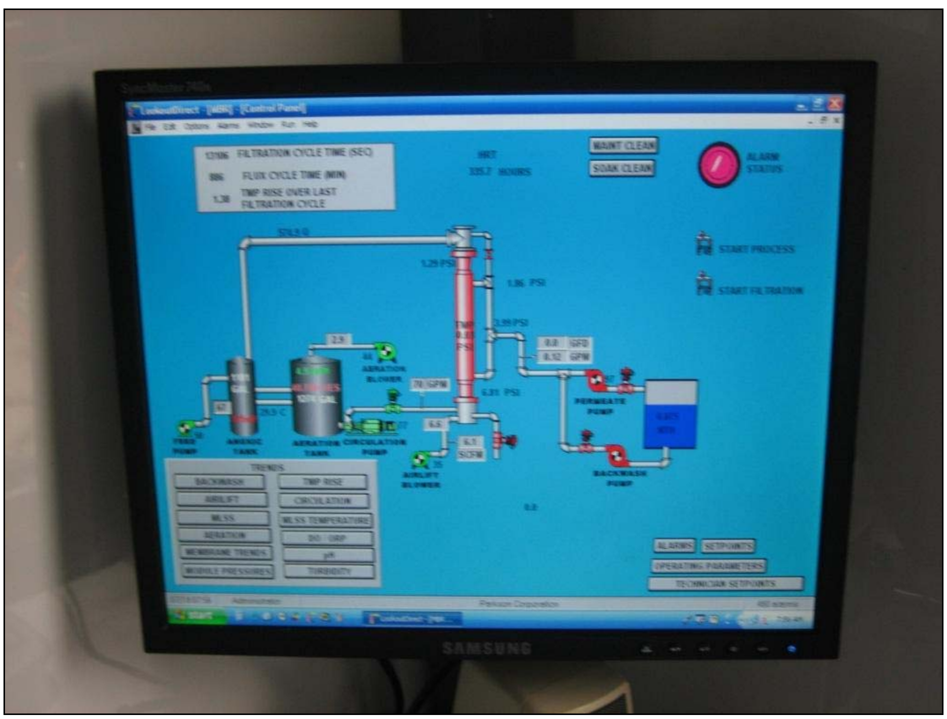
Top View of the Aeration Tank of the Kruger Neosep MBR Pilot System

Photograph of the Control Screen of Kruger Neosep MBR Pilot System

Photograph of the DynaLift MBR Pilot System

Photograph of the DynaLift MBR Membrane Module

Cross section of DynaLift MBR Membrane Module



Photograph of the Control Screen of the DynaLift MBR Pilot System

Photograph of the RO Pilot Unit

Used and Clean Cartridge Filters for RO Membranes

Appendix E

Title 22 Approval Letters for MBR Systems

State of California—Health and Human Services Agency
Department of Health Services

SANDRA SHEWRY
Director

ARNOLD SCHWARZENEGGER
Governor

May 4, 2006

Ms. Merrilee Galloway
Commercial Manager, Municipal Business
Koch Membrane Systems
850 Main Street
Wilmington, MA 01887

Subject: Use of the Koch Membrane Systems Puron™ Membrane Bioreactor (MBR) to comply with California Water Recycling Criteria

Dear Ms. Galloway:

By transmittal letter dated March 21, 2006, Montgomery Watson Harza, Consulting Engineers, requested Departmental acceptance of the Koch Membrane Systems Puron™ Membrane Bioreactor (MBR) filtration treatment unit as an acceptable filtration technology for compliance with the State of California Water Recycling Criteria (Title 22). Accompanying this request was a report prepared by Montgomery Watson Harza entitled "Assessing the Ability of the Puron™ Membrane Bioreactor to Meet Existing Water Reuse Criteria", dated March 2006. The report was prepared under a grant from the U.S. Bureau of Reclamation and outlines findings from a study conducted in the City of San Diego, California. The Department has reviewed this report and offers the following comments.

Division of Drinking Water and Environmental Management
Technical Programs Branch, Recycled Water Unit
1180 Eugenia Place, Suite 200, Carpinteria, CA 93013-2000
(805) 566-1326; (805) 745-8196 fax
Internet Address: jstone1@dhs.ca.gov

The Puron™ MBR filtration system evaluated utilizes the Polyethersulfone hollow fiber PSH 500C2-L1 membrane with a nominal pore size of 0.05 micron. The membranes are submerged and operated under vacuum pressure with a maximum test flux of 35.3 gallons per square foot per day (gfd).

The California Water Recycling Criteria recognize membrane filtration as an acceptable filtration technology provided prescribed performance requirements (i.e. turbidity) are reliably met. The turbidity performance criteria require that the filtered wastewater not exceed any of the following:

1. 0.2 NTU more than 5 percent of the time within a 24-hour period; and

2. 0.5 NTU at any time.

The demonstration studies conducted using the Puron™ MBR filtration process have sufficiently demonstrated the ability to produce an oxidized wastewater and the membranes ability to comply with the above stated turbidity performance requirements. In addition, virus seeding experiments demonstrated the processes ability to achieve greater than 1-log virus reduction at the 50th percentile. Therefore, the Department of Health Services accepts the use of this membrane, identified as the Polyethersulfone hollow fiber L1 membrane with a nominal pore size of 0.05 micron, as a filtration technology for use in compliance with the Water Recycling Criteria.

The acceptance of this technology is specific to the Koch Membrane Systems Puron™ MBR filtration system evaluated which utilizes the Polyethersulfone hollow fiber L1 membrane with a nominal pore size of 0.05 micron. Any proposed changes made in the physical attributes or character of this membrane shall be reviewed in advance by the Department to determine whether the modifications will require additional testing.

The Department will continue to review all proposed projects on a case-by-case basis to determine full compliance with all applicable treatment and reliability features required by the Water Recycling Criteria. This will include the collective review of all treatment unit processes, operational controls (e.g. loading rates, TMP, frequency of integrity tests), 'O&M' procedures, etc.

If you have any questions concerning this letter, please contact the undersigned at (805) 566-9767.

Sincerely,

Jeffrey L. Stone, Chief
Recycled Water Unit
Division of Drinking Water

cc: Montgomery Watson - James DeCarolis
City of San Diego - Larry Wasserman
Recycled Water Committee

Tech.listing disk 6/KochPuron050106apprltr.doc

State of California—Health and Human Services Agency
Department of Health Services

California Department of Health Services
SANDRA SHEWRY
Director

ARNOLD SCHWARZENEGGER
Governor

June 22, 2006

Ms. Sandra Schuler
Membrane Application Engineer
Huber Technology, Inc.
9805 NorthCross Center Court, Suite H
Huntersville, NC 28078

Subject: Use of the Huber Vacuum Rotation Membrane VRM® Bioreactor to comply with California Water Recycling Criteria

Dear Ms. Schuler:

By transmittal letter dated April 11, 2006, Montgomery Watson Harza, Consulting Engineers, requested Departmental acceptance of the Huber Vacuum Rotation Membrane VRM® Bioreactor (MBR) filtration treatment unit as an acceptable filtration technology for compliance with the State of California Water Recycling Criteria (Title 22). Accompanying this request was a report prepared by Montgomery Watson Harza entitled "Assessing the Ability of the Huber Vacuum Rotation Membrane VRM® Bioreactor & Membrane Clearbox® to Meet Existing Water Reuse Criteria", dated April 2006. The report was prepared under a grant from the U.S. Bureau of Reclamation and outlines findings from a study conducted in the City of San Diego, California. The Department has reviewed this report and offers the following comments.

Division of Drinking Water and Environmental Management
Technical Programs Branch, Recycled Water Unit
1180 Eugenia Place, Suite 200, Carpinteria, CA 93013-2000
(805) 566-1326; (805) 745-8196 fax
Internet Address: jstone1@dhs.ca.gov

The Huber Vacuum Rotation Membrane VRM® Bioreactor (MBR) filtration treatment system evaluated utilizes the Polyethersulfone flat sheet NADIR P-150F ultra-filtration membrane with a nominal pore size of 0.038 micron. The membranes are submerged and operated under vacuum pressure with a maximum test flux of 33 gallons per square foot per day (gfd).

The California Water Recycling Criteria recognize membrane filtration as an acceptable filtration technology provided prescribed performance requirements (i.e. turbidity) are reliably met. The turbidity performance criteria require that the filtered wastewater not exceed any of the following:

1. 0.2 NTU more than 5 percent of the time within a 24-hour period; and

2. 0.5 NTU at any time.

The demonstration studies conducted using the Huber Vacuum Rotation Membrane VRM® Bioreactor (MBR) filtration treatment system which utilizes the Polyethersulfone flat sheet NADIR P-150F ultra-filtration membrane with a nominal pore size of 0.038 micron have sufficiently demonstrated the ability to produce an oxidized wastewater and the membranes ability to comply with the above stated turbidity performance requirements. In addition, virus seeding experiments demonstrated the processes ability to achieve greater than 1-log virus reduction at the 50th percentile level. Therefore, the Department of Health Services accepts the use of this membrane, identified as the Huber Vacuum Rotation Membrane VRM® Bioreactor (MBR) filtration treatment system which utilizes the Polyethersulfone flat sheet NADIR P-150F ultra-filtration membrane with a nominal pore size of 0.038 micron as a filtration technology for use in compliance with the Water Recycling Criteria.

The acceptance of this technology is specific to the Huber Vacuum Rotation Membrane VRM® Bioreactor (MBR) filtration treatment system which utilizes the Polyethersulfone flat sheet NADIR P-150F ultra-filtration membrane with a nominal pore size of 0.038 micron. Any proposed changes made in the physical attributes or character of this membrane shall be reviewed in advance by the Department to determine whether the modifications will require additional testing.

The Department will continue to review all proposed projects on a case-by-case basis to determine full compliance with all applicable treatment and reliability features required by the Water Recycling Criteria. This will include the collective review of all treatment unit processes, operational controls (e.g. loading rates, TMP, frequency of integrity tests), 'O&M' procedures, etc.

With respect to the Membrane Clearbox® (MCB), the effectiveness of this treatment process was adequately demonstrated. However, Title 22 applications apply to centralized municipal wastewater treatment facilities as opposed to individual on-site treatment units such as the MCB. Therefore, the Department cannot recognize this particular technology for Title 22 applications.

If you have any questions concerning this letter, please contact the undersigned at (805) 566-9767.

Sincerely,

Jeffrey L. Stone, Chief
Recycled Water Unit
Division of Drinking Water

cc: Montgomery Watson - James DeCarolis
City of San Diego - Larry Wasserman
Recycled Water Committee

Tech.listing disk 6/KochPuron050106apprltr.doc

California Department of Health Services

SANDRA SHEWRY
Director

State of California—Health and Human Services Agency
Department of Health Services

ARNOLD SCHWARZENEGGER
Governor

October 12, 2006

Kruger, Inc.
401 Harrison Oaks Blvd., Ste. 100
Cary, NC 27513

Attn. Sun-Nan Hong, Ph.D
Vice President Engineering

Subject: Use of the Kruger Neosep™ Membrane Bioreactor to comply with California Water Recycling Criteria

Gentlemen:

By transmittal letter dated August 25, 2006, Montgomery Watson Harza, Consulting Engineers, requested Departmental acceptance of the Kruger Neosep™ Membrane Bioreactor (MBR) treatment unit as an acceptable filtration technology for compliance with the State of California Water Recycling Criteria (Title 22). Accompanying this request was a report prepared by Montgomery Watson Harza entitled "Assessing the Ability of the Kruger Neosep™ Membrane Bioreactor to Meet Existing Water Reuse Criteria", dated August 2006. The report was prepared under a grant from the U.S. Bureau of Reclamation and outlines findings from a study conducted in the City of San Diego, California. The Department has reviewed this report and offers the following comments.

The Kruger Neosep™ MBR treatment system evaluated utilizes a flat sheet PVDF ultrafiltration membrane with an average pore size of 0.08 micron with a standard deviation from the average pore size of 0.03 micron. The Kruger Neosep™ MBR configuration consists of an anoxic tank, aerobic tank and the submerged membrane tank. The membranes are operated under vacuum with a transmembrane pressure differential ranging from 0.5 to 4.0 psi

Division of Drinking Water and Environmental Management
Technical Programs Branch, Recycled Water Unit
1180 Eugenia Place, Suite 200, Carpinteria, CA 93013-2000
(805) 566-1326; (805) 745-8196 fax
Internet Address: jstone1@dhs.ca.gov

and a typical design flux of 17 to 38 gallons per square foot per day (gfd).

The California Water Recycling Criteria recognize membrane filtration as an acceptable filtration technology provided prescribed performance requirements (i.e. turbidity) are reliably met. The turbidity performance criteria require that the filtered wastewater not exceed any of the following:

1. 0.2 NTU more than 5 percent of the time within a 24-hour period; and
2. 0.5 NTU at any time.

The demonstration studies conducted using the Kruger Neosep™ MBR treatment system which utilizes the PVDF flat sheet membrane with a nominal pore size of 0.08 micron have sufficiently demonstrated the ability to produce an oxidized wastewater and the membranes ability to comply with the above stated turbidity performance requirements. In addition, virus seeding experiments demonstrated the processes ability to achieve greater than 3-log virus removal at the 50th percentile level. Therefore, the Department of Health Services accepts the use of this membrane, identified as the Kruger Neosep™ MBR filtration treatment system utilizing a flat sheet PVDF membrane module with a nominal pore size of 0.08 micron as a filtration technology for use in compliance with the Water Recycling Criteria.

The acceptance of this technology is specific to the Kruger Neosep™ MBR filtration treatment system utilizing a flat sheet PVDF membrane module with a nominal pore size of 0.08 micron. Any proposed changes made in the physical attributes or character of this membrane shall be reviewed in advance by the Department to determine whether the modifications will require additional testing.

The Department will continue to review all proposed projects on a case-by-case basis to determine full compliance with all applicable treatment and reliability features required by the Water Recycling Criteria. This will include the collective review of all treatment unit processes, operational controls (e.g. loading rates, TMP, type and frequency of integrity tests), 'O&M' procedures, etc.

If you have any questions concerning this letter, please contact the undersigned at (805) 566-9767.

Sincerely,

Jeffrey L. Stone, Chief
Recycled Water Unit
Division of Drinking Water

cc: Montgomery Watson - James DeCarolis
City of San Diego - Larry Wasserman
Recycled Water Committee

techlist/KrugerHeosepappr1tr.doc

SANDRA SHEWRY
Director

State of California—Health and Human Services Agency
Department of Health Services

ARNOLD SCHWARZENEGGER
Governor

RECEIVED
SEP 11 2006
MWH SAN-1

September 7, 2006

Mr. Charles Morgan
Product Group Manager, Membrane Bioreactors
Parkson Corporation
2727 N.W. 62nd Street
Fort Lauderdale, FL 33340-8399

Subject: Use of the Parkson Corporation Dynalift™ Membrane Bioreactor to comply with California Water Recycling Criteria

Dear Mr. Morgan:

By transmittal letter dated July 28, 2006, Montgomery Watson Harza, Consulting Engineers, requested Departmental acceptance of the Dynalift™ Membrane Bioreactor (MBR) filtration treatment unit as an acceptable filtration technology for compliance with the State of California Water Recycling Criteria (Title 22). Accompanying this request was a report prepared by Montgomery Watson Harza entitled "Assessing the Ability of the Dynalift™ Membrane Bioreactor to Meet Existing Water Reuse Criteria", dated July 2006. The report was prepared under a grant from the U.S. Bureau of Reclamation and outlines findings from a study conducted in the City of San Diego, California. The Department has reviewed this report and offers the following comments.

The Parkson Corporation Dynalift™ MBR filtration treatment system evaluated utilizes an external PVDF tubular membrane module with a nominal pore size of 0.03 micron. The Dynalift™ MBR configuration differs from other MBR processes in that the membrane modules are not submerged in the bioreactor but are located externally. The membranes are operated under pressure with a transmembrane pressure ranging from 1.0 to 5.0 psi and a

Division of Drinking Water and Environmental Management
Technical Programs Branch, Recycled Water Unit
1180 Eugenia Place, Suite 200, Carpinteria, CA 93013-2000
(805) 566-1326; (805) 745-8196 fax
Internet Address: jstone1@dhs.ca.gov

typical design flux of 20 to 45 gallons per square foot per day (gfd).

The California Water Recycling Criteria recognize membrane filtration as an acceptable filtration technology provided prescribed performance requirements (i.e. turbidity) are reliably met. The turbidity performance criteria require that the filtered wastewater not exceed any of the following:

1. 0.2 NTU more than 5 percent of the time within a 24-hour period; and

2. 0.5 NTU at any time.

The demonstration studies conducted using the Dynalift™ MBR filtration treatment system which utilizes the PVDF tubular membrane with a nominal pore size of 0.03 micron have sufficiently demonstrated the ability to produce an oxidized wastewater and the membranes ability to comply with the above stated turbidity performance requirements. In addition, virus seeding experiments demonstrated the processes ability to achieve greater than 4-log virus removal at the 50^{th} percentile level. Therefore, the Department of Health Services accepts the use of this membrane, identified as the Parkson Corporation Dynalift™ MBR filtration treatment system utilizing an external PVDF tubular membrane module with a nominal pore size of 0.03 micron as a filtration technology for use in compliance with the Water Recycling Criteria.

The acceptance of this technology is specific to the Dynalift™ MBR filtration treatment system utilizing an external PVDF tubular membrane module with a nominal pore size of 0.03 micron. Any proposed changes made in the physical attributes or character of this membrane shall be reviewed in advance by the Department to determine whether the modifications will require additional testing.

The Department will continue to review all proposed projects on a case-by-case basis to determine full compliance with all applicable treatment and reliability features required by the Water Recycling Criteria. This will include the collective review of all treatment unit processes, operational controls (e.g. loading rates, TMP, frequency of integrity tests), 'O&M' procedures, etc.

If you have any questions concerning this letter, please contact the undersigned at (805) 566-9767.

Sincerely,

Jeffrey L. Stone, Chief
Recycled Water Unit
Division of Drinking Water

cc: Montgomery Watson - James DeCarolis
City of San Diego - Larry Wasserman
Recycled Water Committee

Tech.listing disk 6/Dynalift-Parksonappritr.doc

Appendix F

Support Information for Cost Analysis

Table F-1. Source of Capital Costs (Updated 2003 Costs using 2006 ENRC CI and CE Index)

Capital Cost Items	Source
[1] **Headworks**	
Fine (6 mm) Screening, Vortex Grit Removal	ENRCCI (Sept 2006/ Oct. 2003), Avg. 20 City
Basins	
Basin concrete and ancillaries	ENRCCI (Sept 2006/ Oct. 2003), Avg. 20 City
Basin excavation (Buried to provide 42" exposed concrete)	ENRCCI (Sept 2006/ Oct. 2003), Avg. 20 City
Structural fill	ENRCCI (Sept 2006/ Oct. 2003), Avg. 20 City
Backfill	ENRCCI (Sept 2006/ Oct. 2003), Avg. 20 City
Waste dirt to haul off site	ENRCCI (Sept 2006/ Oct. 2003), Avg. 20 City
Aeration Tank Cover (Membrane Area Only)	ENRCCI (Sept 2006/ Oct. 2003), Avg. 20 City
Membrane Building (Sun Screen over Membranes)	ENRCCI (Sept 2006/ Oct. 2003), Avg. 20 City
5-Ton Bridge Crane	CE Plant Index (Oct. 2003/March 2006) Equipment
MBR System	
Membrane Cassettes, Modules, Units or Tiers	Quotes from New Suppliers
[1] Pumps & Blowers	Quotes from New Suppliers
[1] Miscellaneous Equipment	Quotes from New Suppliers
Equipment installation, 25%	Applied to subtotal
Other Mechanical	
[1] Fine (2 mm) screens	CE Plant Index (Oct. 2003/March 2006) Process Machinery
[1] Mixers	CE Plant Index (Oct. 2003/March 2006) Pipes,valves, fittings
Aeration equipment, diffuser basis	CE Plant Index (Oct. 2003/March 2006) Pipes,valves, fittings
Aeration piping	CE Plant Index (Oct. 2003/March 2006) Pipes,valves, fittings
[1] Recirculation pumps	CE Plant Index (Oct. 2003/March 2006) Pumps/Compressors
Recirculation piping	CE Plant Index (Oct. 2003/March 2006) Pipes,valves, fittings
[1] MLSS Recycle pumps	CE Plant Index (Oct. 2003/March 2006) Pumps/Compressors
Equipment installation, 25%	Applied to updated subtotal
Blower and pump building	
Two story building	ENRCCI (Sept 2006/ Oct. 2003), Avg. 20 City
[1] Blowers - Process	CE Plant Index (Oct. 2003/March 2006) Pumps/Compressors
Blower piping and valving allowance	CE Plant Index (Oct. 2003/March 2006) Pipes,valves, fittings
Blower instrumentation	CE Plant Index (Oct. 2003/March 2006) Process instruments
Equipment installation, 25%	Applied to updated subtotal
Chlorine Contact Basin	
Chlorine dosing system	ENRCCI (Sept 2006/ Oct. 2003), Avg. 20 City
Clear well / effluent storage	ENRCCI (Sept 2006/ Oct. 2003), Avg. 20 City
baffling for chlorination CT	ENRCCI (Sept 2006/ Oct. 2003), Avg. 20 City
Electrical, Instrumentation, and Controls, 15%	Applied to updated subtotal
Mechanical, Plumbing, and HVAC, 13%	Applied to updated subtotal
Sitework, 9%	Applied to updated subtotal
Contractor Overhead and Profit, 15%	Applied to updated subtotal
Land	assumed 10 % increase land cost from 2003
Contingency, 15%	Applied to updated subtotal
Engineering, Legal, and Administration, 15%	Applied to updated subtotal

[1]Used to estimate equipment repair O&M cost (See Table F-2). Note only 20% of the captial cost associated with Headworks was used for estimating O&M costs.

Table F-2. Source of O&M Costs (2003 to 2006)

O&M Cost Item	Source
[1] Electrical power for process/miscellaneous	used 0.10 / kwh (2003 = 0.08 / kwh)
Equipment repairs/lubricants/replacement	2% of revised capital costs related to equipment identified in Table F-1.
[1] Chemical Cleaning	Assume 15% increase in unit cost for chemicals from 2003 to 2006
[1] Chemical Cost for Disinfection	Assume 15% increase in chlorine cost from cost 2003 ($.50/gal)
Diffuser Replacement	CE Plant Index (Oct. 2003/March 2006) Pipes,valves, fittings
Membrane Replacement	based on 8 yr relaplacement cost per quotes received from NEW suppliers
[1] Labor	Adjusted using 2003 costs using ENR common labor index Sept 2006 / Oct 2003

[1] Details on 2003 cost estimates are provided in DWPR Report No. 103 Optimization of Various MBR Systems for Water Reclamation Phase III.

1. MEMORANDUM

MWH
MONTGOMERY WATSON HARZA

Date: July 5, 2006

To: MBR Supplier / Participant USBR 2005-2006 MBR Study PLWTP

From: James DeCarolis / Zakir Hirani

Subject: Request of Full Scale MBR Budgetary Cost Proposals

MWH would like to thank you for participating in the on-going Bureau of Reclamation (USBR) project entitled "Evaluation of Newly Developed Membrane Bioreactor Systems for Water Reclamation" being conducted at the Point Loma Wastewater Treatment Plant (PLWTP). In order to fulfill the costing component of the project, we would like to request each participant provide budgetary cost proposals for 1 & 5 MGD full-scale MBR systems. We ask that the proposals include estimates for capital and operation/maintenance costs associated with only the membrane and ancillary equipment, component of the MBR system. The following memo outlines additional requirements of the costs proposals.

MWH will cost the biological component of the MBR systems by conducting preliminary design calculations based on the following criteria:

1. **Feed Water –** Costs will be generated for operation on municipal wastewater, assuming the following influent wastewater characteristics:

Parameter	Raw Wastewater
BOD_5 (mg/L)	**290**
COD (mg/L)	**630**
TSS (mg/L)	**320**
VSS (mg/L)	**260**
NH_3-N (mg/L)	**30**
TKN (mg/L)	**60**

TDS (mg/L)	**1,200**
Alkalinity (mg/L)	**245**
Temperature (^oC)	**20**

2. **SRT –** The design SRT will between 10-15 days.
3. **MLSS –** MLSS will range from 8,000 – 10,000 mg/L.
4. **MBR Effluent –** The biological portion of the MBR system will be designed to meet the following effluent water conditions:

   - Complete nitrification (i.e. NH_4^+-N<1.0 mg/L),
   - Denitrification (i.e. NO_3-N<10 mg/L)
   - Biological Oxygen Demand (BOD) < 2.0 mg/L

Please use the following design criteria as guidelines when developing costs for the membrane system.

1. **Capacity –** Costs will be generated for 1.0 and 5.0 MGD MBR systems. System will be for a sewer mining (scalping) plant. Residuals controlled through wasting to a downstream treatment facility.
2. **Peaking –** MBR systems will be designed with 1.0 Q.
3. **Operating Flux –** Membrane costs shall be based on the net operating flux rate demonstrated (non-peak operation) during pilot testing.
4. **Operating TMP** - Costs will be based on operating TMP of 2 psi, with a range of 1 – 4 psi.
5. **Screening** – Costs will include 0.8 mm perforated center feed rotary drum screens.
6. **Cleaning Interval** – A minimum of 2 CIPs will be required per year; the frequency of maintenance cleaning will be per the manufacturer's recommendation.
7. **Redundancy –** The MBR systems will be designed at average conditions to operate with two filter units out of service (OOS). One unit OOS to accommodate routine relaxing/backwashing and an additional membrane filter unit OOS for chemical cleaning. System must be designed to accommodate increased flow to remaining filter units due to OOS unit.
8. **Warranty –** Costing will include a 5-year, non-prorated warranty. Warranty to cover manufacturing defects, normal wear and include the cost for providing replacement membranes to the plant site.

Please provide the following capital and operation/maintenance cost information as described below.

CAPITAL COSTS

Please provide the following capital costs for 1.0 and 5.0 capacities:

1. *Membrane Costs* - Please provide membrane costs for the capacities listed above. Include the membrane model number and values for total surface area and total number of membrane filter units. The membrane cost shall be based on the following conditions:

2. Net operating flux - The net operating flux should not include loss of MBR permeate due to downtime and the use of MBR permeate for membrane cleaning (including relaxation or backwashing, CIPs, maintenance cleans, and module flushing, if applicable). The net flux should be determined from the instantaneous flux and relaxation conditions demonstrated at the PLWTP testing: **16 gfd @ 25 C with 9-min. filtration cycle and 1-min. relaxation**.

- Average operating TMP of 2.0 psi

- Assume that 15% of the active membrane area will be lost over a 5 year period due to irreversible fouling

- The number of membrane units used for costing must meet the redundancy criteria listed above

3. *Chemical Cleaning Equipment* – Please provide itemized list of cost for any equipment necessary to perform CIPs and maintenance cleans including: pumps, tanks, valves and ancillary equipment/instrumentation.

4. *Membrane Chamber* – Please provide the sizing requirements for the membrane chamber(s) to accommodate the various MBR system capacities. Include in the costs for the membranes any internal components to the membrane chamber such as membrane support systems, internal beams and ancillary equipment. The membrane chamber must be sized with four feet of free-board for foam control.

5. *Valves, piping and system controls* – Please provide itemized list of costs for all valves piping and system controls necessary in the membrane chamber. Include any costs for standard PLC associated with the membrane tank.

6. *Membrane Aeration System* – Please provide the membrane aeration system design and costs for the various components of the membrane aeration system. The design should include items such as: air flow control valves, isolation valves, flow meters and rotameters. The design should be based on the necessary airflow requirement for membrane scouring. Please include membrane aeration system design and costs for 1.0 & 5.0 MGD facilities. The cost of equipment to provide air for the biological treatment will estimated by MWH.

7. *Permeate Collection System* - Please provide costs for pumps, flow control valves, and isolation valves related to the permeate collection system. In

addition, please provide cost of turbidimeters, flow meters, and TMP measuring equipment and associated transmitters.

8. *Warranty*- Please provide a description and cost for a 5-year non-prorated warranty for the various plant capacities.

OPERATION AND MAINTENANCE COSTS (O&M)

Please provide the following O&M costs for 1.0 and 5.0 MGD capacities:

1. *Personnel* – Please estimate the number of hours per day for operation and maintenance.

2. *Chemical Requirements* – Please provide the amount of chemical required (lbs/year) to perform CIPs and maintenance cleans. This quantity should be adequate to perform a minimum of 2 CIPs per year and the manufacturer's recommended number of maintenance cleans per year. It should be noted the system should be operated to meet the TMP requirement listed above.

3. *Membrane replacement* – Please provide estimated membrane replacement cost over a twenty year period. Assume membrane replacement every 8 years.

4. *Electrical* – Permeate and backwash pump and blower demands associated with membrane air scour (kWh) based on a normal operating TMP of 2 psi. Additionally, electrical demands for all ancillary systems should also be included in the estimate.

5. *Spare parts* – Please identify and estimate the cost of spare parts typically incurred on yearly basis.

To meet the project schedule, we would appreciate if you could provide these costs no later than July 20, 2006. If you would like to discuss any of the information requested above, please contact James DeCarolis (858 751 1225) or Zakir Hirani (619 221 8706).