MEMBRANE BIOREACTORS FOR WATER RECLAMATION-PHASE II

FINAL TECHNICAL REPORT

City of San Diego, CA
Metropolitan Wastewater-Public Works

by

Samer Adham, Ph.D. and Rion P. Merlo (Montgomery Watson)
Paul Gagliardo, P.E. (City of San Diego)

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

GLOSSARY OF TERMS

A-C

BOD_5	5-day Biological Oxygen Demand
BP	Back Pulse
BPR	Biological Phosphorus Removal
cm	centimeter
CAS	Conventional Activated Sludge
CIP	Clean in Place
COD	Chemical Oxygen Demand
CST	Capillary Suction Test
CSTR	Continuously Stirred Tank Reactor

D-F

d	day
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
ENRCCI	Engineering News-Record Construction Cost Index
ft^2	square foot

G-I

gfd	gallons per square foot per day
gpd	gallons per day
gpm	gallons per minute
h	hour
HRT	Hydraulic Retention Time
in	inch

J-L

kg	Kilograms
L	Liter
$L/h\text{-}m^2$	Liters per hour per square meter

M-O

m^2	square meter
m^3	cubic meter
m^3/min	cubic meter per minute

m^3/d	cubic meter per day
MBR	Membrane Bioreactor
MF	Microfilter
mg	Milligram
mg/L	Milligrams per Liter
mg-N/L	Milligrams per Liter as Nitrogen
mL	Milliliter
MGD	Million Gallons per Day
MLSS	Mixed Liquor Suspended Solids
MLVSS	Mixed Liquor Volatile Suspended Solids
mm	millimeter
MPN	Most Probable Number
NaOCl	Sodium Hypochlorite
NCWRP	North City Water Reclamation Plant
ND	Non-Detect
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
OCP	Zenon ultrafilter trade name
OKC	Zenon microfilter trade name
O&M	Operations and Maintenance
OOS	Out of Service

P-R

PFU	Plaque Forming Units
PLC	Process Logic Controller
PO_4-P	Ortho Phosphate as Phosphorus
psi	Pounds per Square Inch
RAS	Return Activated Sludge
RO	Reverse Osmosis
RR	Recycle Ratio

S-U

scfm	Standard Cubic Feet per Minute
SDI	Silt Density Index
SPWRP	San Pasqual Water Reclamation Plant
SRT	Solids Retention Time
$SRT_{7\text{-}Day}$	Average Solids Retention Time over 7 days
TFC	Thin Film Composite
TKN	Total Kjeldahl Nitrogen

TOC	Total Organic Carbon
TSS	Total Suspended Solids
UF	Ultrafilter
UV-254	Ultraviolet absorbance at 254 nanometer

V-Z

USBR	United States Bureau of Reclamation
VSS	Volatile Suspended Solids
WAS	Waste Activated Sludge
y	year

Symbols

°C	Degrees Celsius
$k	Thousands of Dollars
µg	Microgram
µmho	Micromho

1. EXECUTIVE SUMMARY

Water reclamation is a powerful tool for supplementing water supplies in arid environments. The application of water reclamation has resulted in the emergence of new technologies that can efficiently produce a high quality effluent water. The Membrane Bioreactor (MBR) is one of these emerging technologies that proves to be a viable alternative for use in reclaimed water applications. The MBR is an activated sludge system coupled with a low-pressure membrane that is capable of treating primary effluent municipal wastewater. The effluent water produced is substantially better than that produced by conventional activated sludge followed by granular media filtration. The effluent from an MBR process also has the added advantage of producing water suitable for use by a reverse osmosis (RO) membrane system.

The City of San Diego was awarded a cooperative agreement by the Bureau of Reclamation to evaluate the MBR for its potential application to water reclamation. The City of San Diego and their program manager, Montgomery Watson, performed a parallel comparison of MBRs from two leading manufacturers, Zenon Environmental Systems, Inc. and Mitsubishi Rayon Corporation. Both systems were operated on a pilot scale for over 6,500 hours (270 d). Each system was operated in a nitrification/denitrification and nitrification only mode. The effluent from each MBR system was further treated by two RO pilot units operated in a single-stage mode.

The MBR was evaluated both for its ability to produce high quality effluent as as well as its ability to produce water suitable for use by an RO system. Both membranes demonstrated little fouling throughout the testing period. Both systems were capable of producing water with BOD_5 values of less than 3 mg/L, and up to 6-log removal of total coliforms. The effluent water had consistent turbidity values less than 0.1 NTU and SDI values of less than 3 leading to little fouling by the subsequent RO membranes.

The cost competitiveness of the MBR technology with current water reclamation technologies was also evaluated. A cost comparison was performed analyzing several technologies capable of producing conventional secondary effluent, Title 22 reclaimed water, and water suitable for use by an RO system. The cost analysis evaluated capital and O&M costs to assess the feasibility of future MBR application on an economic basis. The analysis revealed that the MBR is a cost competetive alternative to producing water suitable for use by an RO system at a 1 and 5-MGD capacity. However, existing technologies remain more cost competitive for producing Title 22 reclaimed water.

2. INTRODUCTION

2.1 Background

The increased need for reclaimed water in arid environments has encouraged the development of new wastewater reclamation technologies. The membrane bioreactor (MBR) is one of these. It combines activated sludge treatment with a membrane separation process that eliminates the need for a secondary clarifier. A low-pressure membrane, such as a microfilter (MF) or an ultrafilter (UF), performs the solids separation. The MBR process therefore contains the process elements of secondary, tertiary and advanced wastewater treatment in a single unit operation.

The MBR process can produce high quality effluent with high BOD_5 removal (about 98%), complete nitrification and partial denitrification. (Kishino et al, 1996; Fan et al., 1996; Cicek et al., 1998) The MBR process also achieves virtually complete TSS removal. (Cicek et al., 1998) MBR effluents have low turbidity values (<0.3 NTU) and SDI values (<3), and previous work has shown that MBR effluent can be used as RO feed water with moderate success. (Lozier et al., 1999)

The use of a membrane for solids separation instead of a gravity clarifier eliminates many of the solids seperation problems associated with solids/liquid seperation by sedimentation, such as low settling rates caused by high mixed liquor suspended solids (MLSS) concentrations and filamentous bulking, and others such as dispersed growth and pinpoint floc. (Metcalf & Eddy, 1991) The overall footprint of an MBR system is much smaller than of an activated sludge plant with a secondary clarifier. (Cote et al., 1997)

There are two configurations for MBRs: which are in-series and submerged MBRs. (Adham et. al., 1998) In the in-series MBR configuration sludge is pumped from an aeration basin to a pressure-driven membrane system outside the bioreactor where the suspended solids are retained and recycled back to the bioreactor and the effluent passes through the membrane. The membranes are regularly backwashed to remove suspended solids build-up and accumulations, and are chemically cleaned when the operating pressures become too high. Lyonnaise-des-Eaux/Degremont currently markets an in-line configuration MBR.

In the submerged MBR configuration, a low-pressure membrane is submerged in the aeration basin and operated under vacuum pressure. 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. The following three companies are marketing the submerged MBR configuration: Mitsubishi Rayon Corporation (Mitsubishi, Japan), Zenon Environmental Systems, Inc. (Zenon, Canada) and Kubota Corporation (Kubota, Japan).

Full-scale MBR processes exist world-wide. (Adham et al., 1998) To date, the largest U.S. MBR installation treating municipal water is in Arapaho County, CO (Zenon). It is a 1-MGD capacity retrofitted sequencing batch reactor. (Mourato et al., 1999)

2.2 Objectives of the Study

The City of San Diego and their program manager, Montgomery Watson, received a cooperative agreement from the United States Bureau of Reclamation (USBR) to investigate the application of the MBR process for producing reclaimed water. A Mitsubishi pilot-scale MBR and a Zenon pilot-scale MBR were operated in parallel for over 6,500 h (270 d). To evaluate the feasibility of using MBR effluent for RO feed water, the effluents were further treated by a pilot-scale RO unit using Dow/Filmtec thin film composite membranes. The objectives of the study were to:

- Evaluate the MBR performance in both nitrification and nitrification/denitrification modes;
- Evaluate the suitability of the MBR effluent as RO feed water;
- Compare the treatment efficiency and operation reliability of two leading MBR manufacturers; and
- Develop preliminary cost estimates for the MBR technology in comparison to conventional secondary, tertiary and advanced wastewater treatment.

3. CONCLUSIONS AND RECOMMENDATIONS

3.1 Conclusions from Pilot Testing

- The MBR pilot systems were capable of producing a good quality effluent water suitable for use by an RO system.
- Both membranes were operated at reasonable cleaning intervals.
- Both systems showed very high removal of total and fecal coliforms and total coliphage.
- Excellent organic removal was achieved by both MBRs.
- Both MBR pilot systems showed moderate phosphorous removal during Part 1.
- The Zenon MBR pilot system achieved complete nitrification and partial denitrification during Part 1, and complete nitrification during Part 2.
- The Mitsubishi MBR pilot system achieved complete nitrification and partial denitrification during Part 1, and complete nitrification during Part 2.
- The Mitsubishi MBR ran at an 8-hour 15% flux increase over a 5-day period with minimal fouling during Part 1, and both systems ran well at an 8-hour 25% increase in flux over a 5-day period with minimal fouling during Part 2.
- Both RO pilot units showed continuously high salt rejection.
- The RO pilot unit following the Mitsubishi MBR only required one chemical clean during the duration of Part 1, and was not cleaned during Part 2.
- The RO pilot unit following the Zenon MBR did not require a chemical clean during the duration of Part 1, however it was operated at a lower flux than the RO skid following the Mitsubishi MBR , and was not cleaned during Part 2.
- The air flowrate used to agitate the membrane fibers is a critical parameter in respect to membrane cleaning intervals.

3.2 Conclusions from Cost Analysis

To establish relative costs, the MBR was compared to a conventional process using an oxidation ditch as a treatment tool for three different purposes: 1) producing 30/30 secondary effluent; 2) producing California Title 22 tertiary effluent; and 3) producing water suitable for repurification via reverse osmosis. All costs were based on a constant flow, 1 or 5 MGD plant that skims sewage from a regional system and returns the residuals to the sewer. The conclusions were:

- The oxidation ditch is the most cost-effective process for producing secondary effluent quality water.
- The oxidation ditch with tertiary filtration and disinfection is the most cost-effective process for producing California Title 22 reclaimed water.
- The MBR process is the most cost-effective process for producing water suitable for RO membranes.

It should be noted that none of these costs include consideration for the cost of land, a consideration where MBR has substantial advantages.

3.3 Other Conclusions

- Capillary Suction Tests showed a slight relationship between dewaterability and MLSS concentration. The larger MLSS values showed better sludge dewaterability.
- The Zenon MBR was capable of operating with intermittent aeration of the membrane with no decline in membrane performance.
- MBR needs to have sufficient free board and a sprayer system in order to control foaming episodes.
- An appropriate aeration system needs to be designed in order to achieve nitrification all of the time.
- The anoxic tank needs to be well mixed in order to prevent foam build-up.

3.4 Recommended Future Work

This project has demonstrated successful performance of the MBR process at the pilot-scale. It is the team's overall recommendation that the City of San Diego and the USBR carry this forward to a full-scale demonstration at the 1 or 5-MGD level. This will address any scale-up issues with the technology and evaluate the long-term performance of the MBR technology including operation and maintenance (O&M) issues. The demonstration scale project will also develop more accurate and refined capital and O&M costs for MBR.

4. MATERIALS AND METHODS

4.1 Testing Site

All pilot testing was performed at the Aqua 2000 Research Center at the San Pasqual Water Reclamation Plant (SPWRP) in Escondido, California.

4.2 Primary Effluent

The pilot units were operated on the same municipal primary effluent wastewater that was being treated by the SPWRP. The primary treatment processes included a travel screen, a vortex grit chamber, a rotary drum screen, and a rotary disc filter. The charecteristics of the primary effluent are presented in the "Results and Discussion" sections.

4.3 Experimental Set-Up

Figures 4-1 and **4-2** are schematic diagrams of the pilot treatment trains for Part 1: nitrification/denitrification and Part 2: nitrification only, respectively.

4.3.1 Mitsubishi MBR

The Mitsubishi MBR pilot unit was equipped with a 1,259-gal (4.77m^3) serpentine 3-compartment anoxic tank and a 1,706-gal (6.46 m^3) aerobic tank. During the course of the study, two submerged propeller mixers were installed to keep the contents well mixed. The MBR was fed from the primary effluent break tank using a submersible pump controlled by the programmable logic controller (PLC). The primary effluent passed through a 0.5-mm screen before entering the anoxic zone. The mixed liquor was pumped from the anoxic tank to the aerobic tank during Part 1 of the testing. Overflow from the aerobic tank returned by gravity to the anoxic tank. Activated sludge was batch wasted once per day from the transfer line between the anoxic and aerobic tanks. In Part 2 of the testing, when the anoxic tank was not in service, batch wasting was from the aerobic tank overflow pipe. In Part 2, influent screens were taken out of service, and primary effluent was fed directly into the aerobic tank. The volume of the aerobic tank was increased to 1,886 gal (7.14 m^3), and a surface sprayer system spraying mixed liquor was installed to control aeration basin foaming.

Two membrane banks were submerged in the aerobic tank. Coarse bubble air diffusers agitated the membranes continuously as well as aerating the mixed liquor. Schematics of the Mitsubishi MBR during Part 1 and Part 2 of testing are given in **Figure 4-3** and **4-4,** respectively. Pictures of the Mitsubishi MBR pilot unit and the microfilter are shown in **Appendix D**. Each membrane bank consisted of 50, 10.76 ft^2 (1 m^2) Mitsubishi Sterapore HF microfiltration (MF) membranes with a total membrane surface area of 1,076 ft^2 (100 m^2). The hollow fibers are arranged horizontally and attached at both ends to two permeate lines. The membranes are operated under vacuum pressure. Membrane specifications are given in **Table 4-1.**

The first membrane tested during Part 1 had a design flaw that warranted its replacement. Apparently, plastic stitching down the center of the fibers to help support them caused more frequent fiber breakage. After three months of testing this membrane module was replaced with a new module that did not have the plastic stitching.

In Part 1 of the testing, the Mitsubishi MBR was operated at a target flux of 13 gfd (22 L/h-m^2). Initially, an operating cycle of 8 min production and 2 min relaxation was used. To allow production of sufficient water for the RO pilot plant, these conditions were changed to a cycle of 12 min production and a 2 min relaxation. The coarse bubble diffusers air flow rate was 41 scfm (1.2 m^3/min).

4.3.2 Zenon MBR

The Zenon MBR pilot unit was equipped with a 734-gal (2.78 m^3) anoxic tank, a 1,287-gal (4.87 m^3) aerobic tank and a 185-gal (0.7 m^3) ZenoGem unit. The MBR was fed with 3-mm prescreened primary effluent by a PLC-controlled submersible pump, placed in the primary effluent break tank. Anoxic tank mixed liquor flowed by gravity to the aerobic tank, from whence it was pumped to the ZenoGem tank. The ZenoGem tank mixed liquor overflowed back to the anoxic tank. A spray system sprayed mixed liquor on to the surface of the anoxic tank to control foam. During Part 2 of the testing, this spray system was placed in the aerobic tank.. At 1,471 h, the level of the aeration basin was raised in order to improve the suction head to the recirculation pump, causing the aeration basin volume to be 1,375 gal (5.20 m^3). Batch mixed liquor wasting was initially performed from the aerobic tank, and later from the ZenoGem tank. In Part 2 of the testing the anoxic tank was removed from service and the primary effluent was fed directly to the aerobic tank.

One membrane cassette was submerged in the ZenoGem tank where it was agitated with coarse bubble air diffusers. During Part 1, continuous coarse air in the ZenoGem tank was used, and in Part 2 the coarse bubble aeration was operated on a 10 s on and 10 s off cycle. Schematics of the Zenon MBR pilot unit during Parts 1 and 2 of the testing are shown in **Figures 4-5** and **4-6**, respectively. Pictures of the Zenon MBR pilot unit and the ultrafilter are shown in **Appendix D**. During the first 800 h of testing, the ZeeWeed OKC MF was evaluated. The remainder of the testing was performed with ZeeWeed OCP UF membrane. The performance of the MF and the inability to achieve acceptable coliform rejection warranted replacement. The specifications of both membranes are given in **Table 4-2**.

During the start-up period, the ZenoGem system was operated without an anoxic or aerobic tank. Operating conditions were flux = 6 gfd (10 L/h-m^2) using the OKC MF, and a cycle of 10 min production and a 15-s backpulse using product water. Once the full tankage (i.e. aerobic and anoxic tanks) had been installed the MBR was operated as follows: flux = 25 gfd (43 L/h-m^2); ZenoGem tank airflow = 25 scfm (0.7 m^3/min); aerobic tank airflow = 40 scfm (1.1 m^3/min); and the recycle ratio (RR) was set at 6. For the Zenon OCP UF membrane initial operating conditions were flux = 19 gfd (32 L/h-m^2) and ZenoGem tank airflow = 30 scfm (0.8 m^3/min). After demonstrating acceptable performance under these conditions, the flux was increased to 21 gfd (36 L/h-m^2).

4.3.3 RO Pilot Units

Each RO pilot unit housed two pressure vessels in series that were operated in a single pass mode. Each pressure vessel contained 3 spiral-wound 4 in by 40 in (10.2 cm x 101.6 cm) thin film composite (TFC) RO membranes with a surface area of 78 ft^2 (7.2 m^2) per element. Both RO pilot units contained Dow/Filmtec low-pressure polyamide BW30-4040 RO membranes that were operated in a constant flux, variable pressure mode. A target chloramine residual of 1 to 2-mg/L was maintained in the RO feed water to control biological and organic fouling. The RO influent was also dosed with a manufacturer-recommended antiscalant[1] at 1-mg/L, and was filtered through a 5-µm cartridge filter. Cartridge filter effluent was passed through a high-pressure pump to the first pressure vessel. **Table 4-3** contains the RO specifications.

The Mitsubishi MBR was operated with 6 membrane elements at a 12-gfd (20.4 L/h-m^2) flux for the duration of the study. Because the Zenon MBR only produced sufficient effluent to operate the downstream RO unit at 6 gfd (10 L/h-m^2), 3 of the RO elements were replaced with 3 dummy elements to increase the flux to 12 gfd in Part 2.

4.3.4 Determination of Calculated Parameters

Pressure Calculations

The net operating pressure (P_{net}) for the RO systems was calculated as follows:

$$P_{net} = \frac{(P_i - P_o)}{2} - P_p - \Delta p \tag{1}$$

Where,

P_{net} = Net operating pressure (psi)
P_i = Pressure at pressure vessel inlet (psi)
P_o = Pressure at pressure vessel outlet (psi)
P_p = Permeate pressure
$\Delta\pi$ = Net osmotic pressure of the feed and permeate (psi)

The integrated averaging factor (IAF) assuming 100% salt rejection can be used to estimate the osmotic pressure as follows:

$$\Delta p = IAF \times p_f \tag{2}$$

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[1] King Lee Technologies, Pretreatment Plus 0100, San Diego, CA

Where,

π_f = Osmotic pressure of the feed stream (psi)
IAF = 1.386 (for 50% recovery)

For the RO membranes, the following approximate rule of thumb can be used:

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

Flow Calculations

The net permeate rate for the Mitsubishi MBR can be calculated from:

$$Q_{\text{NET}} = \left(\frac{t_{ON} - t_{OFF}}{t_{ON}} \right) \times Q_P \tag{3}$$

Where,

Q_{NET} = Net permeate rate (gpm)
t_{ON} = MBR membrane production time (min)
t_{OFF} = MBR membrane relaxation time (min)
Q_p = Permeate flow rate (gpm)

The Zenon MBR net permeate rate can be calculated from:

$$Q_{NET} = \frac{Q_P t_{ON} - V_{BP}}{t_{ON} + t_{BP}} \tag{4}$$

Where,

V_{BP} = Backpulse volume (gal)
t_{BP} = Backpulse time (min)

Flux Calculation

The flux of the RO membranes and the MBR membranes can be calculated as follows:

$$J = \frac{Q_p \times 1440}{A} \tag{5}$$

Where,

J = Membrane flux (gfd)
A = Total membrane surface area (ft^2)

Temperature Correction

Low-pressure membrane fluxes are normally adjusted to a temperature of 20°C, and RO membrane fluxes are adjusted to a temperature of 25°C using:

$$J\ @\ 20°C = J \times e^{-0.0239(T-20)} \tag{6}$$

Where,

T = Feed water temperature (°C)

The RO membranes were temperature corrected according to manufacturer’s correction factors.

Specific Flux

The specific flux is the relationship between flux and the net operating pressure as follows:

$$J_{SP} = \frac{J}{P_{Net}} \tag{7}$$

Where,

J_{SP} = Specific flux (gfd/psi)

The temperature-corrected specific flux can be calculated using the temperature corrected flux.

Salt Rejection

The salt rejection by the RO membranes can be calculated as follows:

$$R = 100\left(1 - \frac{c_P}{c_f}\right) \tag{8}$$

Where,

R = Rejection (%)
c_p = Permeate conductivity (µmho)
c_f = Feed conductivity (µmho)

Hydraulic Retention Time

The hydraulic retention time (HRT) for the MBR pilot units was calculated from:

$$HRT = \frac{V}{Q_{NET} \times 60} \tag{9}$$

Where,

HRT = Hydraulic retention time (h)
V = MBR volume (gal)

Sludge Retention Time

Activated sludge was wasted directly from the MBR aeration tank, which was assumed to be completely mixed. The sludge retention time (SRT) is defined as the total mass of activated sludge in the MBR divided by the total mass of activated sludge removed. Since the permeate contained a negligible amount of suspended solids, wasting from the aeration tank is the only way in which suspended solids are removed. Using these assumptions, the SRT is:

$$SRT = \frac{VX_R}{Q_W X_W} = \frac{V}{Q_W} \tag{10}$$

Assuming that X_R is equal to X_W.

Where,

SRT = Solids retention time (days)
X_R = Mixed liquor volatile suspended solids (mg/L)
X_W = Waste stream volatile suspended solids (mg/L)
Q_W = Waste stream flow rate (gpd)

The 7-d SRT ($SRT_{7\text{-}d}$) is calculated by averaging the SRT over 7 previous days as follows:

$$SRT_{7-d} = \frac{SRT_{n=1} + SRT_{n=2} +_{...} + SRT_{n=7}}{7} \tag{11}$$

Where,

$SRT_{7\text{-}d}$ = 7-d average SRT
N = day

Recycle Ratio

The recycle ratio (RR) is defined as the ratio of the flow of mixed liquor from the aerobic tank to the anoxic tank, divided by the net permeate rate. Because mixed liquor from the anoxic tank was pumped to the aerobic tank, and returned by gravity, only the flow rate from the anoxic tank to the aerobic tank was recorded. The recycle ratio (RR) was calculated as follows:

$$RR = \frac{Q_R - Q_{NET}}{Q_{NET}} = \frac{Q_R}{Q_{NET}} - 1 \qquad (12)$$

Where,

RR = Recycle ratio
Q_R = Flow rate from the anoxic tank to the aerobic tank (gpm)

4.3.5 Chemical Additions

Combined Chlorine for the RO Influent

To control biological and organic fouling of the RO membranes, a 1-2 mg/L combined chlorine residual was maintained in the RO influent by in-line dosing of MBR effluent with 15% NaOCl solution (using a chemical metering pump[2]) and addition of 12% NH_4Cl solution was added using a chemical metering pump.[3]

RO Membrane Antiscalant Addition

To control inorganic scaling of the RO membranes an antiscalant product[4] was added in-line and upstream of the RO membranes at the manufacturer's recommended dosage of 1 mg/L using a chemical metering pump.[5]

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[2] LMI Milton Roy, Model P121, Acton, MA
[3] LMI Milton Roy, Model P131, Acton, MA
[4] King Lee Technologies, Pretreatment Plus 0100, San Diego, CA
[5] LMI Milton Roy, Model P121, Acton, MA

4.3.6 Chemical Cleaning of Membranes

All chemical cleanings were performed using manufacturers' recommendations. A complete list of cleaning protocols can be found in **Appendix B**.

The Zenon MBR membranes were cleaned with a 2,000-mg/L NaOCl solution. The ZenoGem tank was drained and isolated and the membranes were cleaned in place. A maintenance clean was performed on the Zenon MBR once per week using a 200-mg/L NaOCl solution. The Mitsubishi MBR chemical cleaning was performed using a 3,700-mg/L solution of NaOCl in place in the presence of the mixed liquor.

4.4 WATER QUALITY

4.4.1 On-site Water Quality Analyses

Temperature

The temperatures of the MBR aerobic and anoxic tanks were monitored using a digital temperature probe.[6] RO influent temperature was determined using an on-line pH and temperature probe.[7]

pH

Primary effluent, MBR effluent and RO effluent pH was determined using a portable pH meter.[8]

Particle Count

MBR effluent particle counts were measure using an on-line particle counter[9] and was recorded on a personal computer using data acquisition software.[10] The particle counters were set to monitor 2, 5, 10 and 15-µm sized particles every min.

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[6] VWR Scientific Products

[7] Rosemount Analytical SoluComp

[8] Hach Co., EC20 pH/ISE meter, Loveland, CO

[9] Hach Co., 1900 WPC Particle Counter, Loveland, CO

[10] Hach Co, AquaView+, Loveland, CO

Turbidity

MBR effluent turbidity was determined using an on-line turbidimeter[11] and the data was recorded by a personal computer using acquisition software.[12] MBR effluent and primary effluent turbidities were also determined using a bench top turbidimeter.[13]

Silt Density Index (SDI)

Silt Density Index (SDI) analyses were performed on the MBR effluents using an SDI machine[14], which filters a water sample through a disposable 0.45-µm filter and continuously monitors the flow rate at a constant pressure for 15-min.

Total Organic Carbon (TOC)

MBR effluent and the RO permeate total organic carbon (TOC) concentrations were determined using one of two TOC analyzers.[15] One TOC analyzer was dedicated to make low TOC analyses from the RO effluent, and the second was used for the higher TOC samples from the MBR effluents. Grab samples were collected and analyzed on a routine basis.

UV-254 Absorbency

Samples for TOC analysis were also analyzed for UV-254 absorbence using a spectrophometer.[16]

Conductivity

RO influent and effluent conductivity was determined using two bench top conductivity meters.[17] RO influent and effluent conductivity was also monitored using on-line conductivity meters.[18]

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[11] Hach Co., Model 1720C, Loveland, CO

[12] Hach Co, AquaView+, Loveland, CO

[13] Hach Co, Model 2100N, Loveland, CO

[14] Chemetek, FPA-2000, Portland, OR

[15] Sievers 800 portable Total Organic Carbon Analyzer, Boulder, CO

[16] Hach Co., DR/4000U spectrophotometer, Loveland, CO

[17] Fisher Scientific, Digital Conductivity Meter, Pittsburgh, PA

[18] Myron L Company, Series 750

Chlorine Residual

The total chlorine residual grab samples of the RO influent was monitored using the DPD method.[19]

Ammonia, Nitrate, Nitrite, and Orthophosphate

The ammonia, nitrate, nitrite and orthophosphate concentrations in the primary effluent, MBR effluent and RO effluent were analyzed on grab samples using the Nessler method, cadmium reduction method, diazotization method and the PhosVer 3 method, respectively.[20]

Capillary Suction Test

Grab samples of mixed liquor were analyzed for capillary suction test (CST) using a CST analyzer.[21]

4.4.2 Off-Site Water Quality Analyses

Several water quality parameters were analyzed by off-site laboratories. Throughout the project, the San Diego Marine Microbiology Laboratory, the San Diego North City Water Reclamation Plant Laboratory, the San Diego Water Quality Laboratory and Montgomery Watson Laboratories were used to analyze water quality parameters. **Table 4-4** summarizes the detection limits, sampling frequencies and methods used for all of the laboratory analyses.

4.4.3 Sampling Protocol

All water quality samples were grab samples collected in sample containers provided by the appropriate laboratory. All samples were transported to the appropriate laboratory in a cooler and were processed within the allowable holding period. When sampling from sample ports, they were flushed before sample collection. All microbial samples were collected using aseptic techniques. Sample ports were flamed and flushed before sample collection.

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[19] Hach Co., DR/4000U spectrophotometer, Loveland, CO
[20] Hach Co., DR/4000U spectrophotometer, Loveland, CO
[21] Triton Electronics, Ltd., Type 304B Capillary Suction Timer, Essex, UK

4.4.4 Quality Control/Quality Assurance

Every effort was made at the pilot site to attain the highest amount of quality control and quality assurance. **Appendix C** contains memoranda that document the QA/QC performed at the beginning and the end of the pilot testing.

5. RESULTS AND DISCUSSION PART 1: NITRIFICATION/DENITRIFICATION OPERATION

5.1 MBR Operating Conditions

During Part 1 of the testing, the Mitsubishi MBR system was operated with an anoxic tank and an aerobic tank together having an HRT of 6 h and an internal recycle ratio (RR) of 3. The mixed liquor wasting rate was set to give an SRT of 12 d and an MLSS concentration of 10,000-12,000 mg/L. The HRT and $SRT_{7\text{-d}}$ values are presented in **Figure 5-1**. The DO concentrations, shown in **Figure 5-2,** of the aerobic tank and anoxic tank ranged from 0.5 to 4.0 mg/L and from 0.3 to 1.3 mg/L, respectively. The total MLSS and MLVSS concentrations for the Mitsubishi MBR are shown in **Figure 5-3.** After the initial seeding of the MBR**,** the reactor solids concentration was allowed to increase. The lack of mixing in the anoxic tank at the beginning of the study caused excessive foaming in the anoxic tank, and the anoxic tank had to be drained after 1,141 h (48 d) of operation. Two mixers were installed in the anoxic tank. One of the mixers failed at 4,388 h (183 d) causing an apparent decrease in solids concentration because a foam layer formed again that contained a large portion of activated sludge solids. This foam layer was not included in the TSS sample. After 4,926 h (205 d) of operation, the system was subjected to a shock load[22] that caused it to foam significantly causing a solids loss that substantially decreased the solids concentrations. The lower graph in **Figure 5-3** shows that the normal sludge wasting rate was between 4-6 kg VSS/d.

The Zenon MBR was operated with aerobic and anoxic tanks and with the ZeeWeed OKC MF at a flux of 25 gfd (43 L/h-m^2), an HRT of 5.6 h and an RR of 6. The ZeeWeed UF was initially operated at a flux of 19 gfd (32 L/h-m^2), and later at a flux of 21 gfd (36 L/h-m^2) and an HRT of 5.3 h. The mixed liquor wasting rate was set to give an SRT of 21 d and an MLSS concentration of 8,000-10,000 mg/L. The HRT and $SRT_{7\text{-d}}$ values are presented in **Figure 5-4.** The DO concentrations in the Zenon aerobic and anoxic tanks are shown in **Figure 5-5.** The aerobic tank DO concentrations ranged from 0.43 to 4.5 mg/L after the full system was installed, and from 0.37 to 0.80 mg/L in the anoxic tank. The Zenon MBR MLSS and MLVSS concentrations are shown in **Figure 5-6.** A shock load was detected at 3,651 h (152 d) which caused foaming in the Zenon system, but the solids levels were unaffected because there was sufficient freeboard to keep the foam in the reactor. The lower graph in **Figure 5-6** shows that the sludge wasting rate was between 2-4 kg VSS/d.

5.2 Membrane Performance

5.2.1 MBR Pilot Plants

Figure 5-7 shows the membrane performance of the Mitsubishi MBR during Part 1 of the testing. A chemical cleaning was performed after 1,652 h (69 d) with the original membrane

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[22] Lab analyses of the foam showed that the following chemicals were present: cineole, pinene, camphene, pinane, camphogen, and terpinene. These compounds are typically found in eucalyptus oil, pine oil, pharmaceuticals, disinfectants, deodorants and polishes.

which resulted in a reduction in vacuum pressure from 4.27 psi (0.29 bar) to 1.42 psi (0.10 bar). After the new membrane was installed, the system ran for 1,986 h (83 d) before a chemical clean was performed. The chemical cleaning reduced the vacuum pressure from 3.98 psi (0.27 bar) to 2.56 psi (0.18 bar). Both of these first two cleanings were performed by backpulsing chlorine solution over a 2-h period as recommended by the manufacturer. To achieve better recovery of membrane performance, all subsequent cleanings of the new membranes were performed by backpulsing chlorine solution over a 3-h period. These took place after 864 h (36 d), and again after 823 h (34 d). The second cleaning of the new membranes reduced the vacuum pressure from 4.41 psi (0.30 bar) to 2.13 psi (0.15 bar). The final membrane cleaning during Part 1 reduced the vacuum pressure from 4.27 psi (0.29 bar) to 2.70 psi (0.19 bar).

Figure 5-8a shows the membrane performance of the Zenon MBR during Part 1 of the testing. The membrane was not chemically cleaned during the start-up period. Once the full system was installed, it ran for 185 h (8 d) before reaching a vacuum pressure that required a chemical cleaning. However, rather than doing this, the flux was lowered to 20 gfd (34 L/h-m^2) until the ZeeWeed OCP UF membrane could be installed. The OCP membrane ran for 2,082 h (87 d) before chemical cleaning. The chemical cleaning reduced the vacuum pressure from 8.10 psi (0.56 bar) to 1.47 psi (0.10 bar). At about this time, the manufacturer recommended that the backpulse pressure be decreased. Following the chemical cleaning, the membrane fouled rapidly. It was thought that the cause of fouling was the decreased back pulse pressure, but returning the back pulse pressure to its initial value did not remedy the fouling. Further investigation revealed that the blower airflow in the ZenoGem tank had decreased because of a blower malfunction, and the decrease in airflow corresponded to the rapid fouling events as can be seen in **Figure 5-8b.** This experience indicates that the importance of maintaining a sufficient airflow for preventing membrane fouling in the Zenon system.

5.2.2 RO Pilot Units

Figure 5-9 shows the membrane performance of the RO pilot unit operating at 12 gfd (20 L/h-m^2) and a 50% recovery treating Mitsubishi MBR effluent during Part 1 of the testing. The RO unit ran for 2,345 h (98 d) before a chemical cleaning was needed and following this cleaning it ran for another 1,143 h (48 d) without a need for chemical cleaning.

Figure 5-10 shows the membrane performance of the RO pilot unit treating Zenon MBR effluent during Part 1 of the testing. Because of the changes in flowrate of the Zenon MBR during Part 1, the RO flux was adjusted from 12 gfd (20 L/h-m^2) to 6 gfd (10 L/h-m^2) and finally to 9 gfd (15 L/h-m^2), and producing a recoveries of 50%, 33% and 43%, respectively. The RO unit ran for 3,350 h (140 d) with minimal fouling.

5.3 Water Quality

5.3.1 Primary Effluent

The results of primary effluent grab sample analyses by the San Diego Water Quality Laboratory are presented in **Table 5-1.**

5.3.2 MBR Pilot Plants

Turbidity, Silt Density Index (SDI), and Particle Counts

The Mitsubishi MBR effluent turbidity grab samples and SDI values are shown in **Figure 5-11**. The primary effluent turbidity was in the range of 14-170 NTU. The MBR effluent was below 0.2 NTU when the first membrane was in service and less than 0.1 NTU after the second membrane was installed. SDI values were below 2.6 when the first membrane was in service, and less than 2.0 after the second membrane was installed. The on-line particle count and turbidity data over an 8-h period between 3,986-3,994 h of operation for the Mitsubishi MBR effluent can be seen in **Figures 5-12**. The counts for particles ≥2 µm were between 4 and 20 particles/mL, and the turbidity values were consistently around 0.06 NTU.

The effluent turbidity and SDI values for the Zenon MBR are presented **Figure 5-13**. The primary effluent turbidity ranged from 14-170 NTU, and the MBR effluent was always below 0.1 NTU following the installation of the UF membrane. The MBR effluent SDI values for the Zenon MBR were less than 2.0 following the installation of the UF membrane. The on-line particle count and turbidity data over an 8-hour period between 2,736 and 2,744 h of operation for the Zenon MBR effluent can be seen in **Figure 5-14**. The counts for particles ≥2 µm were between 1 and 20 particles/mL, and turbidity values were consistently around 0.04 NTU.

BOD_5, COD and TOC

The BOD_5, COD and TOC values for the primary effluent and for the Mitsubishi MBR permeate are shown in **Figure 5-15**. A majority of the MBR effluent BOD_5 values were below the detection limit, and where they are above this they correspond to high NH_3-N levels in the MBR effluent. Therefore, since nitrification was not inhibited in the BOD_5 test, the elevated values are most likely due to ammonia oxidation in the BOD_5 test. MBR effluent COD and TOC values were <35 mg/L and <8 mg/L, respectively.

The BOD_5, COD and TOC values for the primary effluent and Zenon MBR permeate are shown in **Figure 5-16**. A majority of the MBR effluent BOD_5 values were below the detection limit. Most of of the MBR COD and TOC effluent samples were <20 mg/L and <7 mg/L, respectively.

Biological Nutrient Removal

The on-site inorganic nitrogen results from the Mitsubishi MBR are shown in **Figure 5-17.** The system completely nitrified at times with effluent NH_3-N values <1 mg-N/L, but not always because the coarse bubble diffusers did not provide enough oxygen producing values as high as 24 mg-N/L. In part 2 of the testing, supplemental aeration was installed to promote nitrification. The effluent NO_3-N values were between 0.5 and 25 mg-N/L and all of the NO_2-N values were less than 5 mg-N/L. The on-site PO_4-P results of the Mitsubishi MBR are shown in **Figure 5-18**. The primary effluent values were between 2 and 7 mg-P/L, and the majority of the effluent values were <1 mg-P/L. There does seem to be a decrease in PO_4-P concentration because of biological phoshporus removal (BPR) due to low NO_3 concentrations in the anoxic tank creating the anaerobic zone necessary for BPR. The beginning and end of the testing period show a decline in BPR that corresponds to a decrease in denitrification. The presence of NO_3 in the anoxic tank created an anoxic environment that was not conducive to BPR.

The on-site inorganic nitrogen results from the Zenon MBR effluent are shown in **Figure 5-19.** The system did show complete nitrification at times with values <1 mg-N/L. The majority of NH_3-N values were less than 5 mg-N/L. The NO_3-N values were between 2 and 25 mg-N/L and all of the NO_2-N values were < 5 mg-N/L. The system did not achieve total denitrification, but did achieve partial denitrification most of the time. The on-site PO_4-P results are shown in **Figure 5-20.** The primary effluent had values between 2 and 7 mg-P/L, and the effluent of the Zenon MBR had values between <1 and 4.5 mg-P/L, with a majority of the samples <1 mg-P/L. There does seem to be a decrease in PO_4-P because of BPR. However, the BPR continues in the presence of NO_3 in the anoxic tank. The Zenon anoxic tank was not mixed, unlike the Mitsubishi anoxic tank, which could have resulted in anaerobic regions in the anoxic tank that caused BPR in the presence of NO_3.

Total Coliform, Fecal Coliform, Total Coliphage

The primary effluent and Mitsubishi MBR effluent total coliform, fecal coliform and total coliphage are shown in **Figure 5-21.** A majority of the samples were <2 MPN/100 mL (coliforms), and <2 PFU/100 mL (coliphage), giving an overall log removal of >6 for the total and fecal coliforms and >3 log removal of coliphage.

The primary effluent and Zenon MBR total coliform, fecal coliform and total coliphage results are shown in **Figure 5-22.** The total coliform values in the MBR effluent ranged from <2 to 1,600 MPN/100 mL. The fecal coliforms in the MBR effluent ranged between 2-1600 MPN/100 mL when the MF was in operation. Upon the installation of the UF, the majority of the fecal coliforms were <2 MPN/100mL. This data suggests that the larger pores in the UF gradually became permanently plugged causing the effluent coliform concentration to gradually decrease. The sudden decrease in MBR effluent fecal coliforms could have been due to the lower fecal coliform concentration in the primary effluent. The total coliphage values gave an overall log removal of >3.

Other Water Quality Parameters

The Mitsubishi MBR grab samples analyzed by the Water Quality Laboratory can be seen in **Table 5-2.** The Zenon MBR samples analyzed by the Water Quality Laboratory can be seen in **Table 5-3.**

5.3.3 RO Pilot Units

Inorganic Nitrogen and Ortho-Phosphate Removal

The Mitsubishi MBR RO pilot unit effluent inorganic nitrogen species are shown in **Figure 5-23.** The RO permeate NH_3-N values were between 0.01 and 1 mg-N/L; the NO_3-N values were between 0.02 and 0.4 mg-N/L; and the NO_2-N values were all between 0.003 and 0.05 mg-N/L. The Mitsubishi MBR RO pilot unit effluent PO_4-P values can be seen in **Figure 5-24.** All samples were collected as grab samples and analyzed on-site. The PO_4-P values were <0.3 mg-P/L.

The Zenon MBR RO pilot unit effluent inorganic nitrogen species are shown in **Figure 5-25.** The RO permeate NH_3-N values were between 0.02 and 1 mg-N/L; the NO_3-N values were between 0.02 and 0.5 mg-N/L; and the NO_2-N values were all between 0.003 and 0.05 mg-N/L. The Zenon MBR RO pilot unit effluent PO_4-P values are shown in **Figure 5-26**. The PO_4-P values were <0.4 mg-P/L.

Salt Rejection

The feed and permeate conductivities for the Mitsubishi MBR RO Pilot unit are shown in **Figure 5-27.** The RO membranes produced a percent rejection, based on conductivity, of greater than 98% throughout the testing.

The feed and permeate conductivities for the Zenon MBR RO Pilot unit are shown in **Figure 5-28.** The RO membranes produced a dito of greater than 98% throughout the testing.

Other Water Quality Parameters

The Mitsubishi MBR RO samples analyzed by the Water Quality Laboratory can be seen in **Table 5-4.** The Zenon MBR RO grab samples analyzed by the Water Quality Laboratory can be seen in **Table 5-5.**

5.4 Peaking Study

The results of the Mitsubishi MBR peaking study can be seen in **Figure 5-29.** The MBR flux was increased from 13 gfd (22 L/h-m^2) to 15 gfd (26 L/h-m^2) over an 8-h period in the day. After the 8-h increase, the flux was returned to the target flux of 13 gfd. There was no significant vacuum increase over the 5-d testing period.

A peaking study was not performed on the Zenon MBR at the end of Part 1 of the testing because one of the blowers malfunctioned and the system had to be shut down until it could be repaired.

6. RESULTS AND DISCUSSION- PART 2: NITRIFICATION TESTING

6.1 MBR Operating Conditions

At the end of Part 1 of the pilot testing, both MBR systems were shut down and retrofitted to operate in a "nitrification-only" mode. The anoxic tanks were taken out of service, and all membranes were chemically cleaned before beginning Part 2 of the pilot testing. The Mitsubishi membrane was soaked overnight in a 1,000 mg-NaOCl/L solution. The Zenon MBR was soaked overnight in a 2,000 mg-NaOCl/L solution, followed by a citric acid soak overnight. Both RO systems were chemically cleaned according to the manufacturer's recommendations. The MBR systems were seeded with activated sludge from the NCWRP and they were operated without activated sludge wasting to allow the MLSS to increase to the target values of 8,000 mg/L. Once these values were reached, activated sludge was wasted once every day.

The Mitsubishi MBR was operated at a target flux of 13 gfd (22 L/h-m^2) during Part 2 of the testing. The membrane was in operation for 12 min and then relaxed for 2 min. The aerobic tank HRT was 3.8 h and the target SRT_{7-d} was 10 days. The HRT and SRT_{7-d} values can be seen in **Figure 6-1.** The DO concentrations in **Figure 6-2** were in the range of 1-5 mg/L. The MLSS and MLVSS concentrations in the Mitsubishi MBR are shown in **Figure 6-3.** The target TSS was 8,000 mg/L for Part 2 of the study to achieve adequate oxygen transfer. A sudden decrease in MLSS at 1,130 h was attributed to a shock load that caused foaming out of the reactor and solids loss. Following the shock load, MLSS was increased back to its target value by stopping the sludge wasting until the MLSS level reached 8,000 mg/L. The overall sludge wasting rate (**Figure 6-3)** was 4-6 kg of VSS/d.

During Part 2 of the pilot testing, the Zenon MBR was operated at a target flux of 19 gfd (32 L/h-m^2). The membrane was in operation for 10 min, after which time it was backpulsed for 15 s using product water. The aerobic tank HRT was 4 h and the target SRT_{7-d} was also 10 days. The HRT and SRT_{7-d} charts can be seen in **Figure 6-4**. The coarse bubble aeration in the ZenoGem tank was operated at 30 scfm (0.8 m^3/min) intermittently (10 s on, 10 s off). The aeration tank air flowrate was set at 40 scfm (1.1 m^3/min). The Zenon aeration basin DO in **Figure 6-5** was maintained between 1-4 mg/L to encourage nitrification. The MLSS and MLVSS concentrations in the Zenon MBR are shown in **Figure 6-6.** The target MLSS was 8,000 mg/L basked on the manufacture's recommendation. The shock load at 817 h did not affect the Zenon system because there was sufficient freeboard to keep the foam in the aeration basin. The overall sludge-wasting rate (**Figure 6-6)** was between 2-4 kg of VSS/d.

6.2 Membrane Performance

6.2.1 MBR Pilot Plants

Figure 6-7 shows the membrane performance of the Mitsubishi MBR during Part 2. A chemical cleaning was conducted at the start-up of testing, then the MBR ran for a 1,337 h (56 d) before another chemical cleaning was required. This cleaning reduced the vacuum pressure from 4.6 psi (0.3 bar) to 2.6 psi (0.18 bar). Prior to the second chemical cleaning, a shock load caused excessive foam that resulted in a significant solids loss. Additional freeboard was constructed to prevent any such future events. Following that chemical cleaning, the MBR ran for 987 h (41 d) before another cleaning was required. This final cleaning lowered the vacuum pressure from 4.1 psi (0.28 bar) to 2.9 psi (0.20 bar). At 1,769 h (74 d), the MBR influent supply was interrupted for 3 d because of a pipe line break, and the MBRs were unable to operate.

Figure 6-8 shows the membrane performance of the Zenon MBR during Part 2. The pilot unit was operated for 1,007 h (42 d) under continuous aeration to observe its fouling trend. After this, intermittent aeration was started, and the fouling trend appeared to be unaffected by the use of intermittent aeration. The membrane ran without chemical cleaning for a period 2,087 h (87 d) during which the vacuum pressure increased from 1.72 psi (0.12 bar) to 3.49 psi (0.24 bar).

6.2.2 RO Pilot Units

During Part 2 of the testing, the RO pilot unit treating the Mitsubishi MBR effluent was operated at a target flux of 12 gfd (20 L/h-m^2) with 50% recovery. **Figure 6-9** shows the RO membrane performance. The RO unit ran for a total of 1,985 h (83 d) without a chemical cleaning.

During Part 2 of the testing, the RO pilot unit treating the Zenon MBR effluent was operated at a target of flux of 12 gfd (20 L/h-m^2) with a 32% recovery. To achieve this target flux using the Zenon MBR permeate flow, the total RO membrane surface area was reduced by replacing 3 of the 6 RO elements with dummy elements. **Figure 6-10** shows the ROmembrane performance. It ran for 1,796 h (75 d) without chemical cleaning.

6.3 Water Quality

6.3.1 Primary Effluent

The primary effluent grab samples analyzed by the Water Quality Laboratory can be seen in **Table 6-1.**

6.3.2 MBR Pilot Plants

Turbidity, Silt Density Index (SDI), and Particle Counts

The primary effluent turbidity (grab sample) ranged from 15 to 250 NTU. The MBR effluent turbidity was consistently below 0.1 NTU. The SDI values were all less than 1.2. The on-line particle count and turbidity data over an 8-h period between 1,398 h-1,406 h for the MBR effluent can be seen in **Figure 6-12**. The particle count data shows all particles ≥2 µm in diameter. The particle counts were between 10 and 40 particles/mL. The minima correspond to the relax when the particle counter shuts off and particle counts are very low. The turbidity values were between 0.06-0.07 NTU.

The effluent turbidity grab samples and SDI values for the Zenon MBR can be seen in **Figure 6-13**. The Zenon MBR effluent turbidity was <0.1 NTU while primary effluent turbidities ranged from 15-250 NTU. The Zenon MBR effluent SDI values were <1.0. The on-line particle count and turbidity data over an 8-h period between 1,121 h-1,129 h for the Zenon MBR effluent can be seen in **Figure 6-14**. The particle count data shows all particles ≥2 µm in diameter. The particle counts were in the range of 20-70 particles/mL. The turbidity values were between 0.04-0.055 NTU.

BOD_5, COD and TOC

The BOD_5, COD and TOC values for the primary effluent and the Mitsubishi MBR permeate are shown in **Figure 6-15**. All of the MBR effluent BOD_5 values were below the detection limit (initially was 3 mg/L, and was later set at 2 mg/L). The primary effluent COD samples ranged from 130 to 586 mg/L, and the MBR effluent samples ranged from 7 to 32 mg/L. The primary effluent DOC ranged from 9 to 17 mg/L and the MBR effluent ranged from 5 to 9 mg/L.

The BOD_5, COD and TOC values for the primary effluent and Zenon MBR permeate are shown in **Figure 6-16**. All BOD values were below the detection limit. The primary effluent COD samples ranged from 130 to 586 mg/L, and the MBR effluent samples ranged from 7 to 39 mg/L. The primary effluent DOC samples ranged from 9 to 17 mg/L, and the MBR effluent samples ranged from 5 to 7 mg/L.

Biological Nutrient Removal

The on-site inorganic nitrogen grab sample results are shown in **Figure 6-17**. The effluent NH_3-N concentration spikes at 53, 1,392 and 2,427 h coincide with chemical cleanings suggesting that the chlorine solution used in the chemical cleaning adversely affects the nitrifiers. Complete nitrification was achieved for some of this testing phase with effluent NH_3-N values <1 mg-N/L. The NO_3-N values were between 5-25 mg-N/L and NO_2-N values were <5 mg-N/L. The on-site PO_4-P results are shown in **Figure 6-18.** During Part 2 of the testing, there was no evidence of BPR in this completely aerobic system. The primary effluent had values between 4 and 7 mg-P/L, and the MBR effluent concentration was between 2-6 mg-P/L.

The on-site inorganic nitrogen grab sample results from the Zenon MBR effluent are shown in **Figure 6-19.** The system did show complete nitrification at times with MBR effluent values <1 mg-N/L. The majority of MBR effluent NH_3-N values were <5 mg-N/L. The effluent NO_3-N values were between 5-25 mg-N/L and the NO_2-N values were <5 mg-N/L. The on-site PO_4-P results are shown in **Figure 6-20.** During Part 2 of the testing, there was no evidence of BPR in this completely aerobic system. The primary effluent values were between 4 and 7 mg-P/L, and the effluent of the Zenon MBR was between 0.5-4 mg-P/L.

Total Coliform, Fecal Coliform, Total Coliphage

The primary effluent and Mitsubishi MBR permeate total coliform, fecal coliform and total coliphage are shown in **Figure 6-21**. A majority of the coliform samples were <2 MPN/100 mL, giving an overall removal of >6 logs. The total coliphage values were mostly <2 cfu/100 mL resulting in an overall removal of >3 logs.

The primary effluent and Zenon MBR permeate total coliform, fecal coliform and total coliphage are shown in **Figure 6-22.** A majority of the samples were <2 MPN/100 mL, giving an overall removal of >6 logs. The total coliphage values showed a removal of >3 logs.

Other Water Quality Parameters

The Mitsubishi MBR grab samples analyzed by the Water Quality Laboratory can be seen in **Table 6-2.** The Zenon MBR grab samples analyzed by the Water Quality Laboratory can be seen in **Table 6-3.**

6.3.3 RO Pilot Units

Inorganic Nitrogen and Ortho-Phosphate Removal

The Mitsubishi MBR RO pilot unit grab sample effluent inorganic nitrogen species are shown in **Figure 6-23.** The NH_3-N values were between 0.1-0.5 mg-N/L. The NO_3-N values were between 0.1-0.8 mg-N/Lm and the NO_2-N values were between .005-0.03 mg-N/L. The Mitsubishi MBR RO pilot unit effluent PO_4-P values can be seen in **Figure 6-24.** The values were <0.2mg-P/L.

The Zenon MBR RO pilot unit grab sample effluent inorganic nitrogen species are shown in **Figure 6-25.** The NH_3-N values were between 0.01-0.25 mg-N/L. The NO_3-N values were between 0.04-0.9 mg-N/L and the NO_2-N values were between 0.006-0.05 mg-N/L. The Zenon MBR RO pilot unit effluent PO_4-P values can be seen in **Figure 6-26.** The PO_4-P values were <0.2 mg-P/L.

Salt Rejection

The feed and permeate conductivies of grab samples for the Mitsubishi MBR RO Pilot unit are shown in **Figure 6-27.** The RO membranes showed a consistent salt rejection, based on conductivity measurement, of greater than 98% throughout the testing.

The feed and permeate conductivies for the Zenon MBR RO Pilot unit are shown in **Figure 6-28.** The RO membranes again showed a consistent rejection of greater than 98% throughout the testing.

TOC

The Mitsubishi MBR and Mitsubishi MBR RO permeate TOC grab sample values are shown in **Figure 6-29**. The RO membranes showed >90% rejection of TOC.

The Zenon MBR and Zenon MBR RO permeate TOC values are shown in **Figure 6-30.** The RO membranes showed >90% rejection of TOC.

Other Water Quality Parameters

The Mitsubishi MBR RO grab samples analyzed by the Water Quality Laboratory can be seen in **Table 6-4.** The Zenon MBR RO grab samples analyzed by the Water Quality Laboratory can be seen in **Table 6-5.**

6.4 Peaking Study

The results of the Mitsubishi MBR peaking study can be seen in **Figure 6-31.** The MBR flux was increased from 13 gfd (22 L/h-m^2) to 16 gfd (27 L/h-m^2) over an 8 h period in a day. After the 8-h increase, the flux was returned to the target flux of 13 gfd. This was repeated for 5 consecutive days to determine whether there was any fouling. The vacuum increase on the second day is probably due to a high influent organic load that caused organic fouling on the membrane surface. Overall the system performed well at a 25% increase in flux.

The results of the Zenon MBR peaking study can be seen in **Figure 6-32.** The MBR flux was increased from 19 gfd (32 L/h-m^2) to 24 gfd (41 L/h-m^2) over an 8-h period in the day. After the 8-h increase, the flux was returned to the target flux of 19 gfd. This was repeated over 5 consecutive days to observe any fouling. The vacuum increase on the second day is probably due to a high influent organic load that caused organic fouling on the membrane surface. Overall the system performed well at a 25% increase in flux.

6.5 Activated Sludge Dewatering

The normalized CST testing results (CST/MLSS) are plotted against MLSS in **Figure 6-33.** As MLSS concentration increases, the normalized CST value decreases somewhat suggesting that there is a slight increase in dewaterability with an increase in MLSS concentration.

7. MBR Performance Comparison

7.1 MBR Operating Conditions

The MBR pilot plants were completely automated and required minor attention. Both pilot plants required a well-mixed anoxic zone and a sprayer system for foam control. Two mixers were installed in the Mitsubishi MBR anoxic tank during Part 1, and a sprayer system was installed in the aerobic tank during Part 2. The Zenon MBR had sufficient free board for foam control, and the Mitsubishi MBR was equipped with additional freeboard during Part 2 of the study.

The Mitsubishi MBR relaxed during operation, and no backpulse was performed. This eliminates the additional pipes and/or valves necessary for the Zenon MBR which typically backpulse the membrane every 15 minutes. The membrane integrity of the Mitsubishi MBR is also less of an issue because the system does not backpulse. The applied vacuum pressure typically causes solids to clog broken fibers. Because the system does not backpulse, the membrane fibers become permanently sealed. If a fiber breakage occurs in the Zenon membrane, the repetitive backwashing will force solids out of the compromised fiber, and it will need to be repaired.

Both MBR pilot plants required coarse bubble aeration to agitate the membranes. The Zenon MBR required 30 scfm (0.8 m^3/min) and the Mitsubishi MBR required 41 scfm (1.2 m^3/min). The Zenon MBR successfully operated under intermittent aeration that decreased the overall air use by 50%. No intermittent aeration was tested for the Mitsubishi MBR. Additional aeration equipment was used in both systems to sufficiently aerate the activated sludge.

The Mitsubishi MBR had a simple clean-in-place procedure that did not require the membranes to be removed from the aeration basin. However, in a full-scale application, a crane and chemical clean tank is recommended for more effective cleanings. The Zenon MBR required a weekly chemical maintenance cleaning to achieve longer membrane run times. This was performed manually during the pilot testing, but is automated in full-scale installations. The Zenon MBR is not typically cleaned in place in full-scale applications, since the membranes need to be removed and placed in a chemical-cleaning tank.

7.2 Membrane Performance

Both membranes performed well throughout the study. There was no apparent compromise to membrane integrity detected in either system during the pilot testing. The Mitsubishi was chemically cleaned three times during Part 1 after 1,986 h (83 d), 864 h (36 d), and 823 h (34 d); and twice during Part 2 after 1,337 h (56 d) and 987 h (41). The Zenon MBR was cleaned once during Part 1 after 2,082 h (87 d), and ran for 2,087 h (87 d) during Part 2 without requiring a chemical cleaning. Overall, the Mitsubishi MBR did have shorter cleaning intervals than the Zenon MBR, however the membrane was operated for a 12-min cycle instead of the recommended 8-min cycle for a majority of the testing.

7.3.1 MBR Effluent Water Quality

7.3.1 Particulate Removal

The Mitsubishi MF and the Zenon UF produced effluent turbidity values of <0.15 NTU in 90% of the samples, as shown in **Figure 7-1**. The Zenon UF produced slightly lower turbidity values than the Mitsubishi membrane. However, the Zenon MF membrane achieved <0.2 NTU in <90% of the samples.

The Mitsubishi MF effluent and the Zenon UF effluent had SDI values <2 in 90% of all samples. (**Figure 7-2)**. The Zenon UF produced SDI values that were lower than the Mitsubishi MBR. However, the Zenon MF did not perform as well, yielding SDI values >3 in 50% of the samples.

7.2.2 Organics Removal

Both pilot plants achieved similar orgnanics removal throughout the duration of the study. The Mitsubishi MBR effluent achieved BOD_5 values <3 mg/L in 80% of all samples, and the Zenon MBR achieved values <3 mg/L in 90% of all samples. (**Figure 7-3)** A majority of the Mitsubishi MBR BOD_5 samples that were >3 mg/L resulted from ammonia oxidation in the BOD_5 test. The Mitsubishi MBR effluent had COD values <30 mg/L in 90% of all samples, and the Zenon MBR had <20 mg/L in 90% of all samples. (**Figure 7-4**) The Mitsubishi MBR effluent had TOC values that were <7 mg/L in 90% of all samples, and the Zenon MBR had values <6 mg/L in 90% of all samples. (**Figure 7-5**)

7.2.3 Biological Nutrient Removal

During Part 1 of the pilot testing, both systems produced effluent water with total inorganic nitrogen values of <10 mg/L in 30% of all samples. (**Figure 7-6)** The nitrification and denitrification of both systems was not consistent during the testing, however both systems exhibited an ability to remove inorganic nitrogen. The aeration system and tank design was not sufficient to achieve high inorganic nitrogen removal, and this needs to be corrected in future work. Both MBR pilot plants showed biological phosphorus removal producing effluent water with PO_4-P values of <1 mg/L in 60% of all samples during Part 1. (**Figure 7-7)**

The total inorganic nitrogen concentrations in the effluent of each pilot plant during Part 1 were much higher than during Part 2. The effluent concentrations were <20 mg-N/L in 50 % of all samples. (**Figure 7-8)** Lower biological phosphorus removal was observed during Part 2 as compared to Part 1 of the study, with 95% of all samples >1 mg/L. (**Figure 7-9)**

7.2.4 Total Coliform, Fecal Coliform, Total Coliphage

Both pilot plants removed total and fecal coliforms throughout the pilot testing. The Mitsubishi MF effluent total coliform concentration was ≤2 MPN/100 mL in 90% of all samples, and the

Zenon UF effluent total coliform was ≤2 MPN/100 mL in 50% of all samples, respectively. (**Figure 7-10)** The Zenon MF membrane produced positive total coliform in all samples.

The fecal coliform concentration in the Mitsubishi MF effluent were ≤2 MPN/100 mL in 99%+ of the samples, and the Zenon UF effluent samples were ≤2 MPN/100 mL in 96% of the samples. (**Figure 7-11**) The Zenon MF effluent contained fecal coliform in all samples.

The Mitsubishi MF effluent total coliphage concentration was ≤1 PFU/100 mL in 80% of all samples, and the Zenon UF effluent was ≤1 PFU/100 mL in 95% of all samples. (**Figure 7-12)** The Zenon MF effluent total coliphage concentration was ≤1 PFU/100 mL in70% of all samples.

8. COST ANALYSIS

8.1 Description of Evaluated Configurations

A cost analysis was performed to determine the feasibility of full-scale applications of the MBR process compared to current wastewater technology. Cost analyses were performed using various configurations to produce: secondary effluent, Title 22 reclaimed water and RO feed water. The following configurations were considered:

- Oxidation ditch capable of producing secondary effluent (Oxidation Ditch)
- Oxidation ditch with tertiary filtration and chlorination capable of producing Title 22 reclaimed water (Ditch+Filtr/Cl_2)
- Oxidation ditch with microfiltration and chlorination capable of producing Title 22 reclaimed water (Ditch+MF/Cl_2)
- Membrane Bioreactor with chlorination capable of production Title 22 reclaimed water (MBR+Cl_2)
- Oxidation Ditch with lime coagulation, flocculation, sedimentation and filtration capable of producing RO feed water (Ditch+C/F/S/F)
- Oxidation Ditch with microfiltration capable of producing RO feed water (Ditch+MF)
- Membrane Bioreactor capable of producing RO feed water (MBR)

Figures 8-1, **8-2** and **8-3** give a detailed breakdown of each wastewater configuration evaluated.

8.2 Design Criteria

Cost analyses were performed for 1 and 5-MGD (3,785 and 18,927 m^3/d) installations. All configurations were assumed to be scalping facilities designed for a constant flow of medium strength municipal wastewater with the following characteristics:

BOD_5	150 mg/L
TSS	150 mg/L
VSS	120 mg/L
NH_3-N	30 mg-N/L
TKN	40 mg-N/L

All installations were designed to completely nitrify (i.e. NH_4^+-N<0.5 mg/L) and meet a total nitrogen value of less than 10 mg-N/L (i.e. TKN+NO_2-N+NO_3-N<10 mg-N/L).

An oxidation ditch was chosen to represent conventional activated sludge treatment because of its cost competitiveness for small-scale applications. The higher HRT and SRT makes the process robust for small-scale applications. The oxidation ditch was designed using the following criteria:

HRT	24 hours
SRT	25 days
MLSS	4,000 mg/L

The MBR was designed using the following criteria:

HRT	4 hours
SRT	15 days
MLSS	10,000 mg/L

8.3 Capital Costs

Tables 8-1 and **8-2** show the capital costs for the 1 and 5-MGD installations, respectively. Each figure gives the total capital cost for each configuration and the amortized cost in $/y assuming an 8% interest rate over 20 y.

The headworks of all installations consisted of bar screens, grit chamber, lift pumps and odor control. The costs of these facilities (Western Consortium for Public Health, 1997) were taken from the existing costs for San Pasqual Water Reclamation Plant (SPWRP) and adjusted to the current Engineering News-Record Construction Cost Index (ENRCCI) value of 7056.

The screening facility for the MBR consisted of rotary disk filter (nominal pore size = 250 μm), rotary drum screen and odor control. Its costs were taken from existing SPWRP facilities and adjusted to the current ENRCCI value. This primary treatment was chosen because it was suitable for the pilot-scale MBR systems.

The costs of the secondary, tertiary and disinfection processes were adjusted to the current ENRCCI value. The original costs (Richard et al., 1992) were also adjusted for a scalping facility that did not experience peak daily flows by designing secondary clarifiers, tertiary filters, chlorine contact chamber, and the flocculation, coagulation, sedimentation and filtration process that operated at a constant flowrate.

The cost of the microfiltration unit was adapted from the current pricing of the US Filter/Memcor recent installations in California. The microfiltration unit is a U.S. Filter Memcor system designed to treat secondary effluent. The MBR capital costs were provided by Zenon Environmental Systems, Inc.

8.4 Operation and Maintenance Costs

Tables 8-3 and **8-4** provide the annual O&M costs for the first year, and the total estimated O&M costs assuming an 8% interest rate over 20 y, respectively. The costs (Richard et al., 1992) associated with personnel, supervision, power, spare parts, chemicals, sludge handling and disposal were all adjusted to the current ENRCCI value. All O&M costs for the MBR and the microfiltration unit were provided by Zenon Environmental Systems, Inc. and U.S. Filter, respectively.

8.5 Total Costs

Table 8-5 provides a summary of the capital and O&M costs for each process configuration. The total capital costs and the total estimated O&M costs were summed to provide the present worth value of each plant shown in **Figure 8-4**. **Table 8-6** gives the cost of each process in terms of cost per kgal of water produced.

The following conclusions can be made for 1 and 5-MGD installations:

- The oxidation ditch is the most cost-effective process for producing water of secondary effluent quality.

- The oxidation ditch with tertiary filtration and disinfection is the most cost effective process for producing Title 22 reclaimed water.

- The MBR process is the most cost-effective process for producing feed water suitable for RO membranes

- **REFERENCE LIST**

Adham, S., Gagliardo, P., *Membrane Bioreactors for Water Repurification- Phase I*, Desalination Research and Development Program Report No. 34, Bureau of Reclamation, November, 1998.

Cicek, N., Franco, J., Suidan, M., and Urbain, V. *Recycling Municipal Wastewater Using a Membrane Bioreactor*. **Amer. Water Works Assoc**., **90**(11):105-113., November, 1998.

Coté, P., Buisson, H., Pound, C., and Arakaki, G., *Immersed Membrane Activated Sludge for the Reuse of Municipal Wastewater*. **Desalination**, **113**: 189-196, 1997.

Fan, X., Urbain, V., Qian, Y, and Manem, J., *Nitrification and Mass Balance with a Membrane Bioreactor for Municipal Wastewater Treatment*. Water Sci. Tech., **34**:1-2:129-136, 1996.

Kishino, H., Ishida, H., Iwabi, H., and Nakano, I., *Domestic Wastewater Reuse using a Submerged Membrane Bioreactor*. **Desalination, 106**:115-119, 1996.

Lozier, J., Fernandez, A., Hines, B., and Carns, K., *Using a Membrane Bioreactor/Reverse Osmosis System for Indirect Potable Reuse*. Amer. Water Works Assoc. Membrane Conf., 1999.

Metcalf & Eddy. *Wastewater Engineering Treatment, Disposal, and Reuse, Third Edition*, Irwin McGraw-Hill, 1991.

Mourato, D., Thompson, D., Schneider, C., Wright, N., Devol, M., and Roger, S., *Upgrade of a Sequential Batch Rector into a ZenoGem Membrane Bioreactor*, WEFTEC Conference, New Orleans, LA., October, 1999.

Richard, D., Asano, T., and Tchobanoglous, G. *The Cost of Wastewater Reclamation in California*, Department of Civil and Environmental Engineering, University of California, Davis, November, 1992.

Western Consortium for Public Health. Total Resource Recovery Project Aqua III San Pasqual Health Effects Study Final Summary Report, January, 1997.

APPENDIX A

Table 4-1 Specification for the Mitsubishi Sterapore HF Microfiltration Membrane

	Units	Value
Approximate Size of Element (L x W x H)	mm	886x606x1483
Active Membrane Area (outside)	ft2 (m2)	1076 (100)
Flow Direction	---	outside-in
Nominal Membrane Pore size	mm	0.4
Membrane Material/Construction	---	polyethylene, hollow fiber
Membrane Surface Characteristics	---	hydrophilic, symmetric
Membrane Charge	---	slightly negative
Design Flux	gfd (L/hr-m2)	9.9 (16.8)
Vacuum Pressure for System	psi (bar)	<5.8 (<0.4)

Table 4-2 Specifications for the Zenon OKC and OCP Membranes

	Units	Value (OKC Membrane)	Value (OCP Membrane)
Approximate Size of Element (L x W x H)	mm	2 x 0.75 x 0.2	2 x 0.75 x 0.2
Active Membrane Area (outside)	ft2 (m2)	500 (46.5)	519 (48.2)
Number of Fibers	---	~4700	~4700
Inside Diameter of Fiber	mm	0.75	0.75
Outside Diameter of Fiber	mm	1.95	1.95
Approximate Length of Fiber	m	1.65	1.65
Flow Direction	---	Outside-In	Outside-In
Nominal Membrane Pore size	μm	0.4	0.035
Membrane Material/Construction	---	Proprietary	Proprietary
Membrane Surface Characteristics	---	Hydrophilic	Hydrophilic
Membrane Charge	---	Neutral	Neutral
Design Flux	gfd (l/hr-m2)	25 (42)	20 (34)
Acceptable Range of Operating pH Values	---	5-9 (cleaning range 2-10.5)	5-9 (cleaning range 2-10.5)
Vacuum Pressure for System	psi (bar)	-1 to -8	-1 to -8 (-0.07 to -0.55)

Table 4-3 Specification for the RO Membranes

	Units	Value
Manufacturer	---	Filmtec/Dow
Commercial Designation	---	BW30HP-4040
Memrane Material	---	Polyamide (thin film composite)
Operating pH Range	---	2.0-10.0
Maximum Feedwater Turbidity	NTU	1.0
Maximum Feedwater SDI (15 minute)	---	5.0
Maximum Operating Temperature	deg F (deg C)	113 (45)
Free Chlorine Resistance	mg/L	<0.1
Maximum Operating Pressure	psi (bar)	600 (40)

Table 4-4a Anaylytical Methods and Detection Limits for the City of San Diego Water Quality Laboratory

Analyte or Parameter	Units	Method Number and Type	Detection Limit
Ammonia-N	mg/L	EPA350.1	0.015
BOD_5	mg/L	SM5210B	2.0
Bromide	mg/L	EPA300A	0.1
Chloride	mg/L	EPA300A	0.5
Nitrate-N	mg/L	EPA300A	0.2
Nitrite-N	mg/L	SM4500B	0.005
Ortho-Phosphate-P	mg/L	EPA300A	0.2
Total Phosphorus-P	mg/L	EPA365.1TP	0.07
Sulfate	mg/L	EPA300A	0.5
Total Kjeldahl Nitrogen (TKN)	mg/L	EPA351.2	0.08
Dissolved Organic Carbon (DOC)	mg/L	SM5310B	0.25

Table 4-4b Analytical Methods and Detection Limits for the On-Site Laboratory

Analyte or Parameter	Units	Method Number and Type	Detection Limit
Ammonia-N	mg/L	SM4500B&C*	0.017
Nitrate-N	mg/L	SM4500*	0.22
Nitrite-N	mg/L	DR/4000 Hach Spectro-photometer	0.0008
Dissolved Organic Carbon (DOC)	µg/L	Sievers 800 Portable Total Organic Analyzer	2

* Modified method used with Hach DR/4000 Spectrophotometer

Table 4-4c Analytical Methods and Detection Limits for the City of San Diego North City Water Reclamation Plant Laboratory

Analyte or Parameter	Units	Method Number and Type	Detection Limit
Chemical Oxygen Demand (COD)	mg/L	SM5220D	5
Total/Volatile Suspended Solids	mg/L	SM2540D&E	1.6

SM = Standard Methods for the Examination of Water and Wastewater
EPA = United States Environmental Protection Agency

Table 5-1 Primary Effluent Water Quality Laboratory Data During Part 1

	No. of Analyses	Units	Median	Maximum	Minimum
Ammonia-N	8	mg/L	19.0	26.4	3.8
Nitrate-N	9	mg/L	ND	0.055	ND
Nitrite-N	8	mg/L	0.01	0.02	ND
TKN	9	mg/L	30.1	53.6	11.5
Ortho-Phosphate-P	8	mg/L	2.3	12.1	1.2
Total Phosphorus	9	mg/L	4.2	11.5	2.3
Bromide	7	mg/L	0.33	0.42	0.17
Chloride	7	mg/L	210	316	157
Sulfate	7	mg/L	257	296	147
BOD_5	36	mg/L	61.2	98.2	28.6

Table 5-2 Mitsubishi MBR Permeate Water Quality Data During Part 1

	No. of Analyses	Units	Median	Maximum	Minimum
Ammonia-N	5	mg/L	2.3	13.8	0.2
Nitrate-N	9	mg/L	0.4	12.7	ND
Nitrite-N	8	mg/L	0.22	0.51	0.01
TKN	7	mg/L	2.9	16.0	1.8
Ortho-Phosphate-P	8	mg/L	0.1	17.9	ND
Total Phosphorus	9	mg/L	0.1	19.1	0
Bromide	7	mg/L	0.26	0.34	0.21
Chloride	7	mg/L	181	347	170
Sulfate	7	mg/L	247	259	232
BOD_5	40	mg/L	<3	14.8	<2

Table 5-3 Zenon MBR Permeate Water Quality Data During Part 1

	No. of Analyses	Units	Median	Maximum	Minimum
Ammonia-N	5	mg/L	0.31	2.08	ND
Nitrate-N	7	mg/L	2.7	14.2	0.1
Nitrite-N	5	mg/L	0.05	0.11	ND
TKN	8	mg/L	1.08	3.24	0.61
Ortho-Phosphate-P	8	mg/L	0.04	0.22	ND
Total Phosphorus	8	mg/L	0.08	0.22	ND
Bromide	7	mg/L	0.26	0.39	0.245
Chloride	7	mg/L	188	307	174
Sulfate	7	mg/L	243	291	229
BOD_5	36	mg/L	<3	10.3	<2

Table 5-4 Mitsubishi MBR RO Permeate Water Quality Data During Part 1

	No. of Analyses	Units	Median	Maximum	Minimum
Ammonia-N	8	mg/L	0.24	0.74	0.03
Nitrate-N	6	mg/L	ND	0.11	ND
Nitrite-N	7	mg/L	ND	0.01	ND
TKN	9	mg/L	0.46	1.16	0.27
Ortho-Phosphate-P	6	mg/L	ND	ND	ND
Total Phosphorus	9	mg/L	ND	3.04	ND
Bromide	6	mg/L	ND	ND	ND
Chloride	6	mg/L	1.19	2.96	0.59
Sulfate	6	mg/L	0.71	2.43	ND

Table 5-5 Zenon MBR RO Permeate Water Quality Data During Part 1

	No. of Analyses	Units	Median	Maximum	Minimum
Ammonia-N	5	mg/L	0.21	0.54	0.10
Nitrate-N	7	mg/L	0.30	0.67	0.12
Nitrite-N	5	mg/L	ND	ND	ND
TKN	7	mg/L	0.27	0.65	0.11
Ortho-Phosphate-P	6	mg/L	ND	ND	ND
Total Phosphorus	7	mg/L	ND	ND	ND
Bromide	6	mg/L	ND	ND	ND
Chloride	6	mg/L	2.37	3.64	1.78
Sulfate	6	mg/L	0.89	1.93	ND

Table 6-1 Primary Effluent Water Quality Data During Part 2

	No. of Analyses	Units	Median	Maximum	Minimum
Ammonia-N	5	mg/L	28.7	37.7	1.9
Nitrate-N	7	mg/L	ND	ND	ND
Nitrite-N	4	mg/L	0.01	0.03	ND
TKN	8	mg/L	32.4	59.6	15.6
Ortho-Phosphate-P	7	mg/L	3.59	4.24	2.95
Total Phosphorus	7	mg/L	7.04	8.57	4.68
Bromide	8	mg/L	0.24	0.30	0.18
Chloride	8	mg/L	160	173	141
Sulfate	8	mg/L	162	180	142
BOD_5	20	mg/L	72	102	38
DOC	22	mg/L	11.3	24.8	8.9

Table 6-2 Mitsubishi MBR Permeate Water Quality During Part 2

	No. of Analyses	Units	Median	Maximum	Minimum
Ammonia-N	6	mg/L	2.3	18.1	0.1
Nitrate-N	7	mg/L	9.2	24.9	1.1
Nitrite-N	3	mg/L	1.78	2.00	1.44
TKN	7	mg/L	5.6	14.5	1.9
Ortho-Phosphate-P	7	mg/L	2.92	3.25	2.42
Total Phosphorus	7	mg/L	2.99	3.50	2.51
Bromide	8	mg/L	0.26	0.30	0.19
Chloride	8	mg/L	248	280	207
Sulfate	8	mg/L	241	245	226
BOD_5	22	mg/L	ND	ND	ND

Table 6-3 Zenon MBR Permeate Water Quality During Part 2

	No. of Analyses	Units	Median	Maximum	Minimum
Ammonia-N	4	mg/L	0.83	1.94	ND
Nitrate-N	6	mg/L	20.5	24.4	10.0
Nitrite-N	2	mg/L	1.10	1.92	0.28
TKN	6	mg/L	1.1	24.4	10.0
Ortho-Phosphate-P	6	mg/L	2.40	3.12	1.52
Total Phosphorus	6	mg/L	2.59	3.12	1.57
Bromide	7	mg/L	0.23	0.30	0.17
Chloride	7	mg/L	242	263	183
Sulfate	7	mg/L	242	248	230
BOD_5	6	mg/L	ND	ND	ND

Table 6-4 Mitsubishi MBR RO Permeate Water Quality During Part 2

	No. of Analyses	Units	Median	Maximum	Minimum
Ammonia-N	4	mg/L	0.25	0.52	0.21
Nitrate-N	6	mg/L	0.17	0.33	0.05
Nitrite-N	3	mg/L	ND	0.01	ND
TKN	6	mg/L	0.39	1.72	0.30
Ortho-Phosphate-P	6	mg/L	ND	ND	ND
Total Phosphorus	6	mg/L	ND	ND	ND
Bromide	7	mg/L	ND	ND	ND
Chloride	7	mg/L	0.78	1.98	0.68
Sulfate	7	mg/L	ND	0.98	ND

Table 6-5 Zenon MBR RO Permeate Water Quality During Part 2

	No. of Analyses	Units	Median	Maximum	Minimum
Ammonia-N	4	mg/L	0.16	0.19	0.07
Nitrate-N	5	mg/L	0.72	0.90	0.63
Nitrite-N	4	mg/L	ND	0.10	ND
TKN	5	mg/L	ND	ND	ND
Ortho-Phosphate-P	5	mg/L	ND	ND	ND
Total Phosphorus	5	mg/L	ND	ND	ND
Bromide	6	mg/L	ND	ND	ND
Chloride	6	mg/L	1.66	3.02	1.14
Sulfate	6	mg/L	ND	2.81	ND

Table 8-1 Capital Costs for 1-MGD Installations, $K

	Secondary Standards	Title 22 Standards			Pre-RO Water		
Capital Costs	**Oxidation Ditch**	**Ditch + Filtr/Cl_2**	**Ditch + MF/Cl_2**	**MBR + Cl_2**	**Ditch + C/F/S/F**	**Ditch + MF**	**MBR**
Headworks	**$ 834**	**$ 834**	**$ 834**	**$ 834**	**$ 834**	**$ 834**	**$ 834**
Screening Facility				**$ 816**			**$ 816**
Secondary Treatment	**$ 2,103**	**$ 2,103**	**$ 2,103**		**$ 2,103**	**$ 2,103**	
Rapid Mix					**$ 14**		
Flocculation					**$ 50**		
Tertiary Clarifiers					**$ 529**		
Traveling Bridge Filters		**$ 97**			**$ 158**		
Backwash Pumping Station		**$ 50**			**$ 81**		
Chlorination Handling and Storage		**$ 191**	**$ 191**	**$ 191**			
Chlorine Contact Tank		**$ 127**	**$ 127**	**$ 127**			
Chemical Handling, Storage, Metering					**$ 640**		
Microfiltration Unit			**$ 784**			**$ 784**	
MBR Process Costs				**$ 1,750**			**$ 1,750**
MBR Tank				**$ 180**			**$ 180**
Operations-laboratory building	**$ 368**	**$ 368**	**$ 368**	**$ 368**	**$ 368**	**$ 368**	**$ 368**
Maintenance Building	**$ 154**	**$ 154**	**$ 154**	**$ 154**	**$ 154**	**$ 154**	**$ 154**
Subtotal	**$ 3,459**	**$ 3,925**	**$ 4,561**	**$ 4,420**	**$ 4,932**	**$ 4,243**	**$ 4,102**
Site Development, 15%	$ 519	$ 589	$ 684	$ 663	$ 740	$ 636	$ 615
Installation of MF/MBR, 30%			$ 235	$ 525		$ 235	$ 525
Process Piping, 15%	$ 519	$ 589	$ 684	$ 663	$ 740	$ 636	$ 615
Instrumentation, 2%	$ 69	$ 78	$ 91	$ 88	$ 99	$ 85	$ 82
Electrical distribution and controls, 16 %	$ 553	$ 628	$ 730	$ 707	$ 789	$ 679	$ 656
Electrical Service, 5%	$ 173	$ 196	$ 228	$ 221	$ 247	$ 212	$ 205
Subtotal	**$ 5,293**	**$ 6,005**	**$ 7,213**	**$ 7,287**	**$ 7,546**	**$ 6,727**	**$ 6,801**
Contigency, 10%	**$ 529**	**$ 600**	**$ 721**	**$ 729**	**$ 755**	**$ 673**	**$ 680**
Total Capital Cost, $K	**$ 5,822**	**$ 6,605**	**$ 7,934**	**$ 8,016**	**$ 8,301**	**$ 7,399**	**$ 7,481**
Interest Rate	8%	8%	8%	8%	8%	8%	8%
Number of Years	20	20	20	20	20	20	20
P/A Factor	9.82	9.82	9.82	9.82	9.82	9.82	9.82
Amortized Capital Cost, $/yr	**$ 593**	**$ 673**	**$ 808**	**$ 816**	**$ 845**	**$ 754**	**$ 762**

Table 8-2 Capital Costs for 5-MGD Installations, $K

	Secondary Standards	Title 22 Standards			Pre-RO Water		
Capital Costs	**Oxidation Ditch**	**Ditch + Filtr/Cl_2**	**Ditch + MF/Cl_2**	**MBR + Cl_2**	**Ditch + C/F/S/F**	**Ditch + MF**	**MBR**
Headworks	**$ 2,573**	**$ 2,573**	**$ 2,573**	**$ 2,573**	**$ 2,573**	**$ 2,573**	**$ 2,573**
Screening Facility				**$ 2,517**			**$ 2,517**
Secondary Treatment	**$ 5,853**	**$ 5,853**	**$ 5,853**		**$ 5,853**	**$ 5,853**	
Rapid Mix					**$ 23**		
Flocculation					**$ 68**		
Tertiary Clarifiers					**$ 891**		
Travelling Bridge Filters		**$ 584**			**$ 584**		
Backwash Pumping Station		**$ 113**			**$ 113**		
Chlorination Handling and Storage		**$ 221**	**$ 221**	**$ 221**			
Chlorine Contact Tank		**$ 407**	**$ 407**	**$ 407**			
Chemical Handling, Storage, Metering					**$ 927**		
Microfiltration Unit			**$ 2,417**			**$ 2,417**	
MBR Process Costs				**$ 5,703**			**$ 5,703**
MBR Tank				**$ 555**			**$ 555**
Operations-laboratory building	**$ 485**	**$ 485**	**$ 485**	**$ 485**	**$ 485**	**$ 485**	**$ 485**
Maintenance Building	**$ 265**	**$ 265**	**$ 265**	**$ 265**	**$ 265**	**$ 265**	**$ 265**
Subtotal	**$ 9,176**	**$ 10,500**	**$ 12,221**	**$ 12,725**	**$ 11,781**	**$ 11,593**	**$ 12,098**
Site Development, 15%	$ 1,376	$ 1,575	$ 1,833	$ 1,909	$ 1,767	$ 1,739	$ 1,815
Installation of MF/MBR, 30%			$ 725	$ 1,711		$ 725	$ 1,711
Process Piping, 15%	$ 1,376	$ 1,575	$ 1,833	$ 1,909	$ 1,767	$ 1,739	$ 1,815
Instrumentation, 2%	$ 184	$ 210	$ 244	$ 255	$ 236	$ 232	$ 242
Electrical distribution and controls, 16 %	$ 1,468	$ 1,680	$ 1,955	$ 2,036	$ 1,885	$ 1,855	$ 1,936
Electrical Service, 5%	$ 459	$ 525	$ 611	$ 636	$ 589	$ 580	$ 605
Subtotal	**$ 14,039**	**$ 16,065**	**$ 19,423**	**$ 21,181**	**$ 18,025**	**$ 18,463**	**$ 20,220**
Contigency, 10%	**$ 1,404**	**$ 1,607**	**$ 1,942**	**$ 2,118**	**$ 1,803**	**$ 1,846**	**$ 2,022**
Total Capital Cost, $K	**$ 15,443**	**$ 17,672**	**$ 21,365**	**$ 23,299**	**$ 19,828**	**$ 20,309**	**$ 22,242**
Interest Rate	8%	8%	8%	8%	8%	8%	8%
Number of Years	20	20	20	20	20	20	20
P/A Factor	9.82	9.82	9.82	9.82	9.82	9.82	9.82
Amortized Capital Cost, $/yr	**$ 1,573**	**$ 1,800**	**$ 2,176**	**$ 2,373**	**$ 2,020**	**$ 2,068**	**$ 2,265**

Table 8-3 Operations and Maintenance Costs for 1-MGD Installations, $K

	Secondary Standards	Title 22 Standards			Pre-RO Water		
O&M Costs, $/yr	**Ditch Only**	**Ditch + Filtr/Cl_2**	**Ditch + MF/Cl_2**	**MBR + Cl_2**	**Ditch + C/F/S/F**	**Ditch + MF**	**MBR**
Personnel	$ 85	$ 85	$ 85	$ 85	$ 106	$ 85	$ 85
Supervision-administration	$ 31	$ 31	$ 31	$ 31	$ 31	$ 31	$ 31
Power	$ 115	$ 115	$ 115	$ 115	$ 126	$ 115	$ 115
Spare Parts- replacement	$ 65	$ 65	$ 65	$ 6	$ 91	$ 65	$ 6
Chemicals		$ 4	$ 4	$ 4	$ 218		
Sludge Handling and Disposal	$ 84	$ 84	$ 84	$ 84	$ 182	$ 84	$ 84
MBR Chemicals				$ 1			$ 1
Maintenance Clean				$ 2			$ 2
Membrane Replacement				$ 26			$ 26
Total Microfilter O&M Costs			$ 51			$ 51	
Total O&M Costs in First Year, $K	**$ 379**	**$ 384**	**$ 435**	**$ 355**	**$ 754**	**$ 430**	**$ 351**
Interest Rate	8%	8%	8%	8%	8%	8%	8%
Number of Years	20	20	20	20	20	20	20
P/A Factor	9.82	9.82	9.82	9.82	9.82	9.82	9.82
Total estimated O&M costs, $K	**$ 3,724**	**$ 3,767**	**$ 4,269**	**$ 3,487**	**$ 7,404**	**$ 4,225**	**$ 3,443**

Table 8-4 Operations and Maintenance Costs for 5-MGD Installations, $K

	Secondary Standards	Title 22 Standards			Pre-RO Water		
O&M Costs, $/yr	**Ditch Only**	**Ditch + Filtr/Cl_2**	**Ditch + MF/Cl_2**	**MBR + Cl_2**	**Ditch + C/F/S/F**	**Ditch + MF**	**MBR**
Personnel	$ 151	$ 151	$ 151	$ 151	$ 179	$ 151	$ 151
Supervision-administration	$ 90	$ 90	$ 90	$ 90	$ 90	$ 90	$ 90
Power	$ 469	$ 469	$ 469	$ 469	$ 478	$ 469	$ 469
Spare Parts- replacement	$ 160	$ 160	$ 160	$ 16	$ 212	$ 160	$ 16
Chemicals		$ 22	$ 22	$ 22	$ 1,085		
Sludge Handling and Disposal	$ 419	$ 419	$ 419	$ 419	$ 917	$ 419	$ 419
MBR Chemicals				$ 3			$ 3
Maintenance Clean				$ 6			$ 6
Membrane Replacement				$ 81			$ 81
Total Microfilter O&M Costs			$ 309			$ 309	
Total O&M Costs in First Year, $K	**$ 1,289**	**$ 1,311**	**$ 1,620**	**$ 1,258**	**$ 2,961**	**$ 1,598**	**$ 1,235**
Interest Rate	8%	8%	8%	8%	8%	8%	8%
Number of Years	20	20	20	20	20	20	20
P/A Factor	9.82	9.82	9.82	9.82	9.82	9.82	9.82
Total estimated O&M costs, $K	**$ 12,657**	**$ 12,874**	**$ 15,903**	**$ 12,347**	**$ 29,067**	**$ 15,687**	**$ 12,130**

Table 8-5 Summary of Capital and O&M Costs, $K

	1-MGD			5-MGD		
	Capital Costs, $K	Total Estimated O&M Costs, $K	Present Worth Value, $K	Capital Costs, $K	Total Estimated O&M Costs, $K	Present Worth Value, $K
Oxidation Ditch	5,822	3,724	9,546	15,443	12,657	28,100
Ditch+Filtration+Cl2	6,605	3,767	10,372	17,672	12,874	30,546
Ditch+MF/Cl2	7,934	4,269	12,203	21,365	15,903	37,268
MBR+Cl2	8,016	3,487	11,503	23,299	12,347	35,645
Ditch+C/F/S/F	8,301	7,404	15,704	19,828	29,067	48,895
Ditch+MF	7,399	4,225	11,624	20,309	15,687	35,995
MBR	7,481	3,443	10,924	22,242	12,130	34,372

Table 8-6 Summary of Costs, $/kgal

	1-MGD				5-MGD			
	Amortized Capital Costs, $K/yr	O&M Costs, $K/yr	Total Cost per Year, $K/yr	Total Cost $/1000 gal	Amortized Capital Costs, $K/yr	O&M Costs, $K/yr	Total Cost per Year, $K/yr	Total Cost $/1000 gal
Oxidation Ditch	593	379	972	2.66	1,573	1,289	2,862	1.57
Ditch+Filtration+Cl2	673	384	1,056	2.89	1,800	1,311	3,111	1.70
Ditch+MF/Cl2	808	435	1,243	3.41	2,176	1,620	3,796	2.08
MBR+Cl2	816	355	1,172	3.21	2,373	1,258	3,631	1.99
Ditch+C/F/S/F	845	754	1,600	4.38	2,020	2,961	4,980	2.73
Ditch+MF	754	430	1,184	3.24	2,068	1,598	3,666	2.01
MBR	762	351	1,113	3.05	2,265	1,235	3,501	1.92

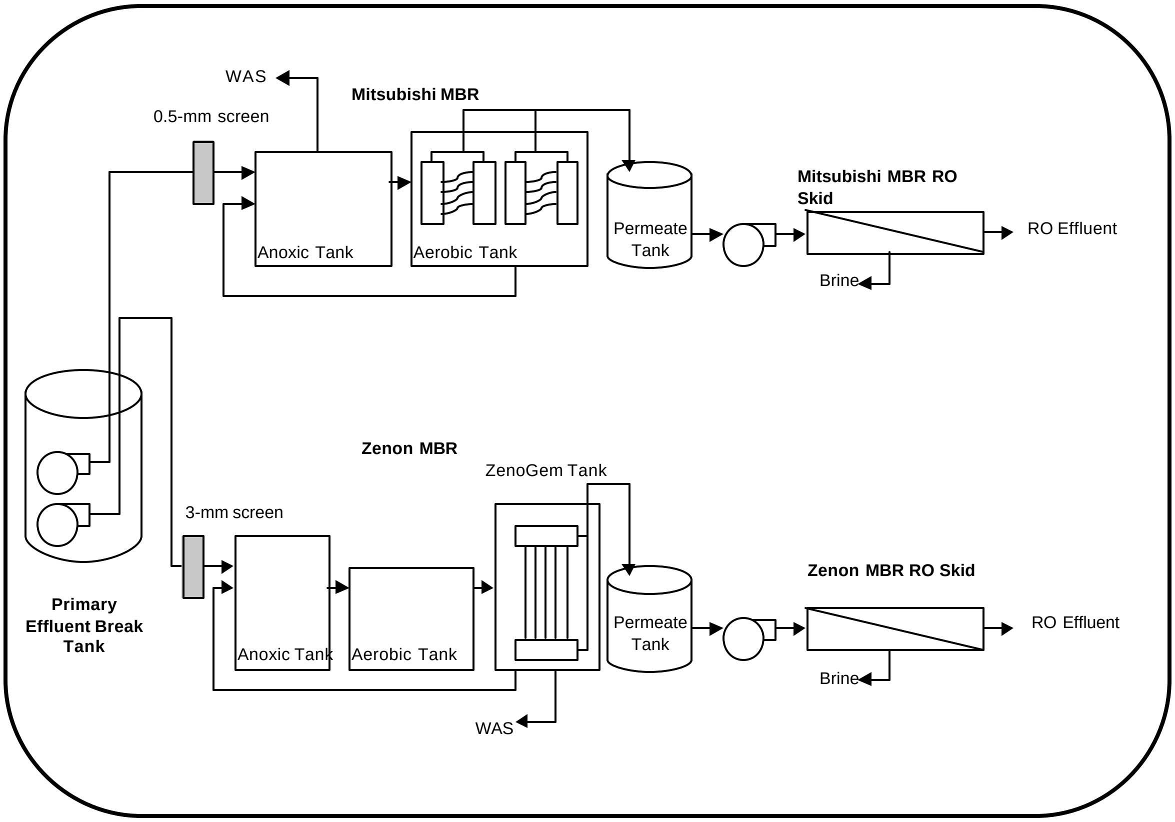


Figure 4-1 Schematic Diagram of the Treatment Trains During Part 1

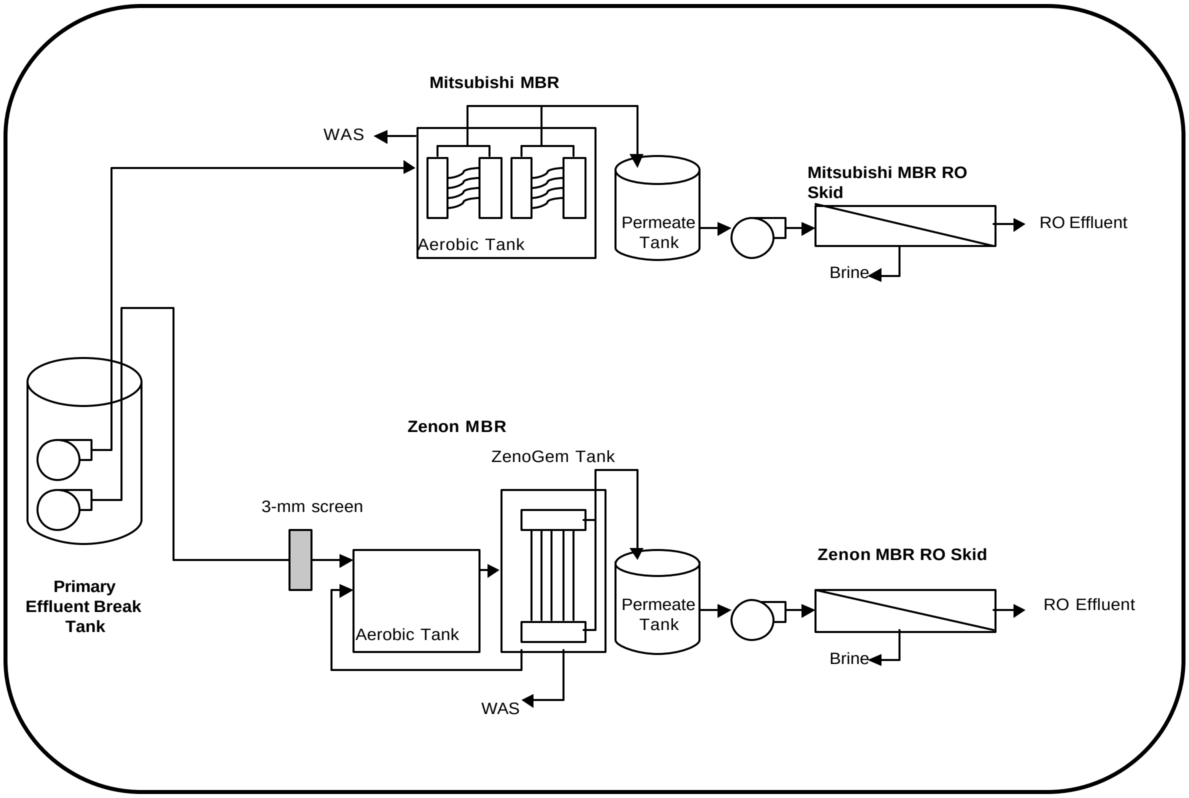


Figure 4-2 Schematic Diagram of Treatment Trains During Part 2

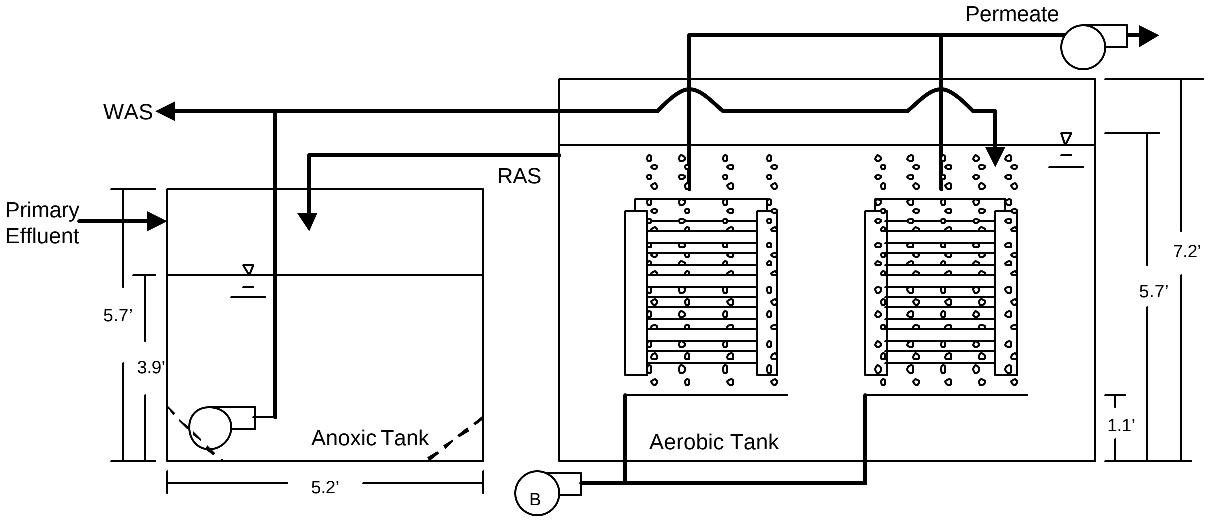


Figure 4-3a Mitsubishi MBR Side View During Part 1

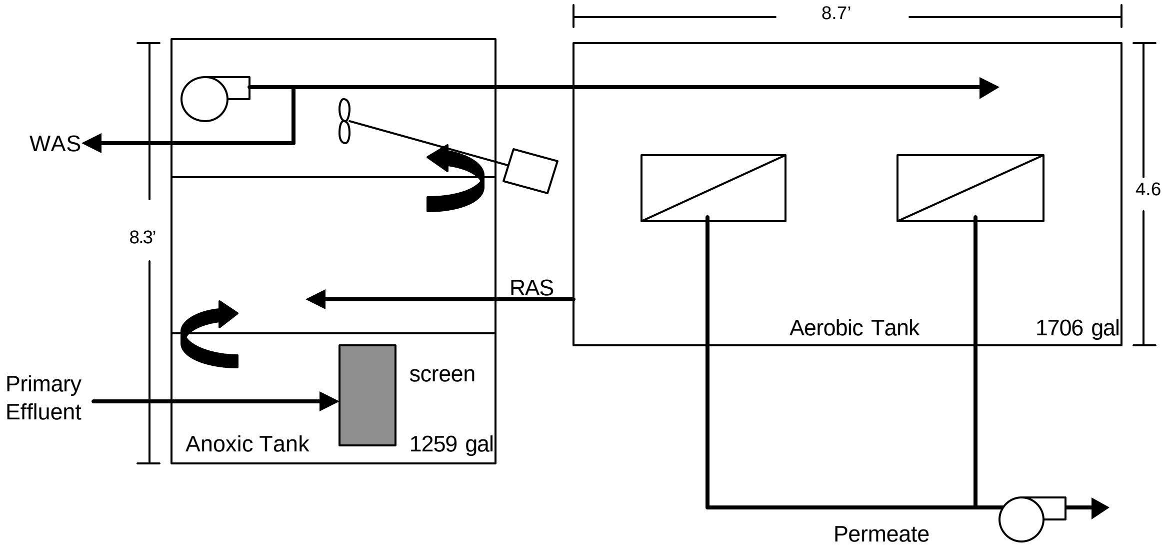


Figure 4-3b Mitsubishi MBR Plan View During Part 1

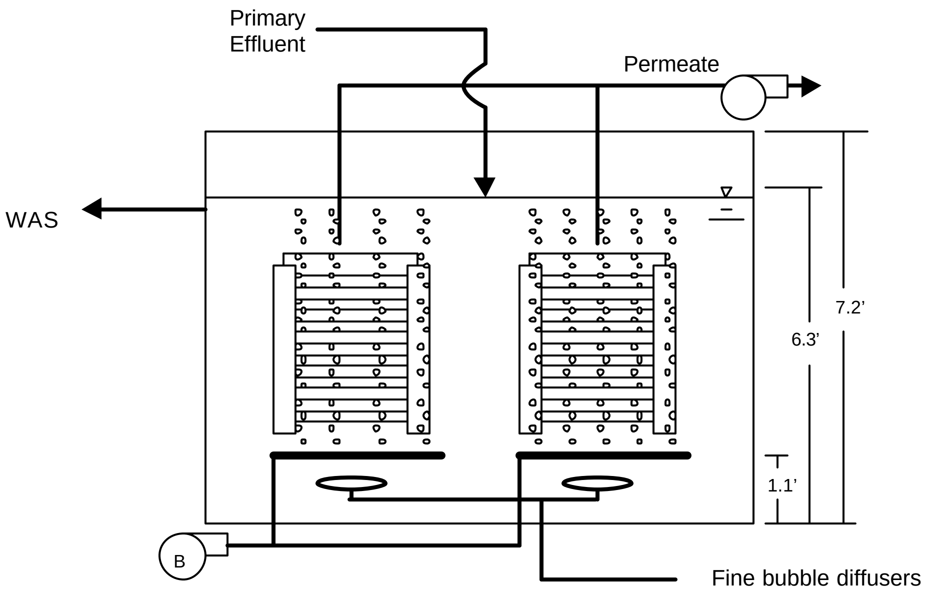


Figure 4-4a Mitsubishi MBR Side View During Part 2

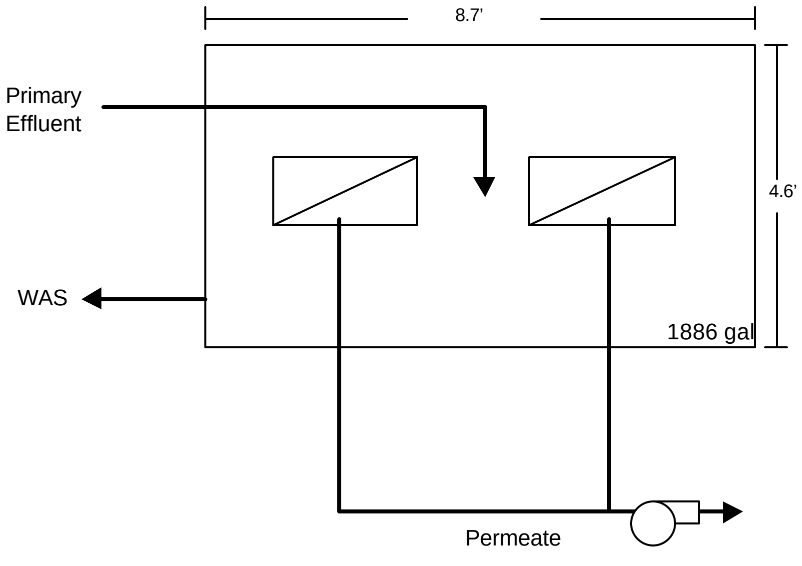


Figure 4-4b Mitsubishi MBR Plan View During Part 2

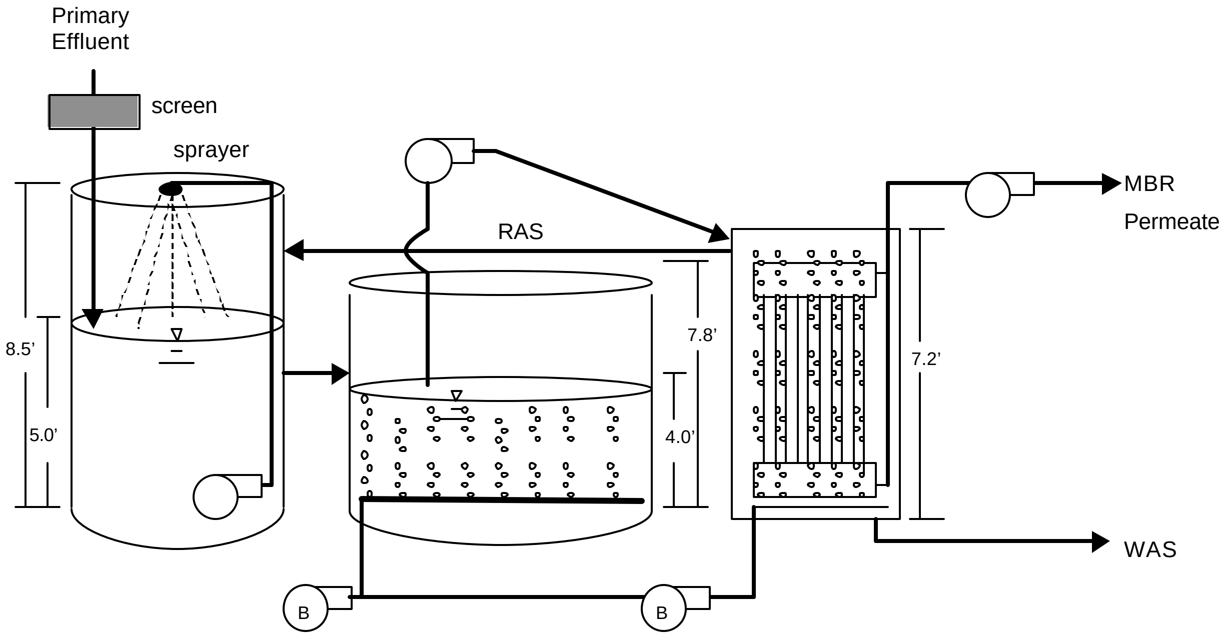


Figure 4-5a Zenon MBR Side View During Part 1

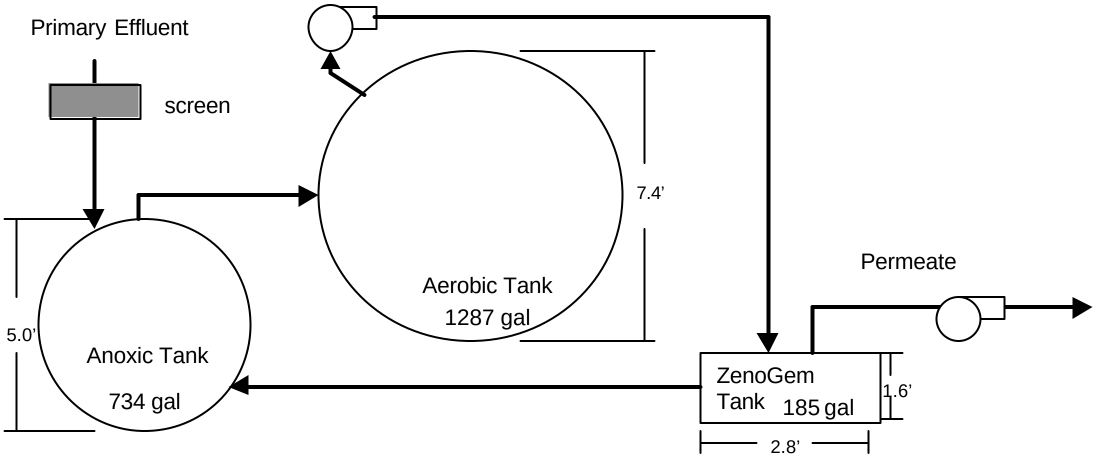


Figure 4-5b Zenon MBR Plan View During Part 1

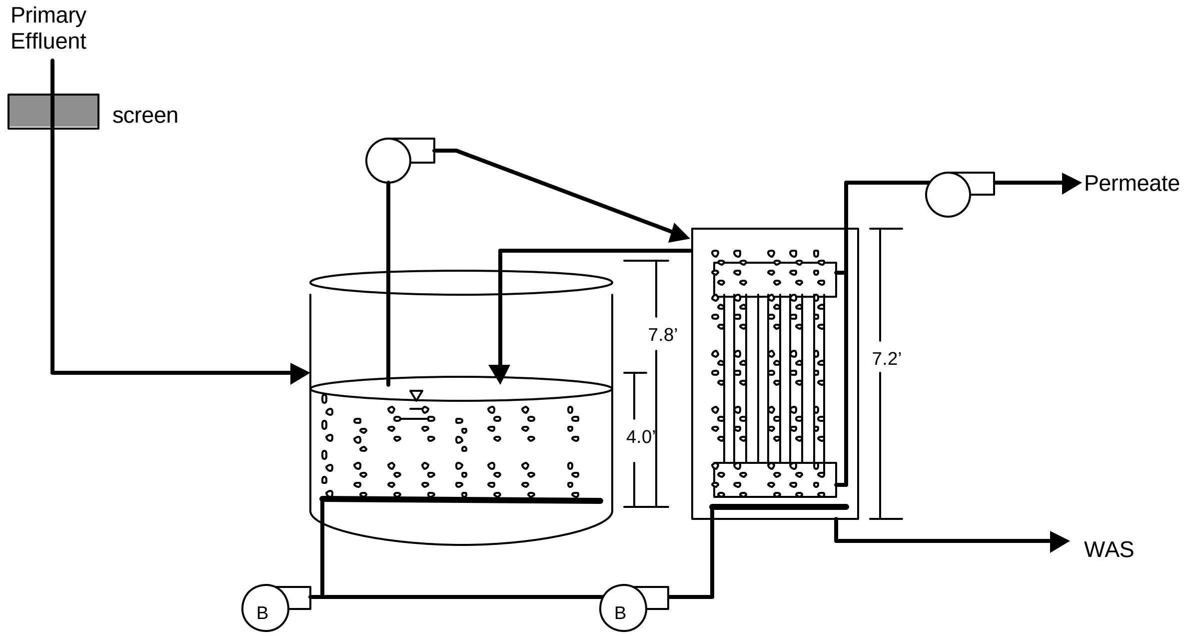


Figure 4-6a Zenon MBR Side View During Part 2

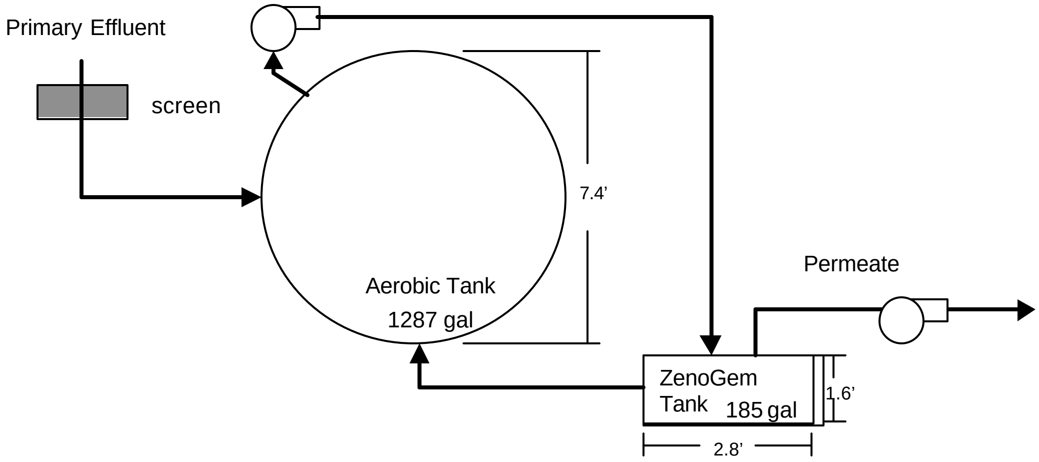
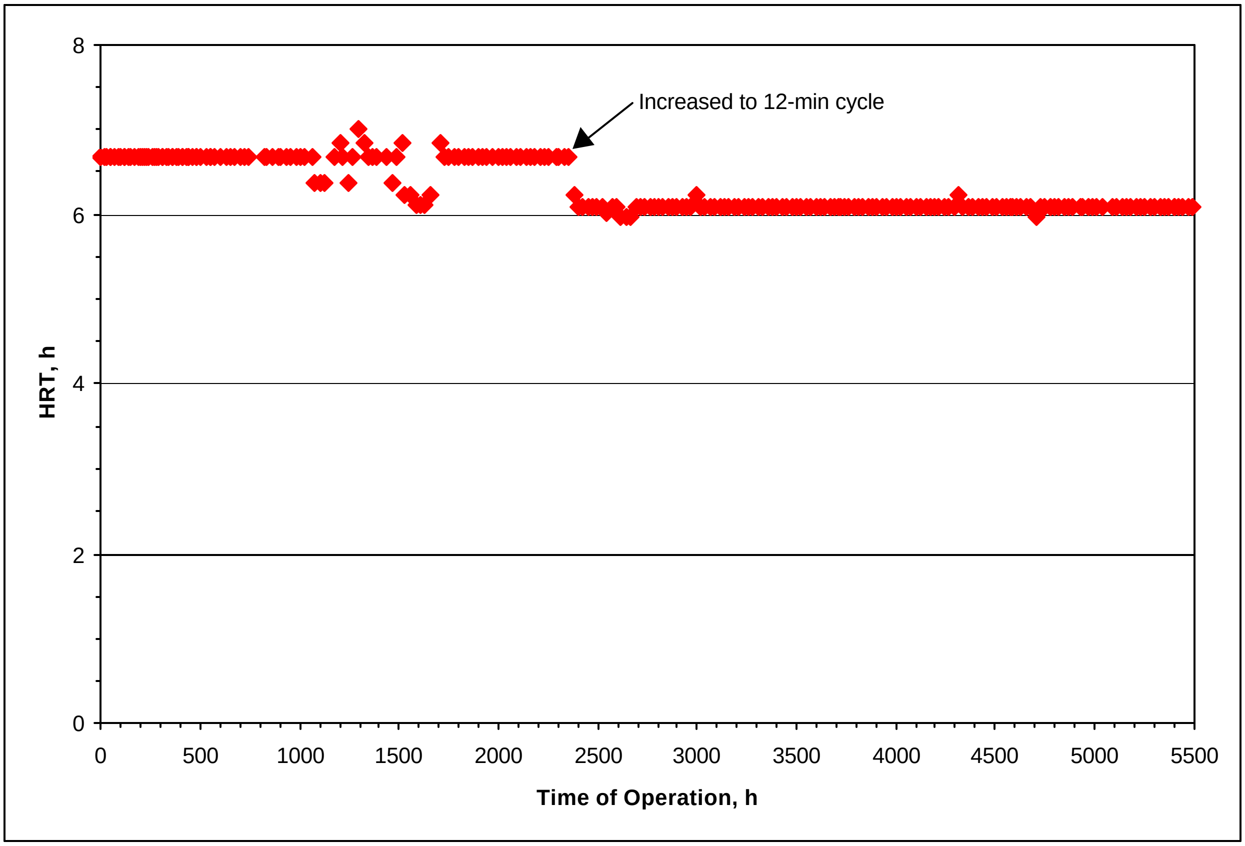


Figure 4-6b Zenon MBR Plan View During Part 2



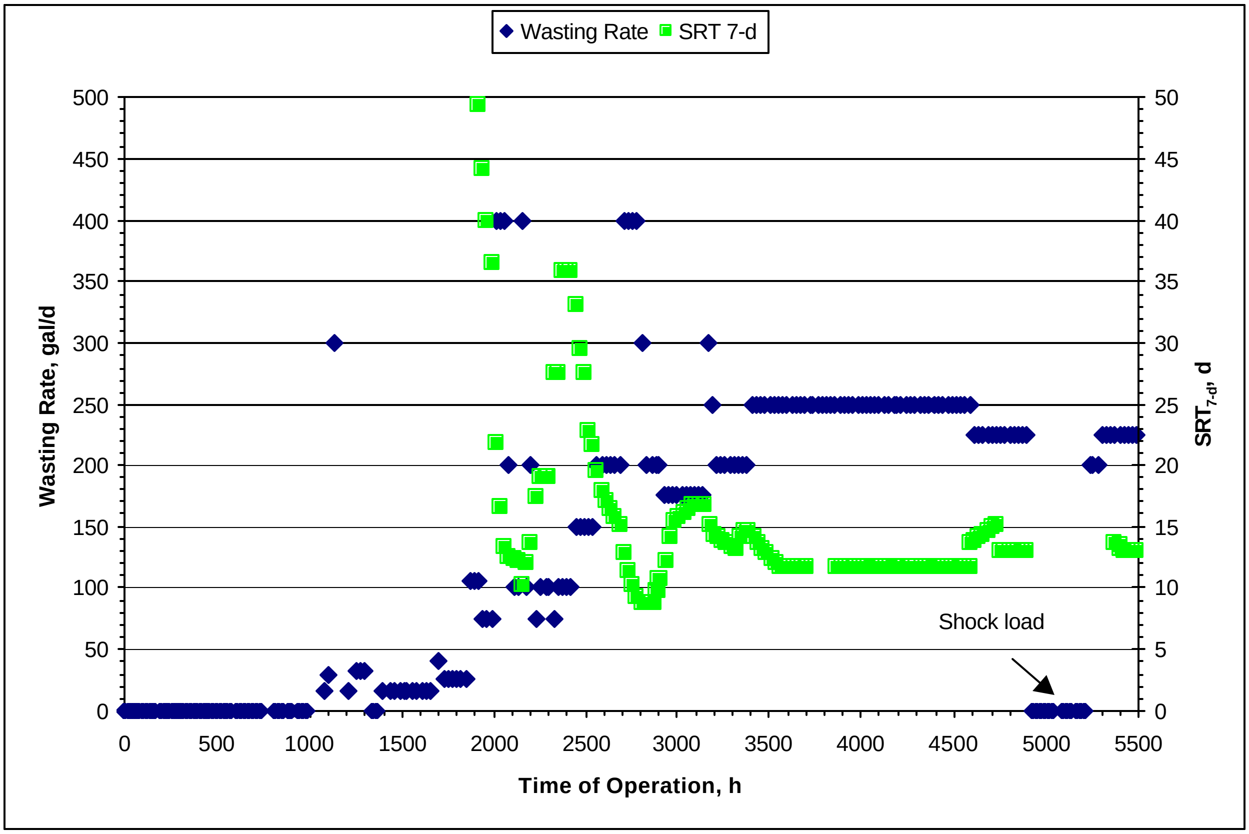


Figure 5-1 HRT and SRT$_{7\text{-d}}$ of the Mitsubishi MBR During Part 1

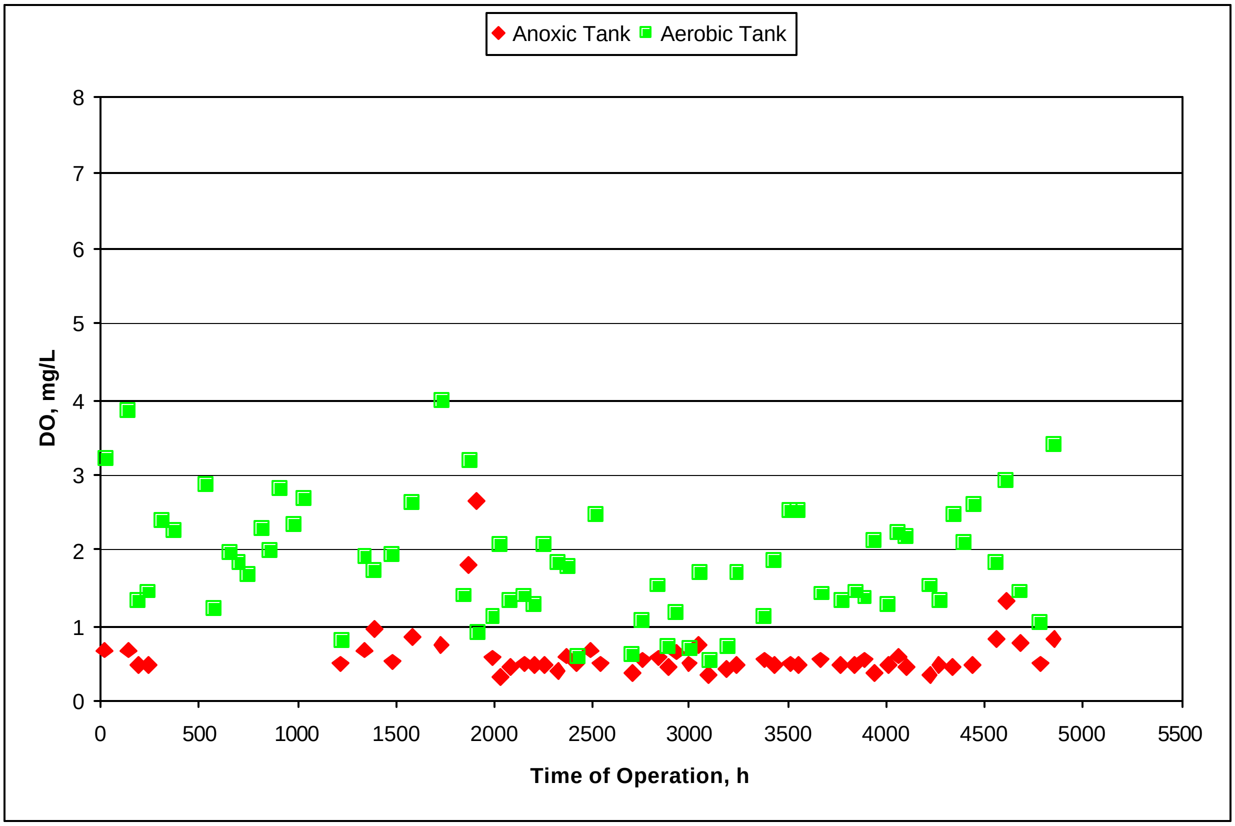
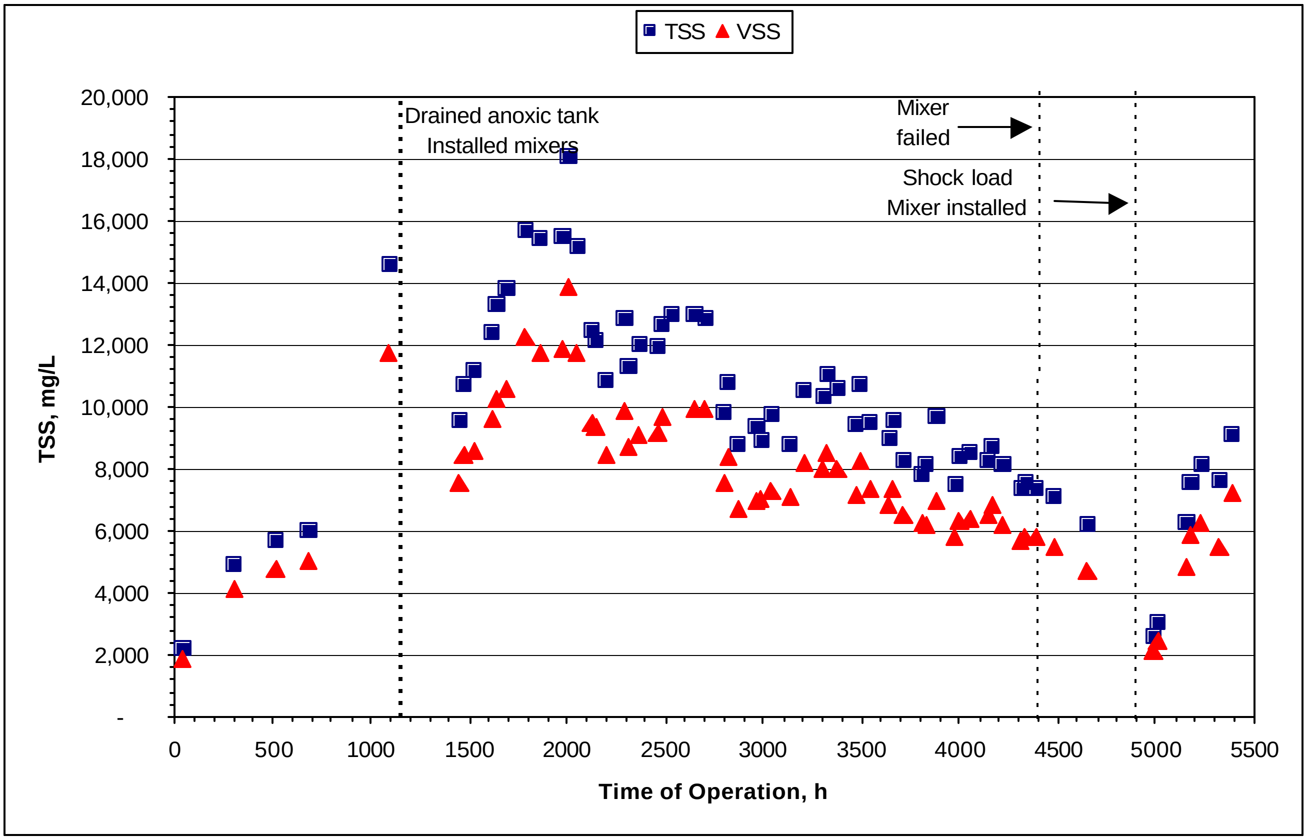


Figure 5-2 DO Concentration in the Mitsubishi MBR During Part 1



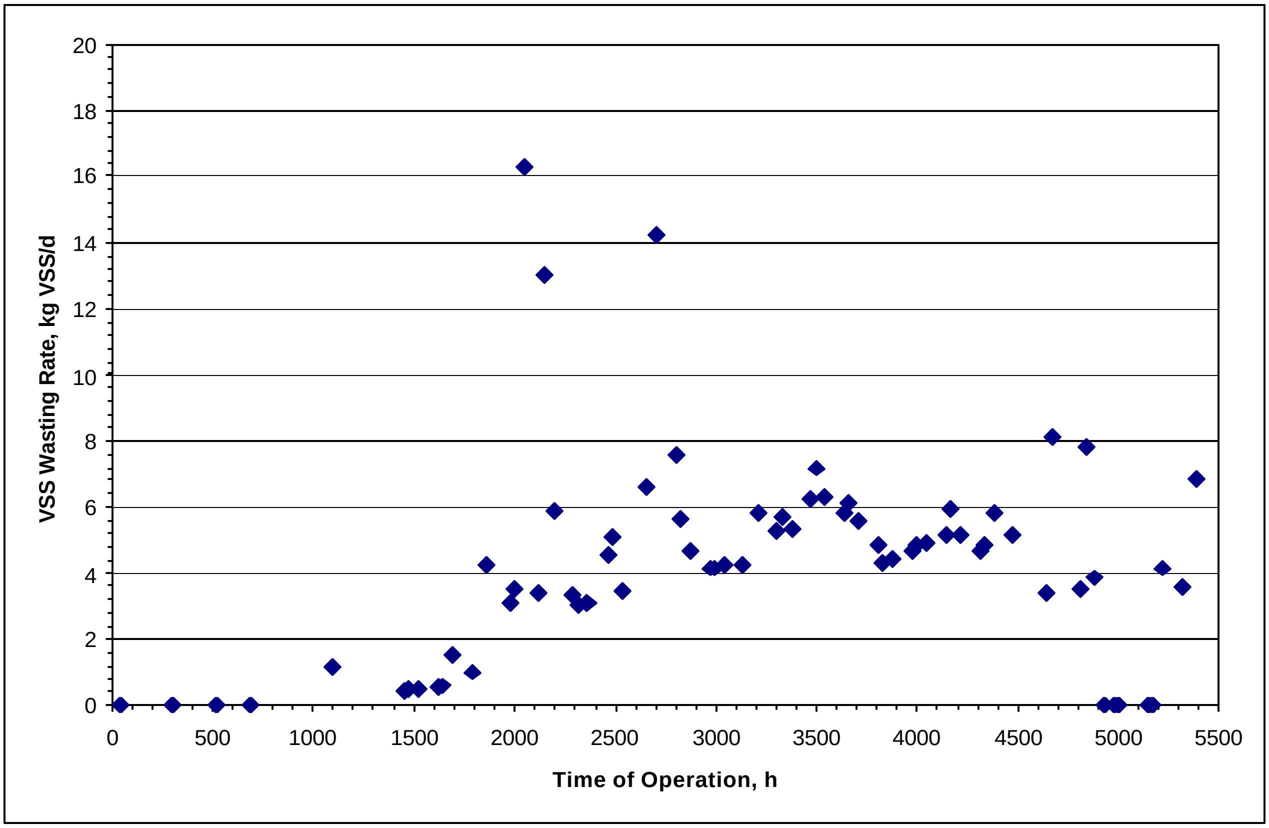
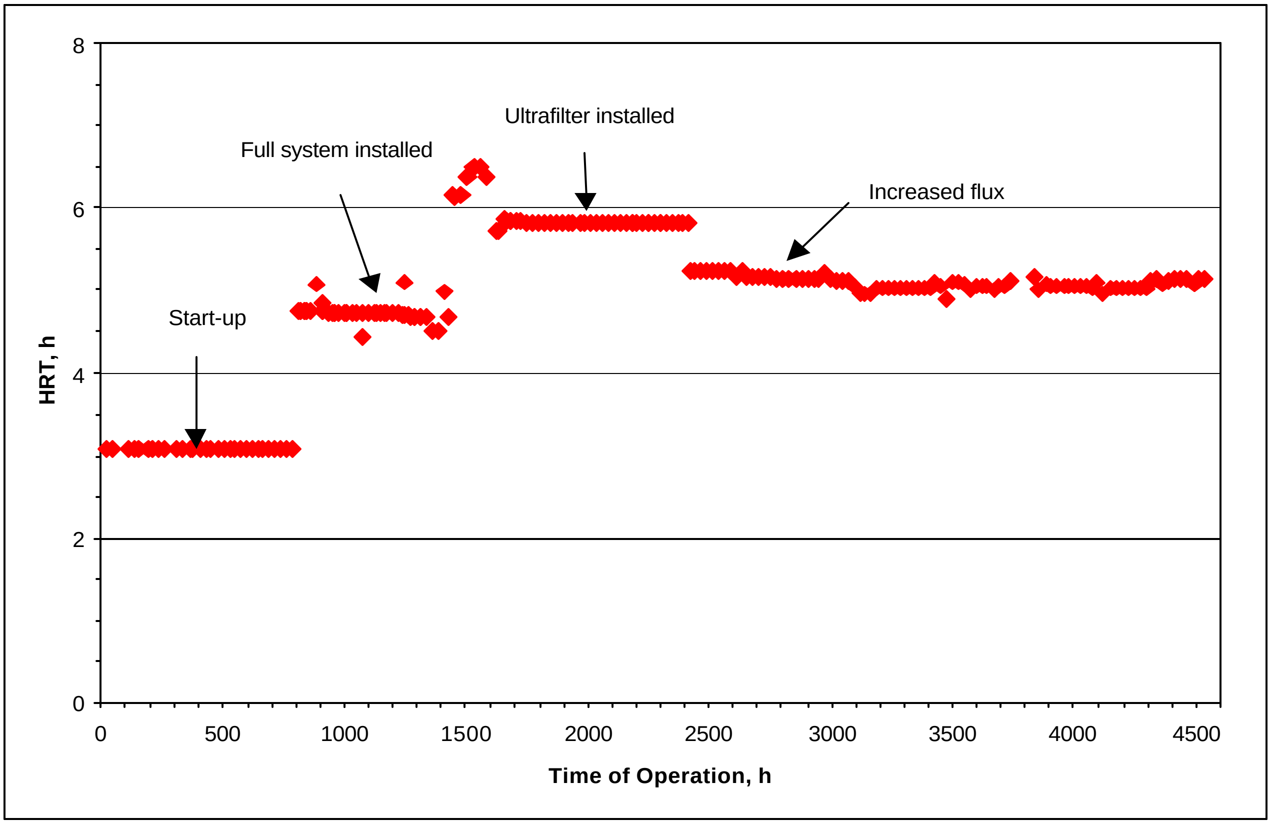


Figure 5-3 Mixed Liquor Solids Data for the Mitsubishi MBR During Part 1



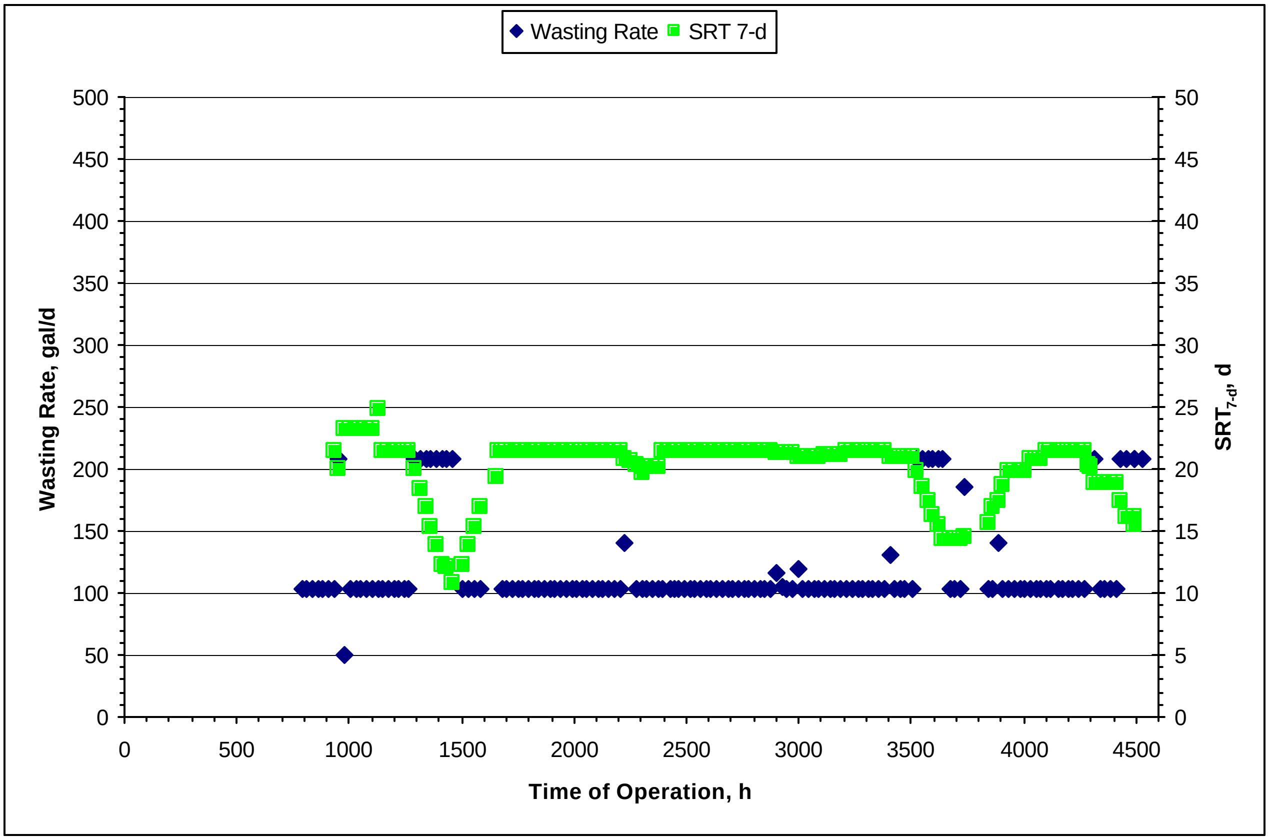


Figure 5-4 HRT and SRT$_{7\text{-d}}$ of the Zenon MBR During Part 1

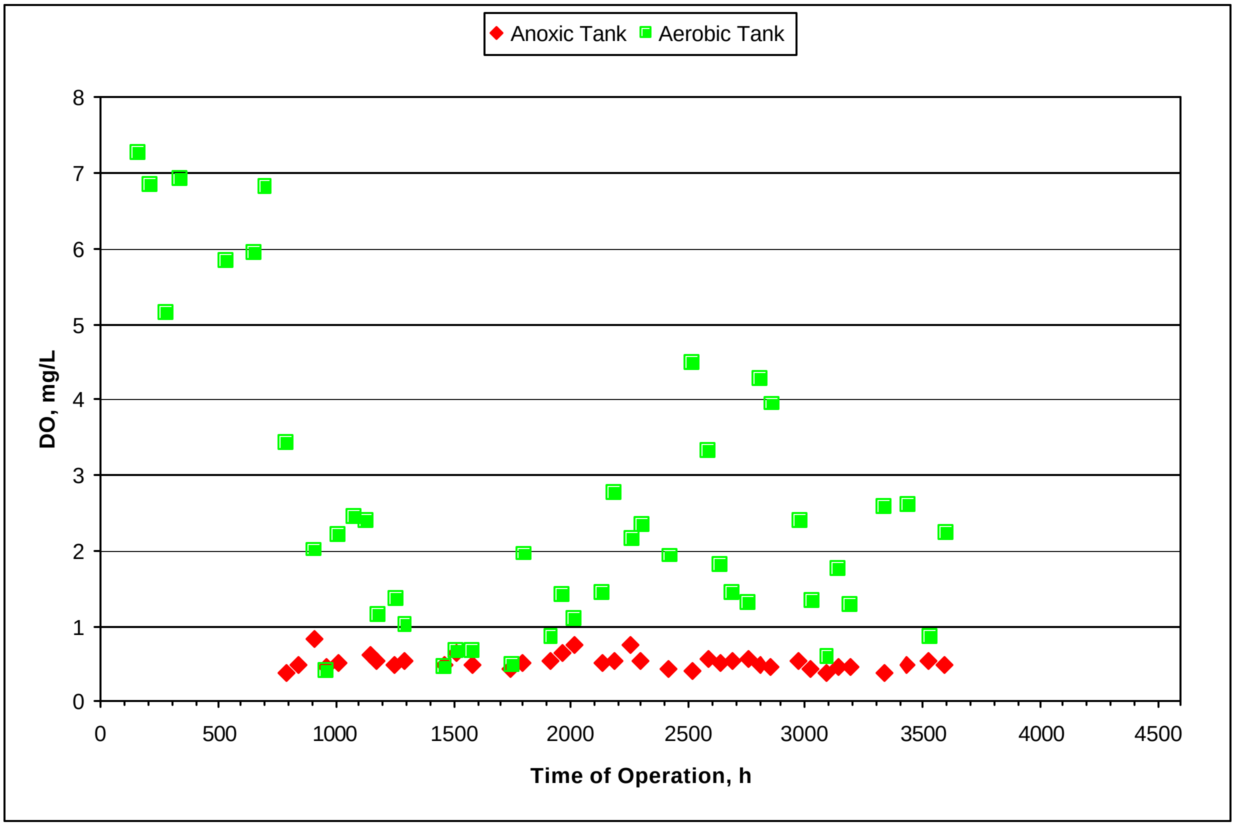
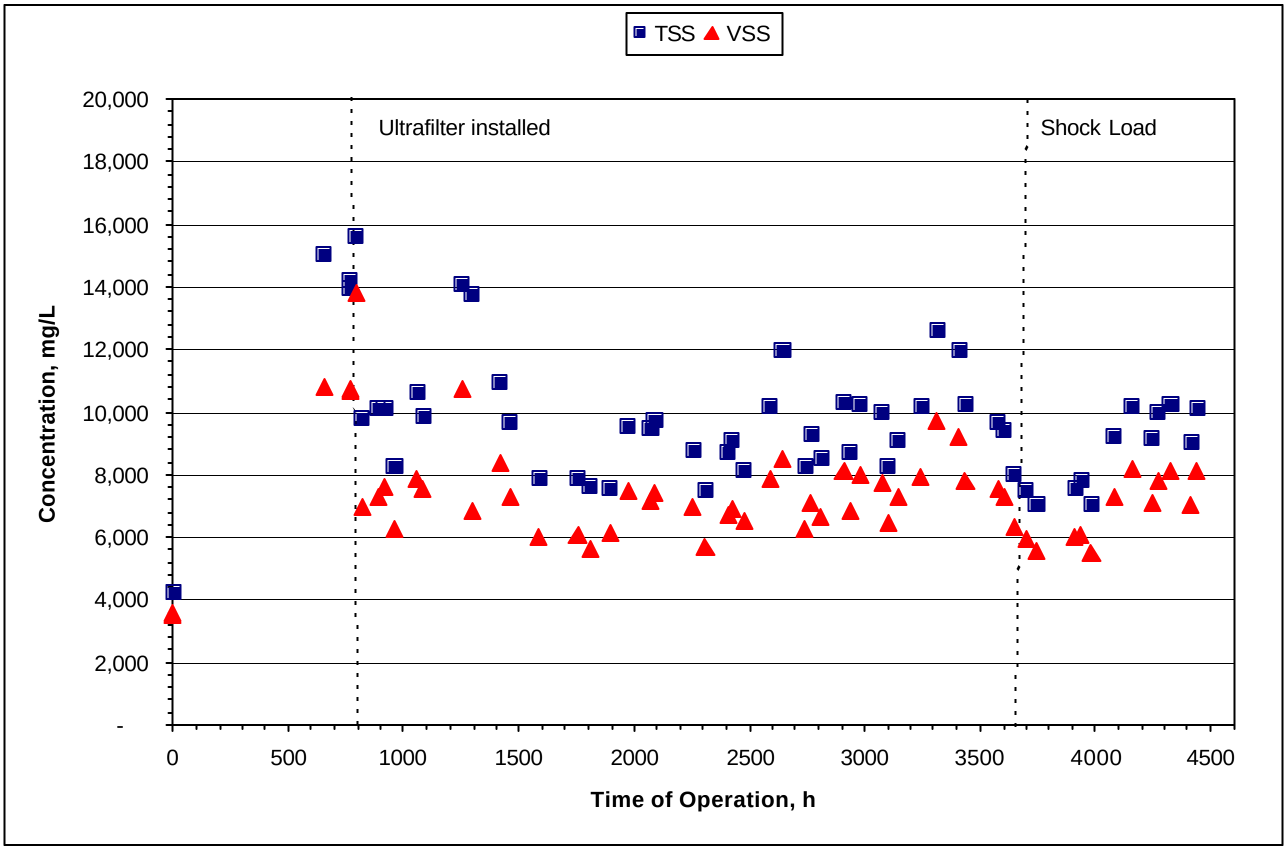


Figure 5-5 DO Concentration in the Zenon MBR During Part 1



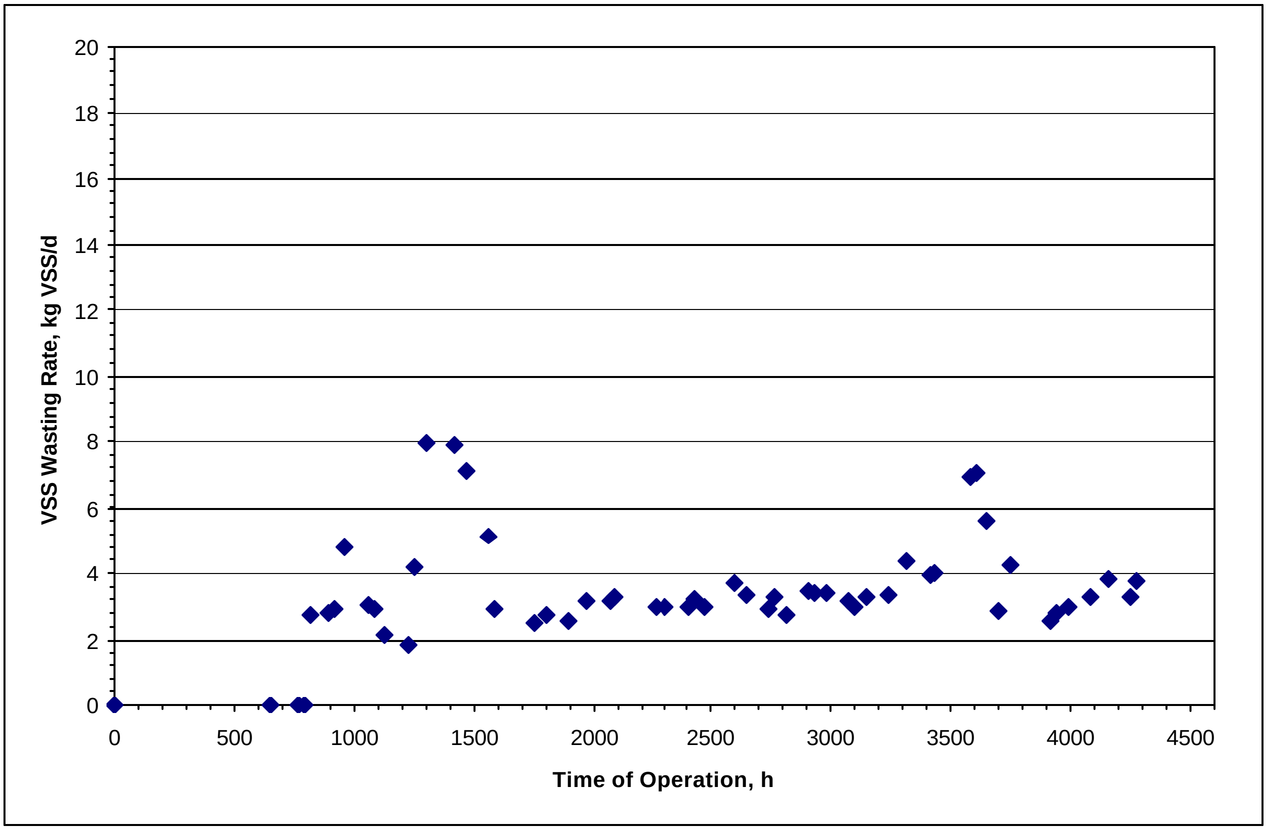


Figure 5-6 Mixed Liquor Solids Concentration in the Zenon MBR During Part 1

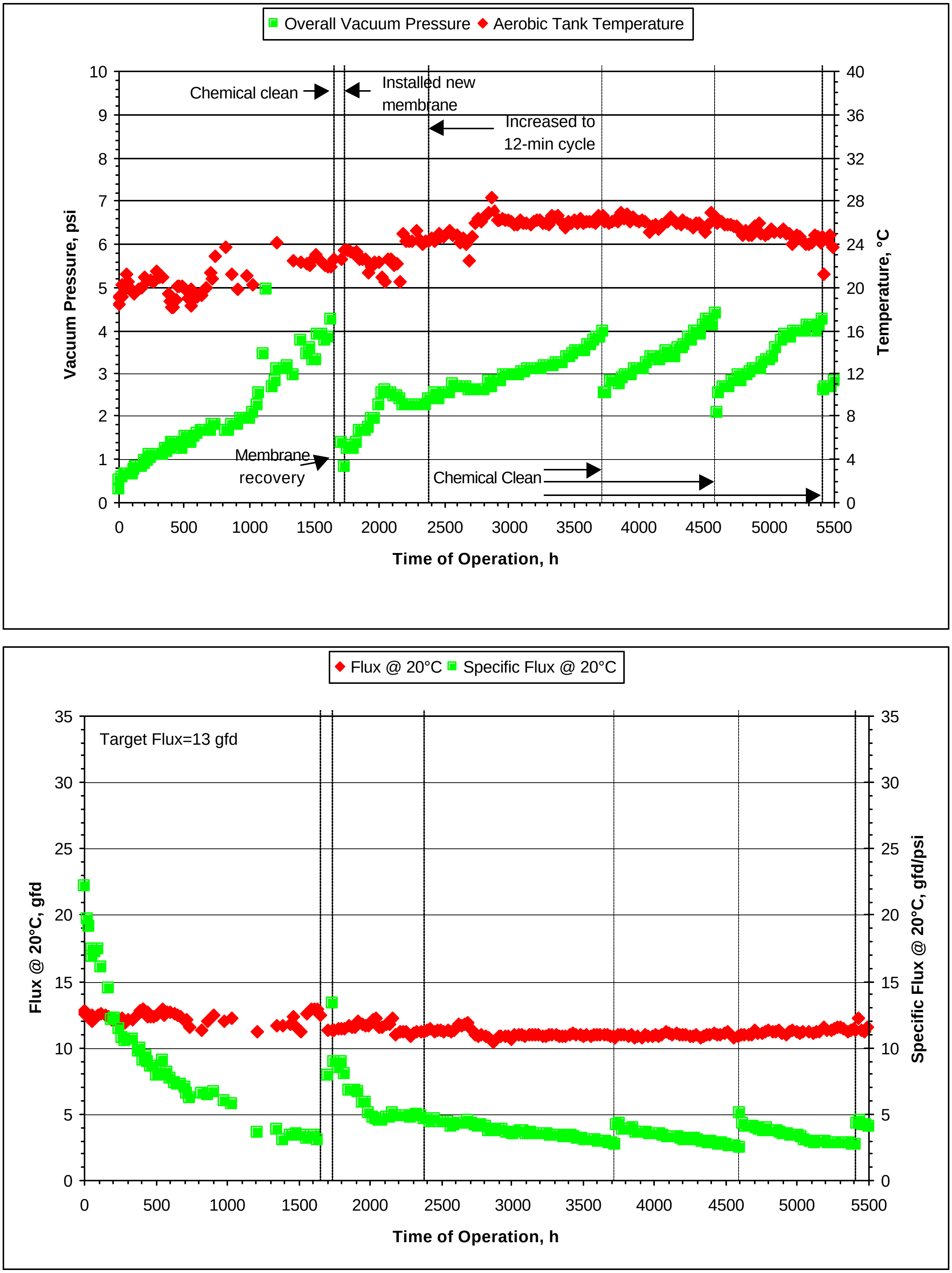


Figure 5-7 Membrane Performance of the Mitsubishi MBR During Part 1

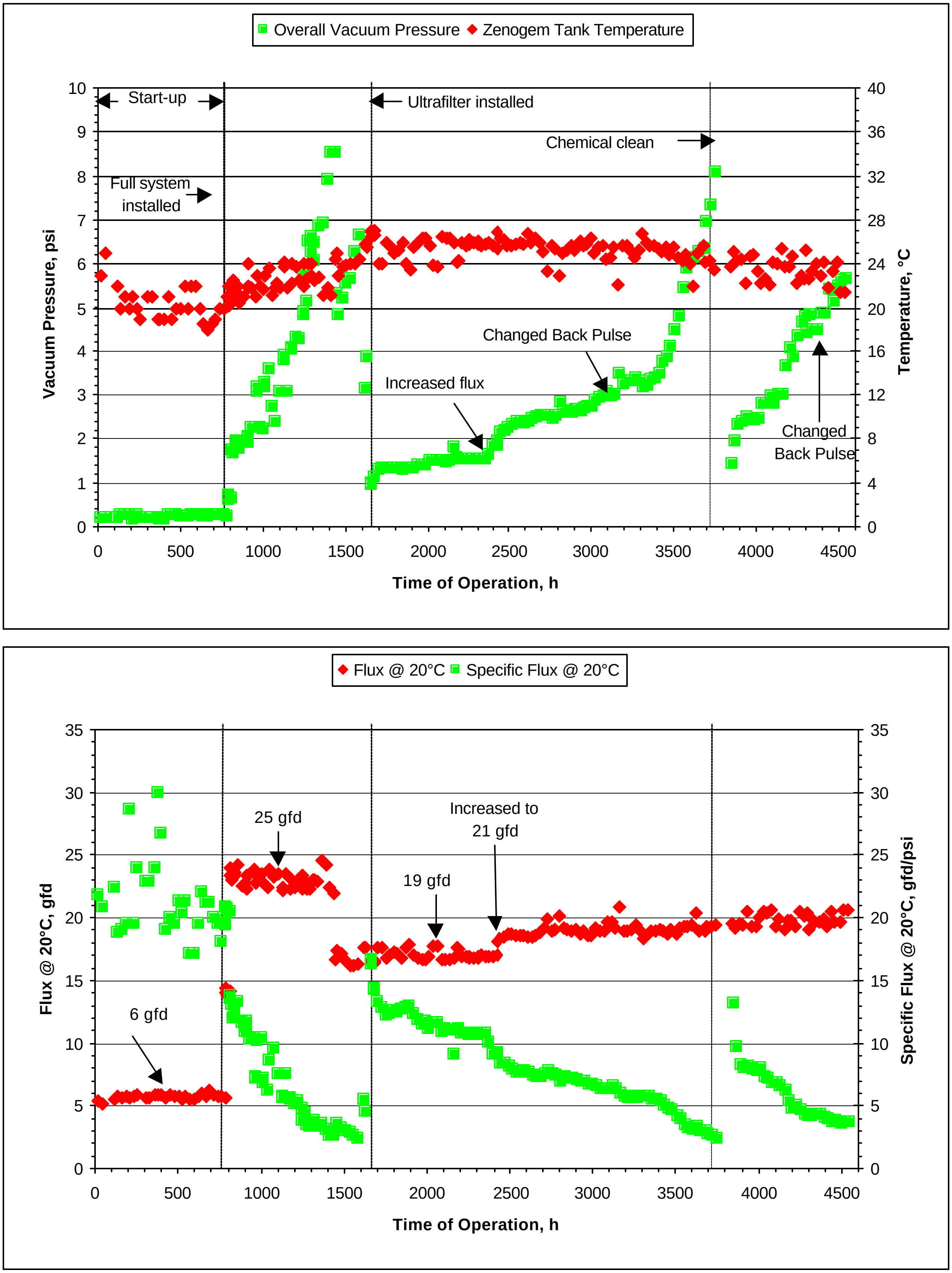


Figure 5-8a Membrane Performance of the Zenon MBR During Part 1

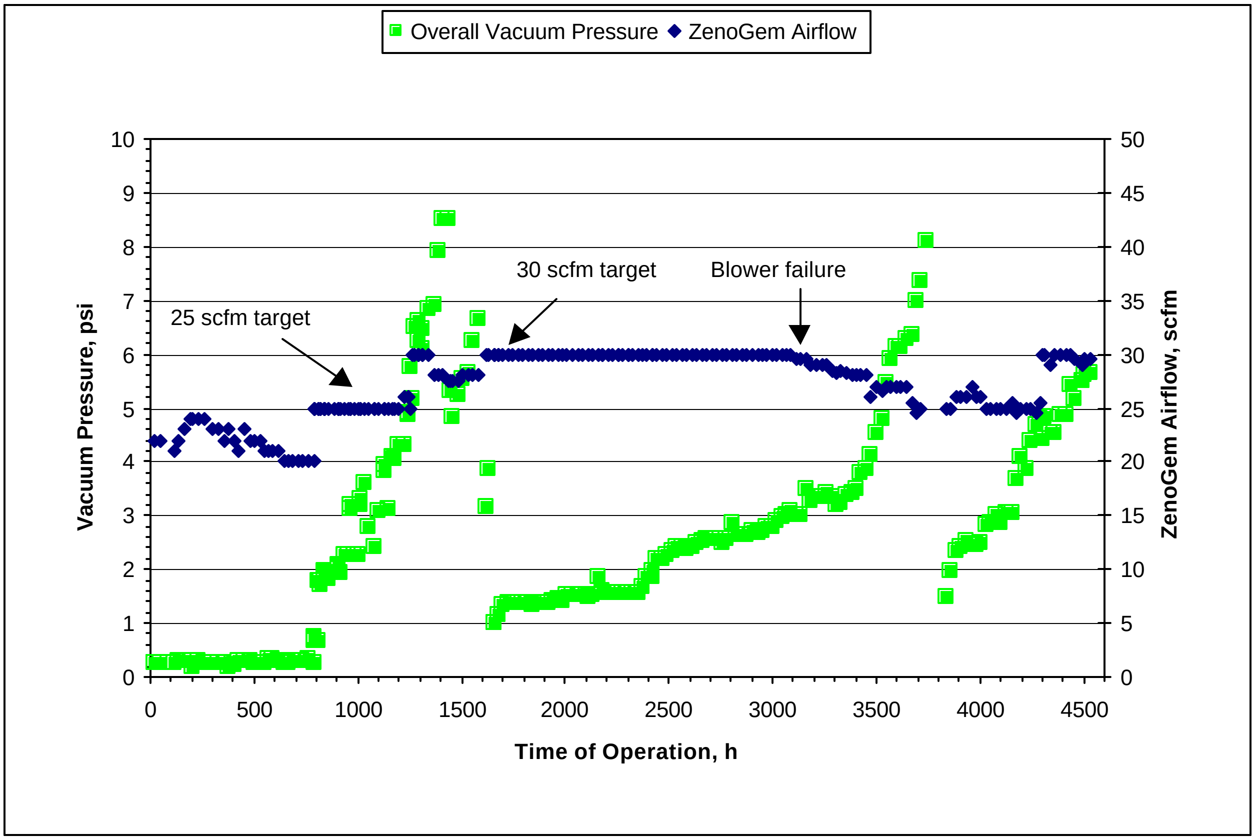
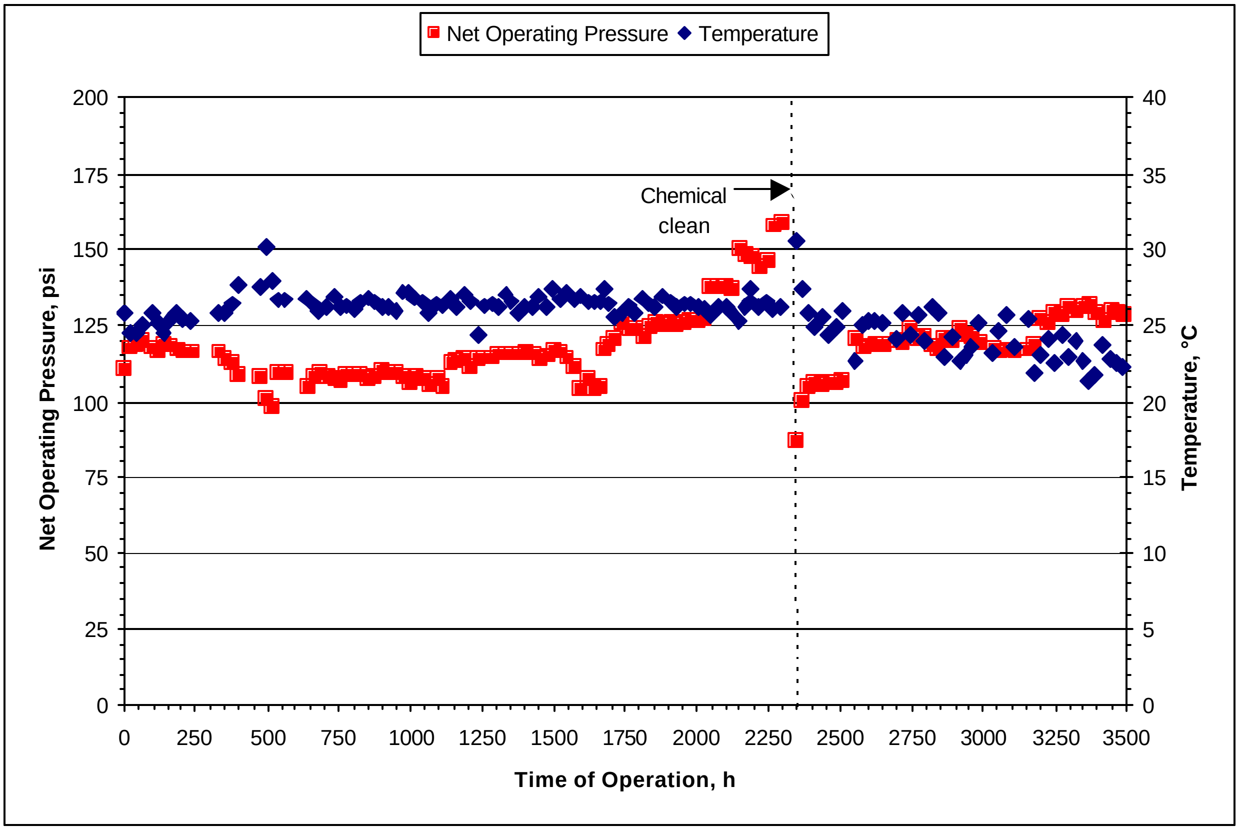


Figure 5-8b Zenon MBR Airflow and Vacuum Pressure During Part 1



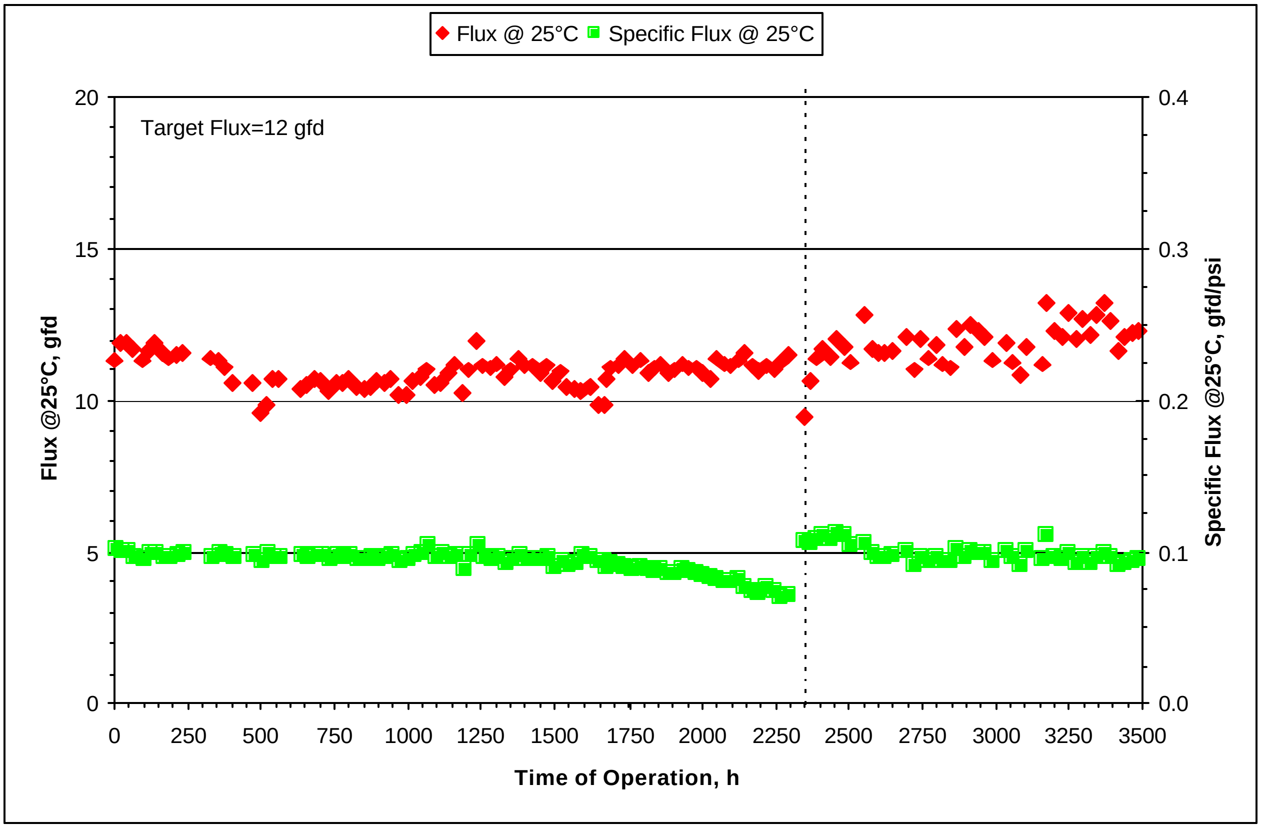


Figure 5-9 Mitsubishi MBR RO Membrane Performance During Part 1

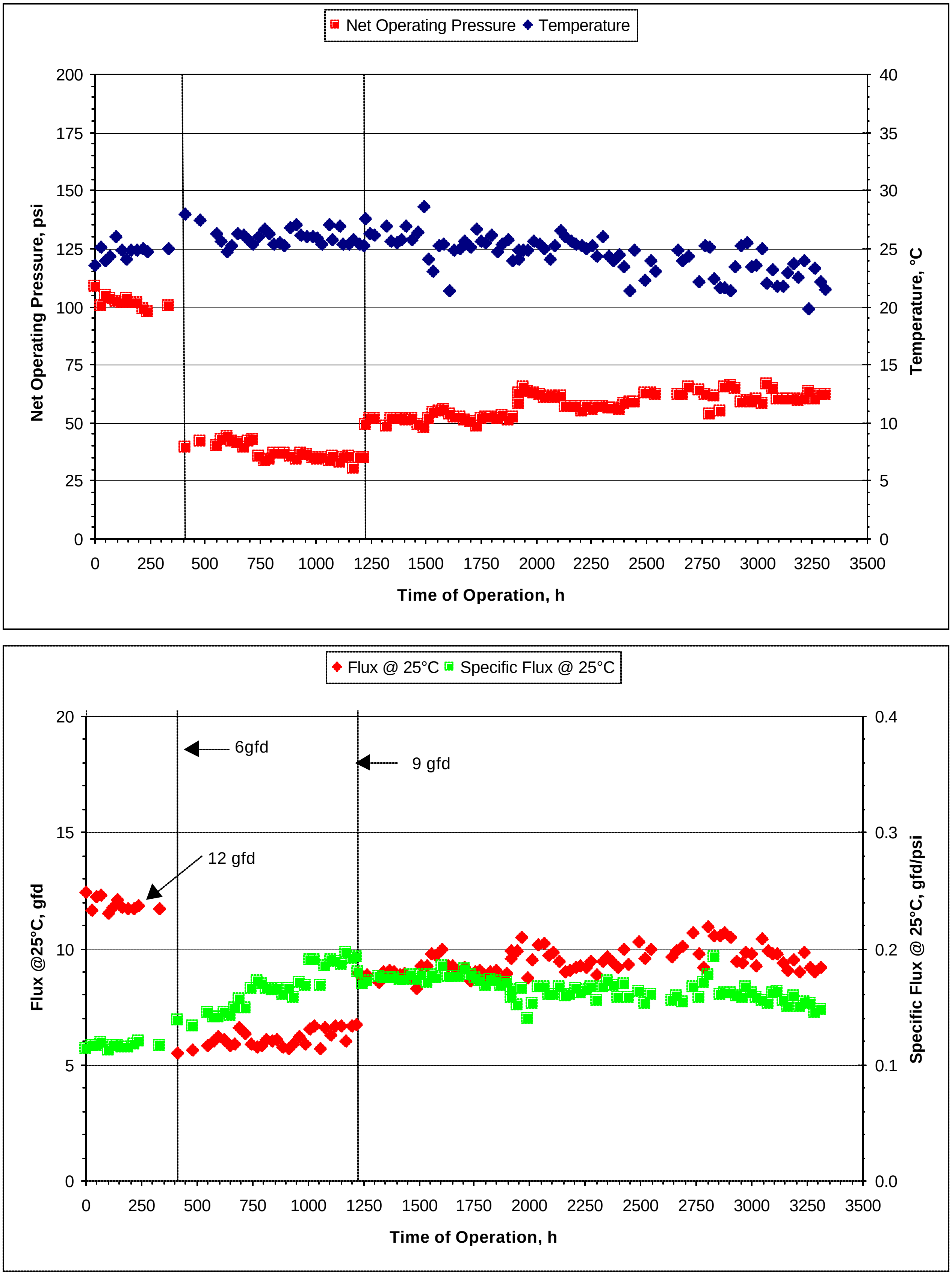


Figure 5-10 Zenon MBR RO Performance During Part 1

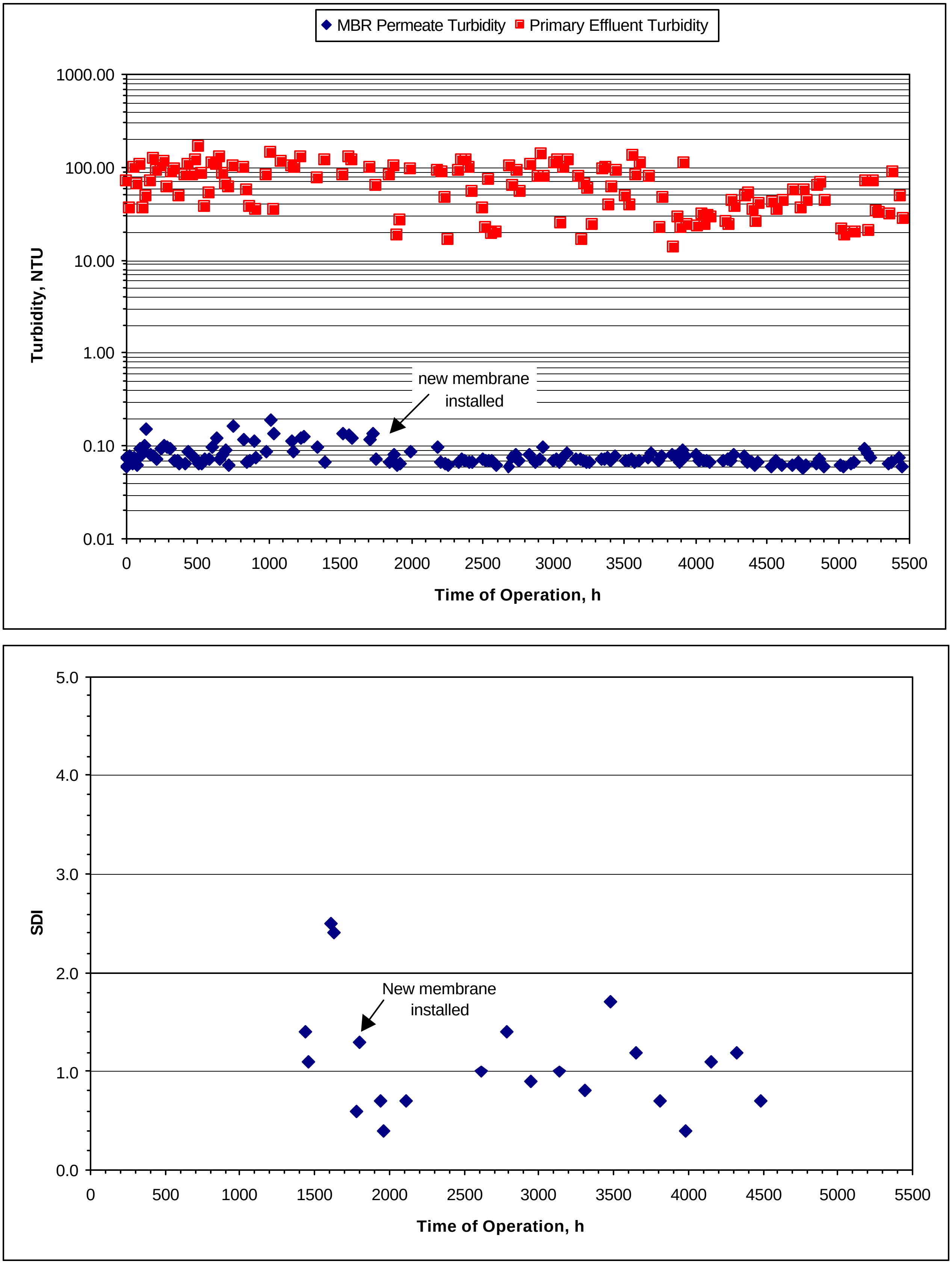
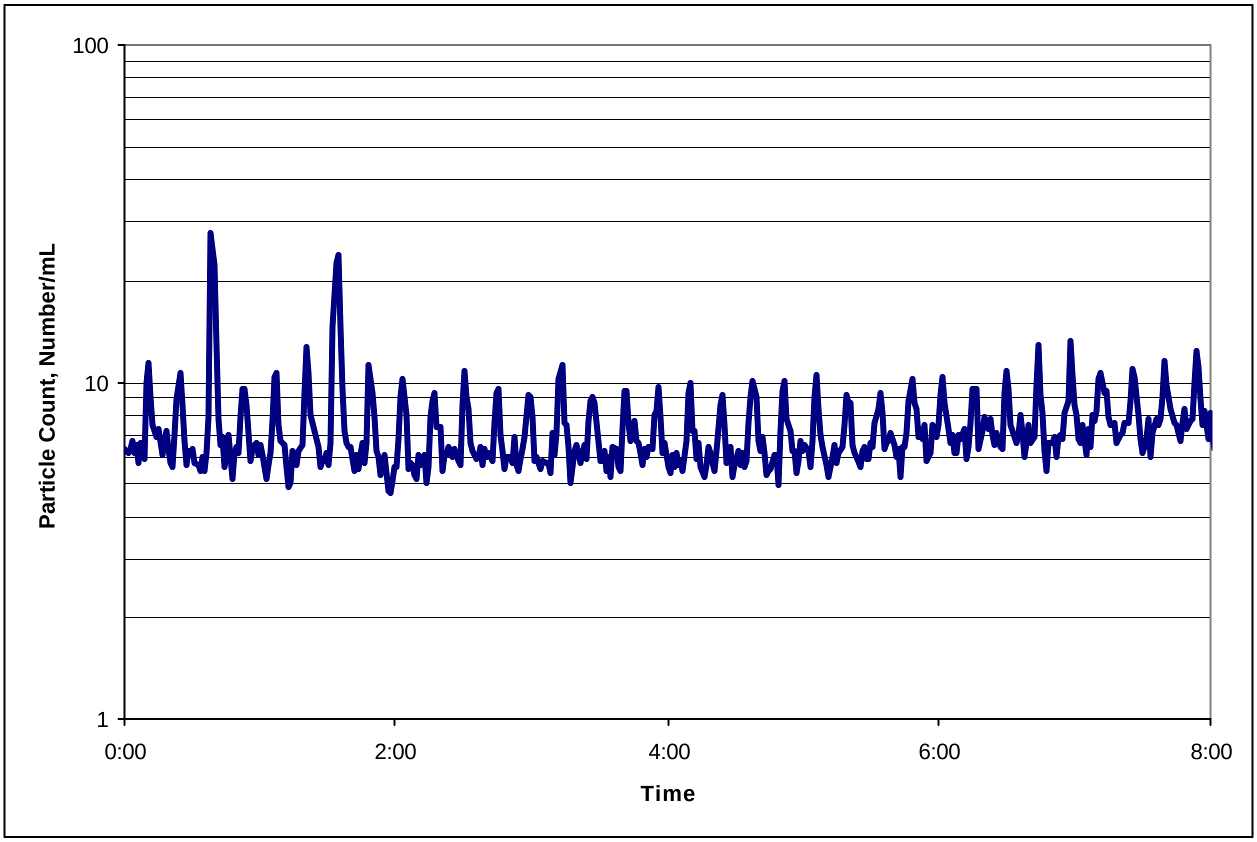


Figure 5-11 Turbidity and SDI Value for the Mitsubishi MBR During Part 1



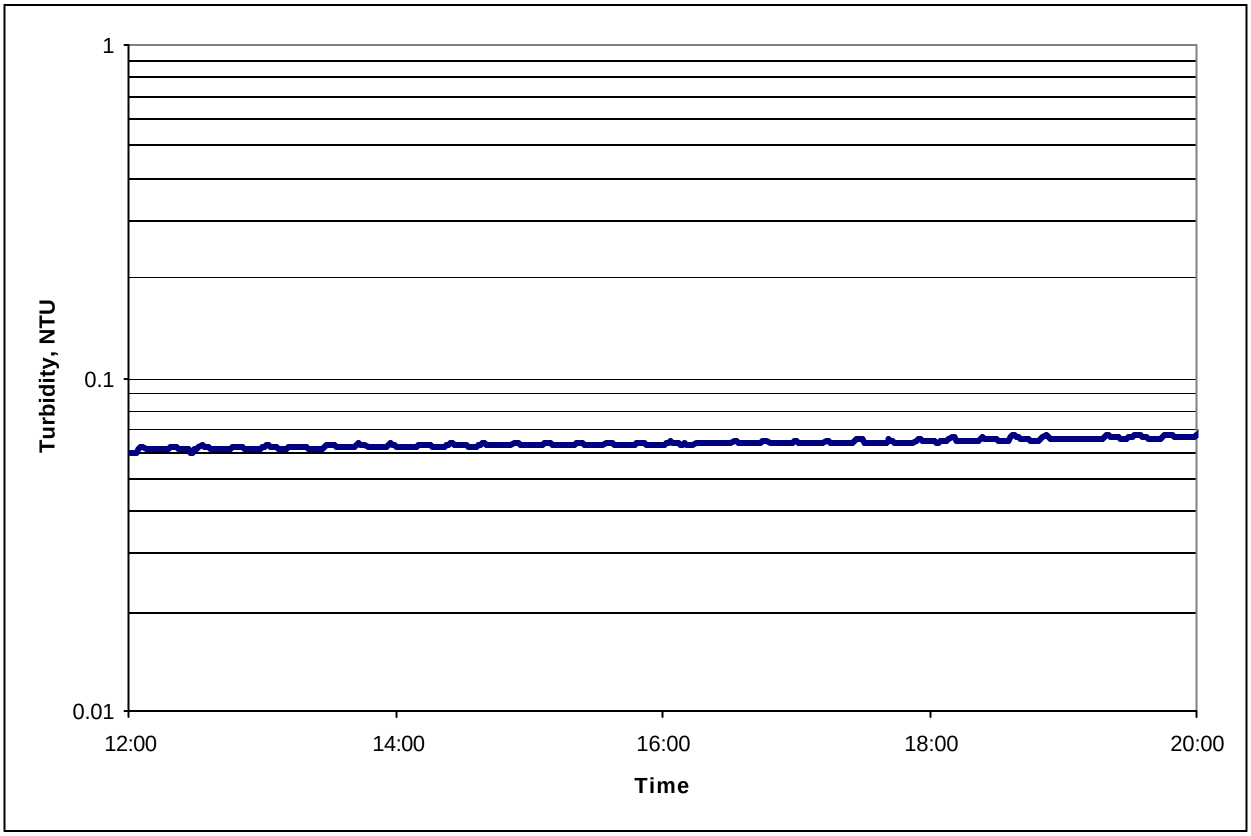
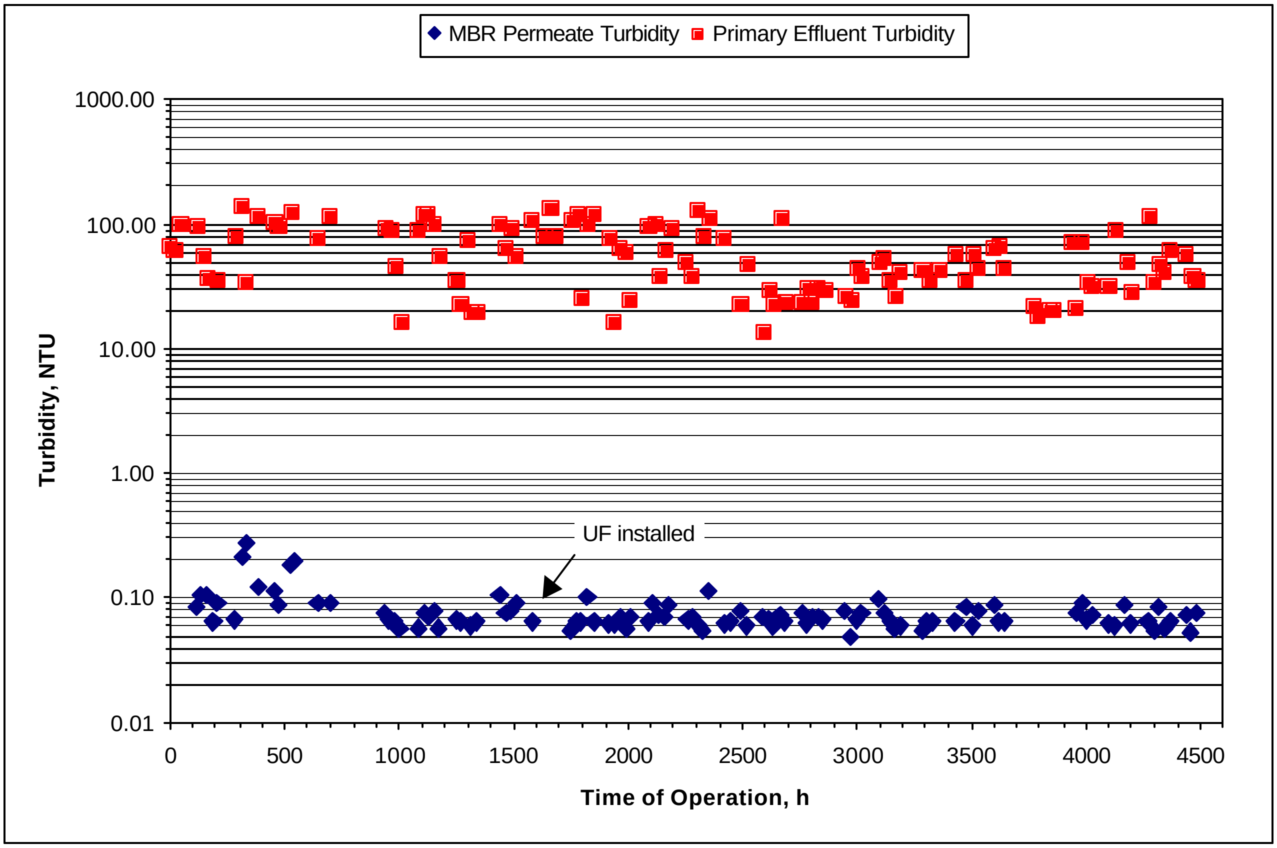


Figure 5-12 On-line Monitoring of the Mitsubishi MBR During Part 1



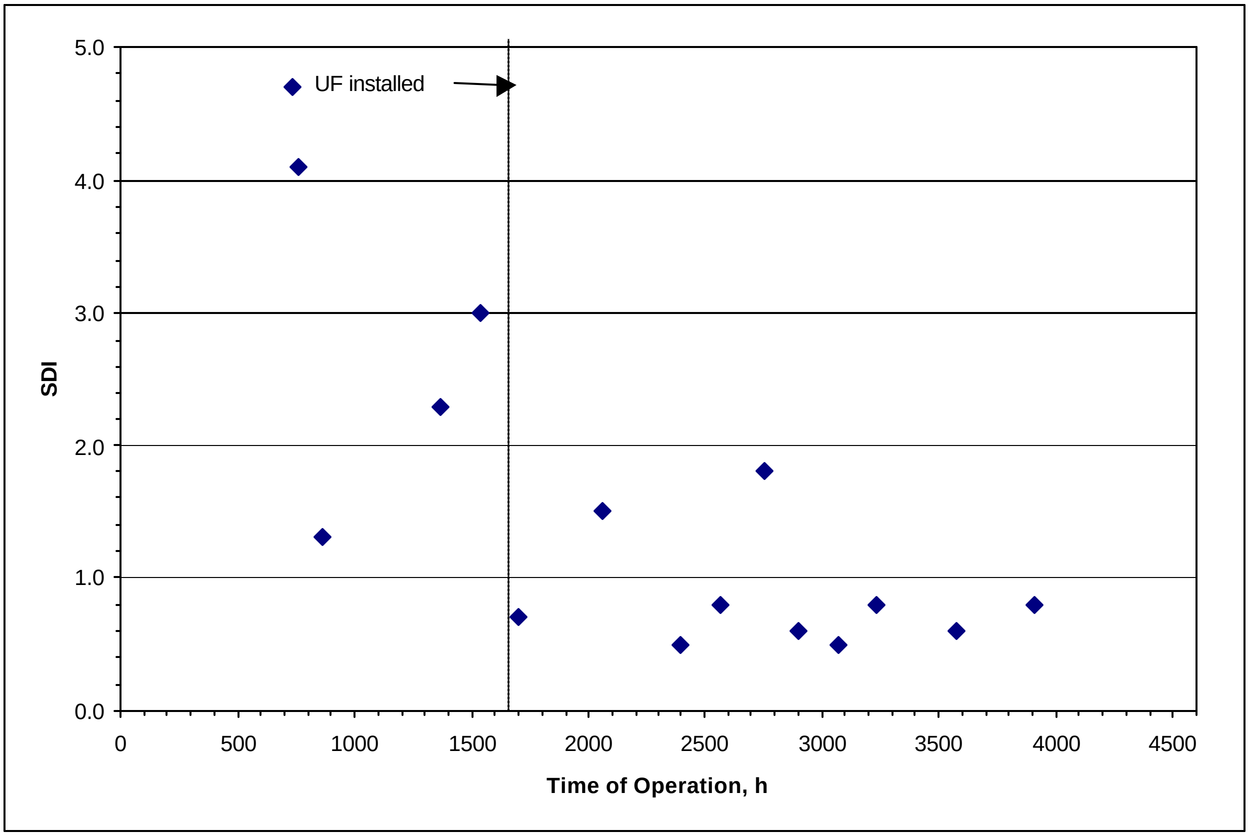


Figure 5-13 Turbidity and SDI Values for the Zenon MBR Permeate During Part 2

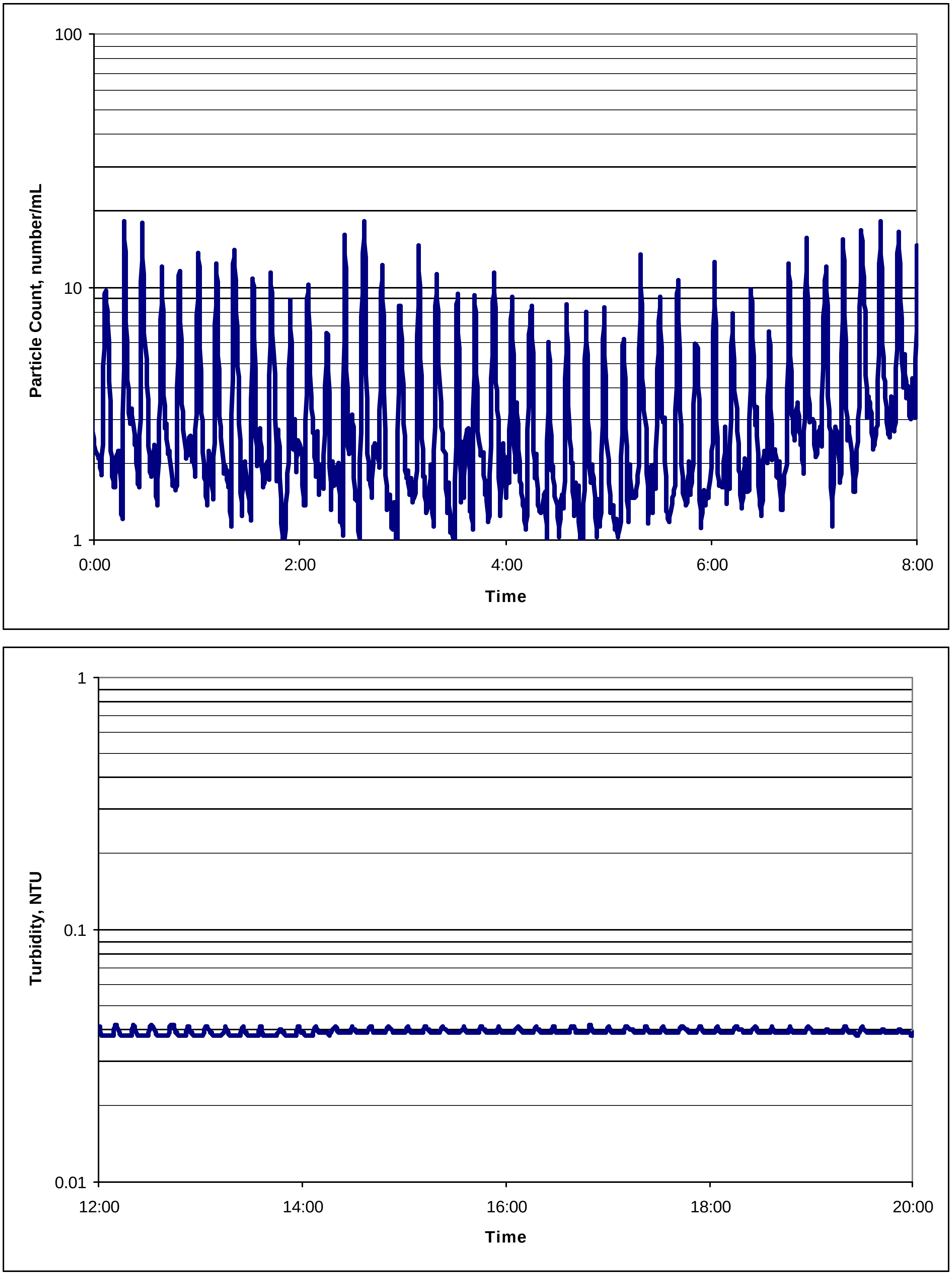
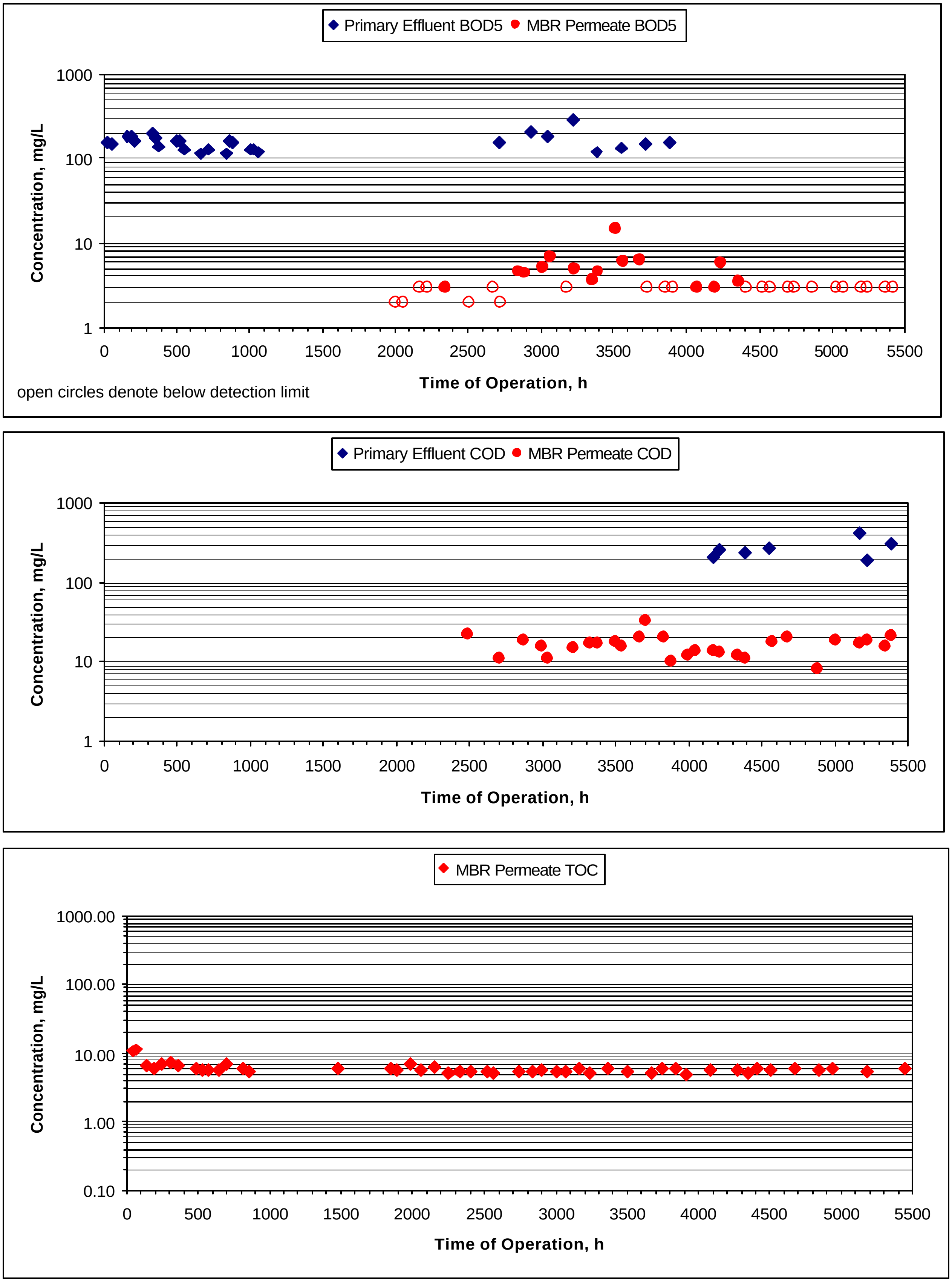
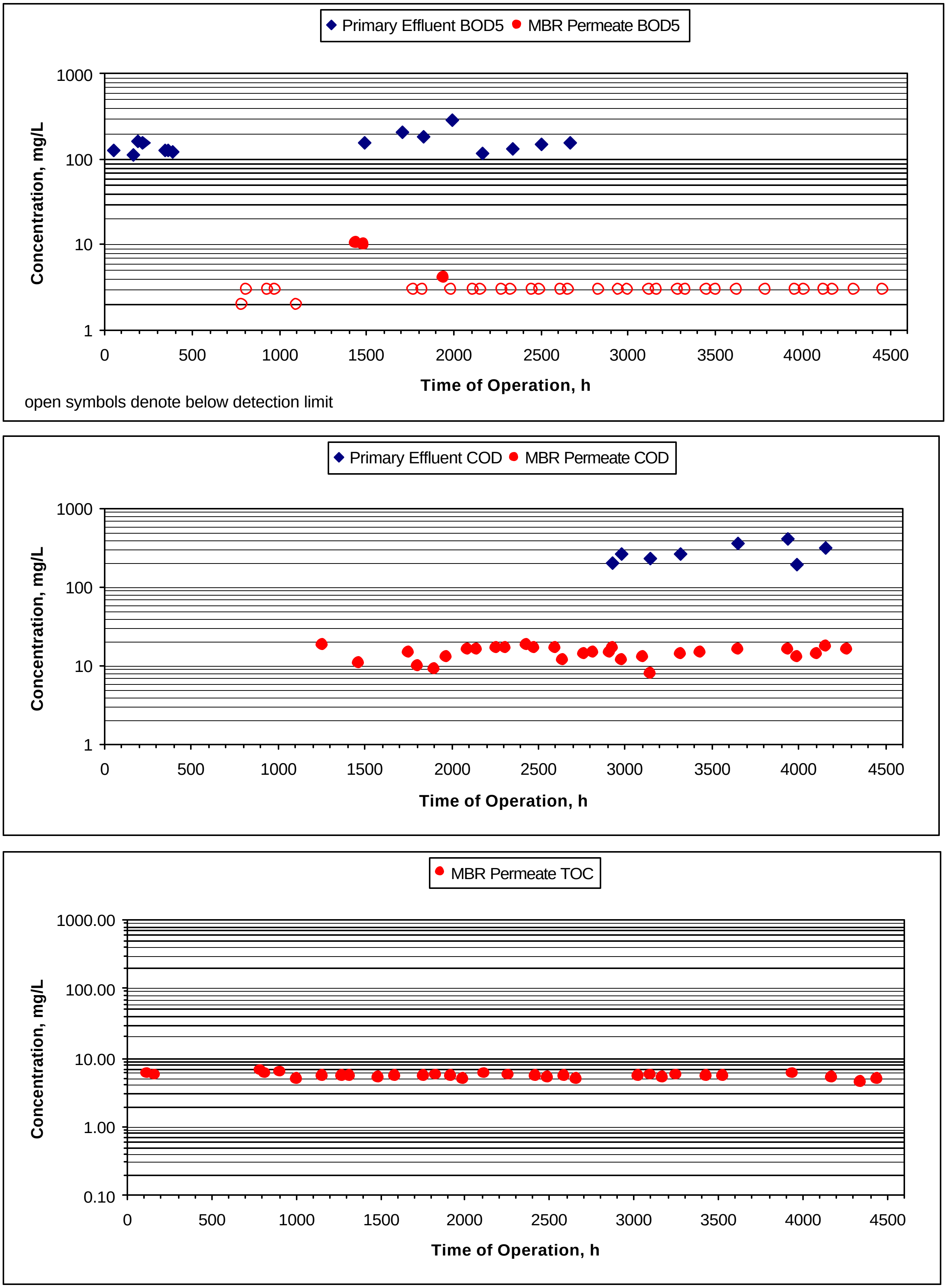


Figure 5-14 On-line Monitoring of the Zenon MBR Permeate During Part 1



open circles denote below detection limit

Figure 5-15 Organics Removal by the Mitsubishi MBR During Part 1



open symbols denote below detection limit

Figure 5-16 Organics Removal by the Zenon MBR During Part 1

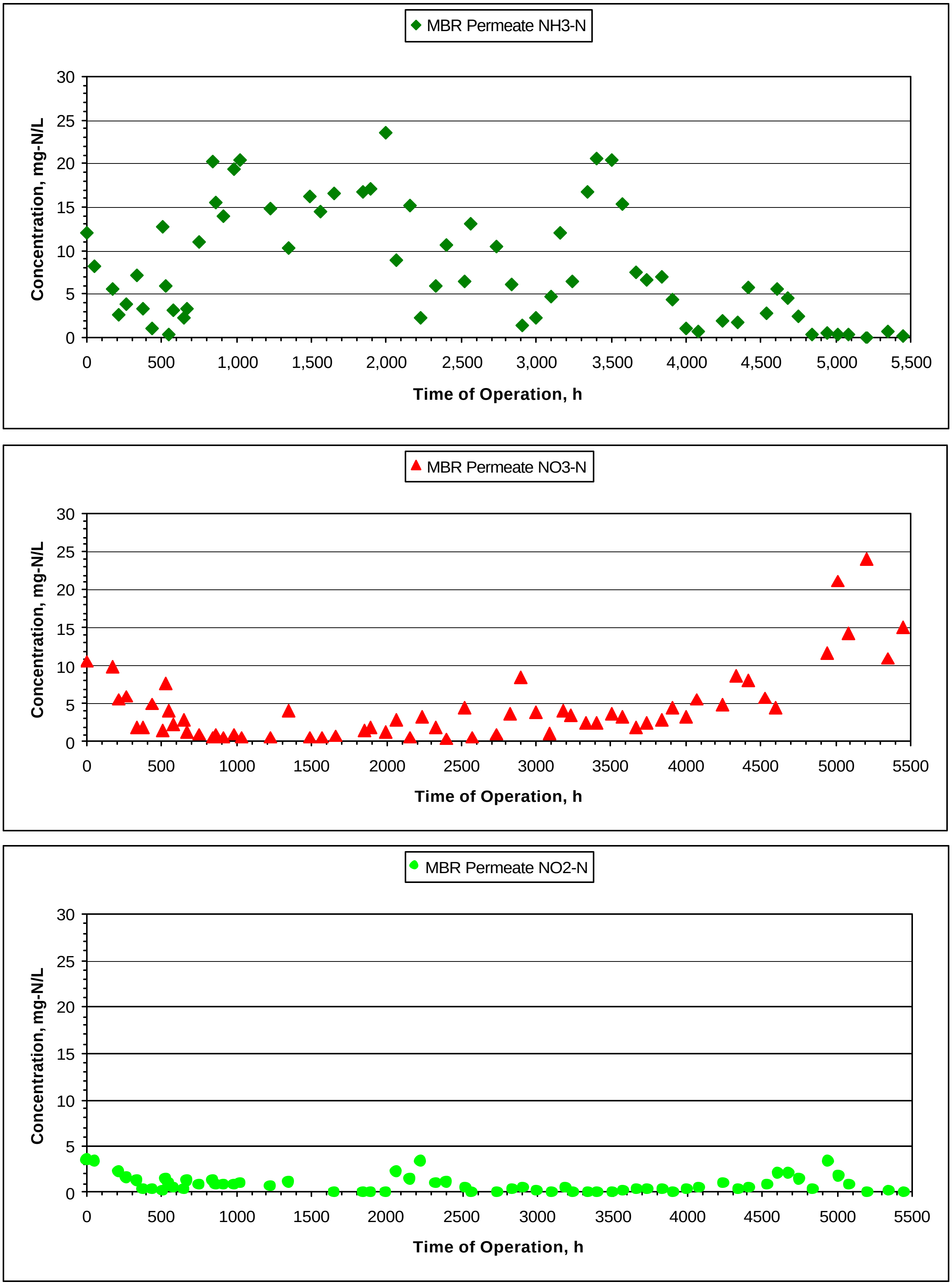


Figure 5-17 Inorganic Nitrogen Species in the Mitsubishi MBR Permeate During Part 1

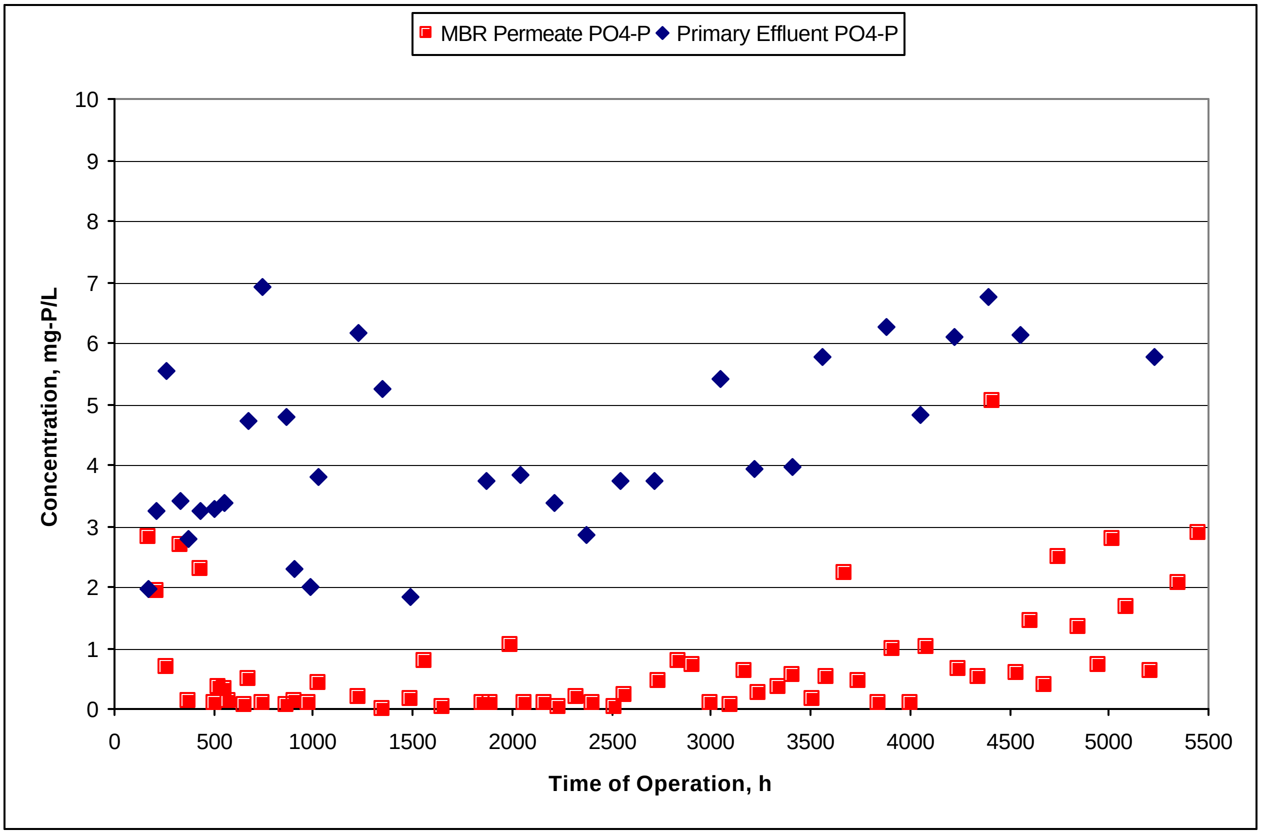


Figure 5-18 Ortho-Phosphate in the Mitsubishi MBR Permeate During Part 1

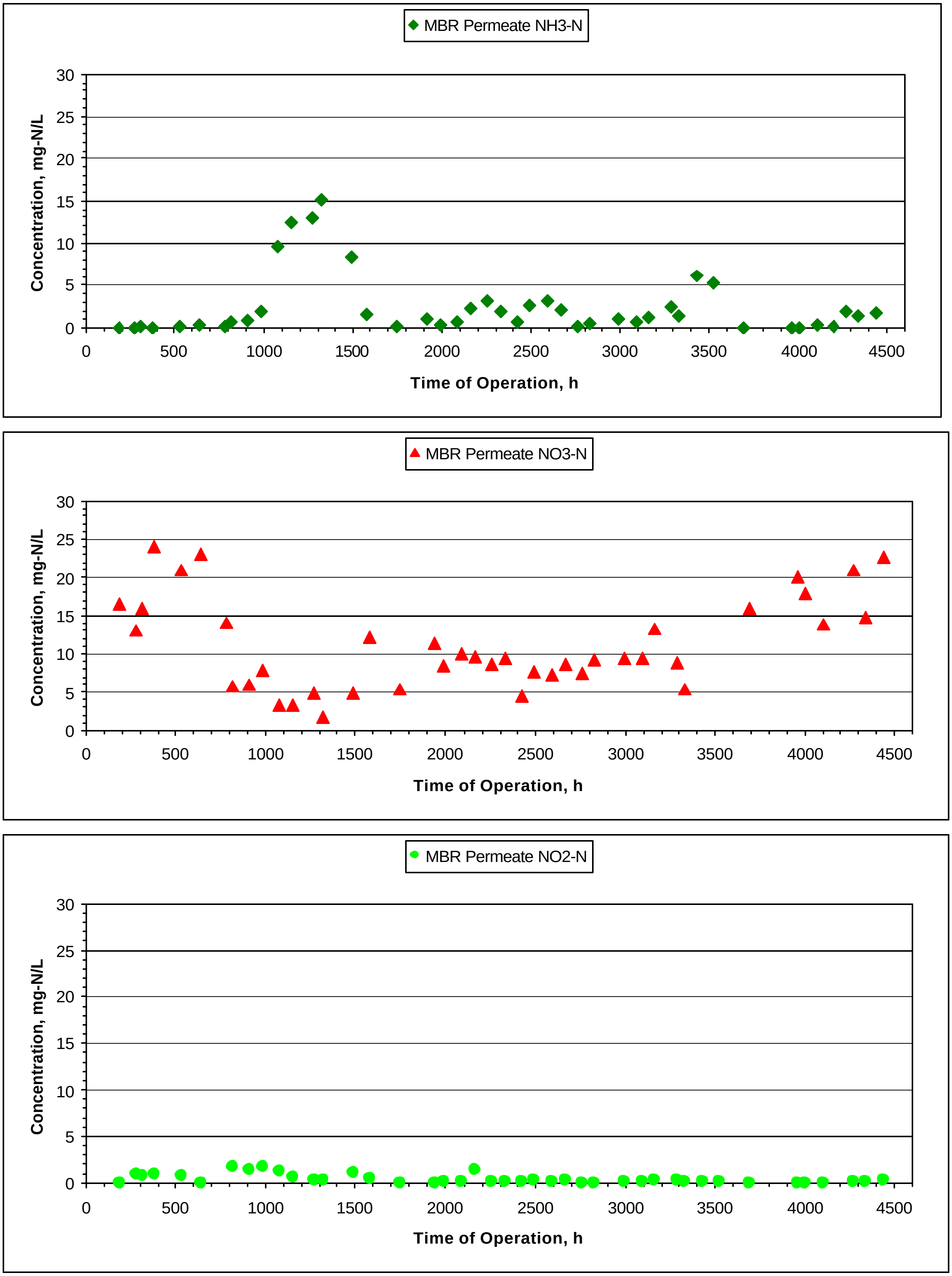


Figure 5-19 Inorganic Nitrogen Species in the Zenon MBR Effluent During Part 1

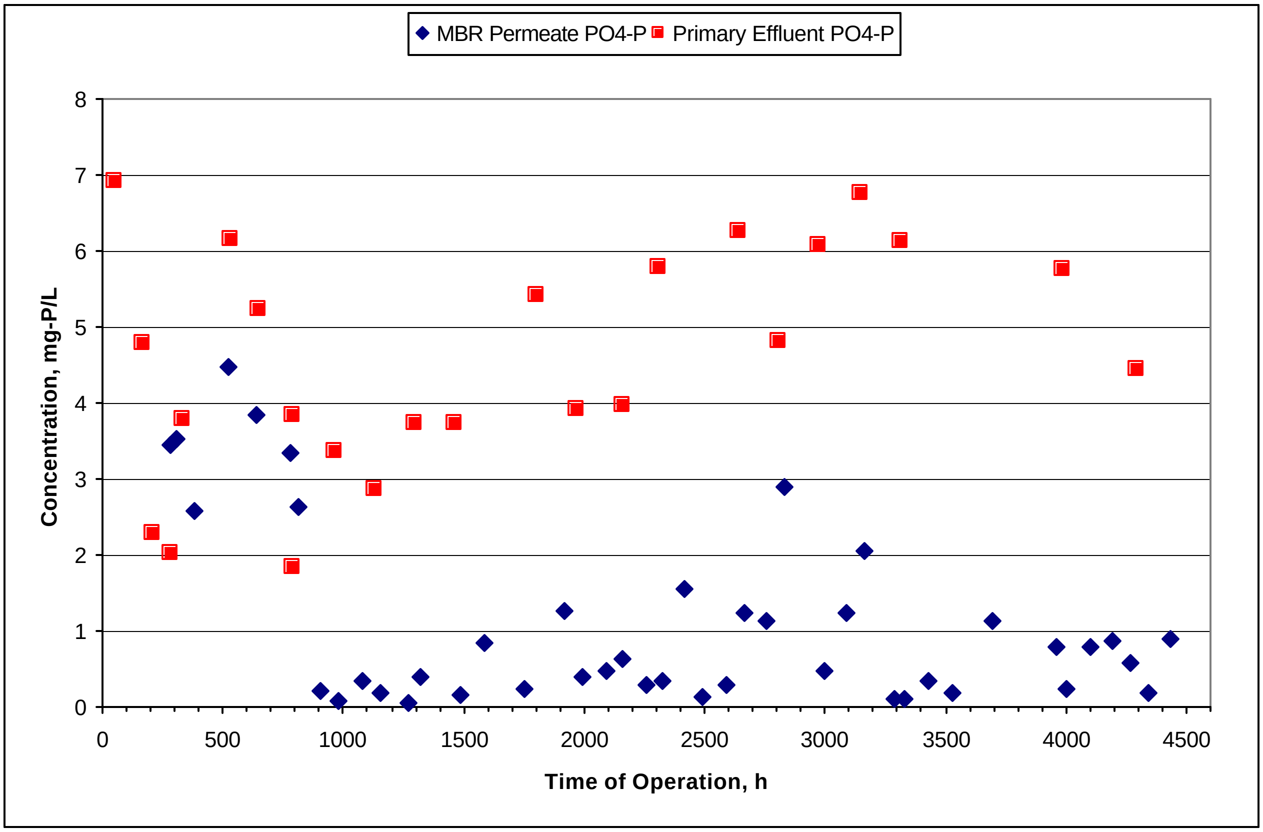


Figure 5-20 Ortho-Phosphate Removal by the Zenon MBR During Part 1

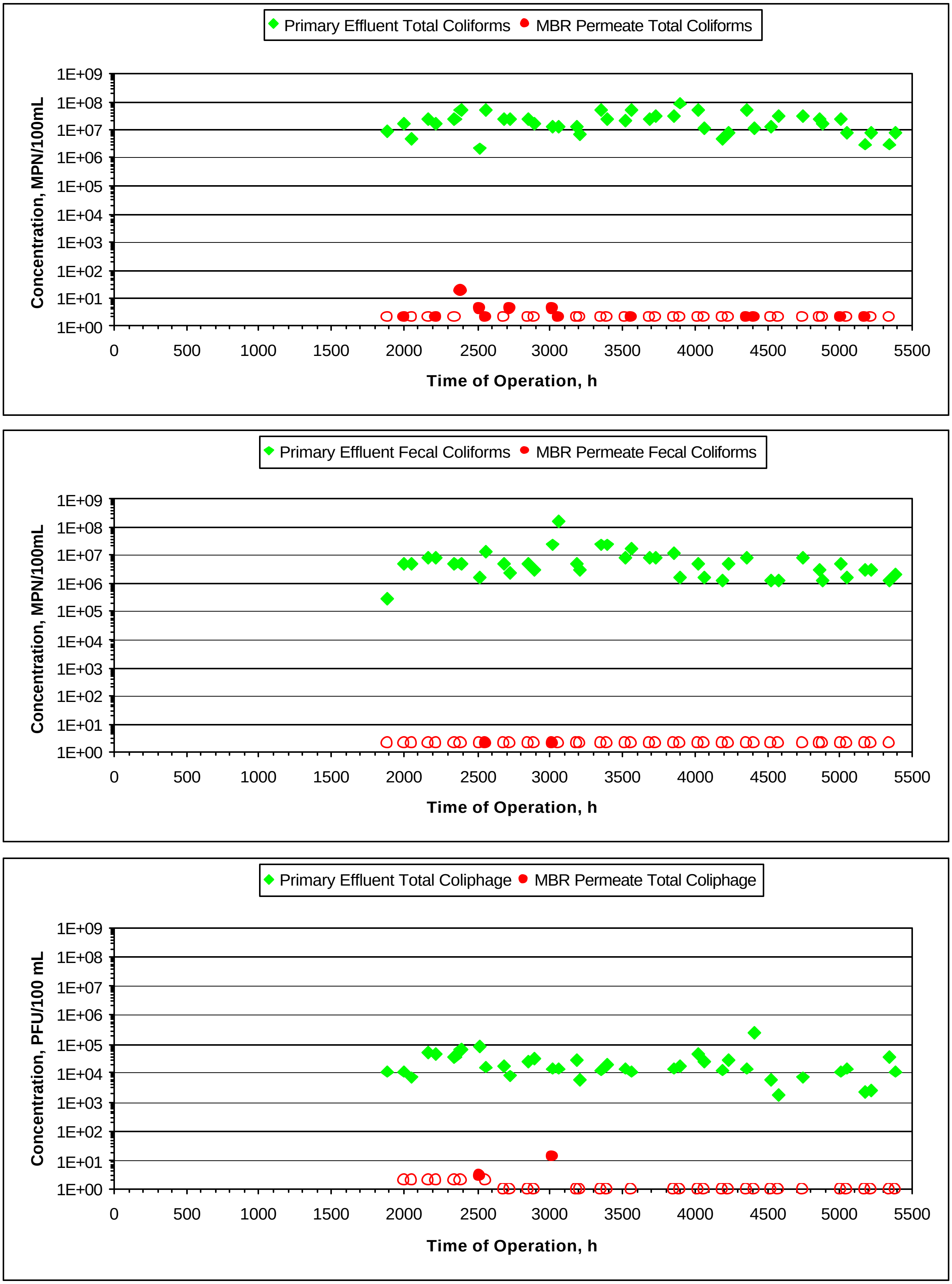
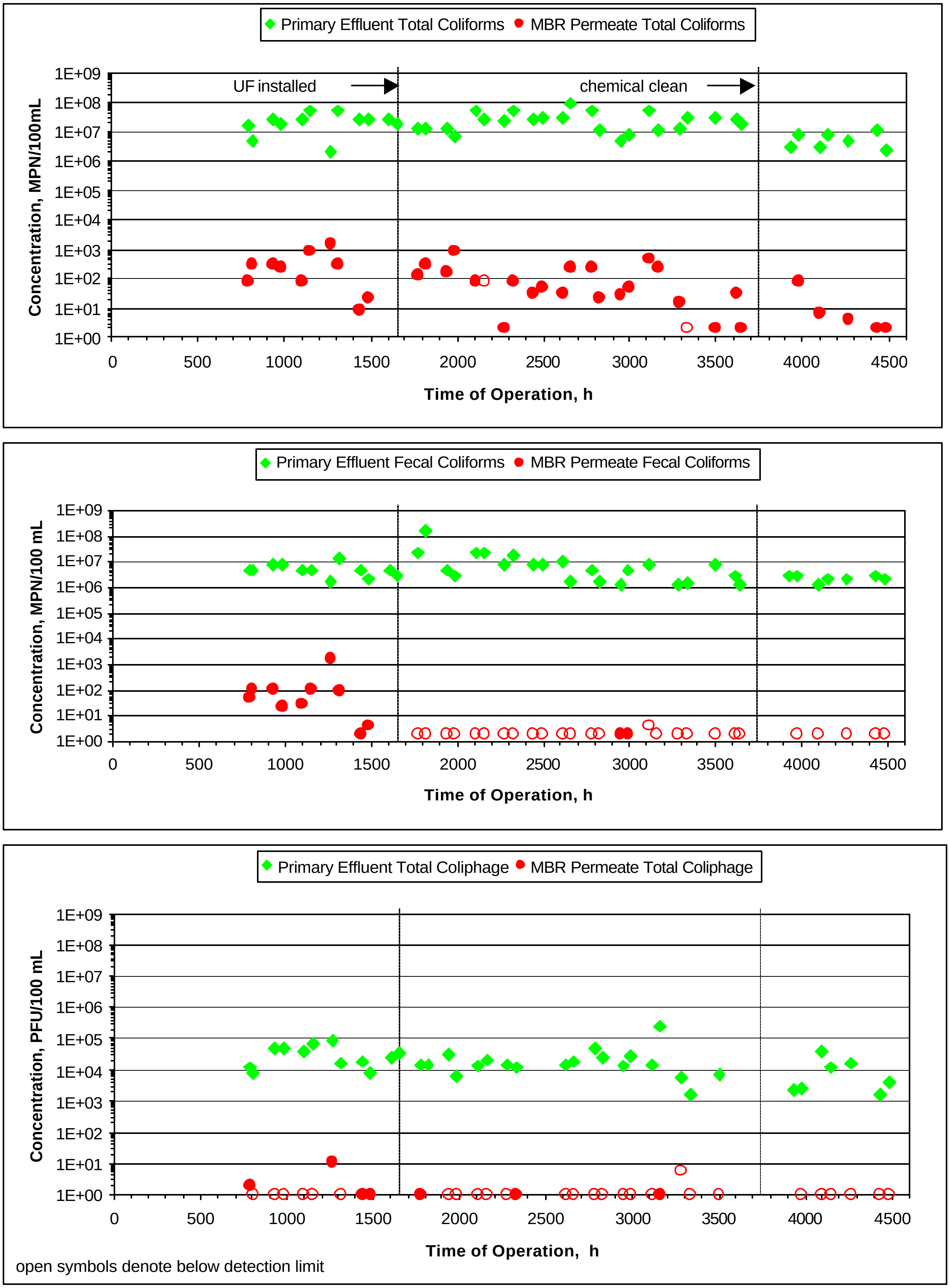


Figure 5-21 Microbial Removal by the Mitsubishi MBR During Part 1



open symbols denote below detection limit

Figure 5-22 Microbial Removal by the Zenon MBR During Part 1

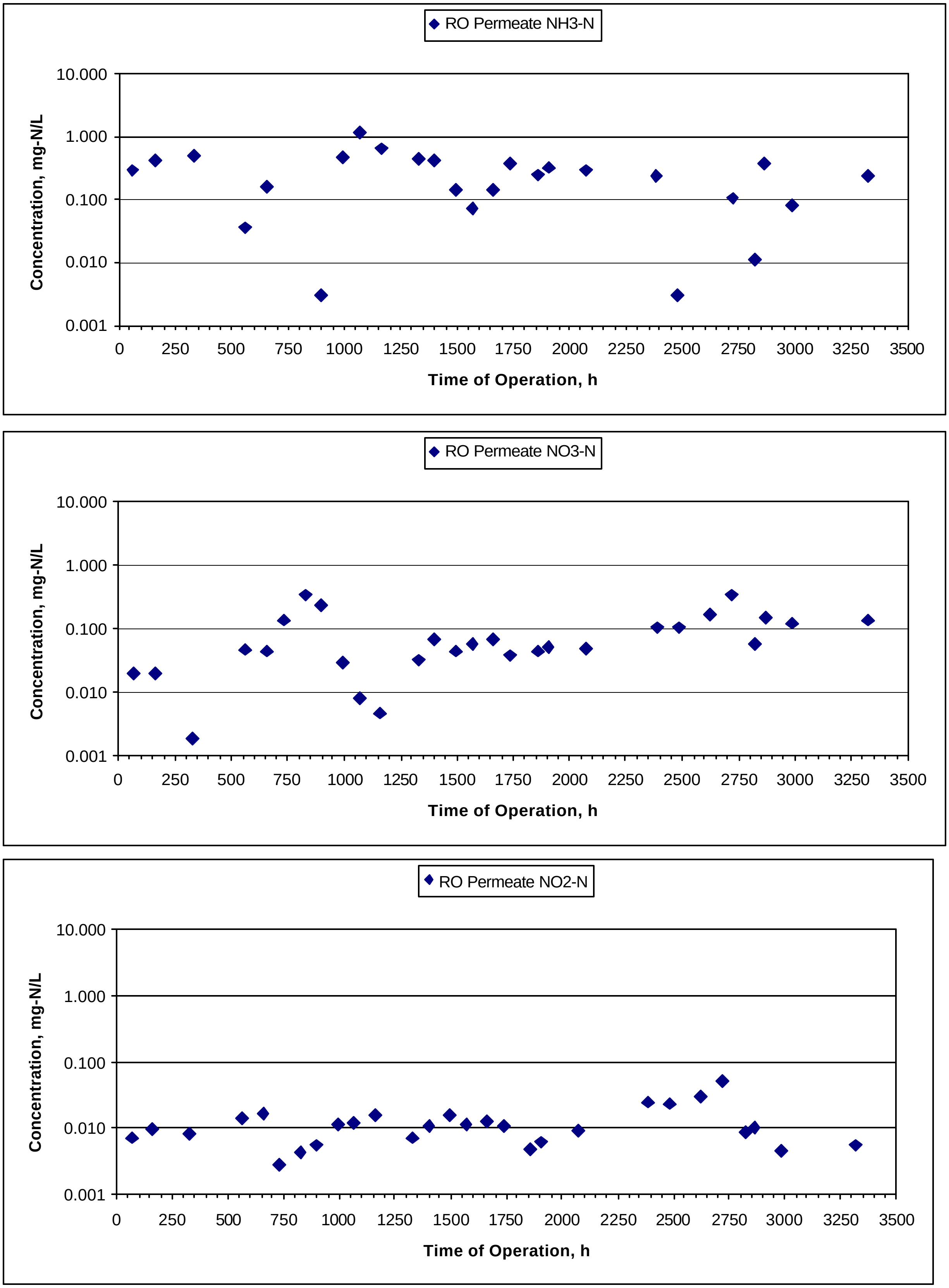


Figure 5-23 Inorganic Nitrogen Species in the Mitsubishi MBR RO Permeate During Part 1

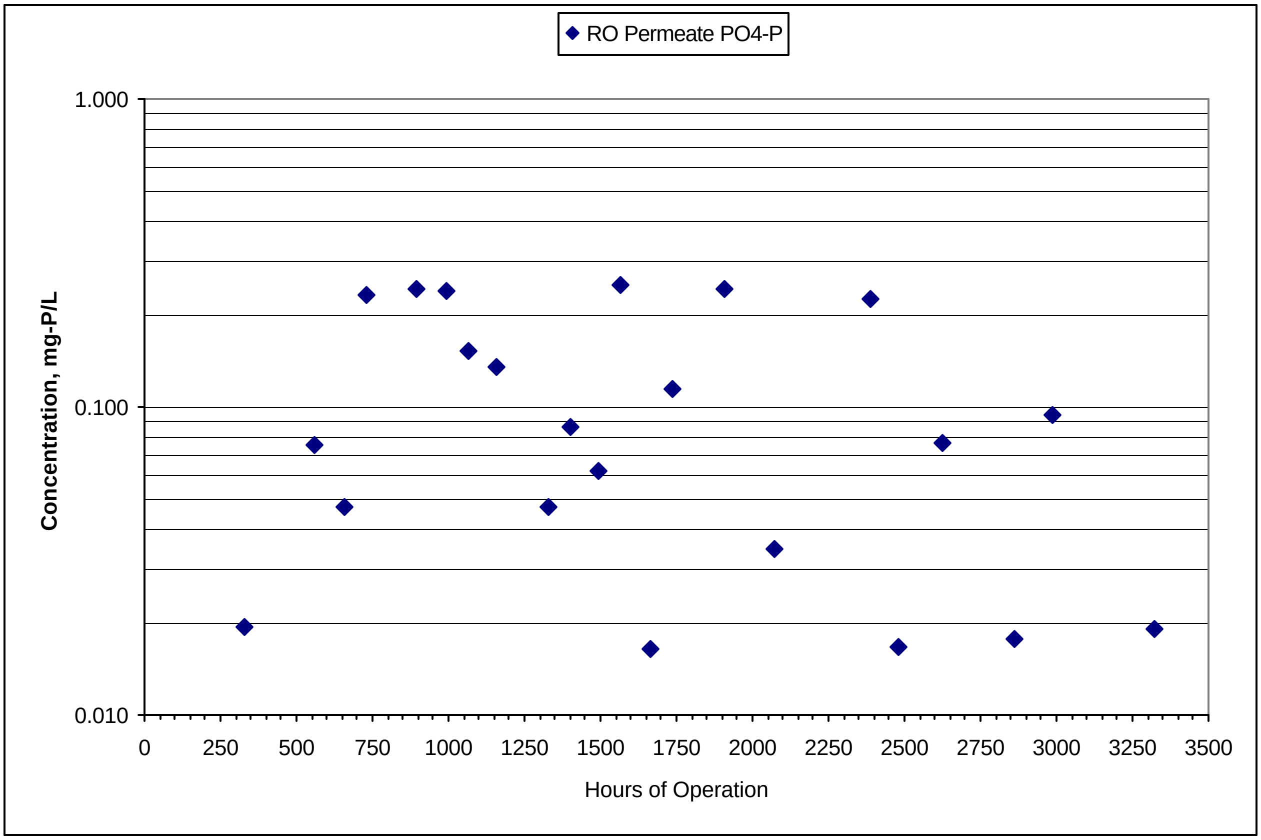


Figure 5-24 Ortho-Phosphate in the Mitsubishi MBR RO Permeate During Part 1

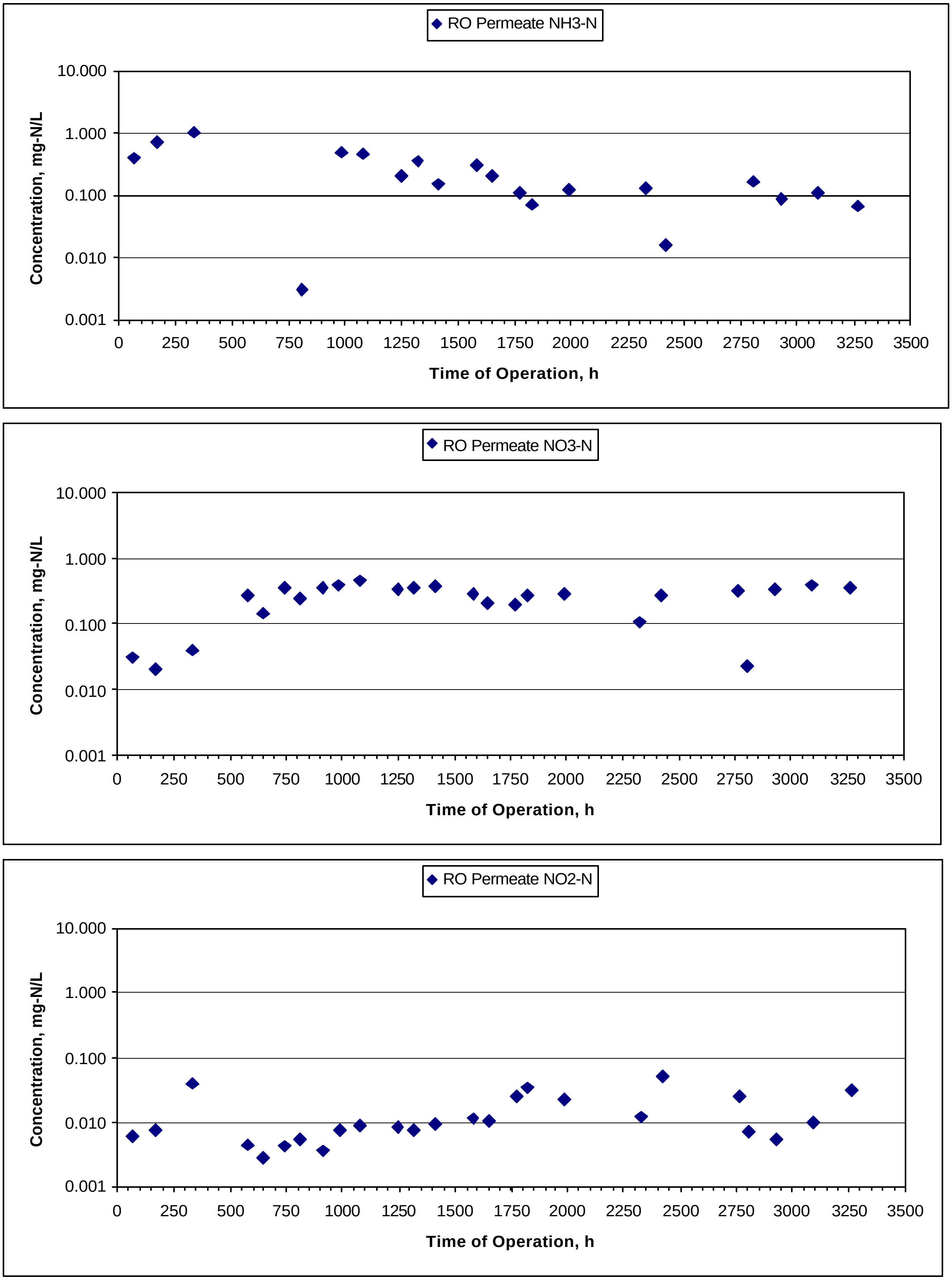


Figure 5-25 Inorganic Nitrogen Species in the Zenon MBR RO Permeate

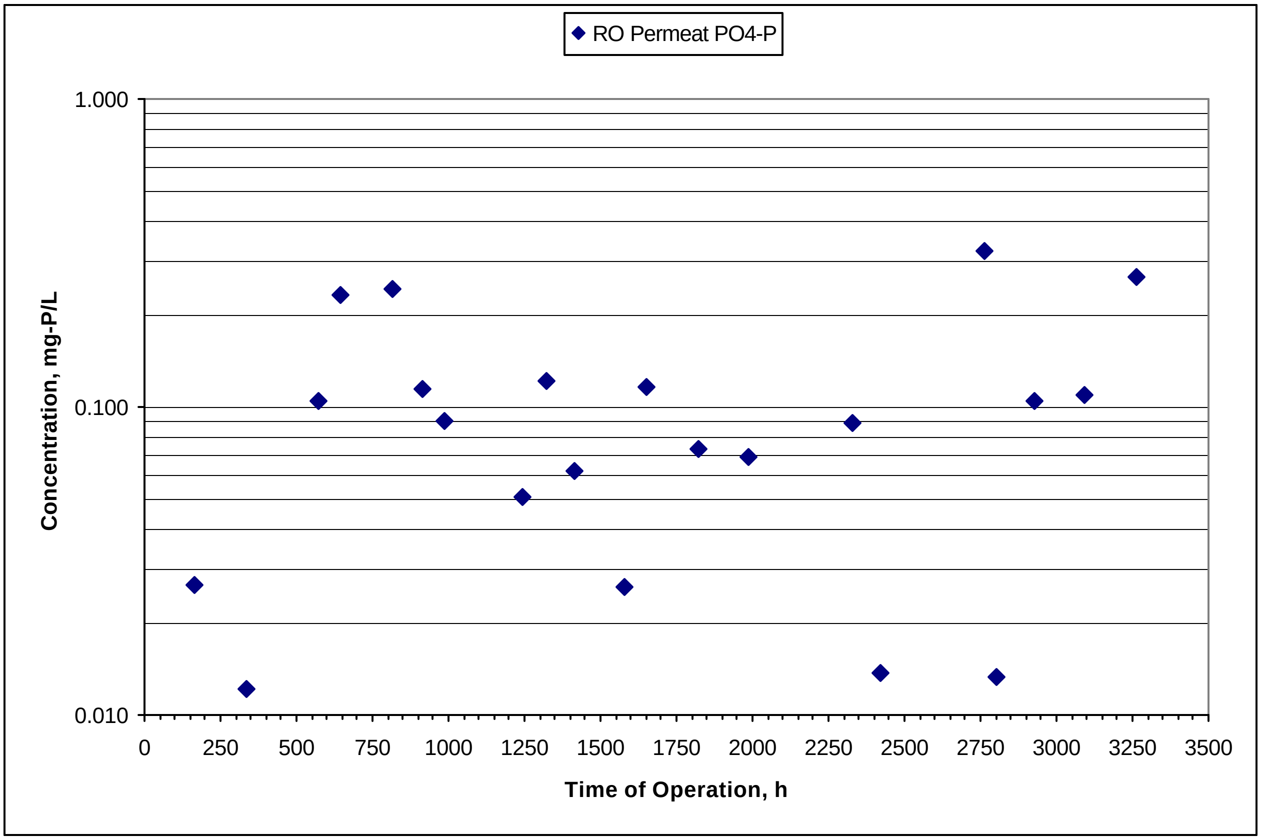


Figure 5-26 Ortho-Phosphate Concentration in the Zenon MBR RO Permeate

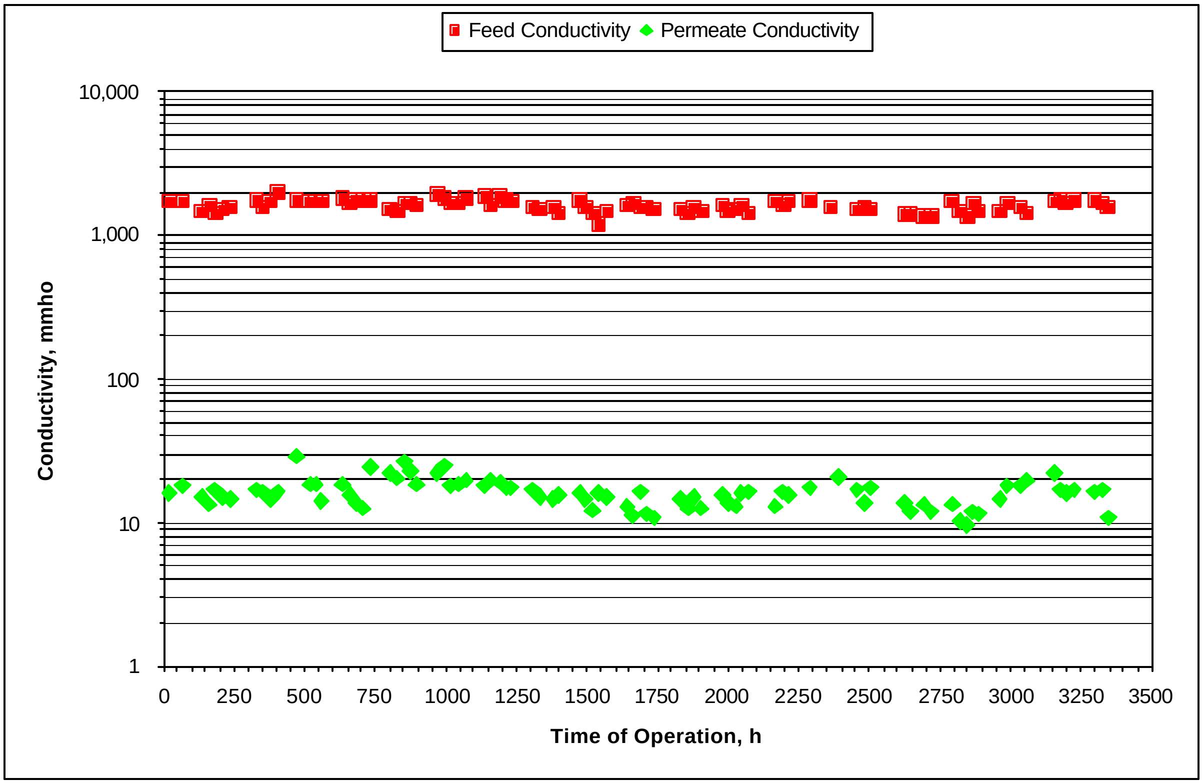


Figure 5-27 Conductivities of the Mitsubishi MBR RO Feed and Permeate During Part 1

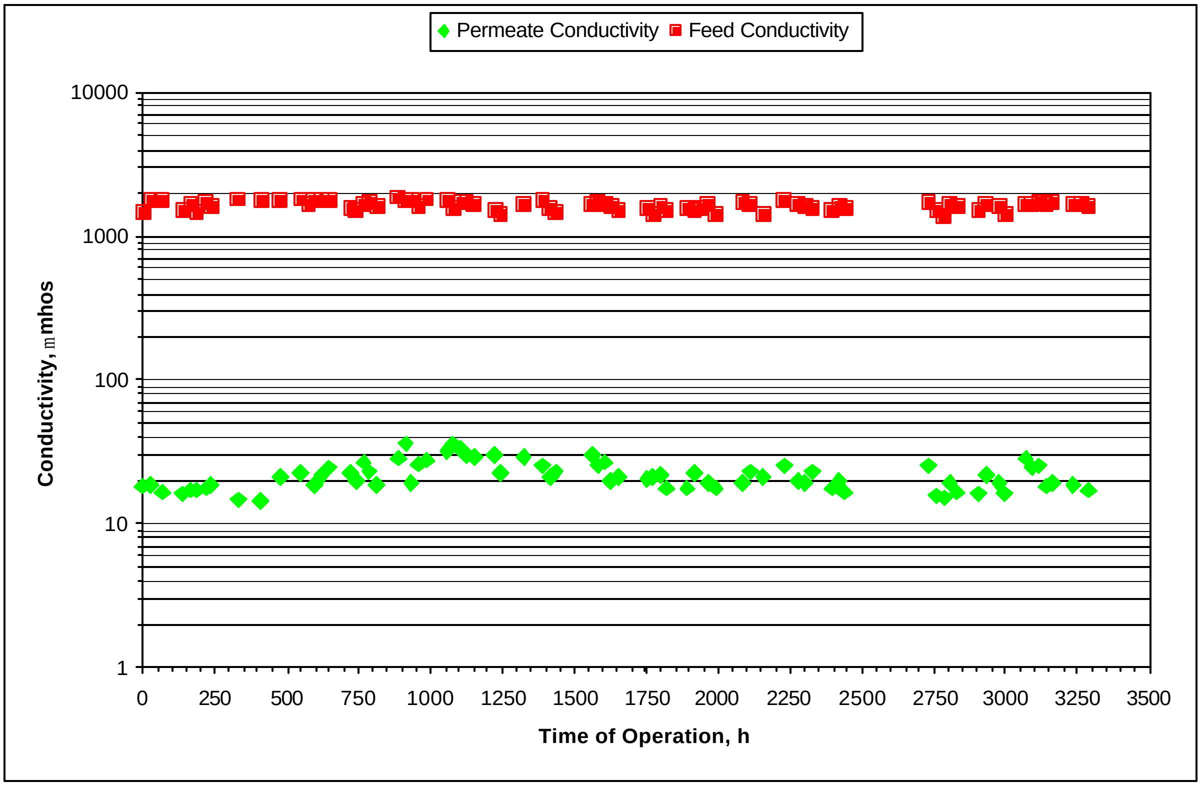


Figure 5-28 Conductivities of the Zenon MBR RO Feed and Permeate Permeate During Part 1

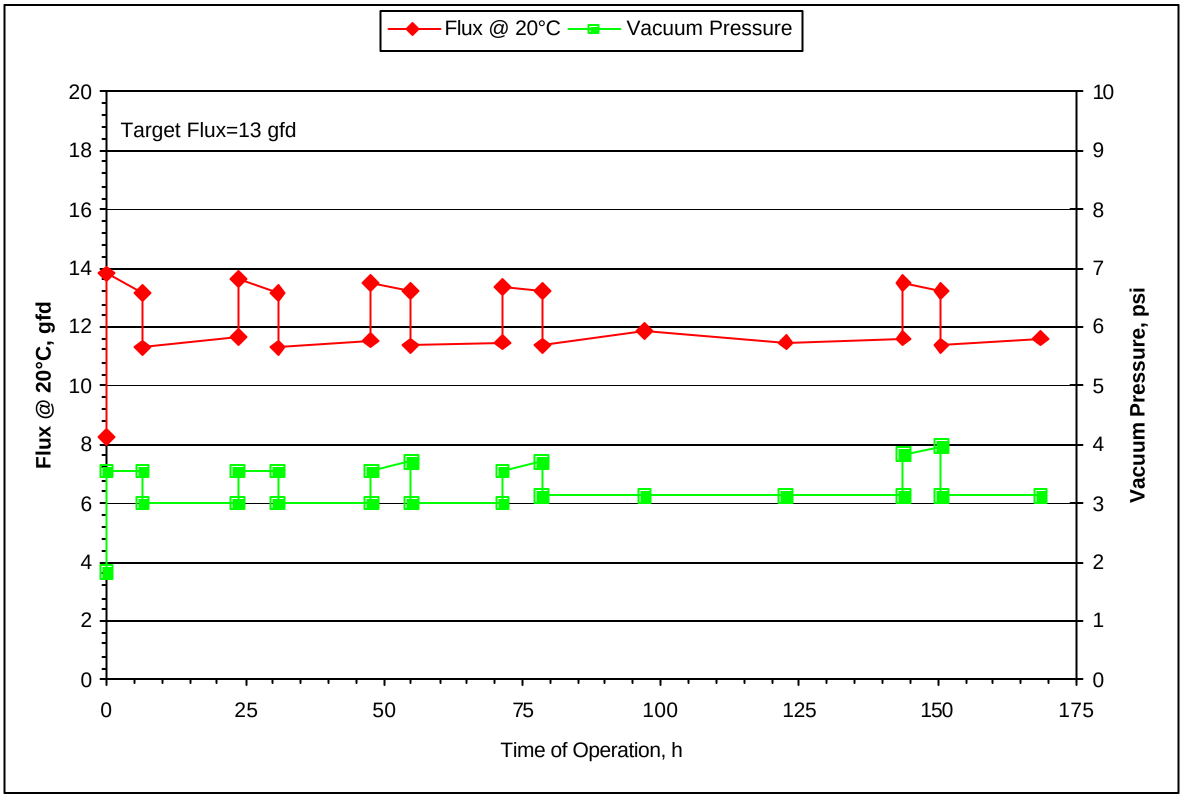
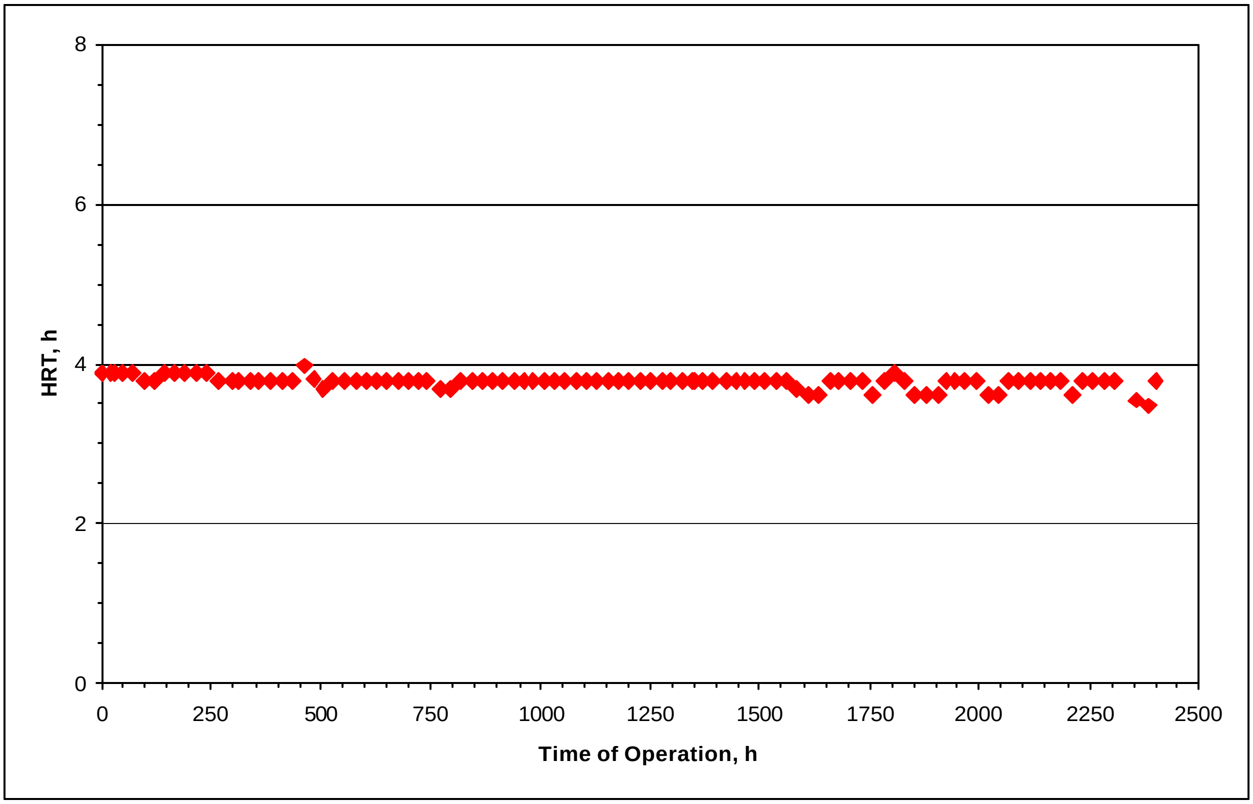


Figure 5-29 Peaking Study for the Mitsubishi MBR During Part 1



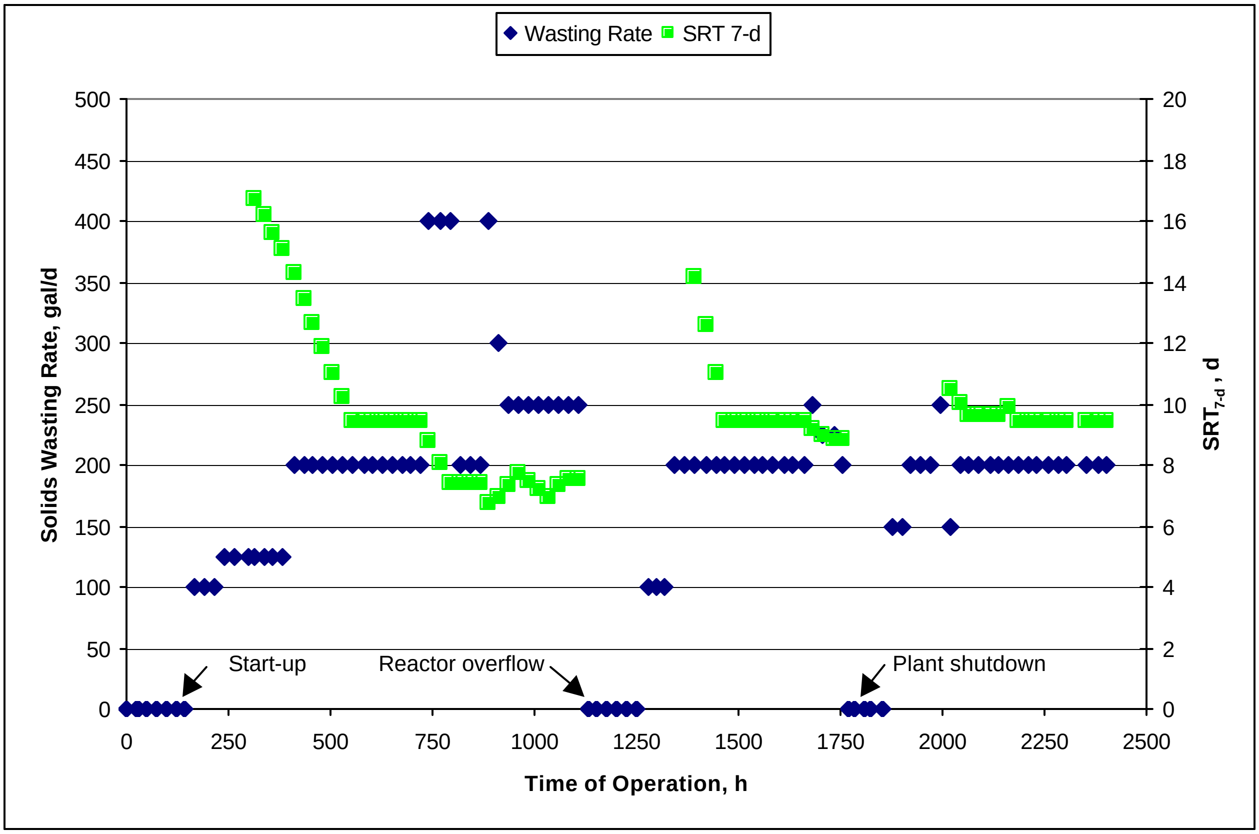


Figure 6-1 SRT and HRT of the Mitsubishi MBR during Part 2

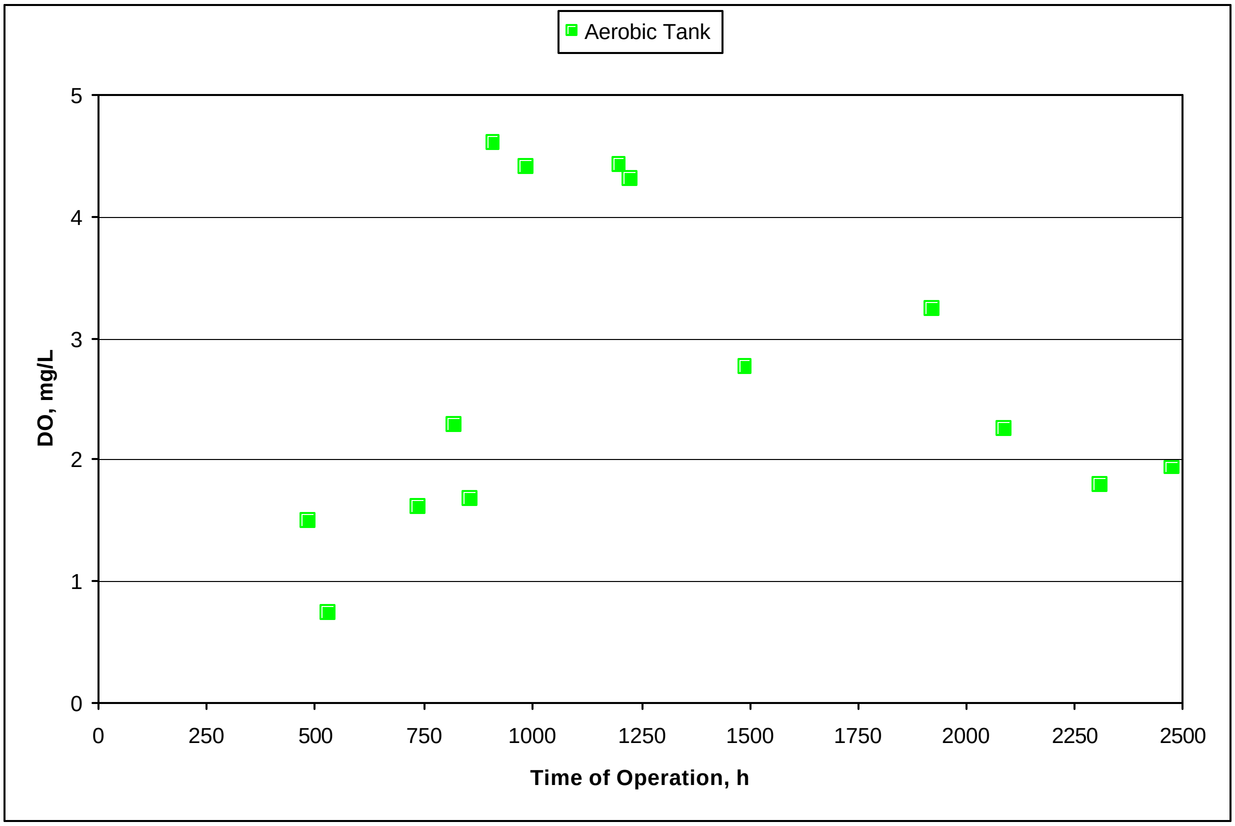
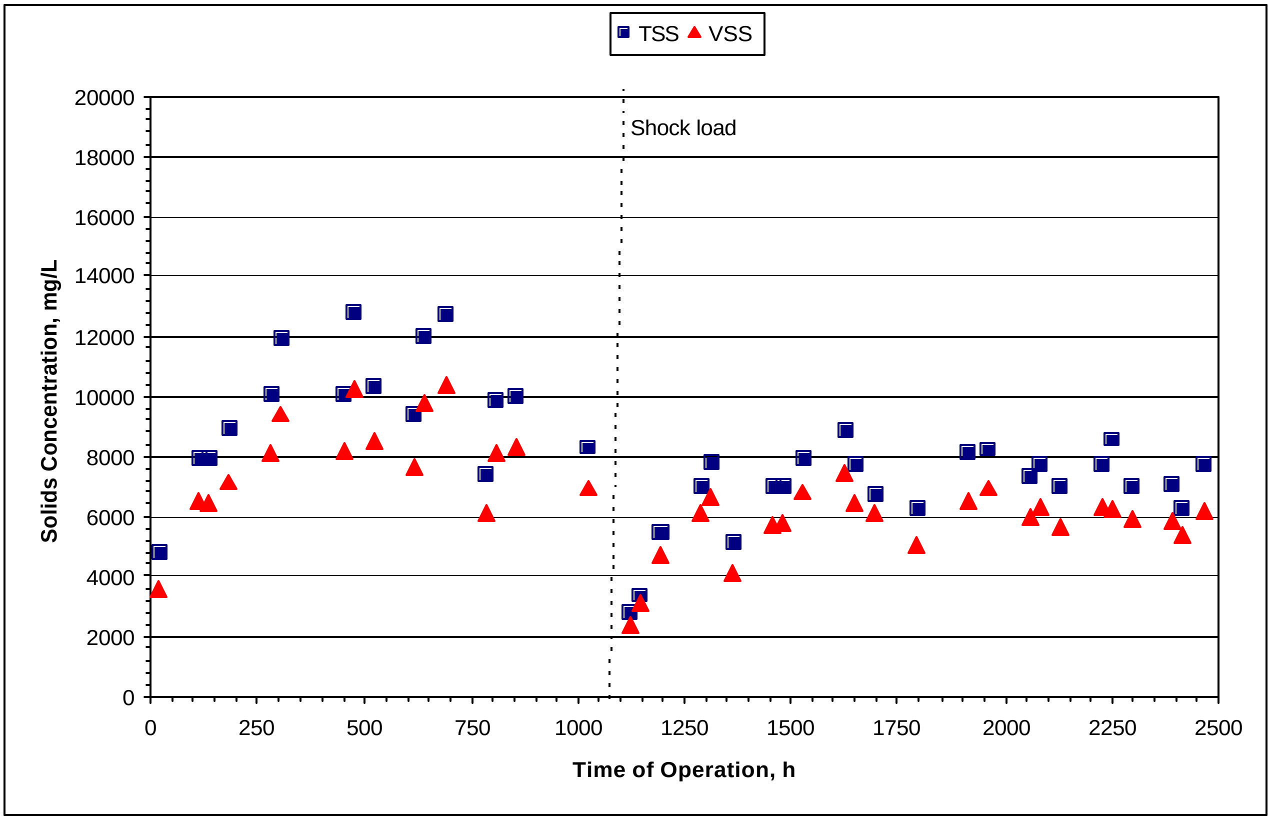


Figure 6-2 DO Concentrations in the Mitsubishi MBR During Part 2



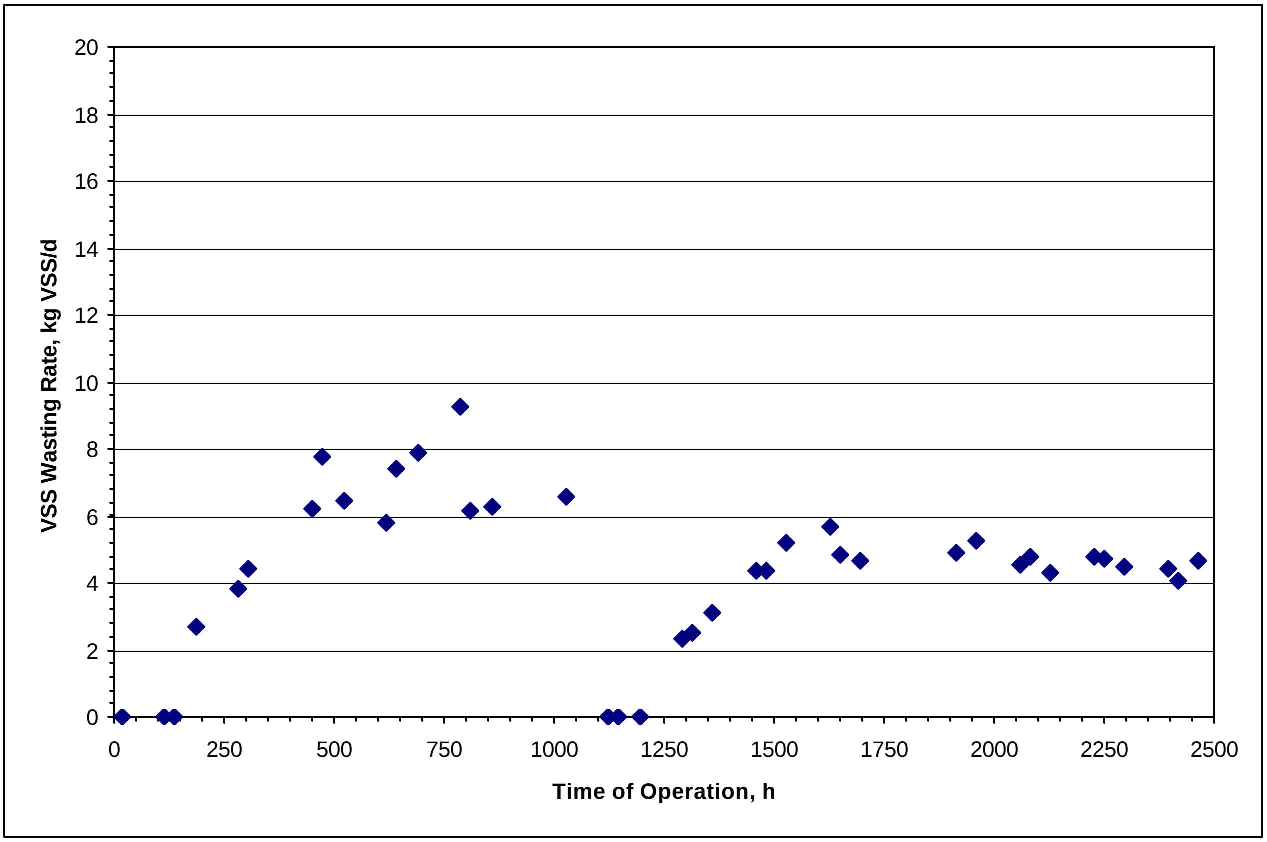
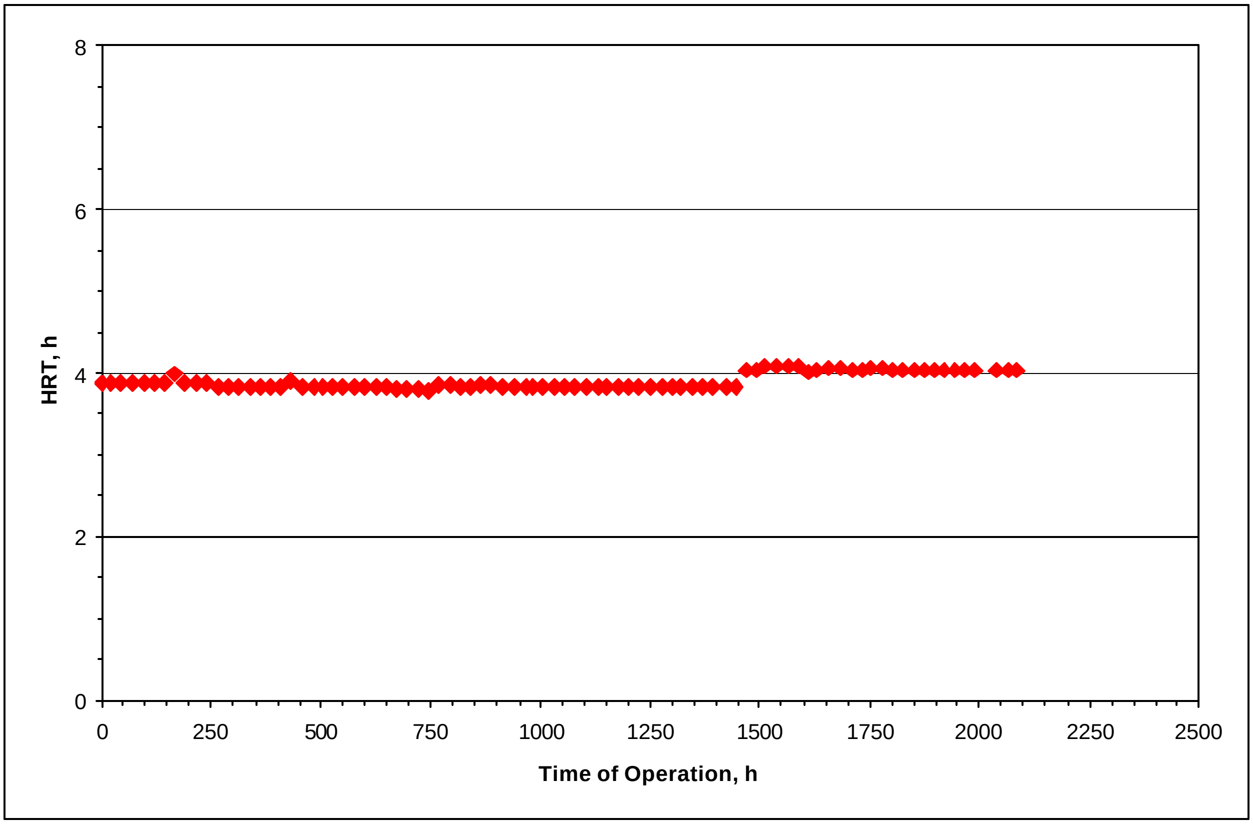


Figure 6-3 Mixed Liquor Solids Concentration for the Mitsubishi MBR During Part 2



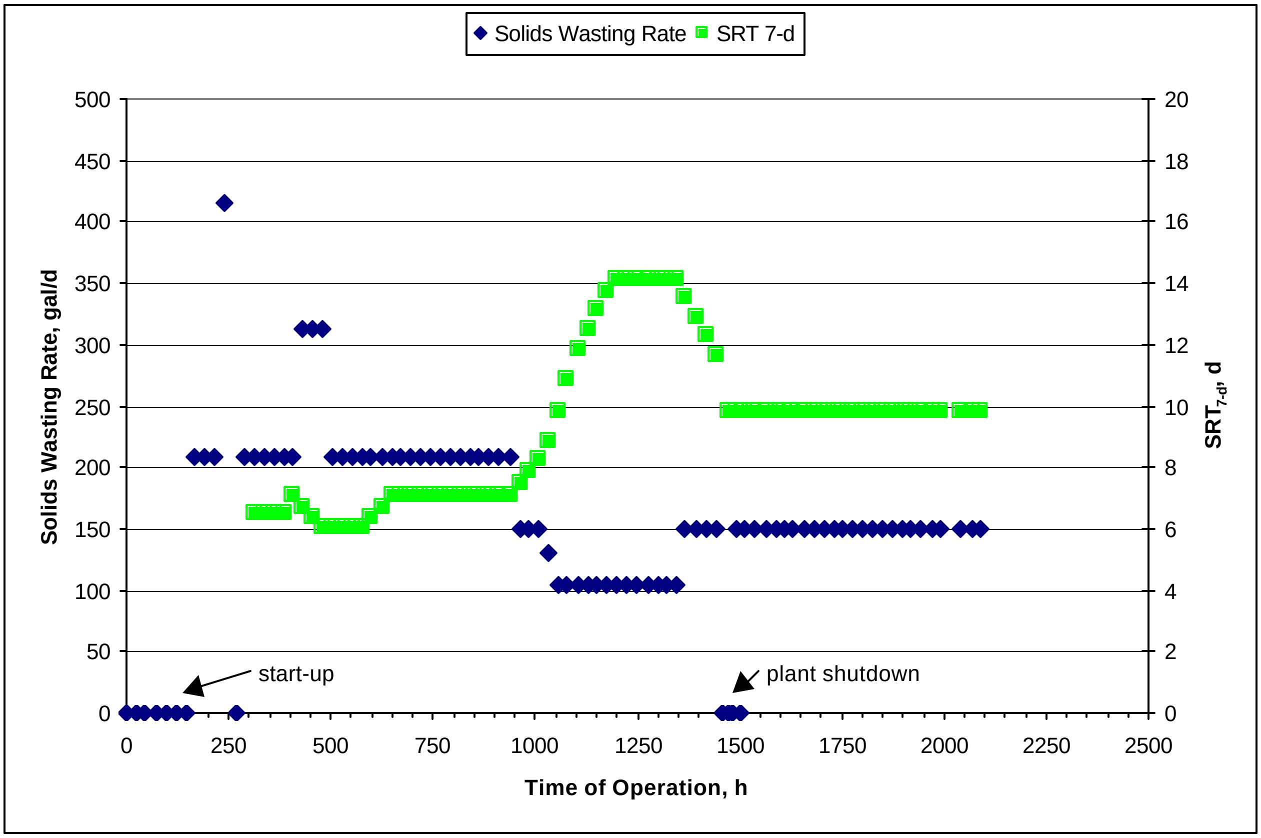


Figure 6-4 SRT and HRT of the Zenon MBR During Part 2

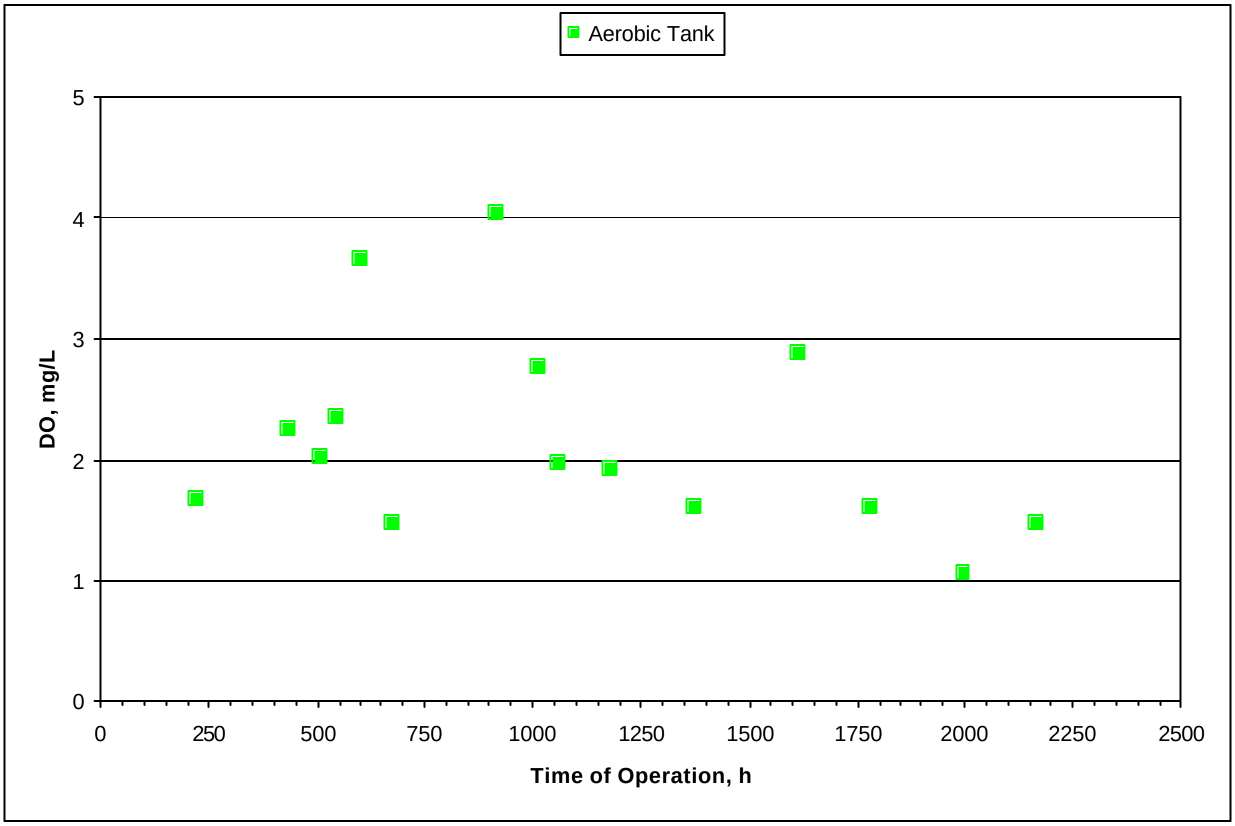
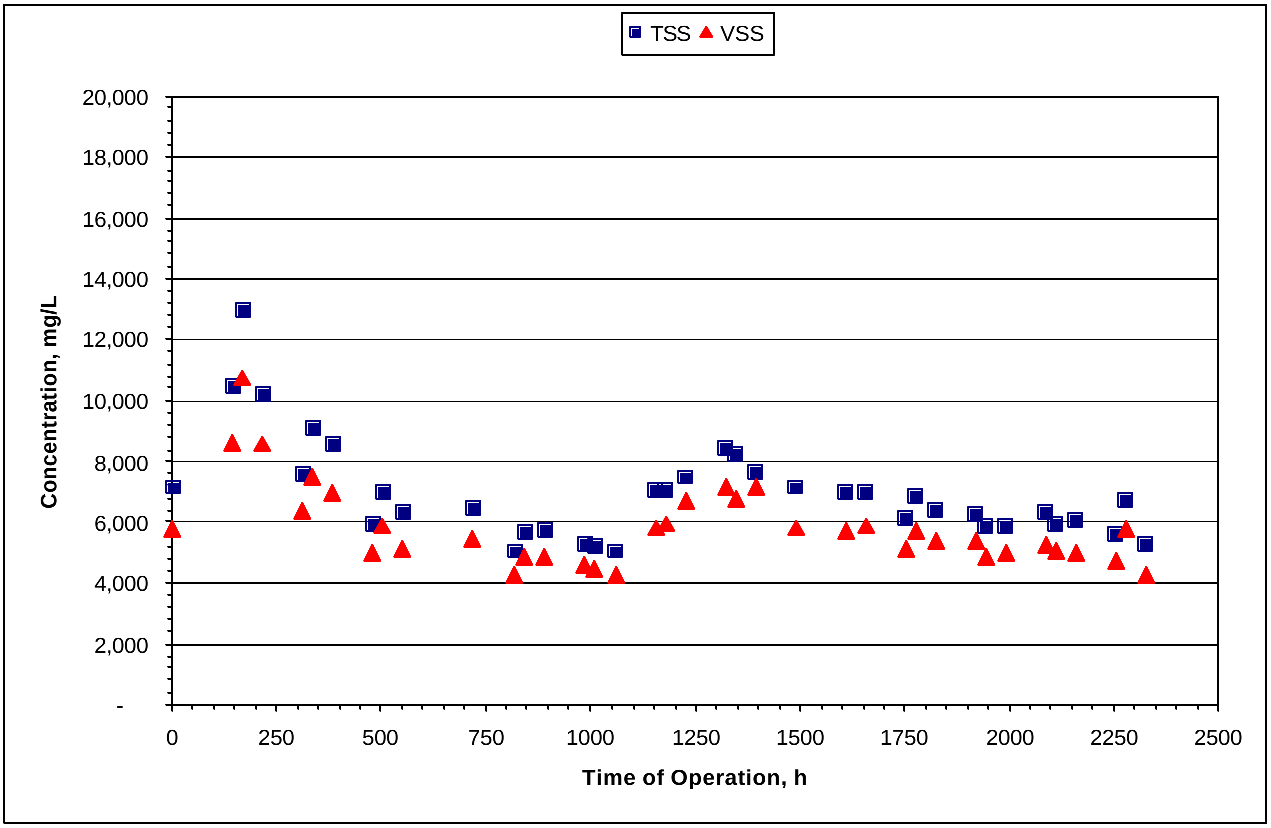


Figure 6-5 DO Concentration in the Zenon MBR During Part 2



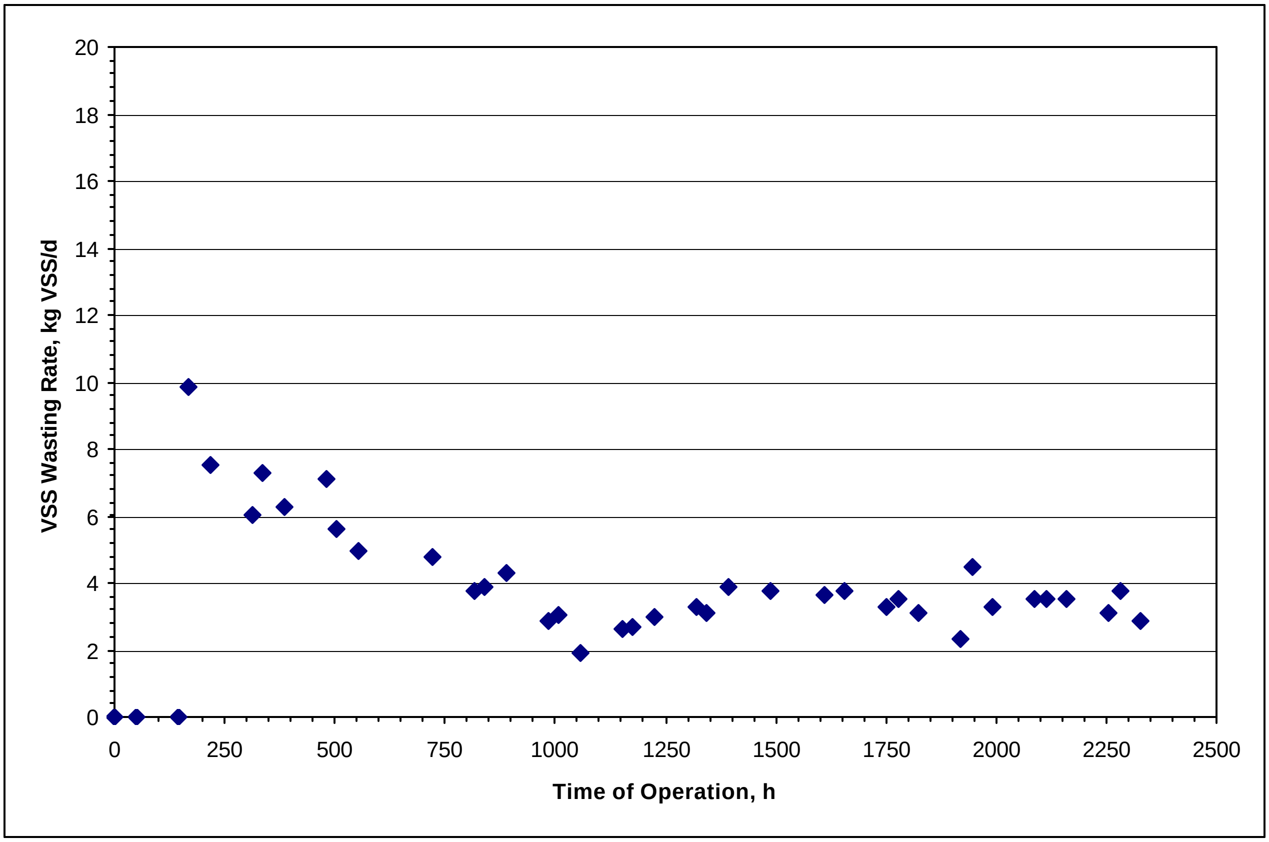


Figure 6-6 Mixed Liquor Solids Data of the Zenon MBR During Part 2

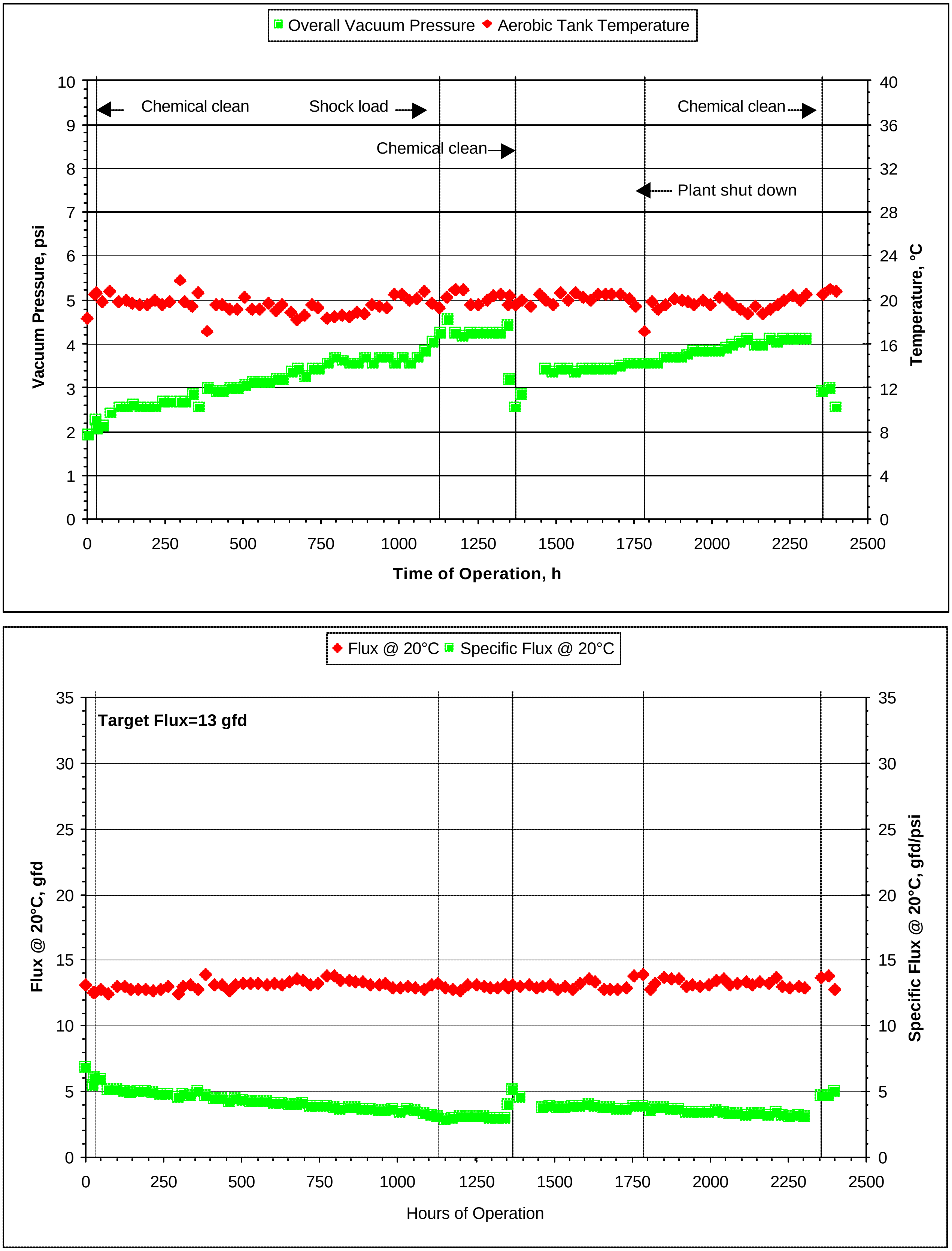


Figure 6-7 Membrane Performance of the Mitsubishi MBR During Part 2

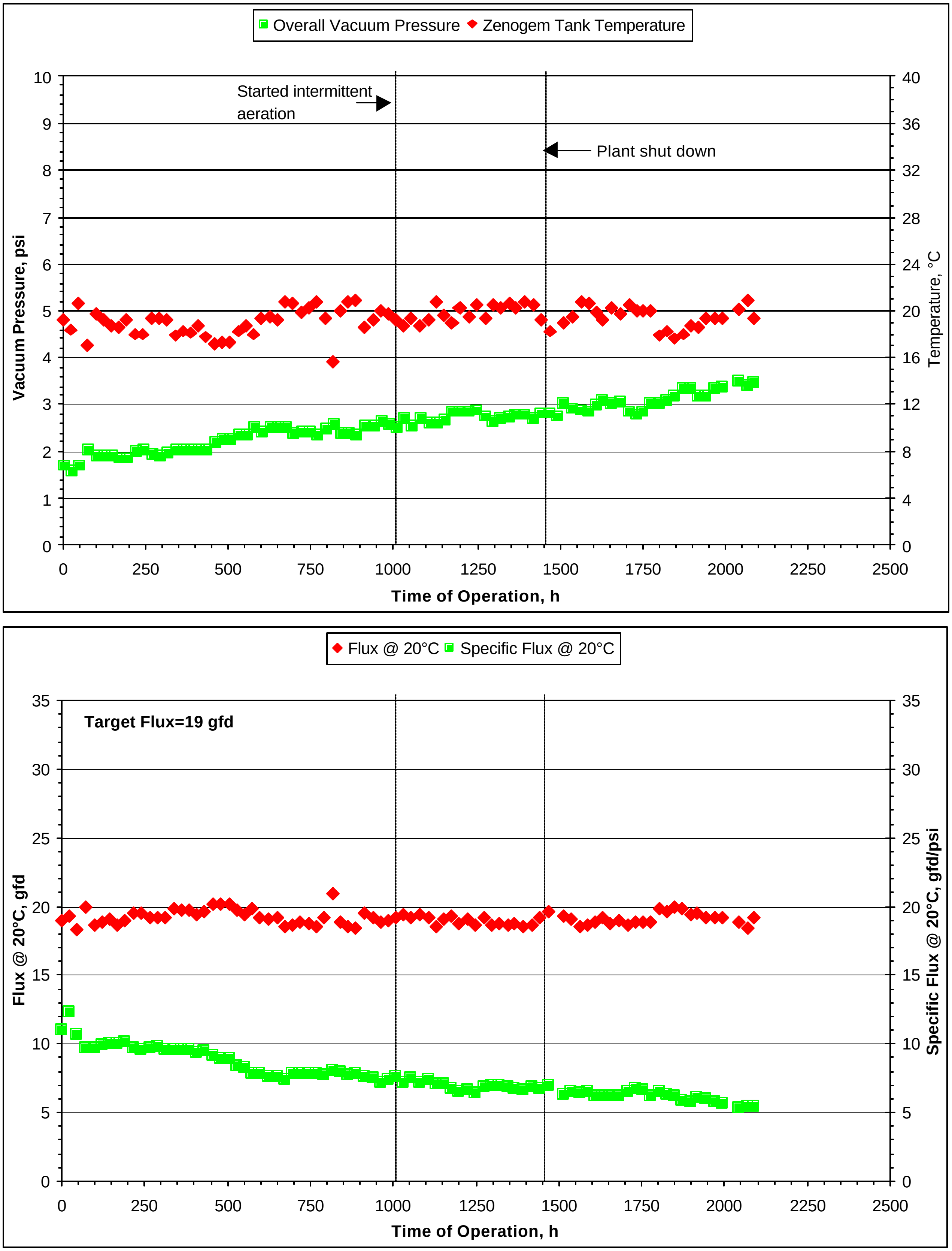


Figure 6-8 Membrane Performance of the Zenon MBR During Part 2

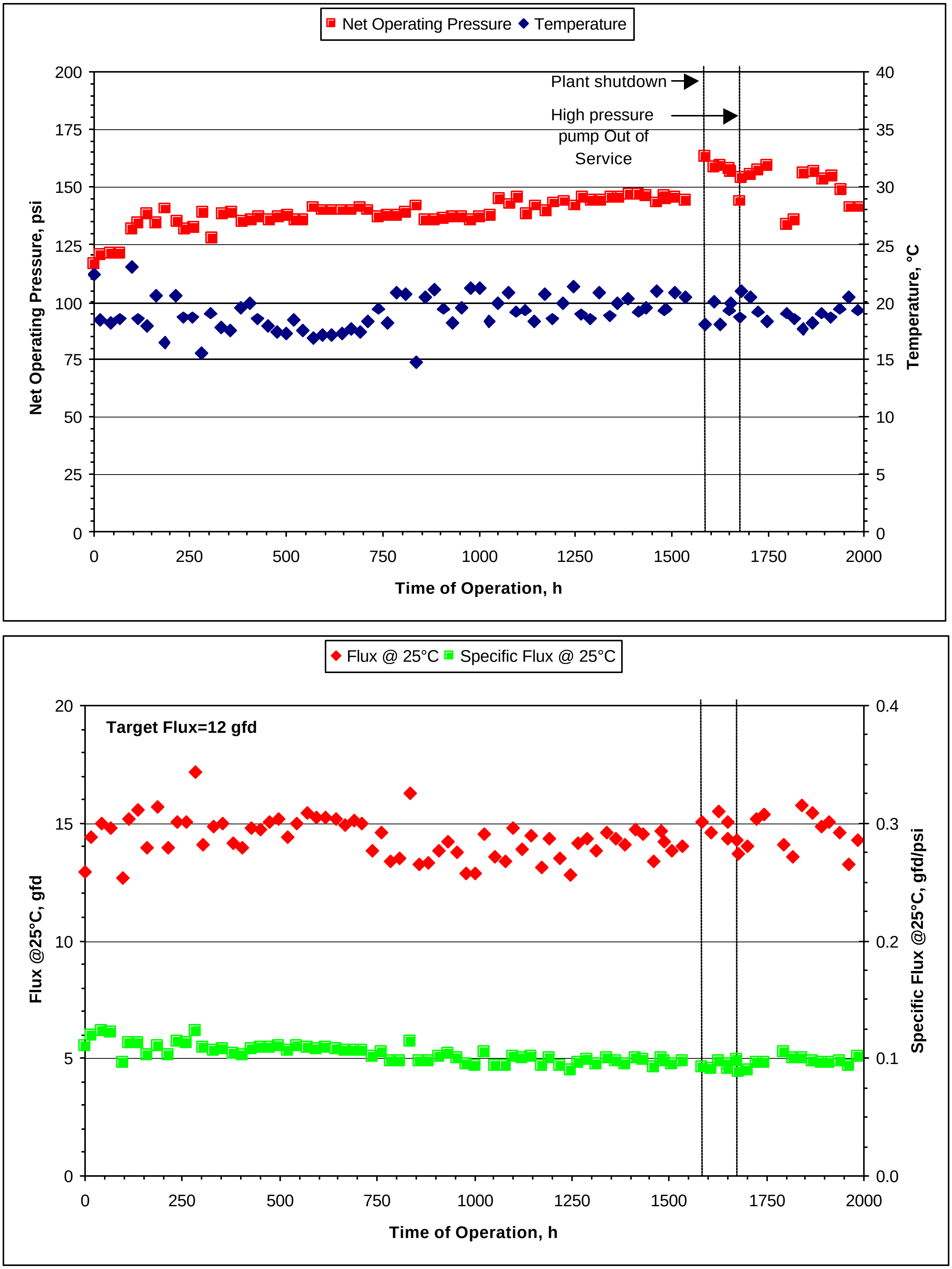


Figure 6-9 Mitsubishi MBR RO Membrane Performance During Part 2

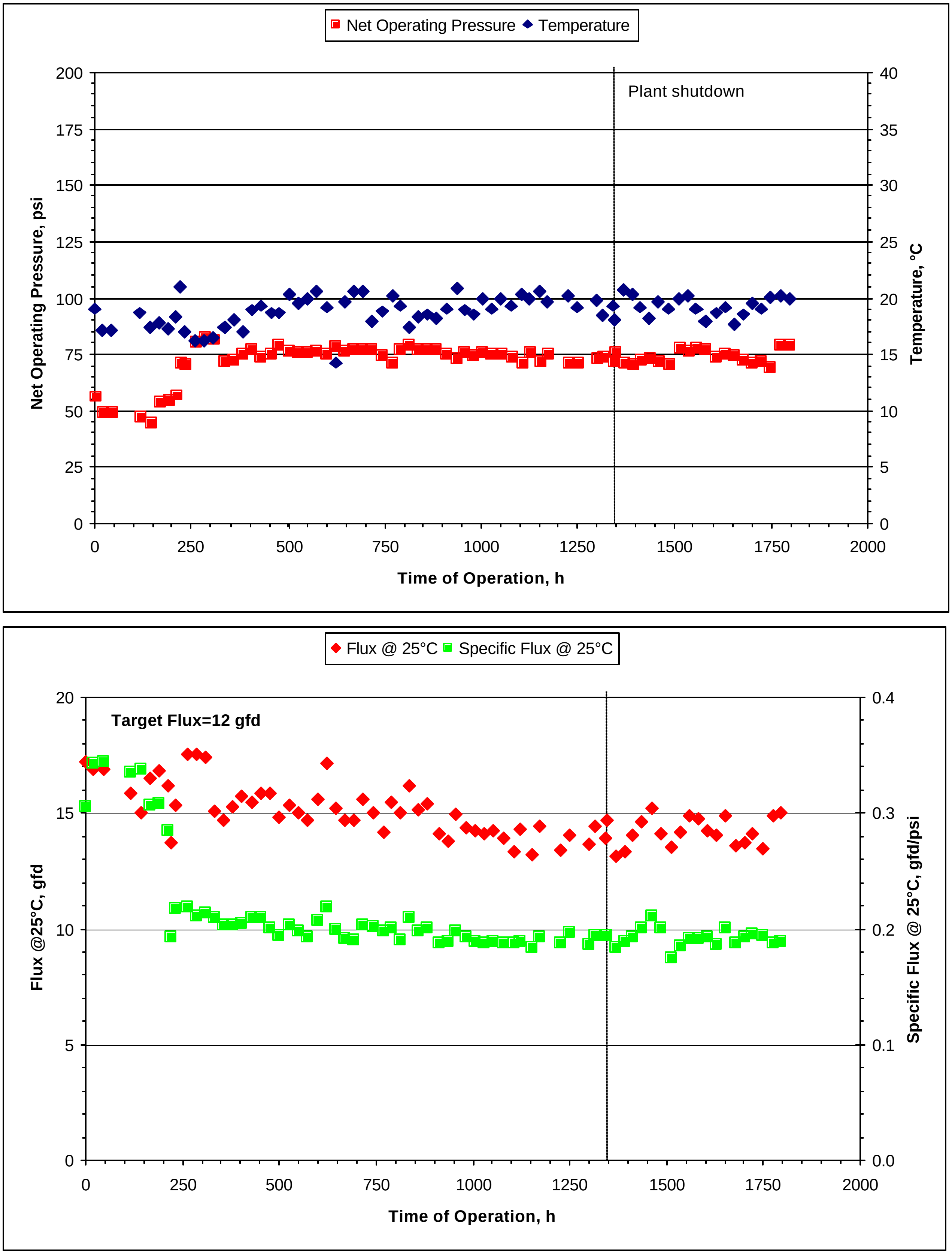


Figure 6-10 Zenon MBR RO Membrane Performance During Part 2

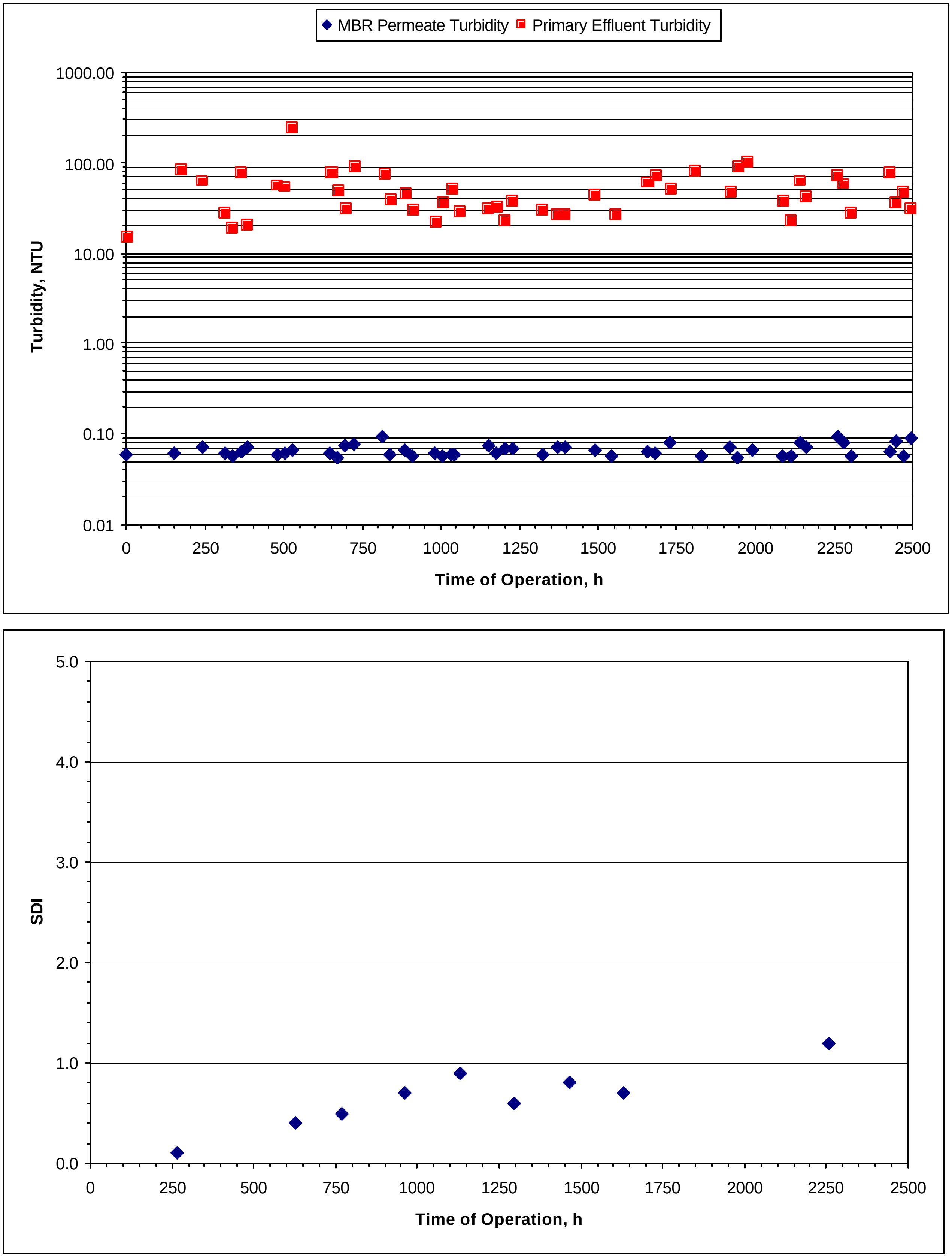


Figure 6-11 Particulate Removal by the Mitsubishi MBR During Part 2

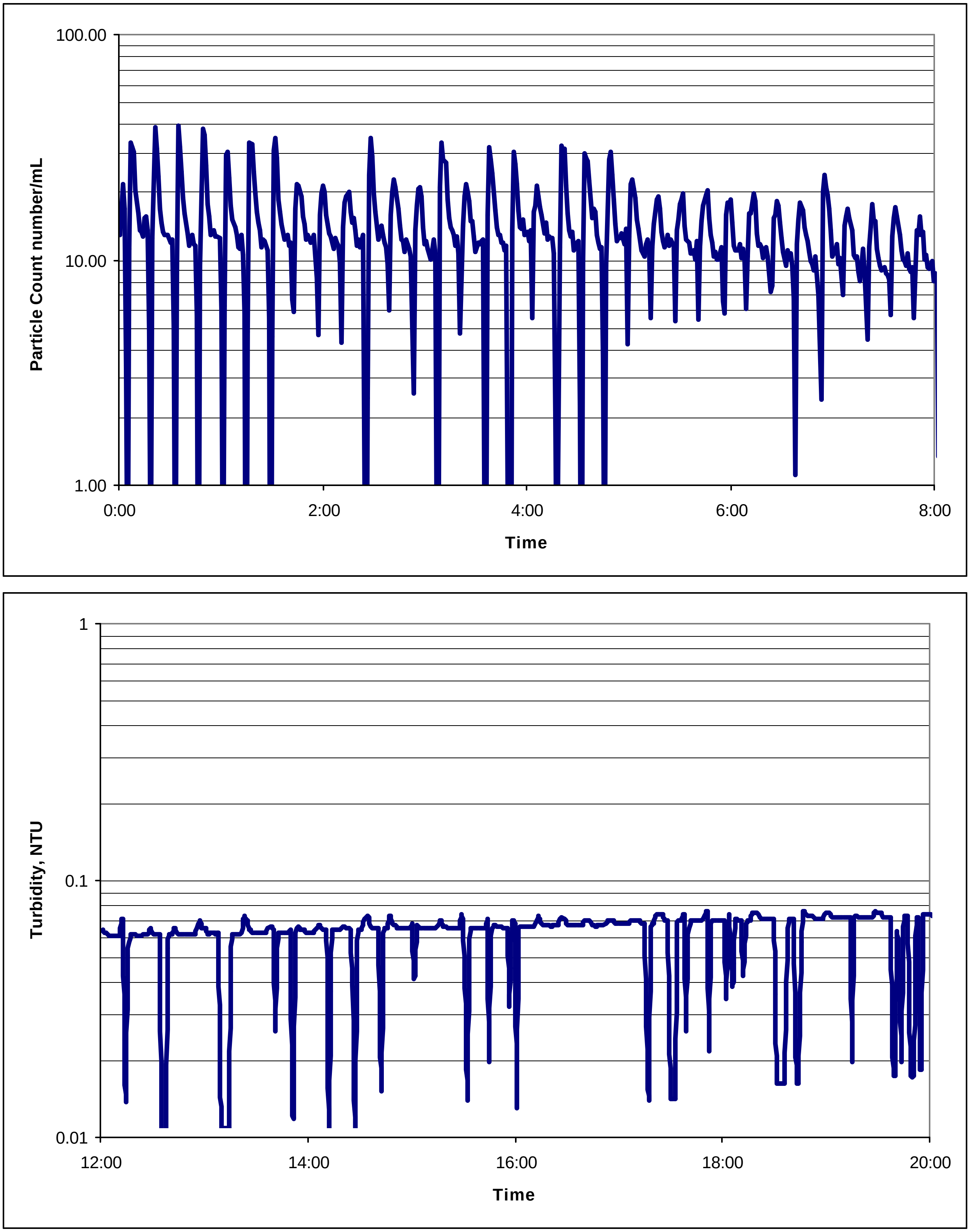


Figure 6-12 On-line Monitoring of the Mitsubishi MBR Permeate During Part 2

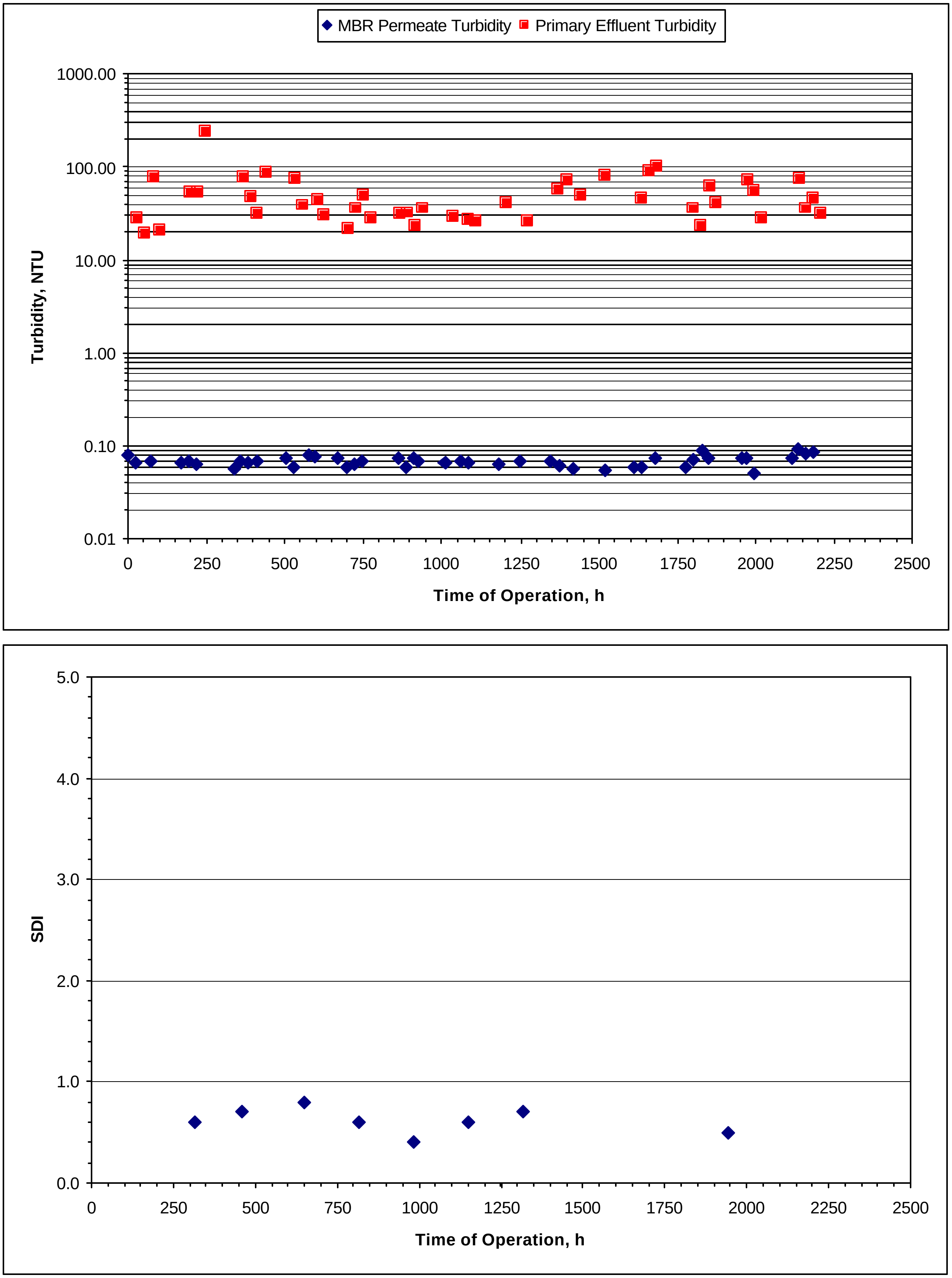
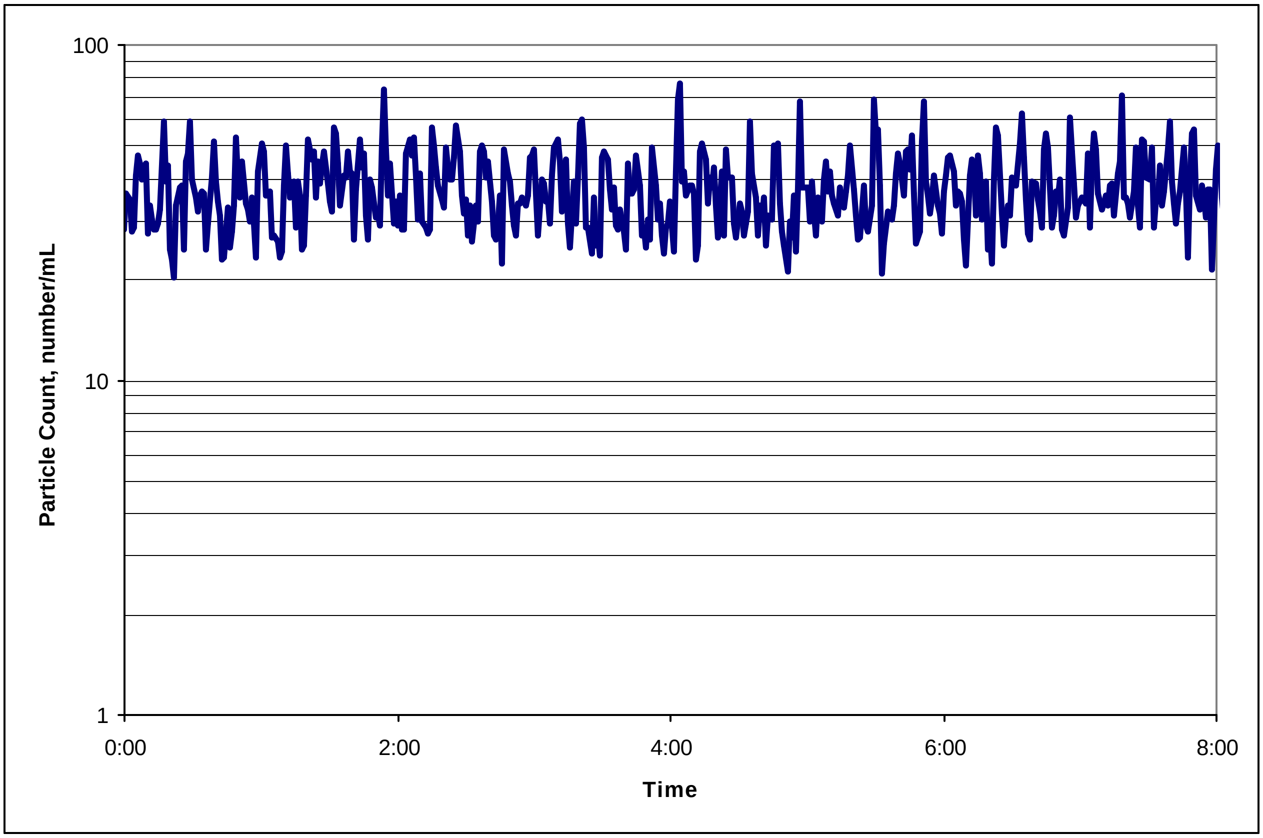


Figure 6-13 Particulate Removal by the Zenon MBR During Part 2



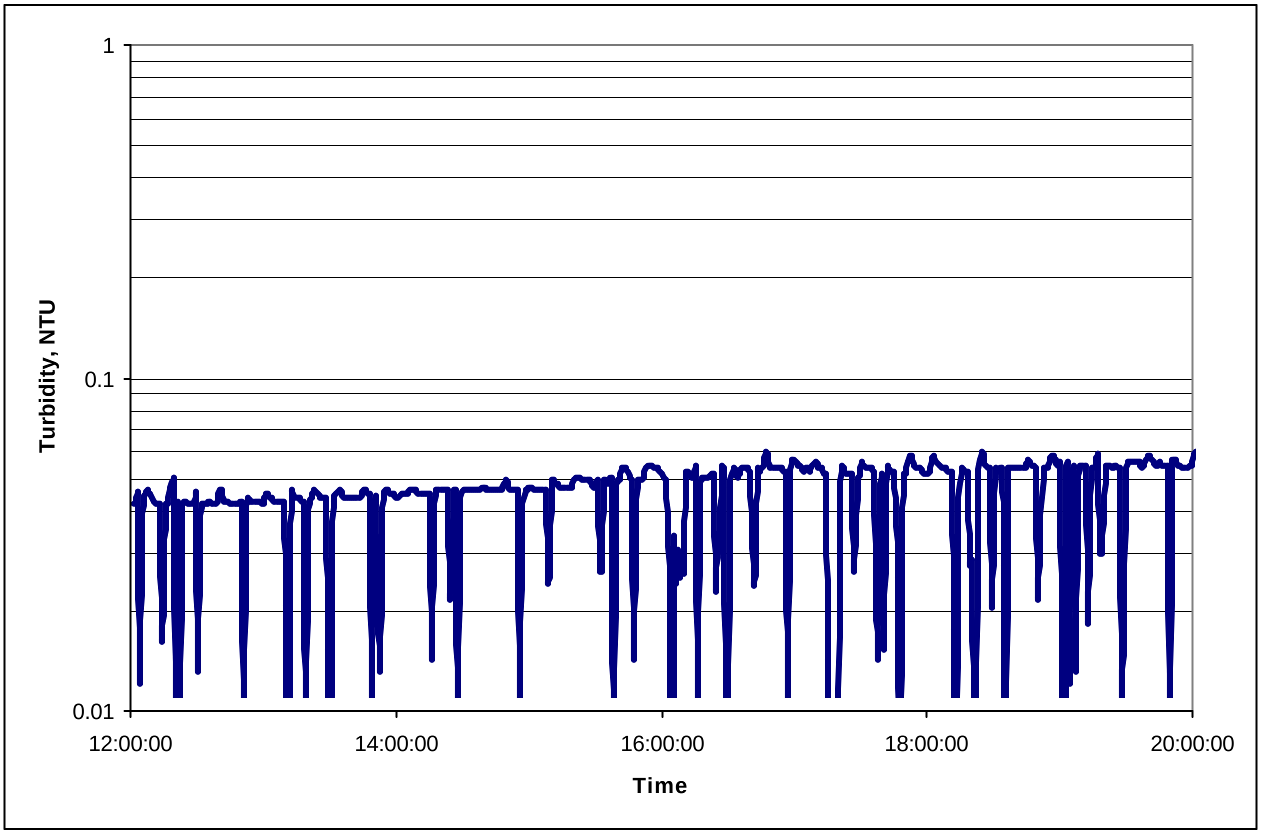


Figure 6-14 On-line Monitoring of the Zenon MBR Permeate During Part 2

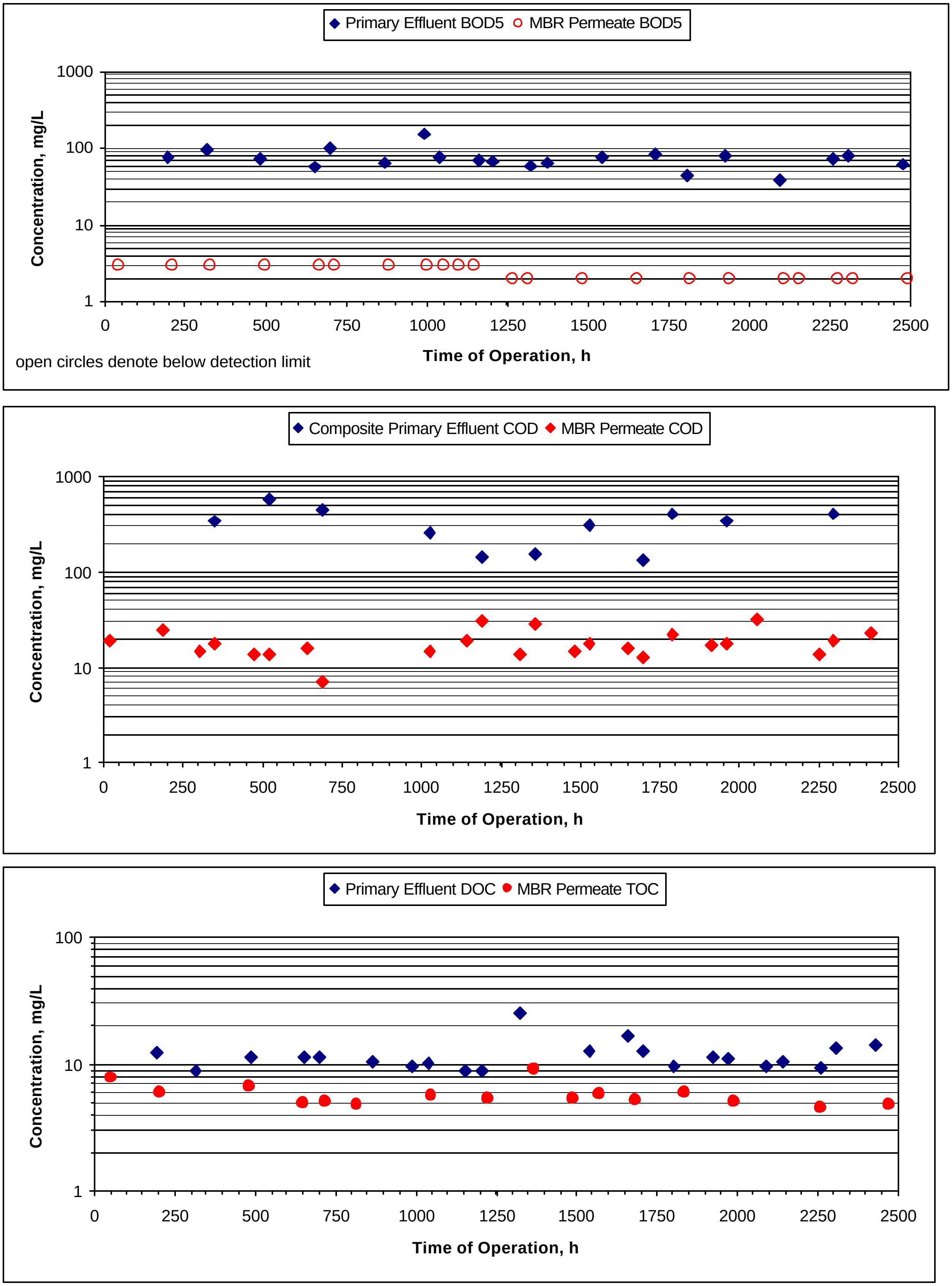
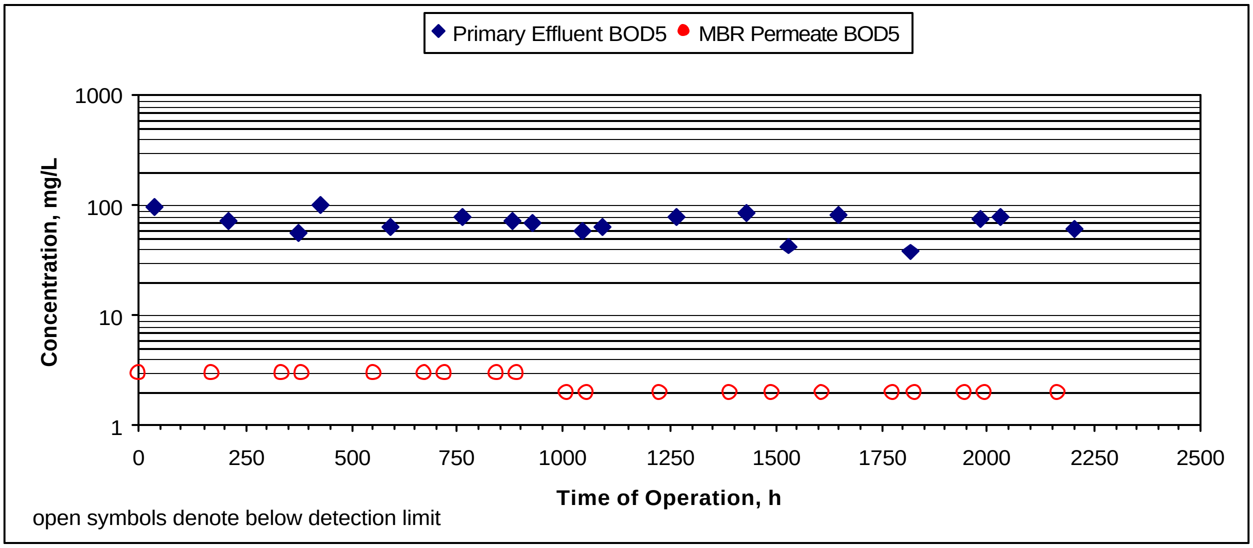
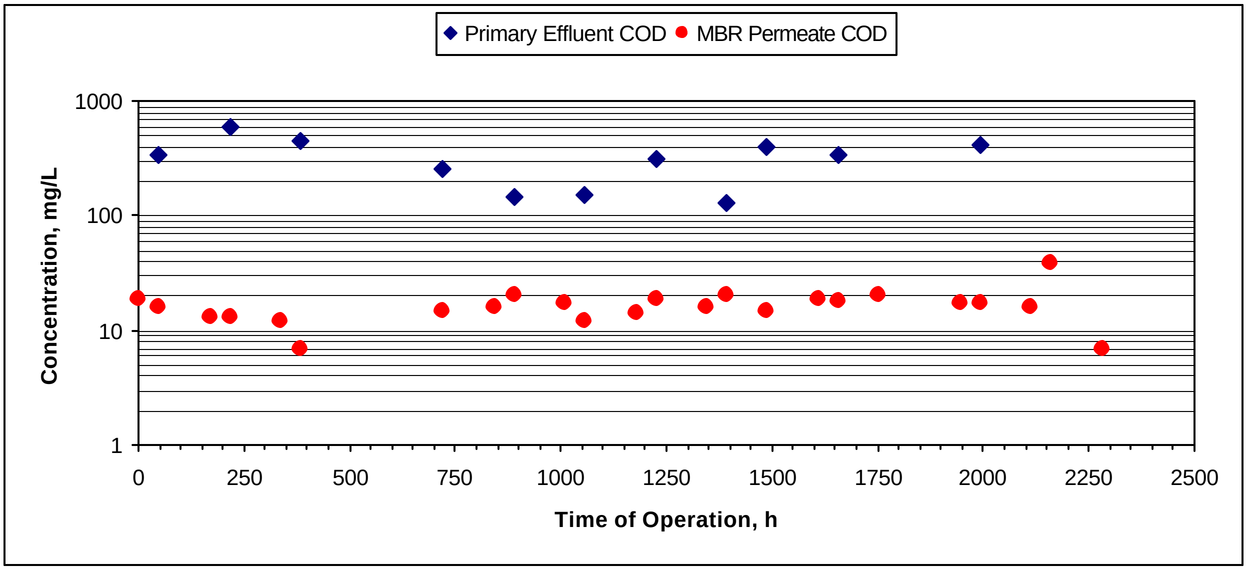


Figure 6-15 Organics Removal by the Mitsubishi MBR During Part 2





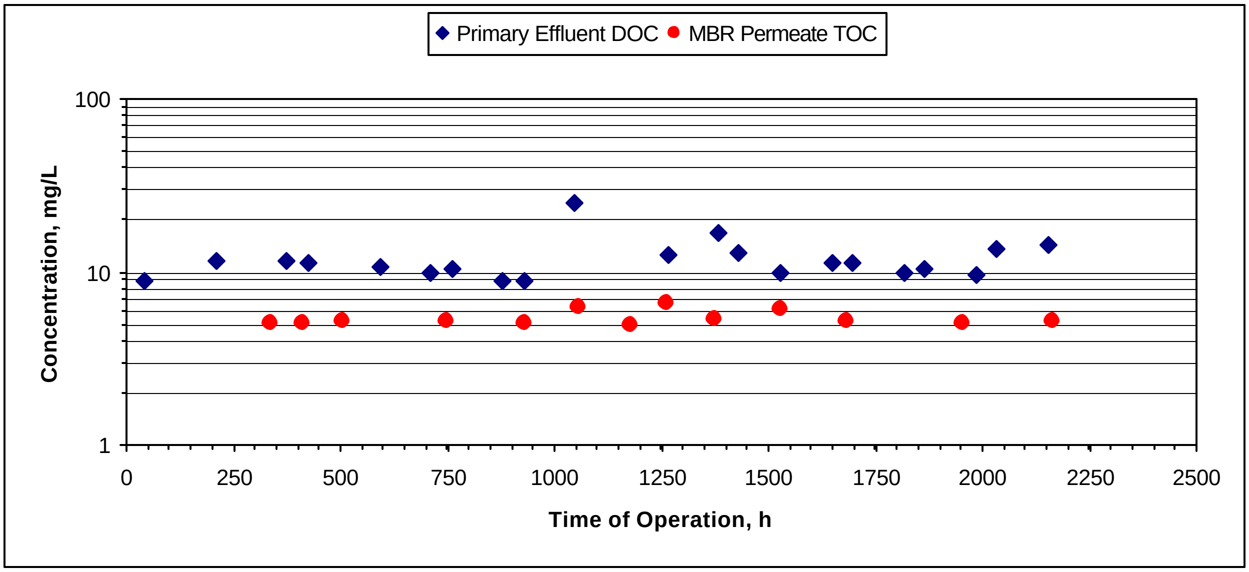


Figure 6-16 Organics Removal by the Zenon MBR During Part 2

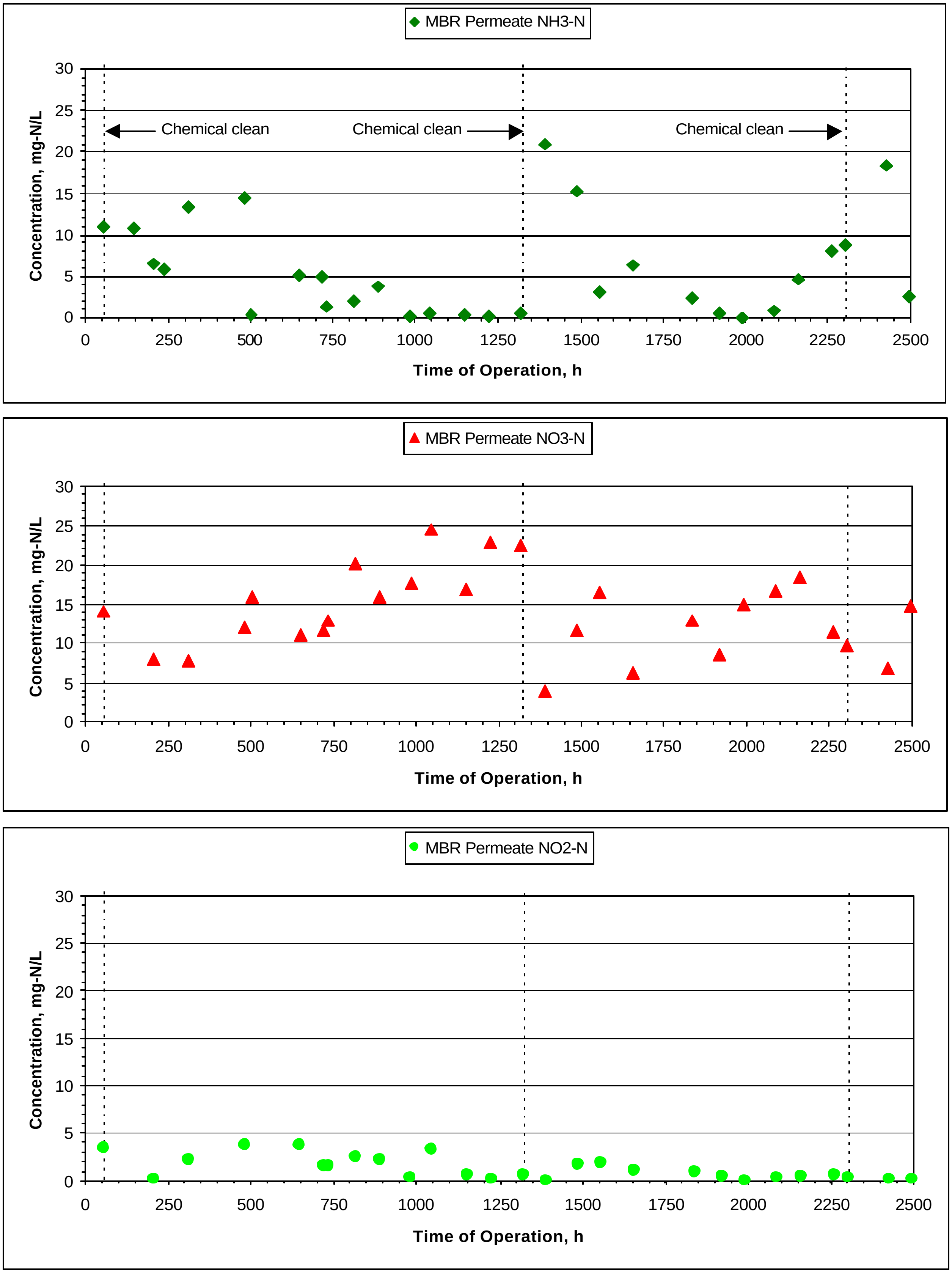


Figure 6-17 Inorganic Nitrogen Species in the Mitsubishi MBR Permeate During Part 2

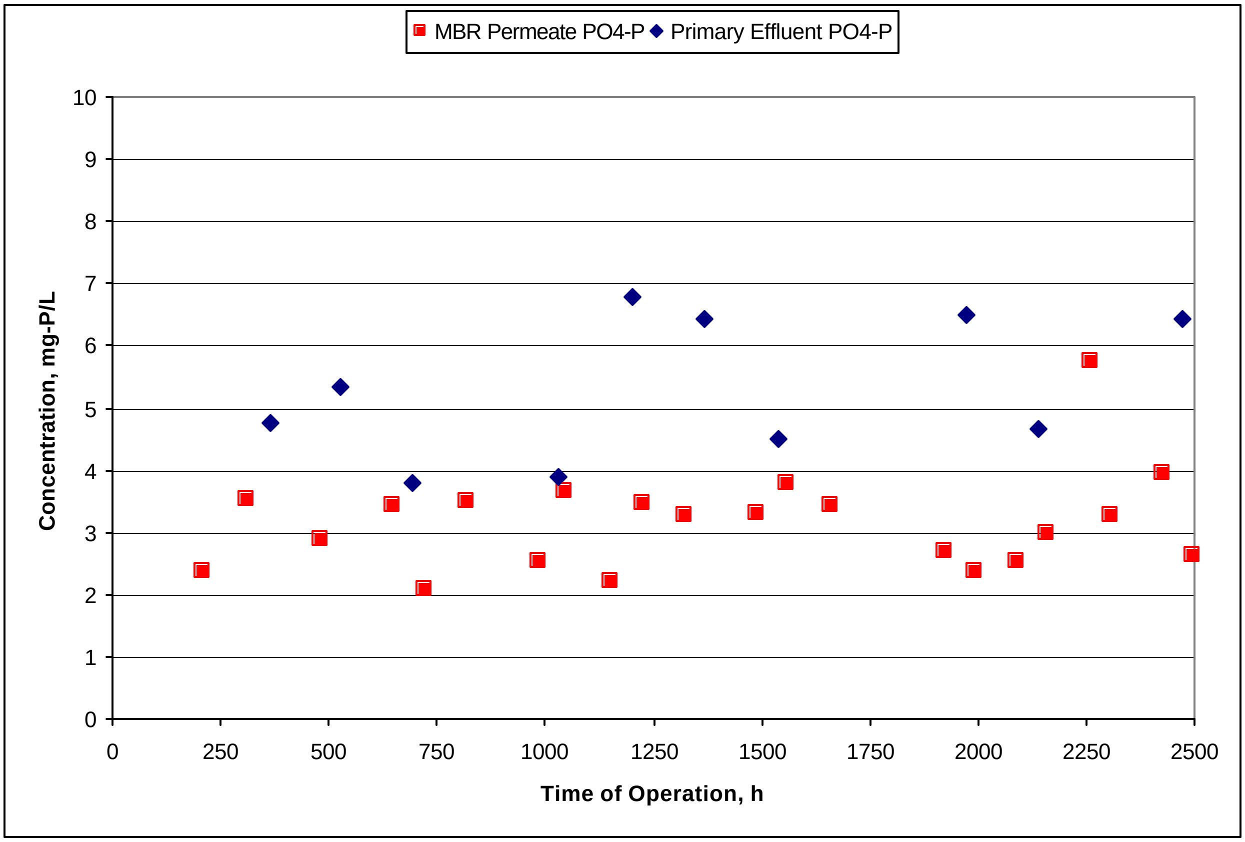


Figure 6-18 Ortho-Phosphate Concentrations in the Mitsubishi MBR During Part 2

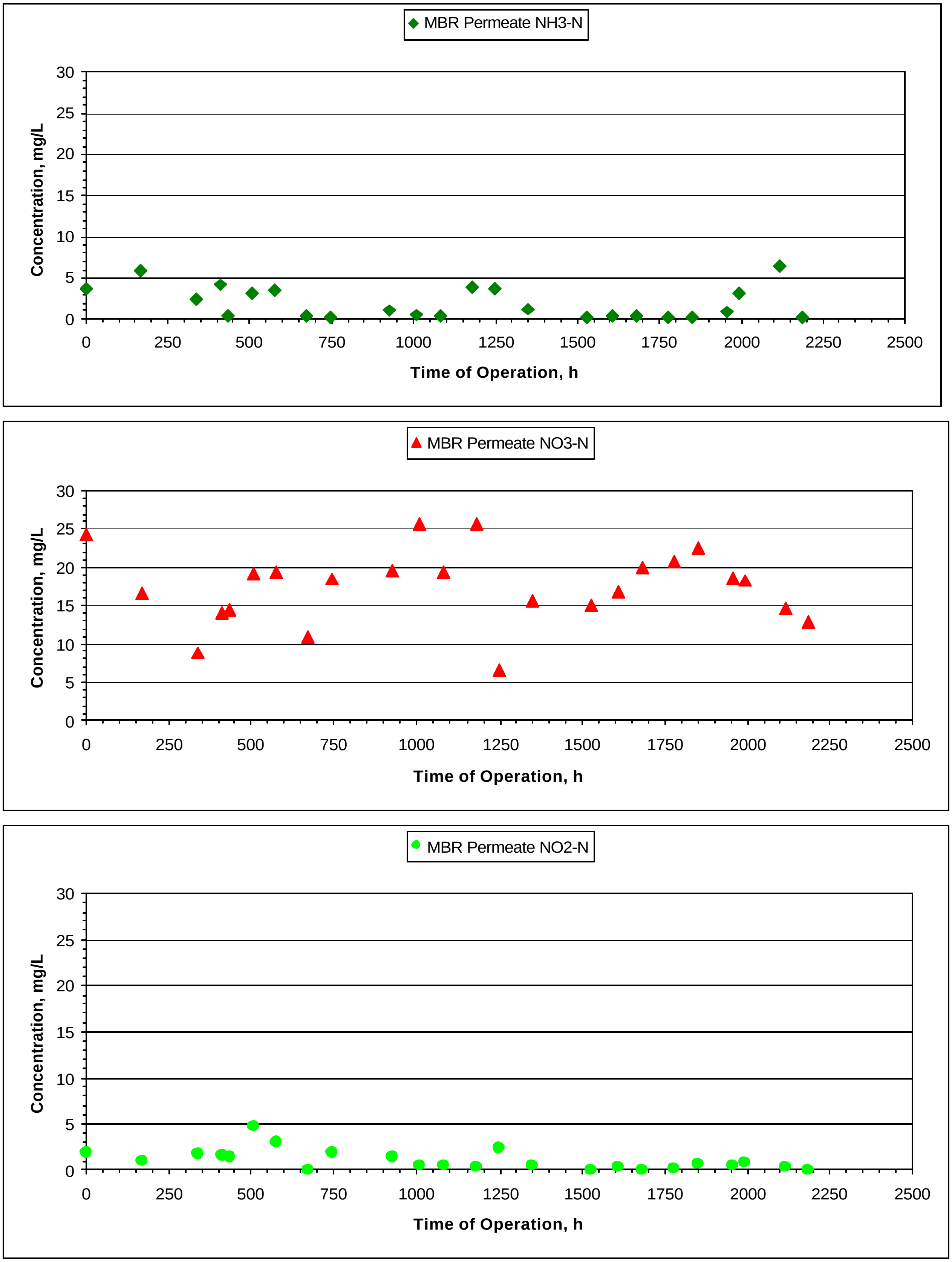


Figure 6-19 Inorganic Nitrogen Species in the Zenon MBR Permeate During Part 2

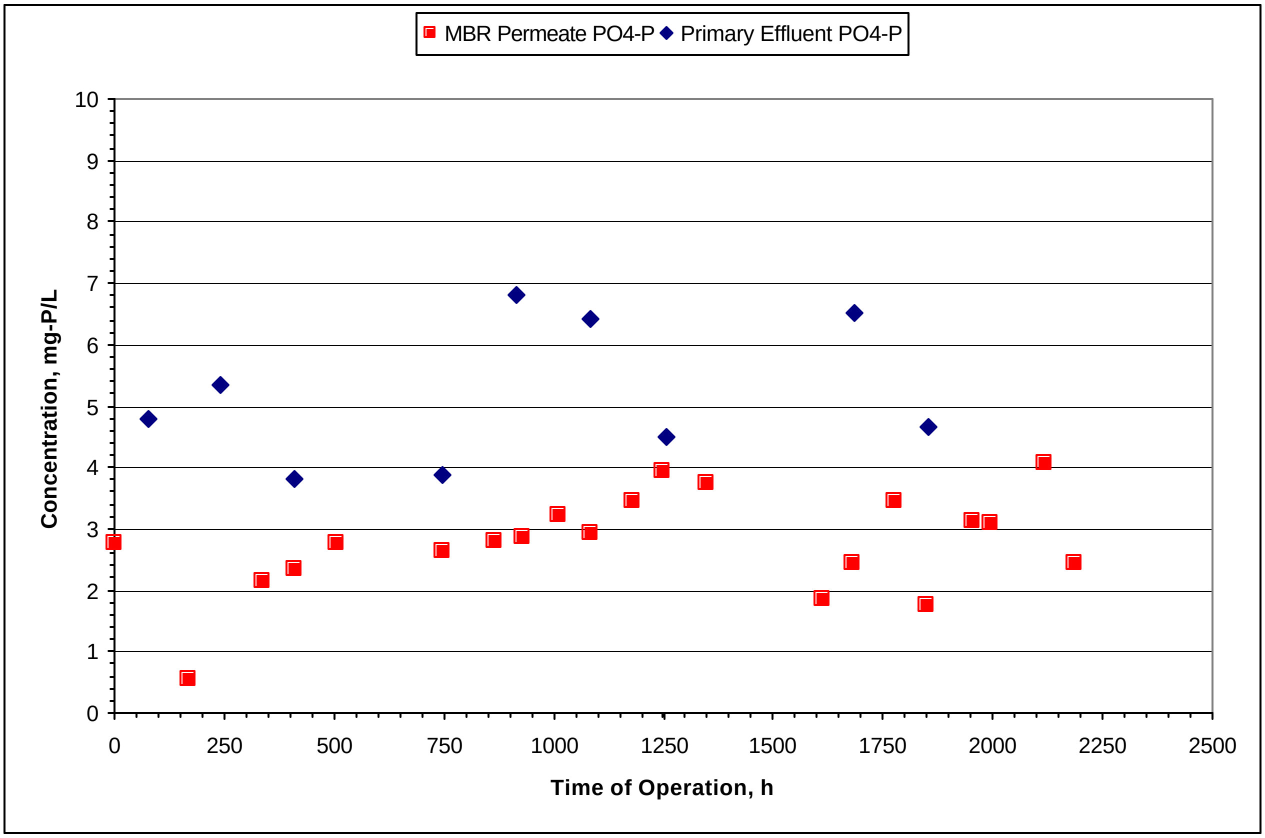


Figure 6-20 Ortho-Phosphate Concentration in the Zenon MBR Permeate During Part 2

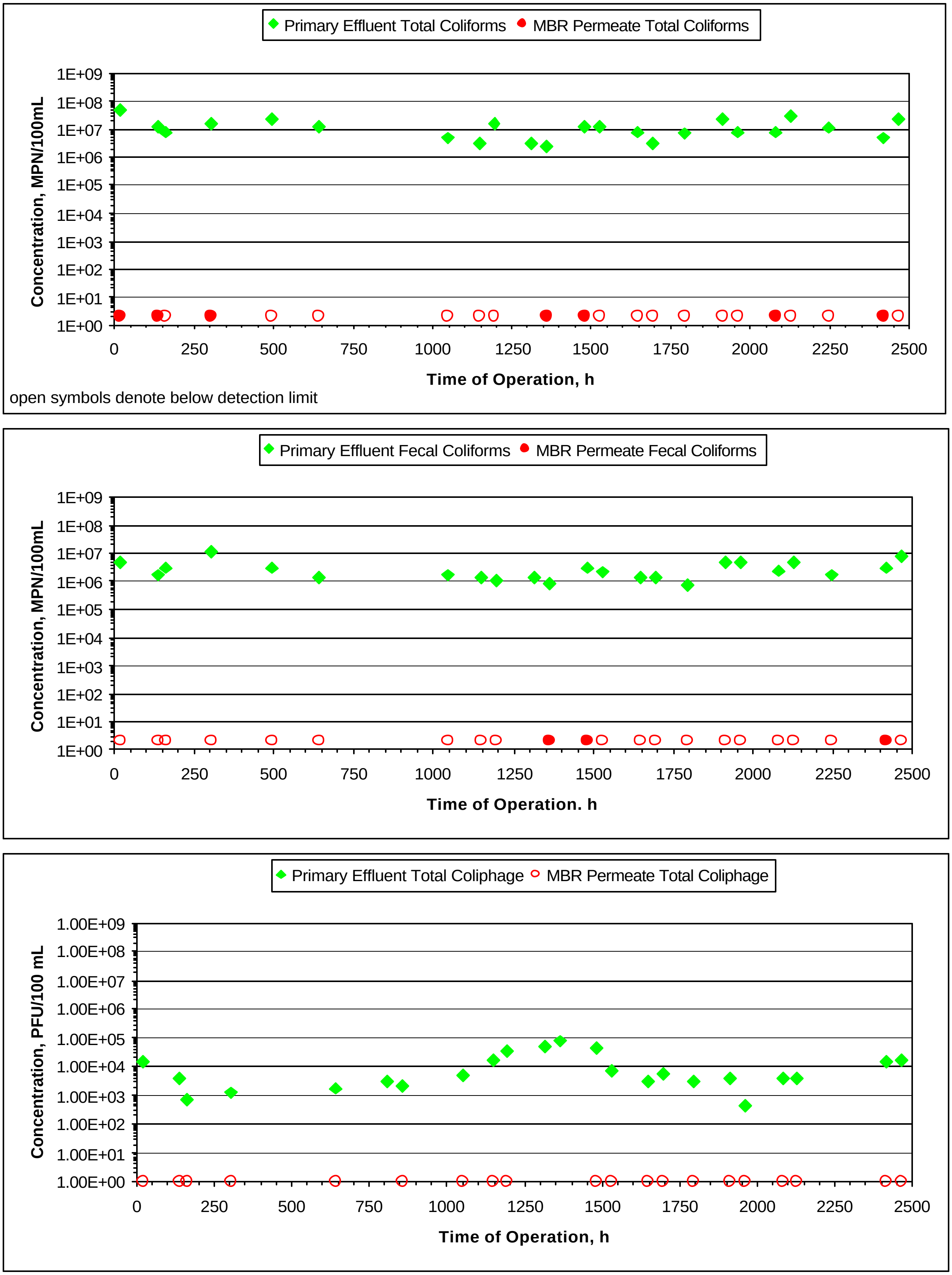
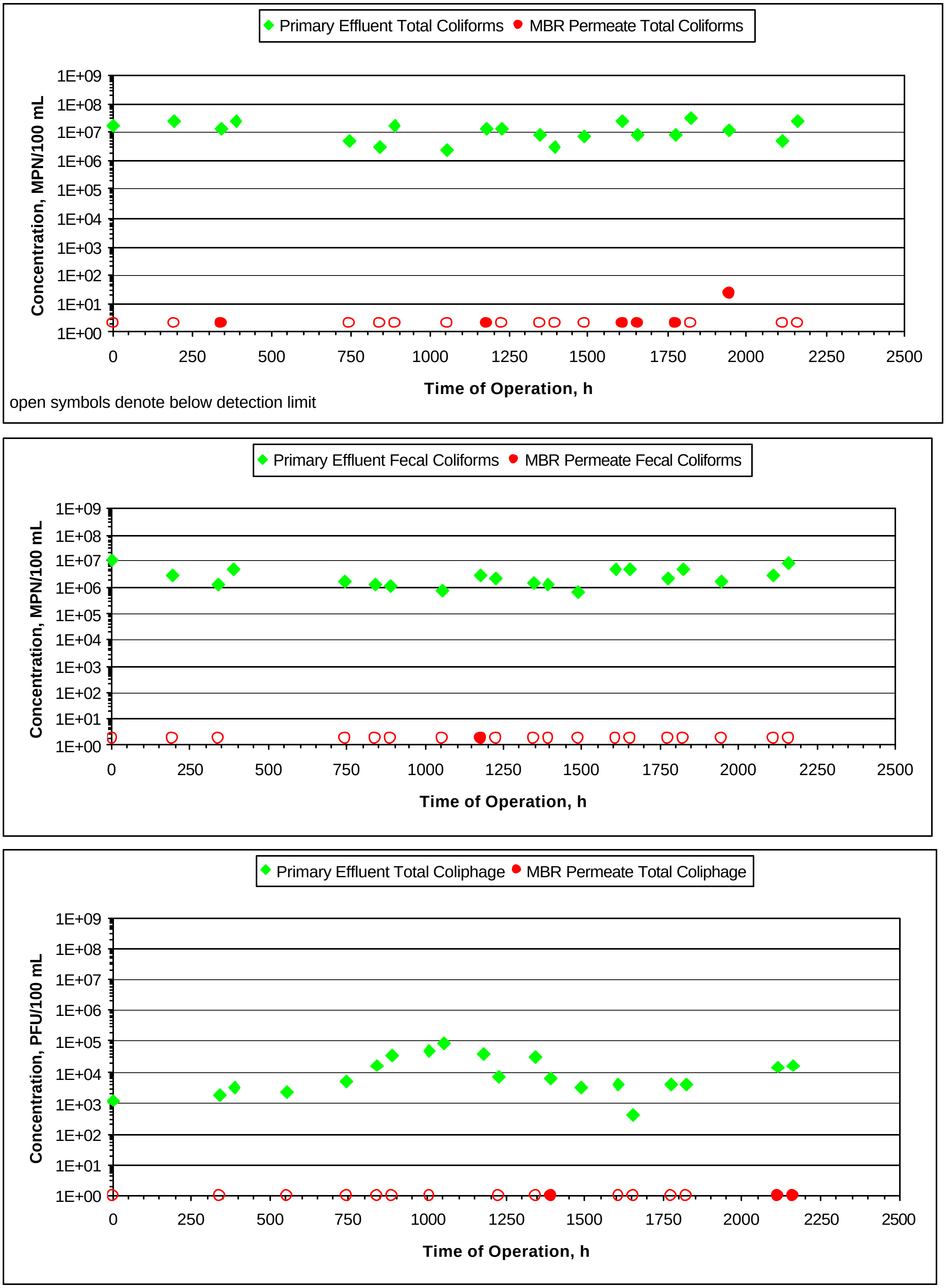


Figure 6-21 Coliform and Coliphage Removal by the Mitsubishi MBR During Part 2



open symbols denote below detection limit

Figure 6-22 Coliform and Coliphage Removal by the Zenon MBR During Part 2

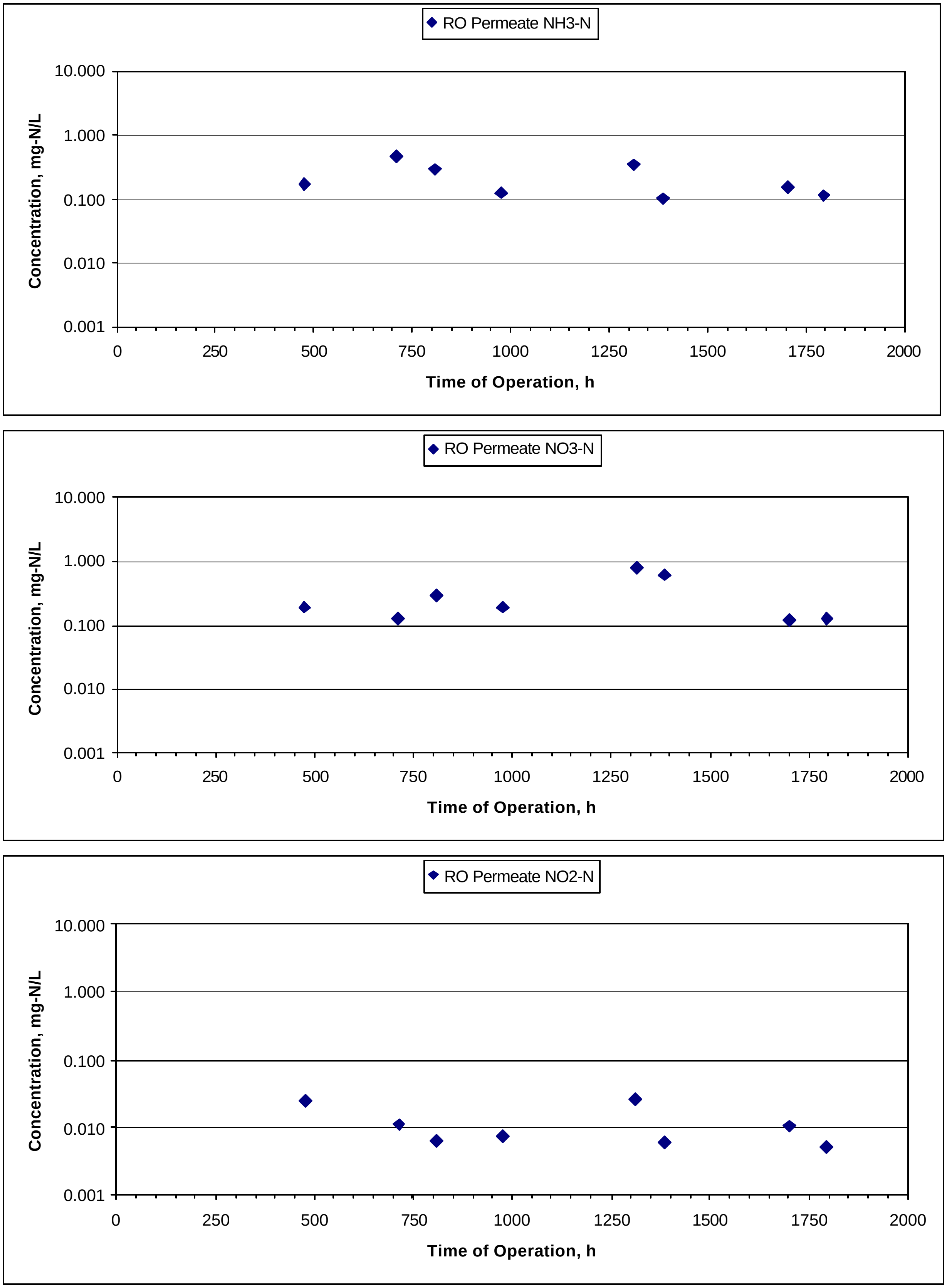


Figure 6-23 Inorganic Nitrogen Removal by the Mitsubishi MBR RO During Part 2

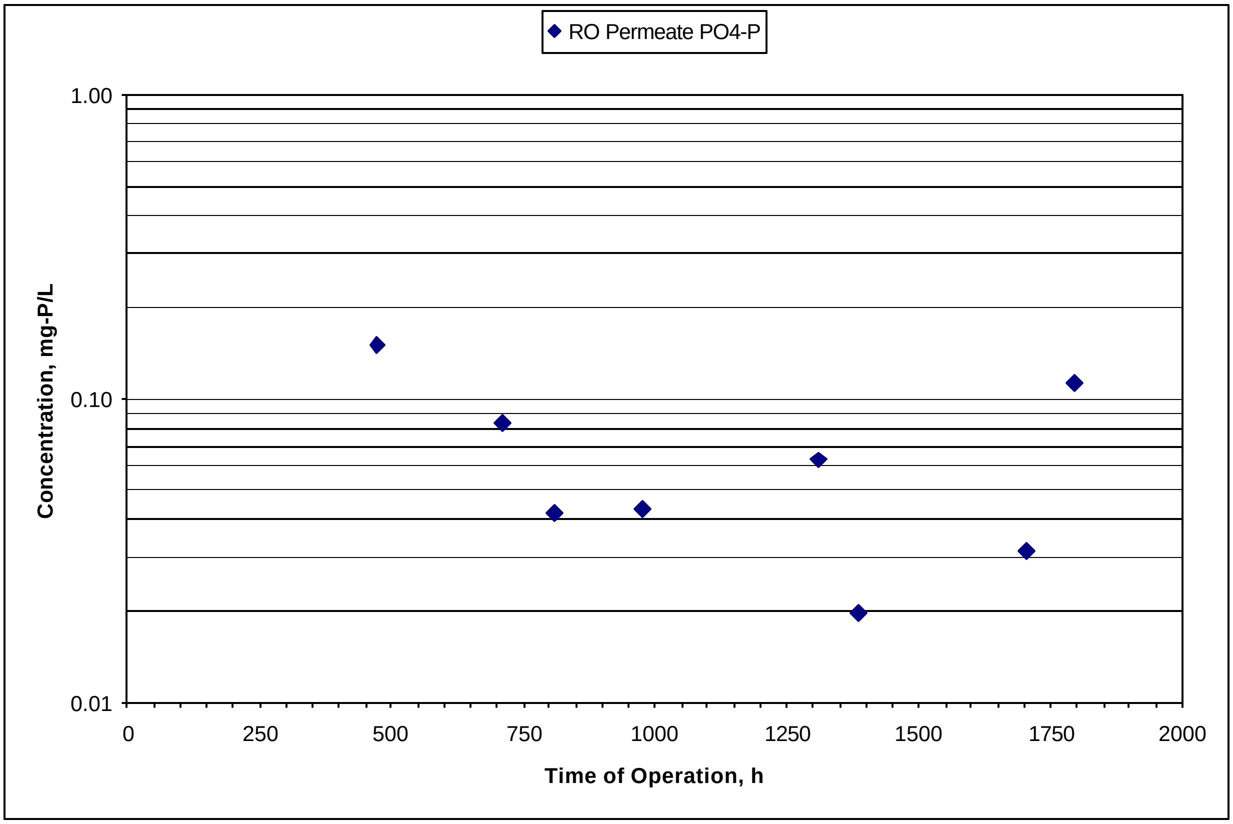


Figure 6-24 Ortho-Phosphate Removal by the Mitsubishi MBR RO During Part 2

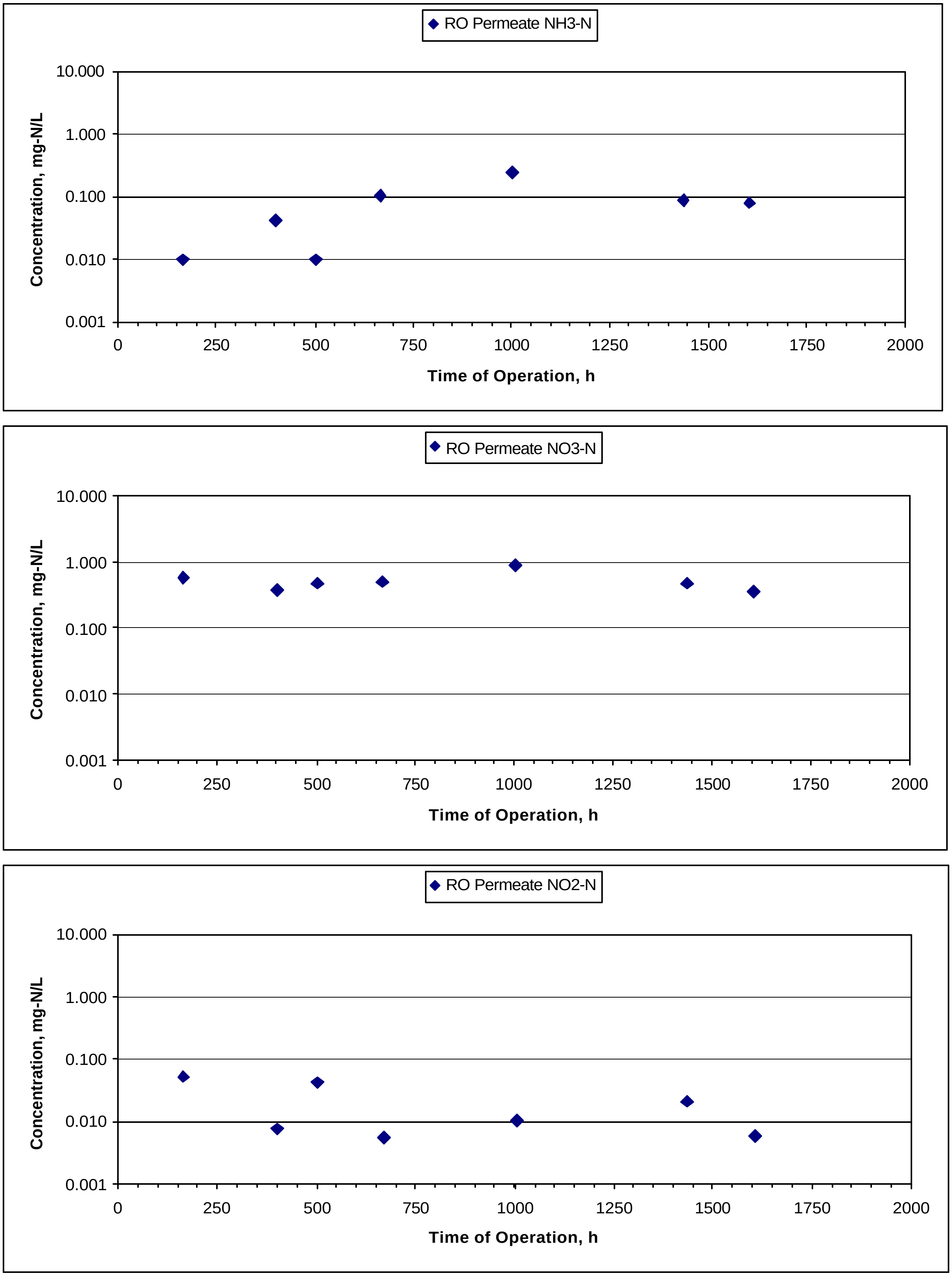


Figure 6-25 Inorganic Nitrogen Species in the Zenon MBR RO Permeate During Part 2

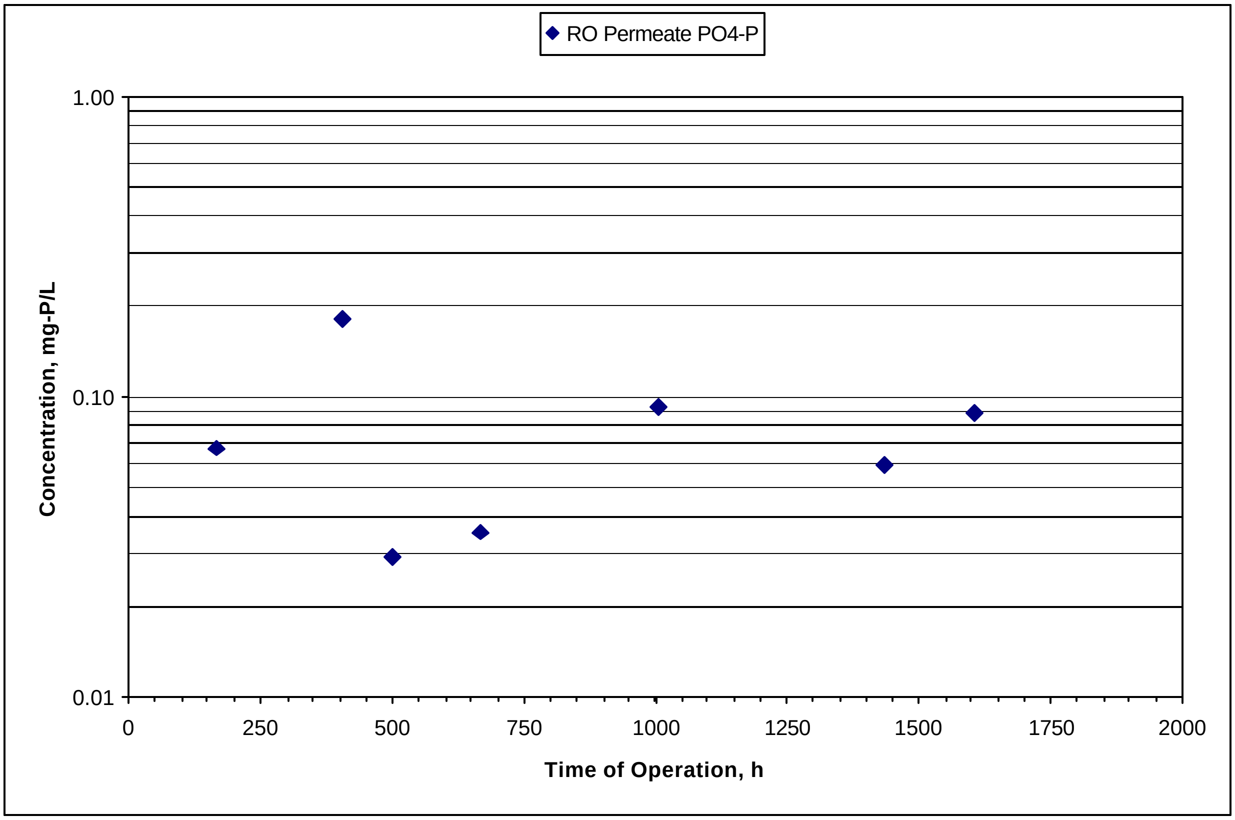


Figure 6-26 Ortho-Phosphate Concentration in the Zenon MBR RO Permeate During Part 2

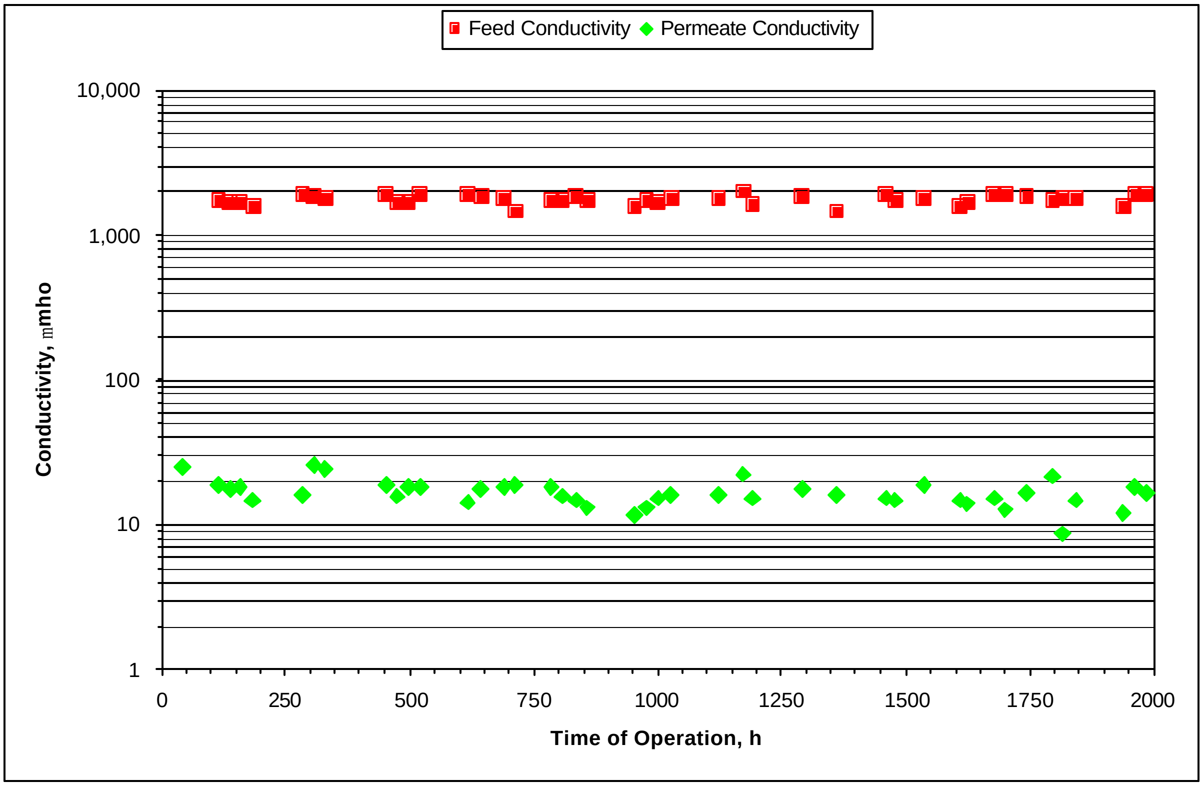


Figure 6-27 Conductivity Profile Across the Mitsubishi MBR RO During Part 2

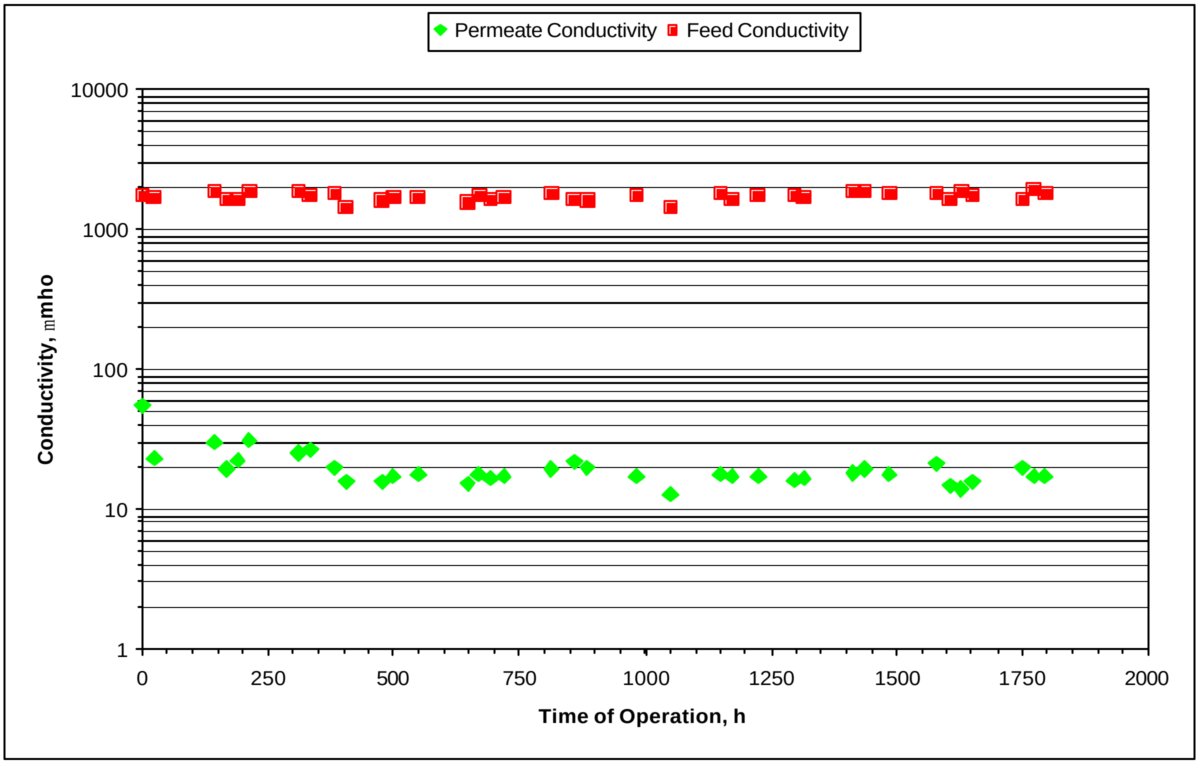


Figure 6-28 Conductivity Profile Across the Zenon MBR RO During Part 2

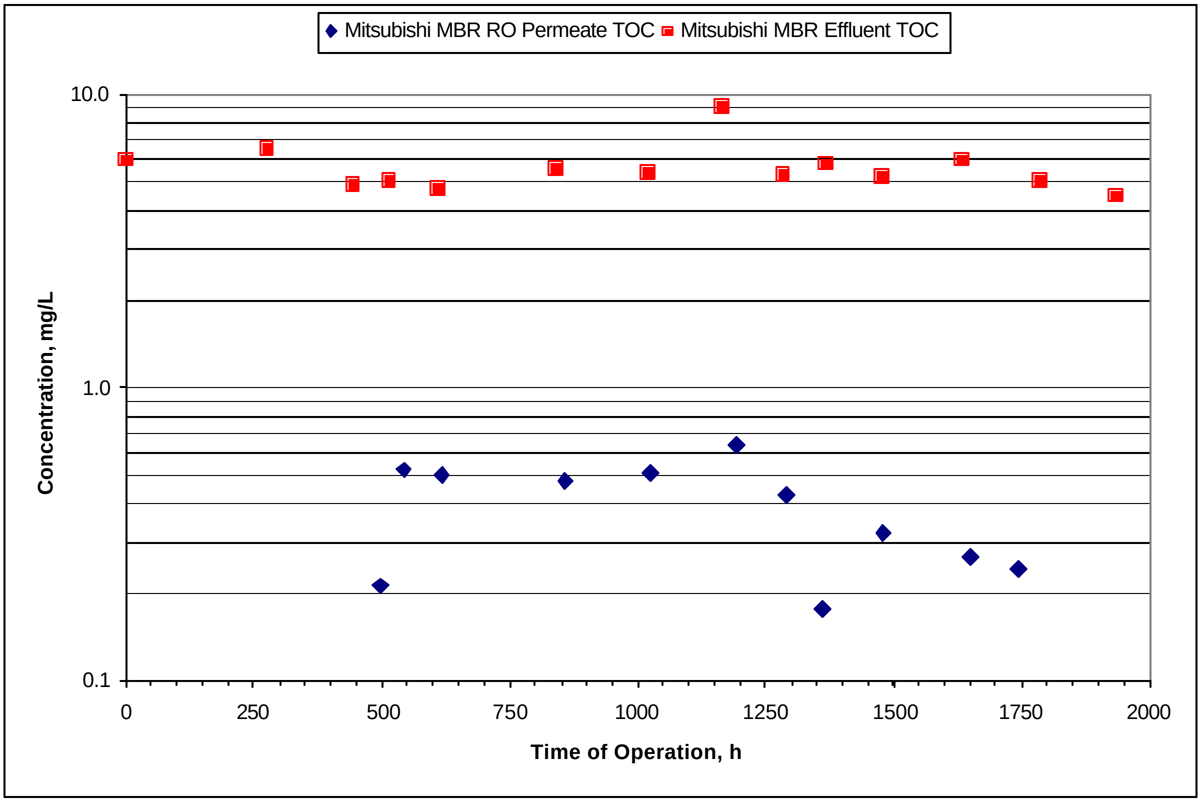


Figure 6-29 TOC Rejection by the Mitsubishi MBR RO During Part 2

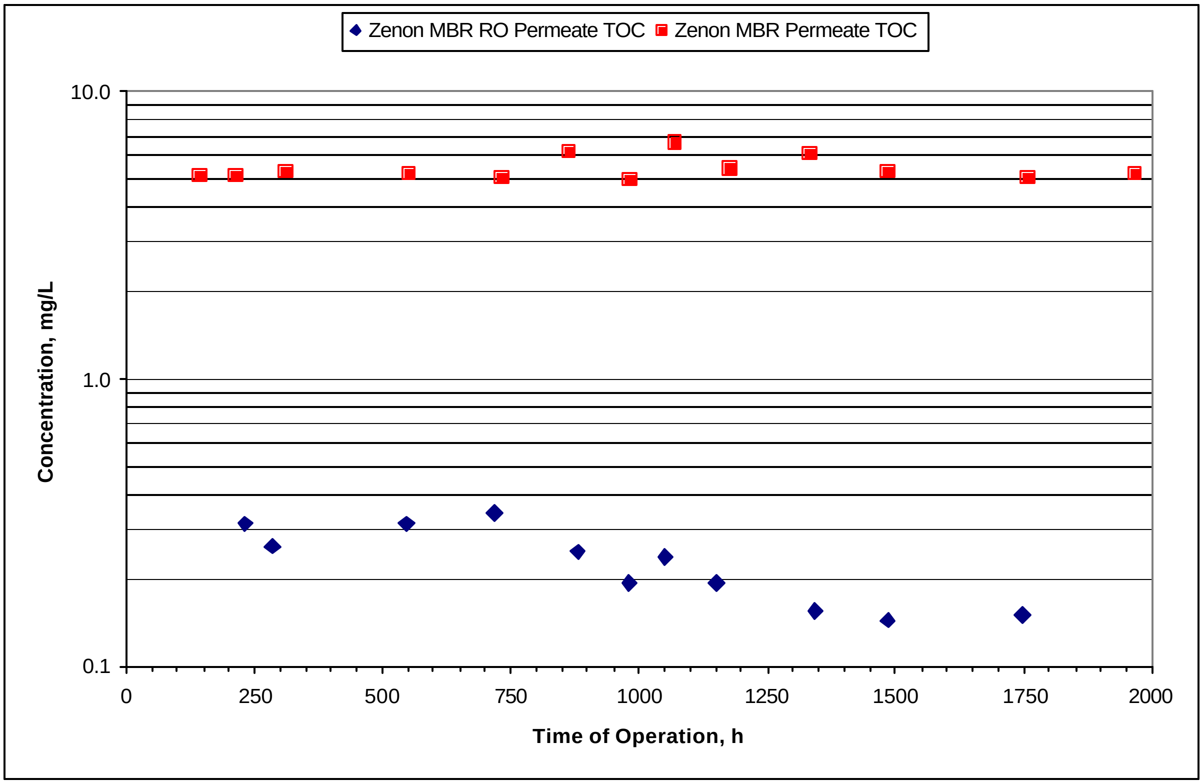


Figure 6-30 TOC Rejection by the Zenon MBR RO During Part 2

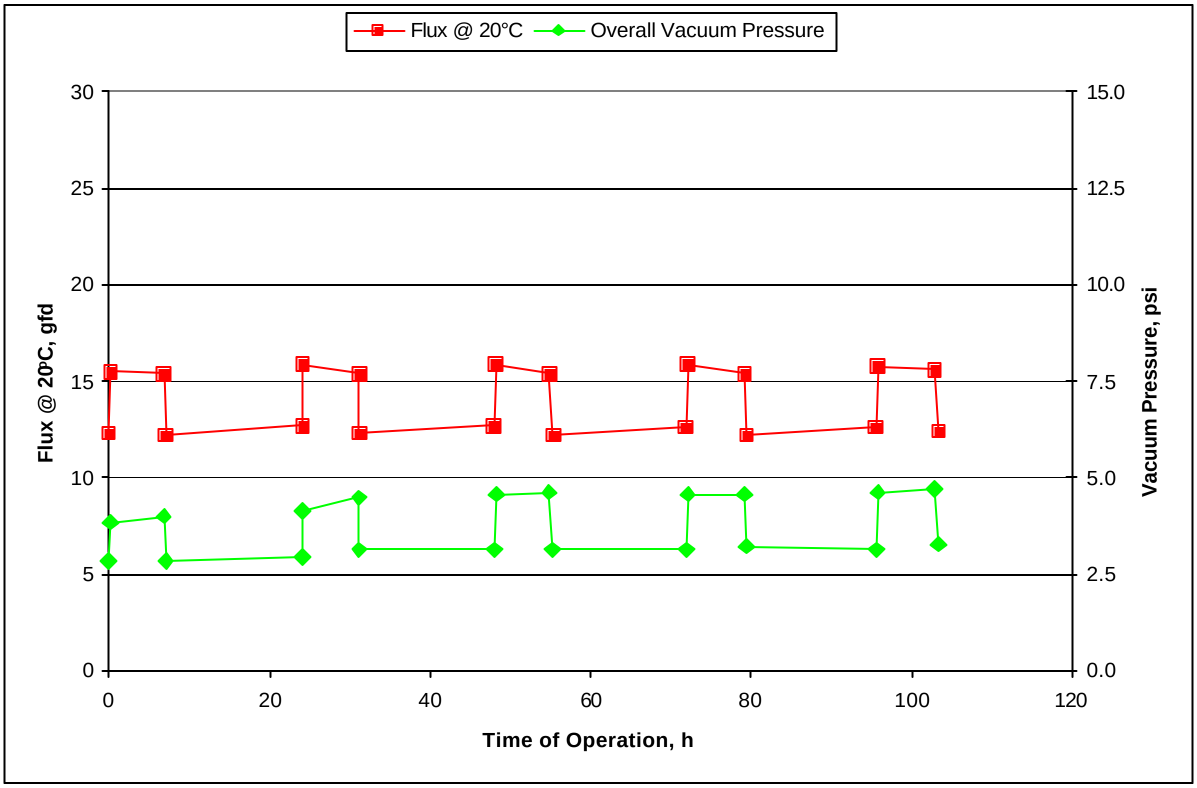


Figure 6-31 Mitsubishi MBR Peaking Study During Part 2

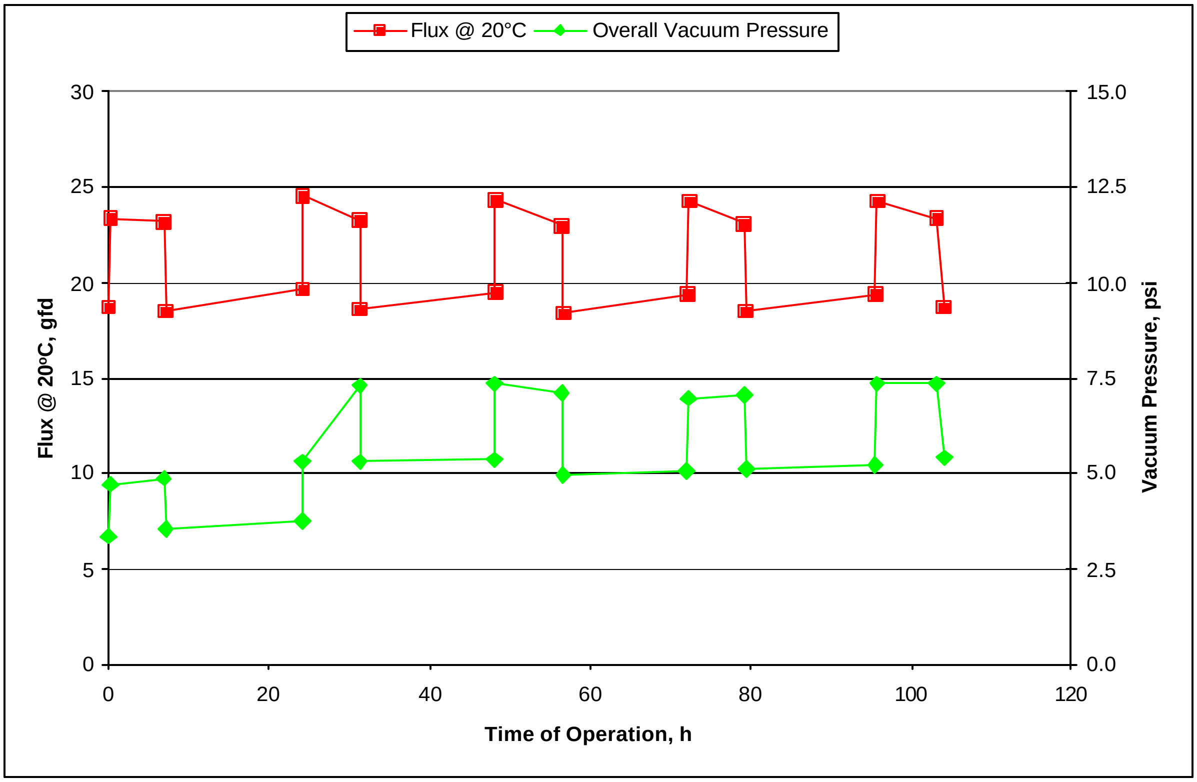


Figure 6-32 Zenon MBR Peaking Study During Part 2

	Zenon MBR			Mitsubishi MBR		
Date	CST (s)	TSS (mg/L)	CST/TSS (s/g/L)	CST (s)	TSS (mg/L)	CST/TSS (s/g/L)
Part 1						
11/11/99	13.6	12900	**1.05**	14.6	5720	**2.55**
11/12/99	14.5	12900	**1.12**	11.3	5720	**1.98**
11/16/99				11.4	5720	**1.99**
Part 2						
01/05/00	11.3	9640	**1.17**	8.3	12720	**0.65**
01/10/00	11.8	8680	**1.36**	9.0	9880	**0.91**
01/21/00	10.1	7160	**1.41**	7.3	8280	**0.88**
01/27/00	9.4	6440	**1.46**	7.8	5440	**1.43**
02/04/00	9.1	8040	**1.13**	11.1	7000	**1.59**
02/07/00	13	8200	**1.59**	8.7	7040	**1.24**
02/15/00	13.1	9520	**1.38**	10.9	6760	**1.61**
03/02/00	7.1	7960	**0.89**	7.6	8240	**0.92**

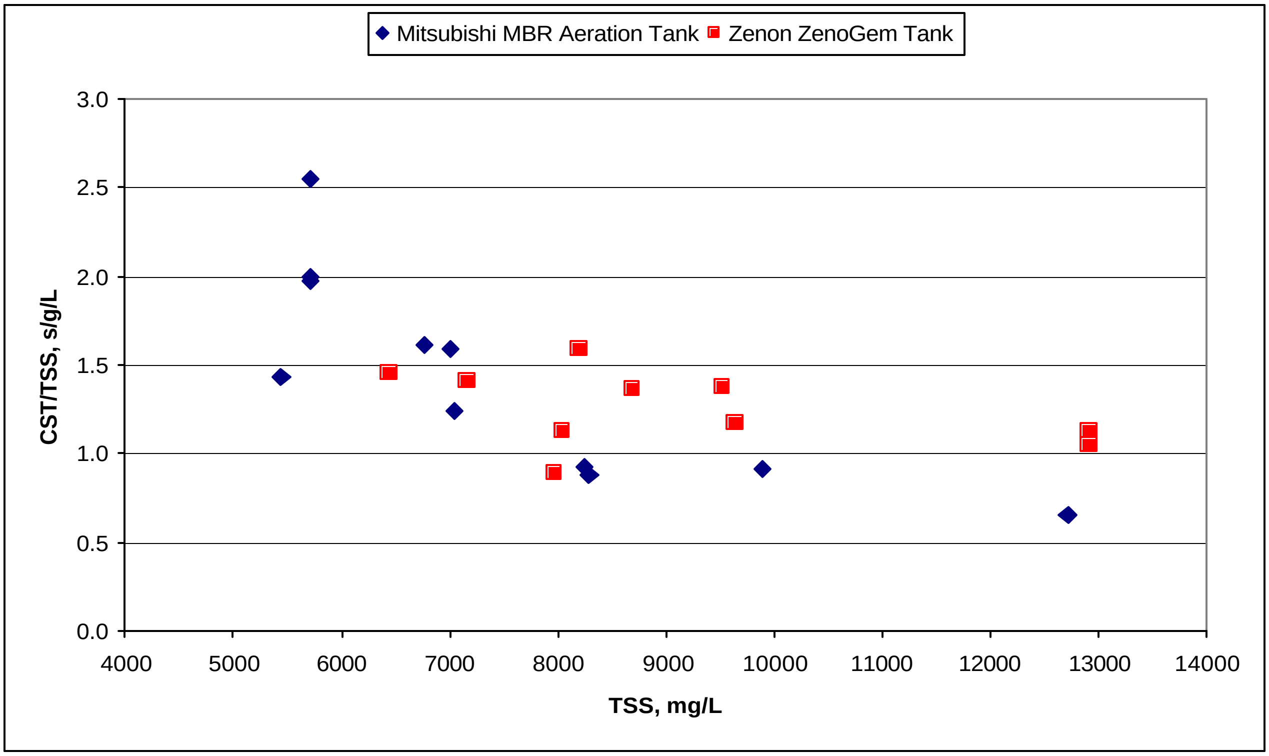


Figure 6-33 CST Results for the MBR Sludge

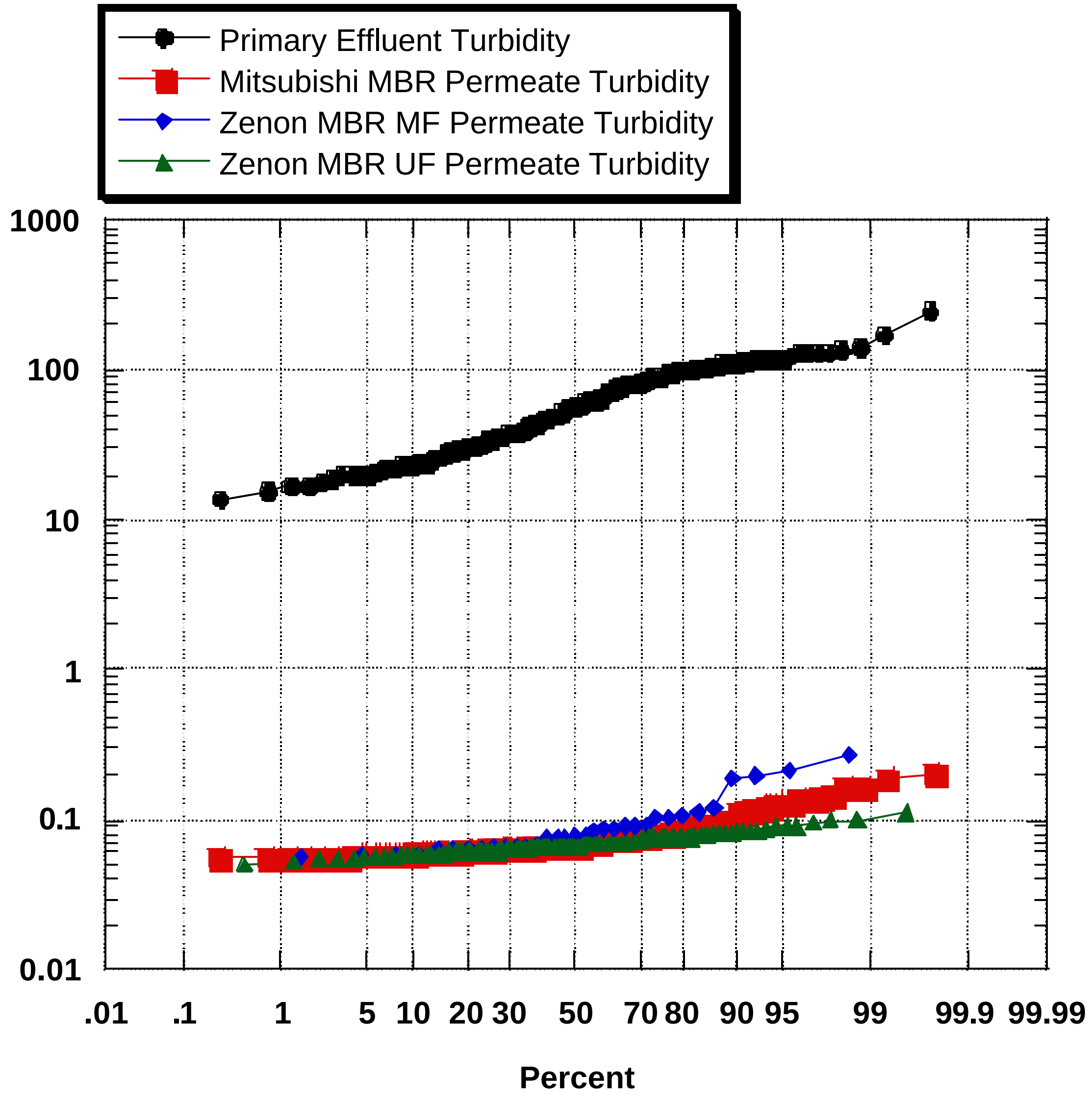


Figure 7-1 Probability Plot of the Turbidity Removal by the MBR Pilot Plants

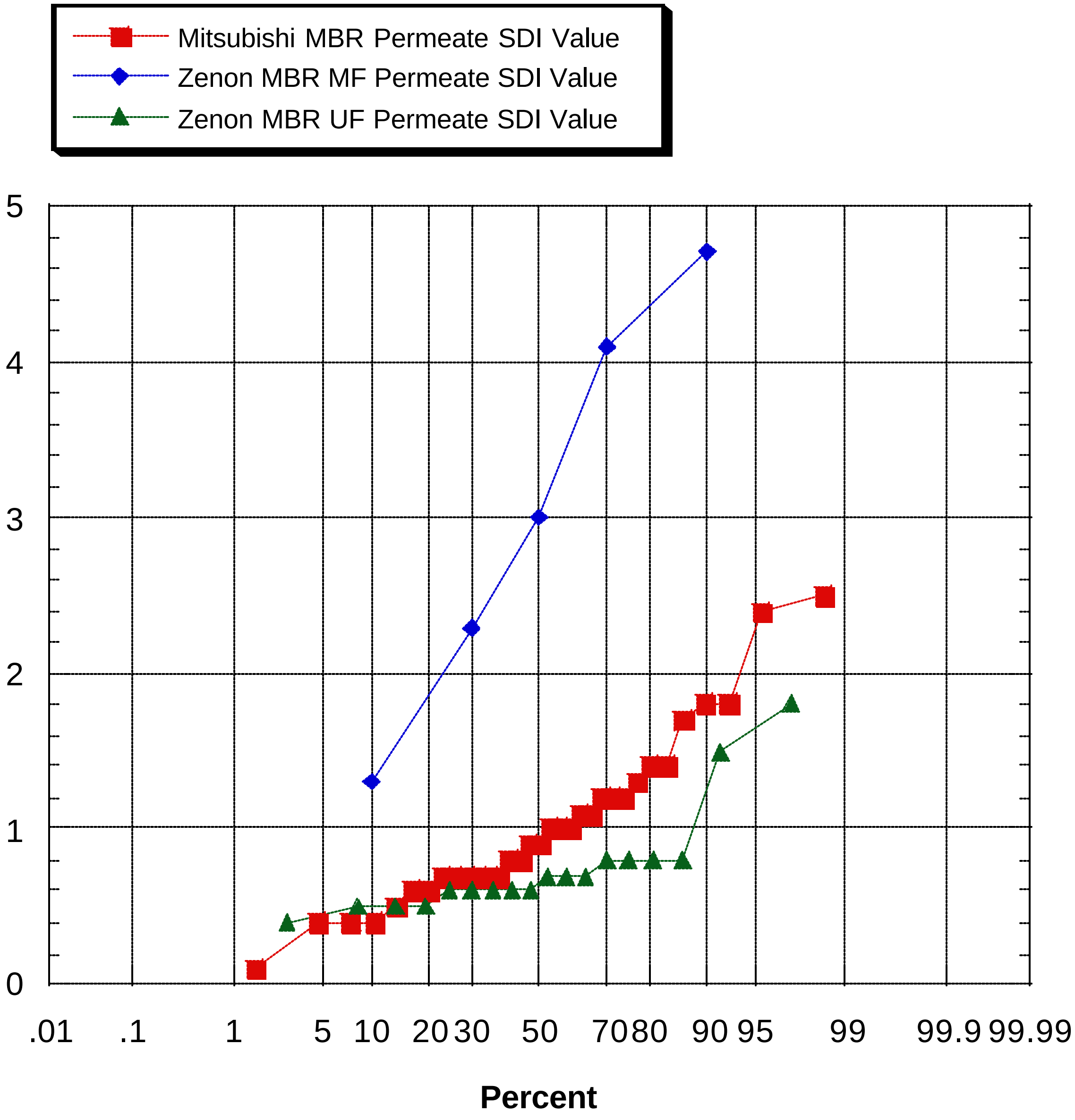


Figure 7-2 Probability Plot of the SDI Values for the MBR Permeate

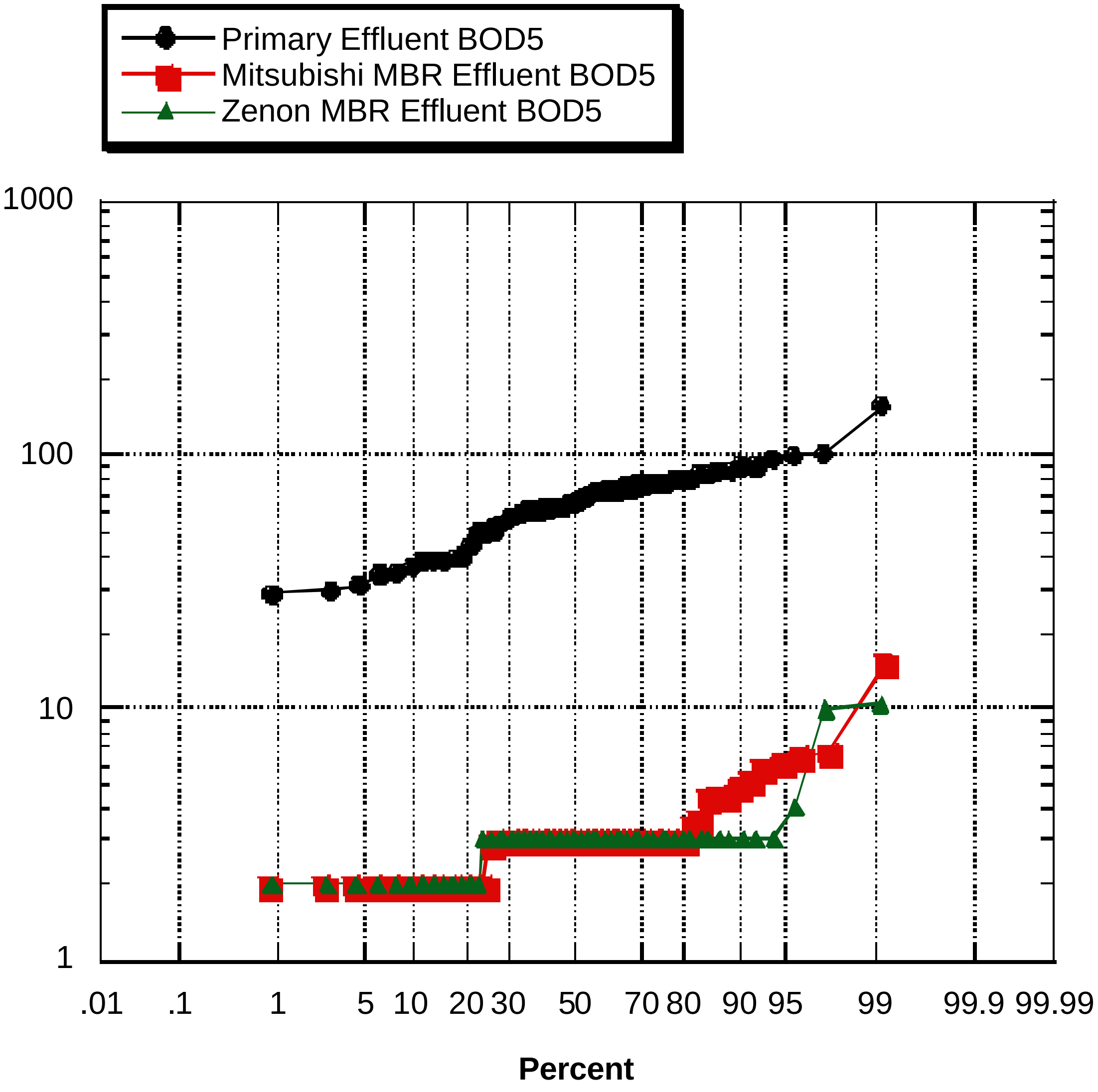


Figure 7-3 **Probability Plot of the BOD$_5$ Removal by the MBR Pilot Plants**

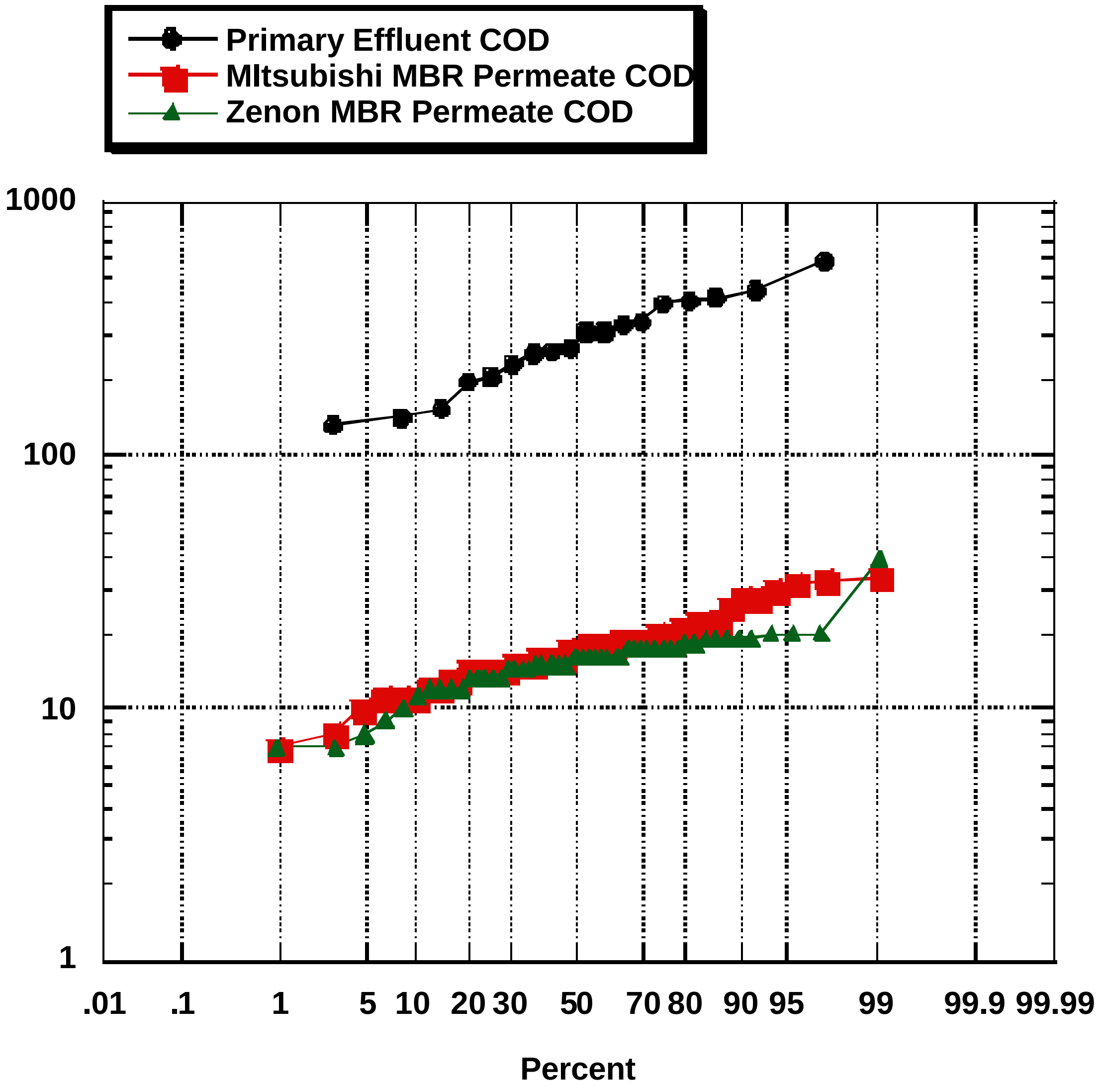


Figure 7-4 Probability Plot of the COD Removal by the MBR Pilot Plants

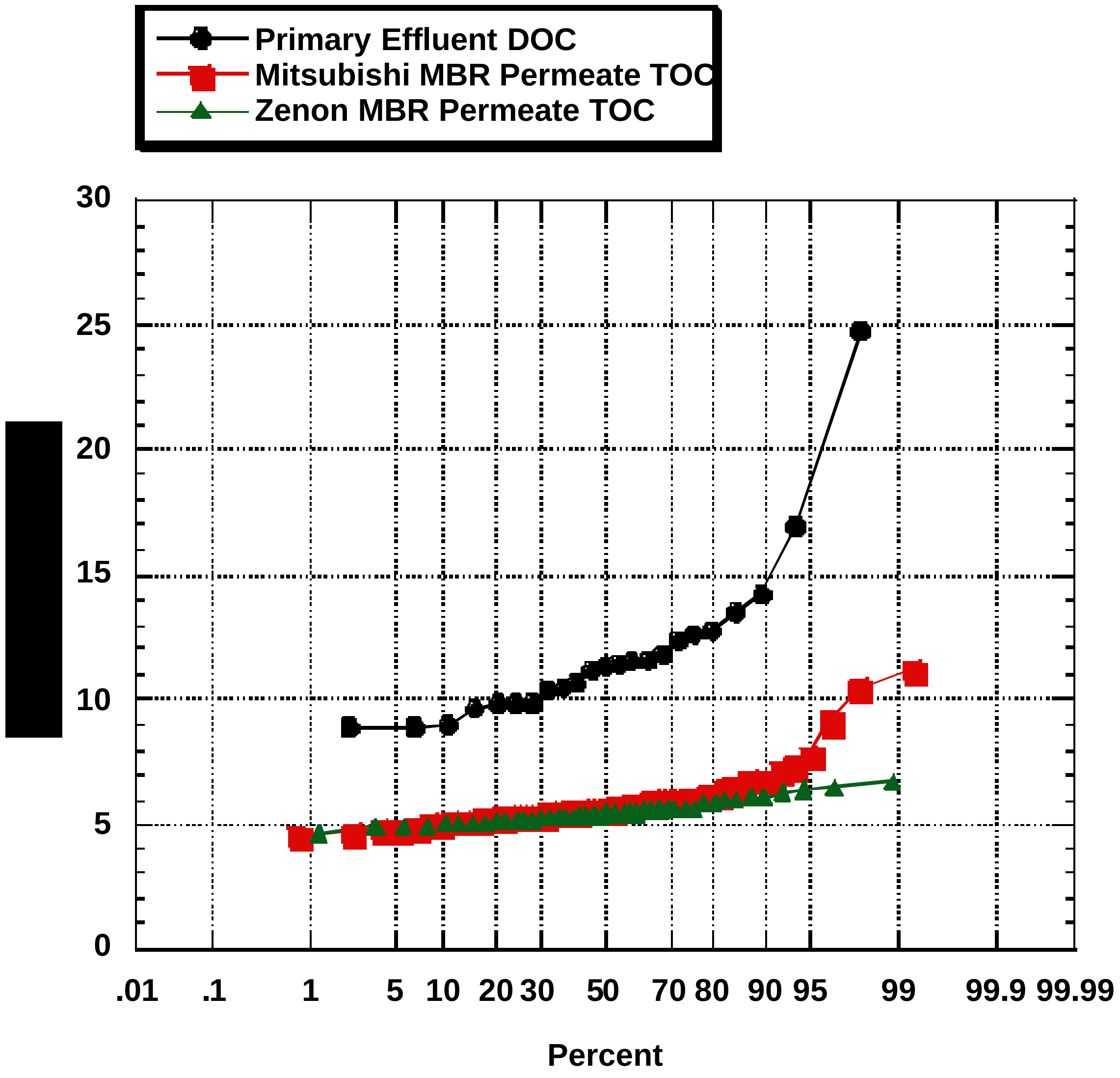


Figure 7-5 Probability Plot of the Organic Carbon Removal by the MBR Pilot Plants

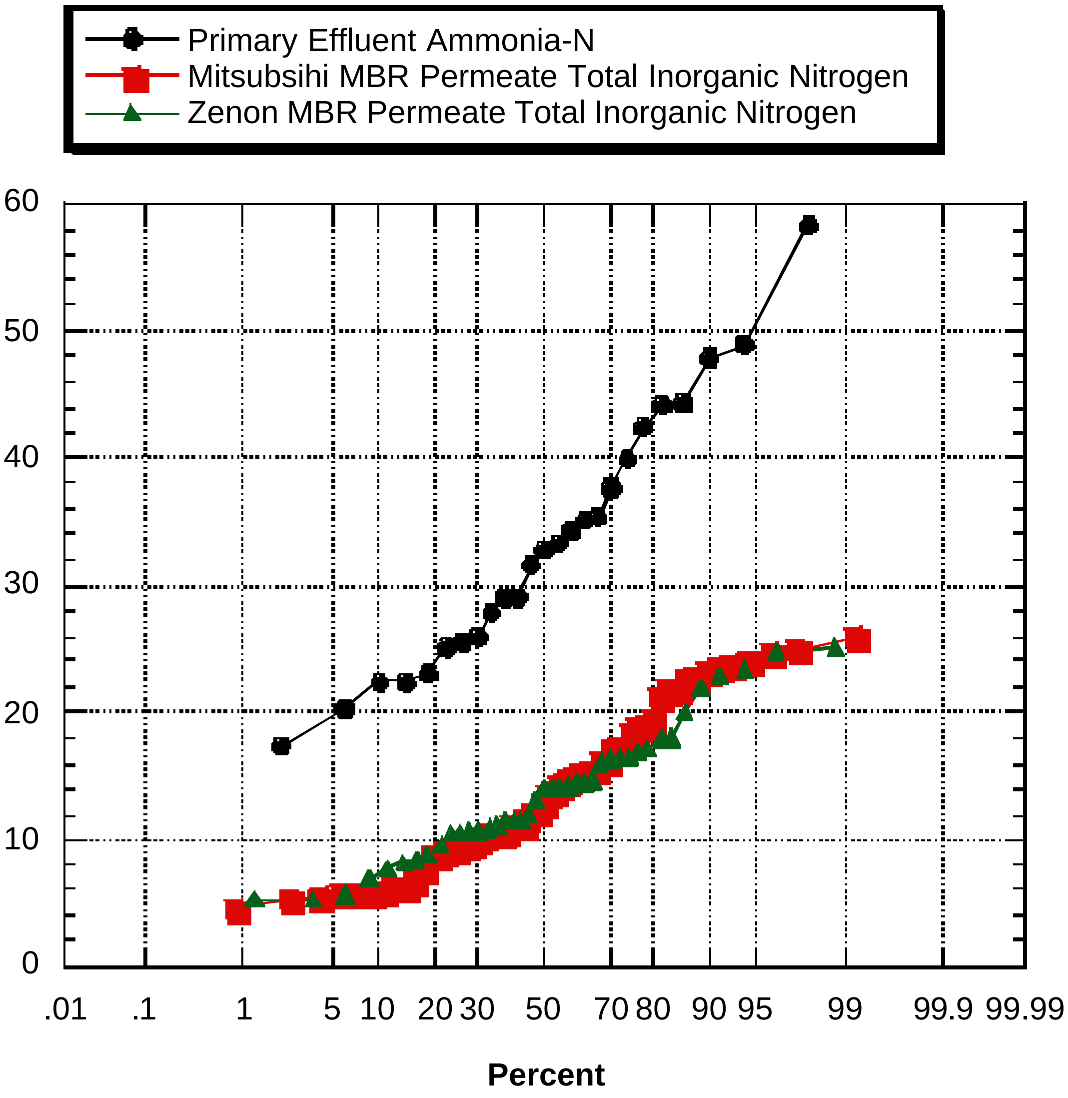


Figure 7-6 Probability Plot of the Inorganic Nitrogen Removal by the MBR Pilot Plants During Part 1

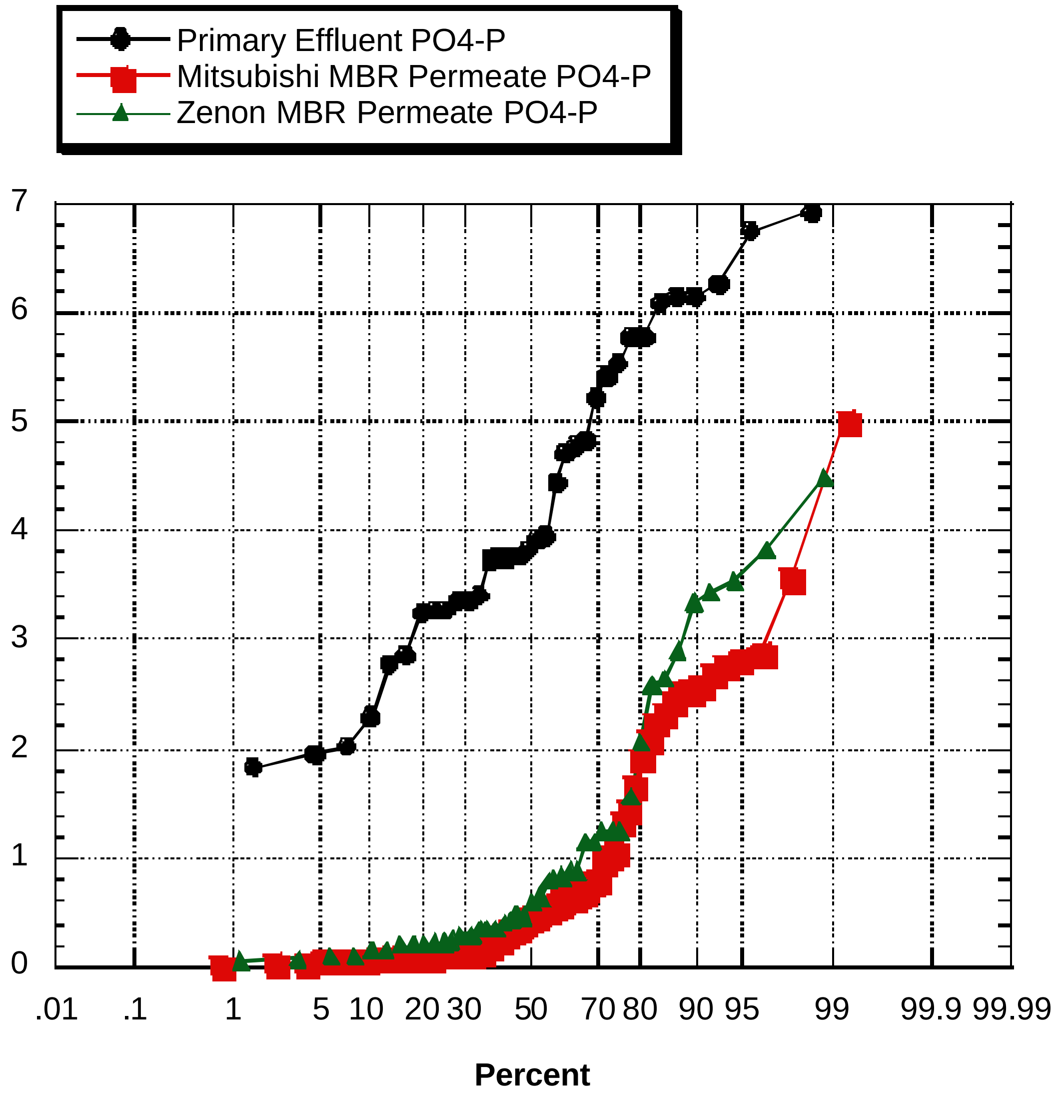


Figure 7-7 Probability Plot of the Ortho-Phosphate Removal by the MBR Pilot Plants During Part 1

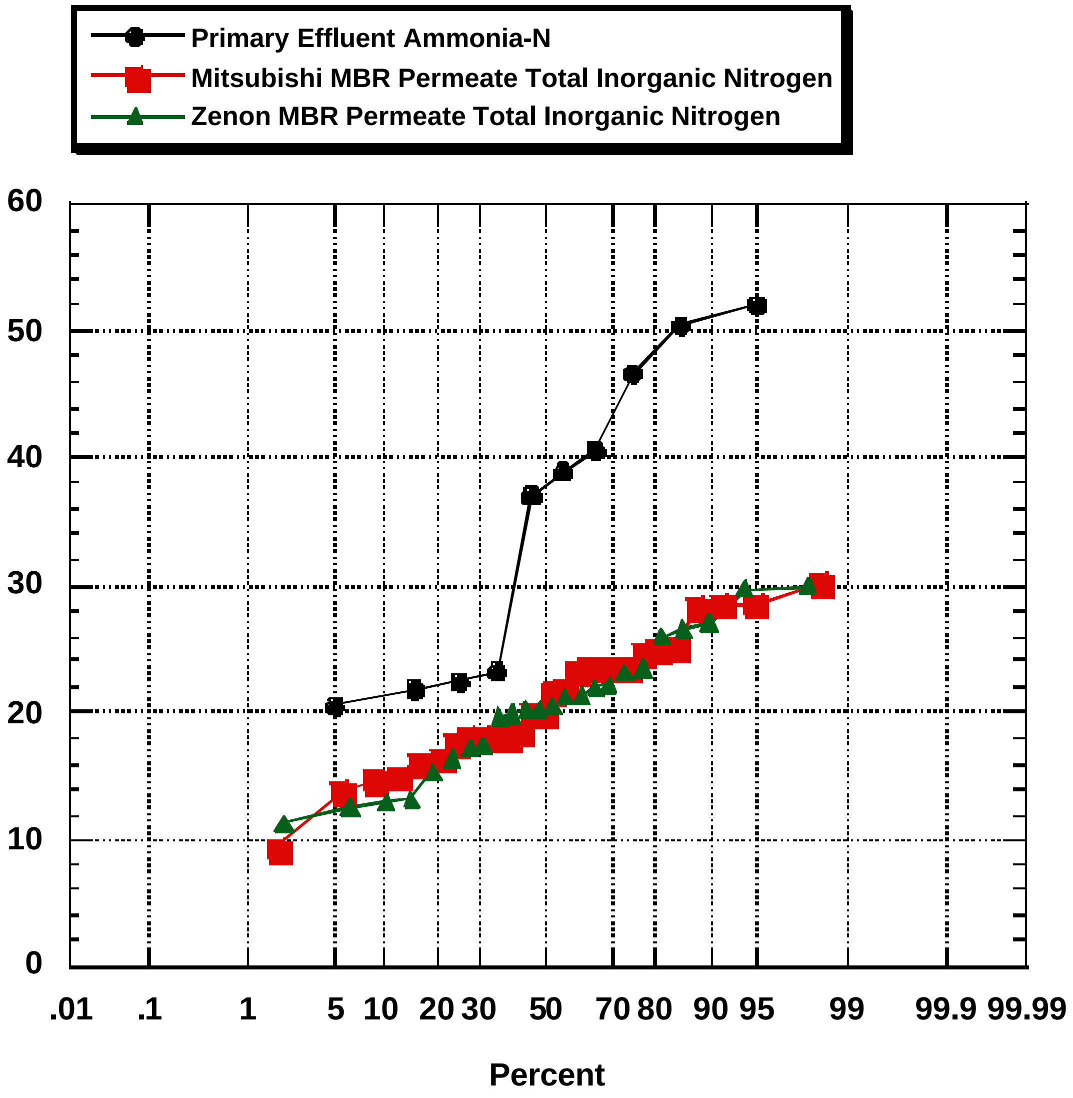


Figure 7-8 Probability Plot of the Inorganic Nitrogen Removal by the MBR Pilot Plants During Part 2

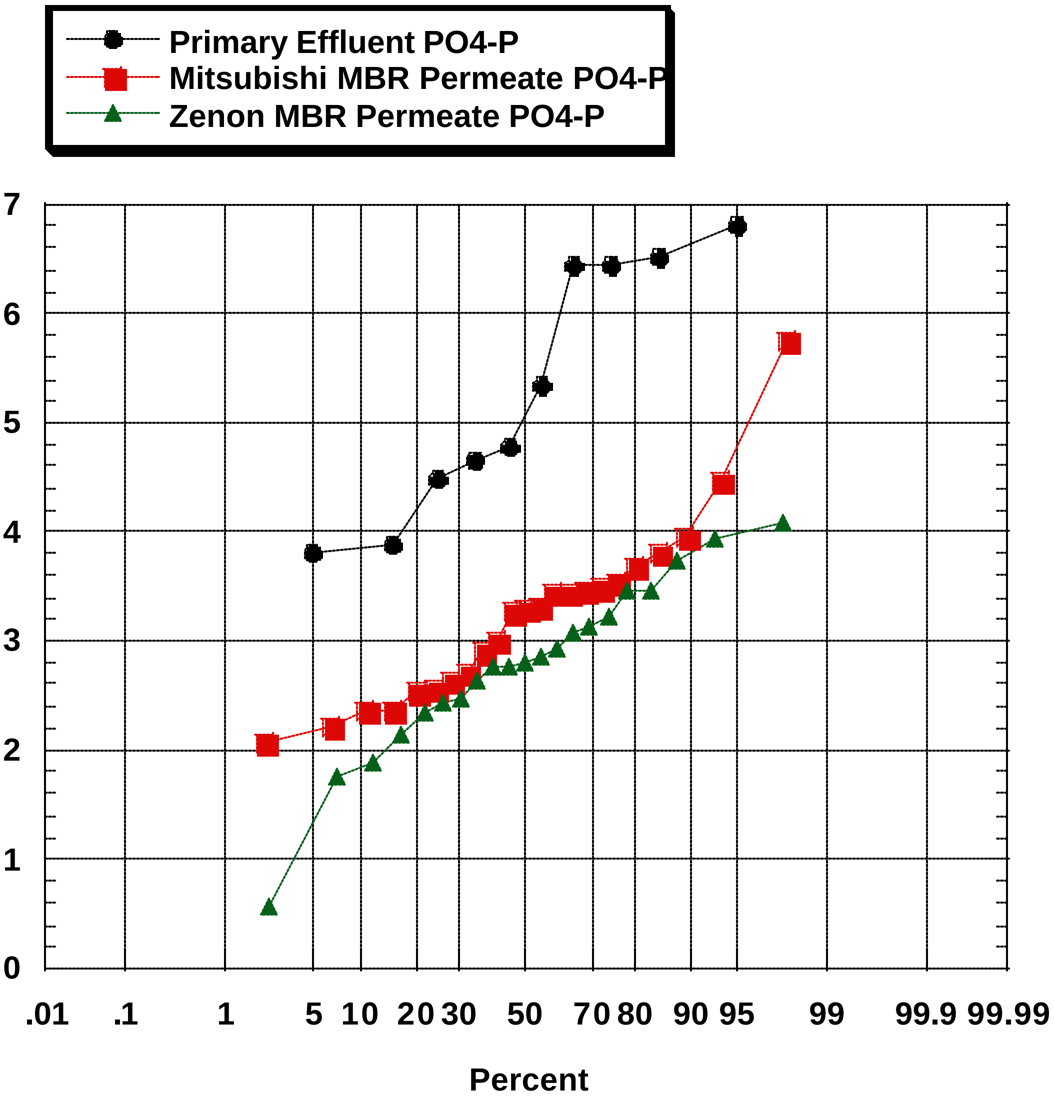


Figure 7-9 Probability Plot of the Ortho-Phosphate Removal by the MBR Pilot Plants During Part 2

[redacted]

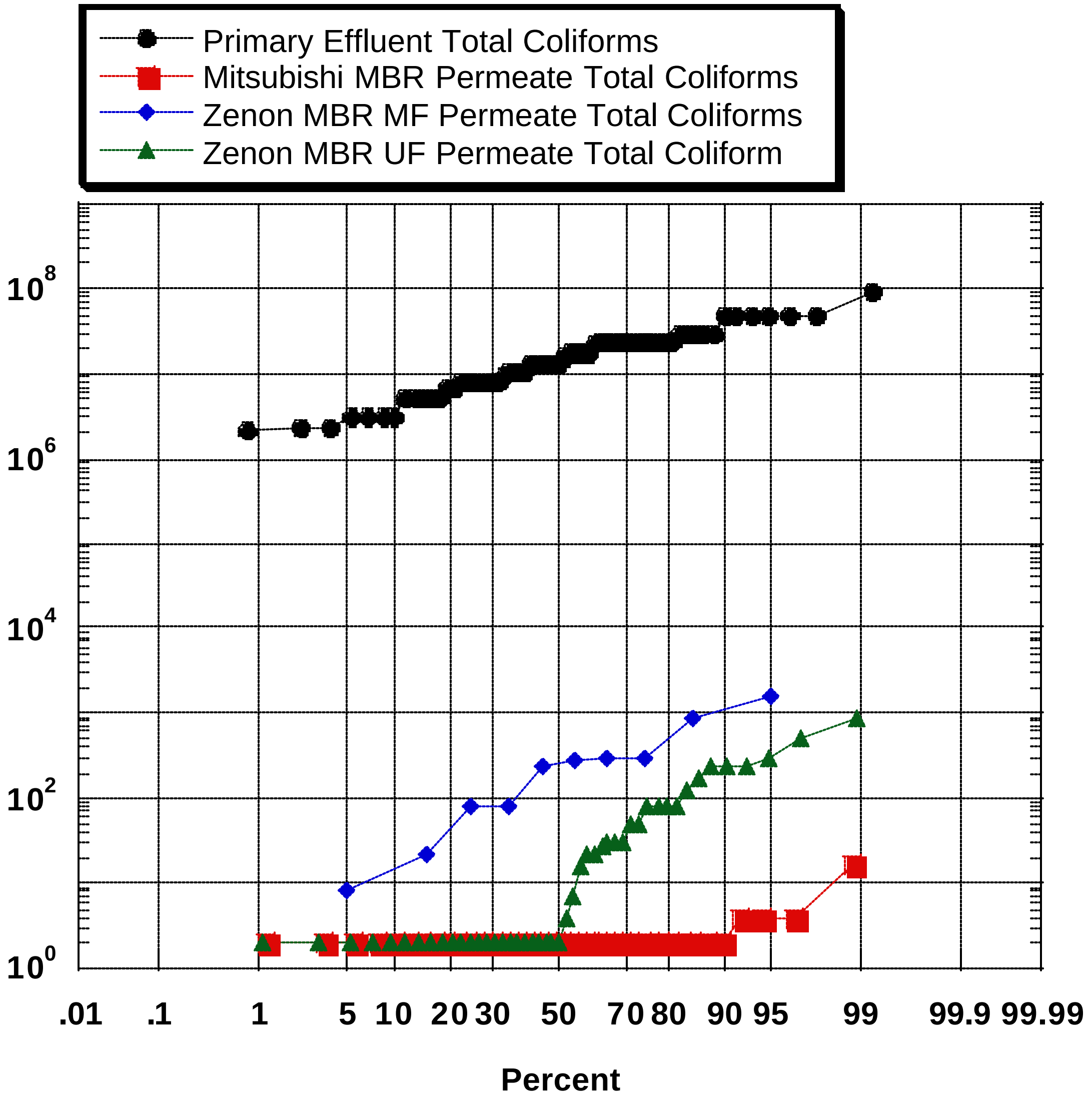


Figure 7-10 Probability Plot of the Total Coliform Removal by the MBR Pilot Plants

[redacted]

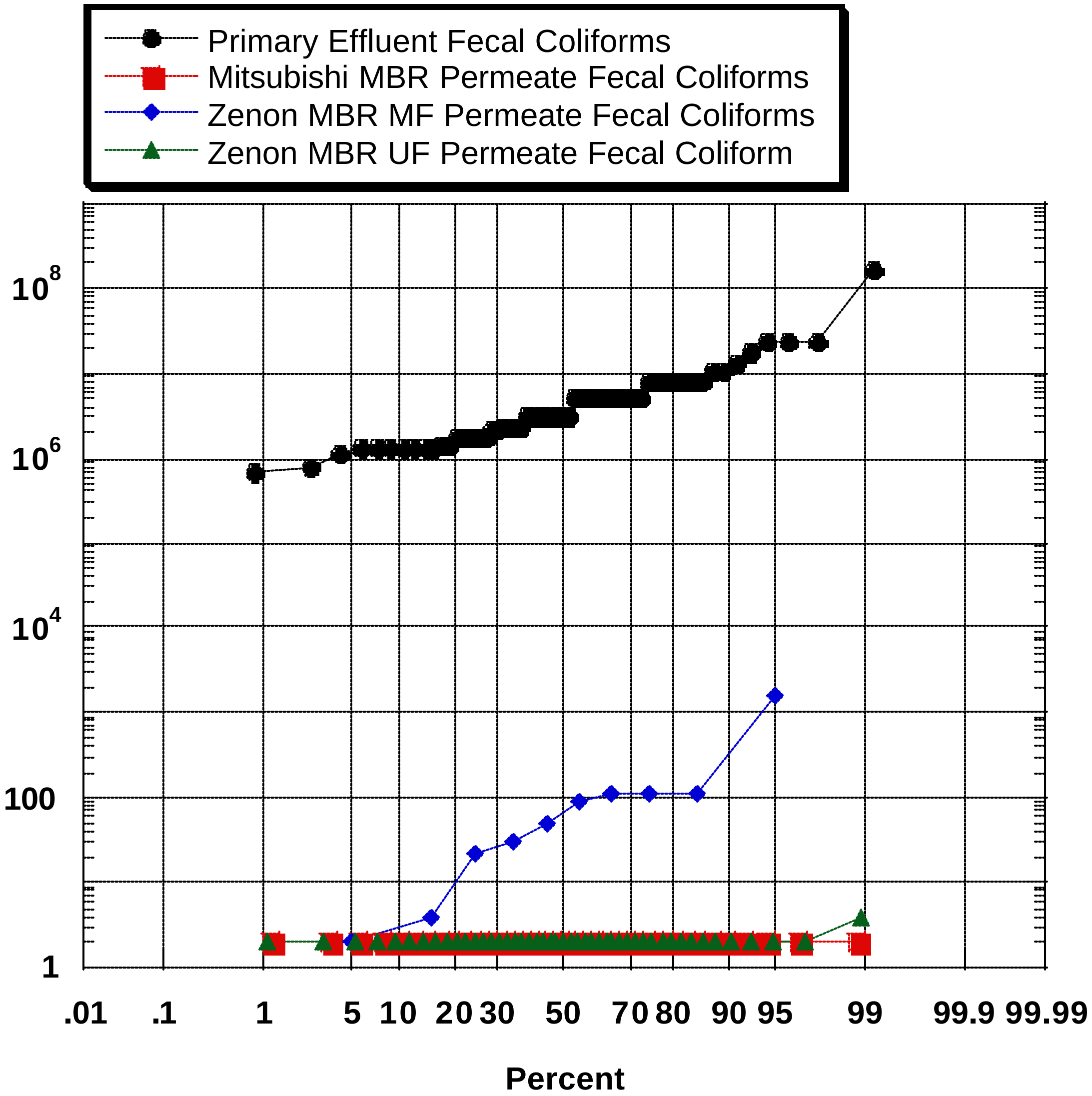


Figure 7-11 Probability Plot of the Fecal Coliform Removal by the MBR Pilot Plants

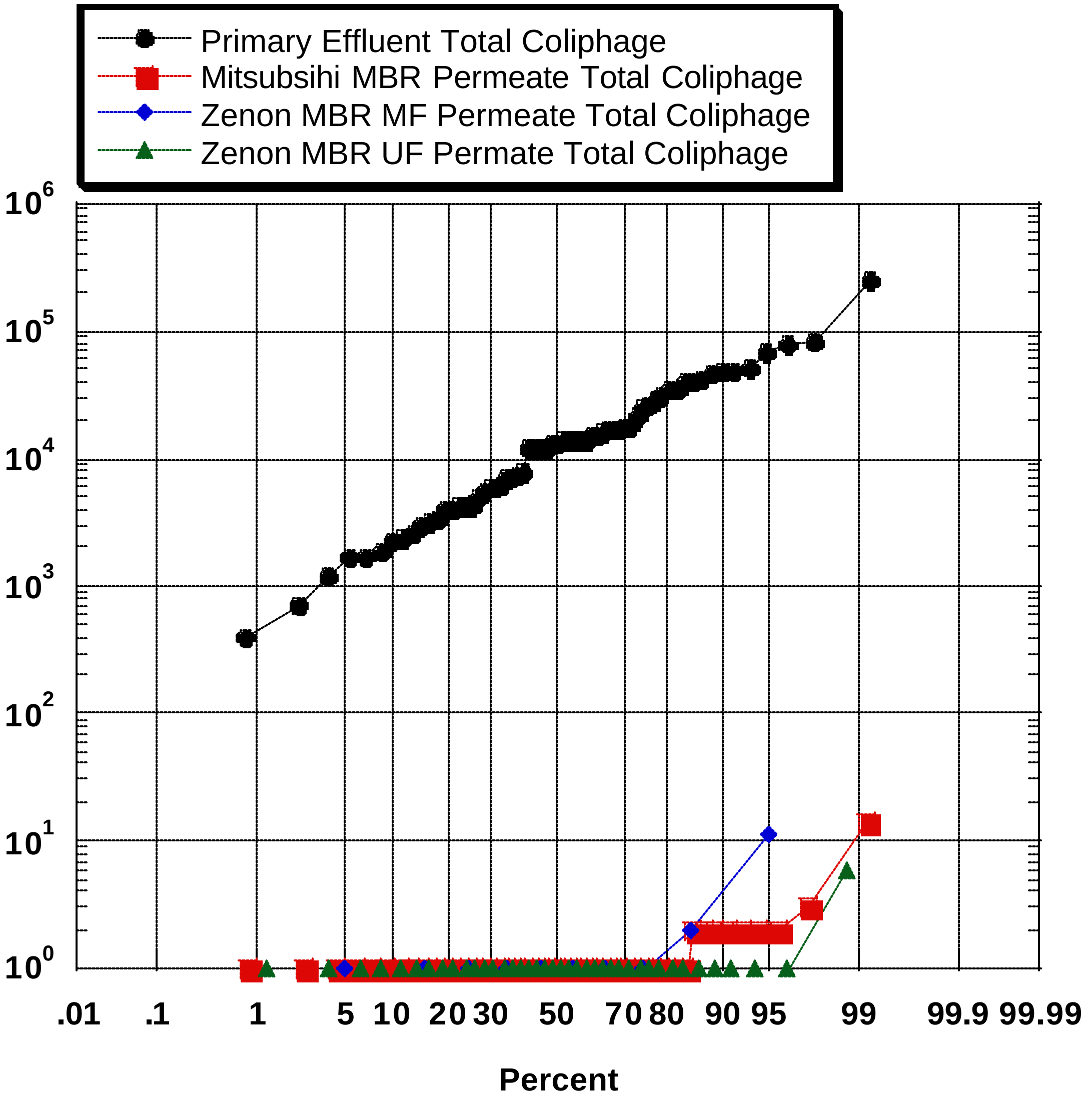


Figure 7-12 Probability Plot of the Total Coliphage Removal by the MBR Pilot Plants

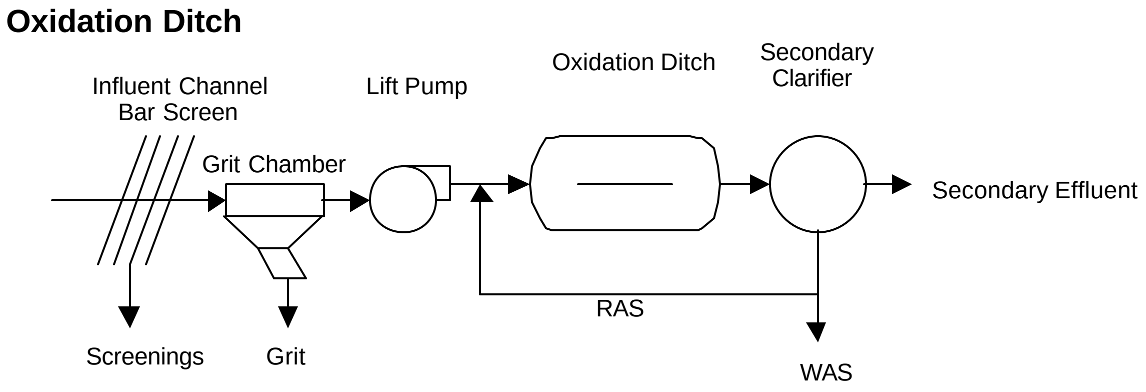
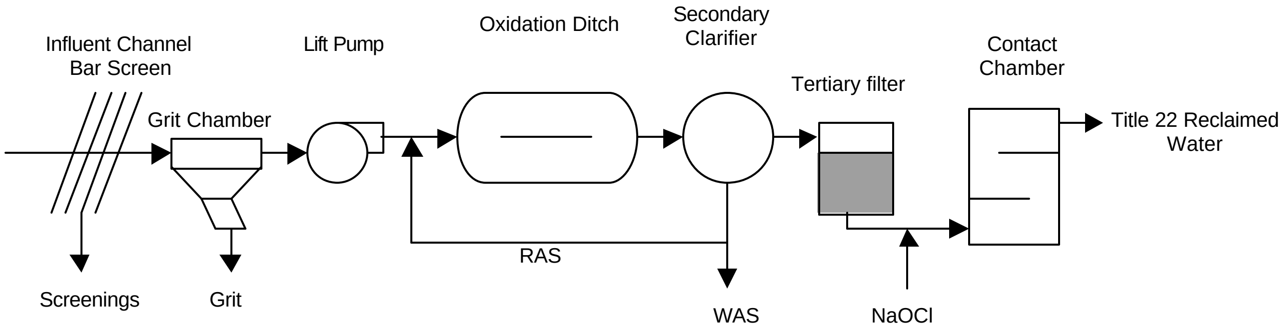
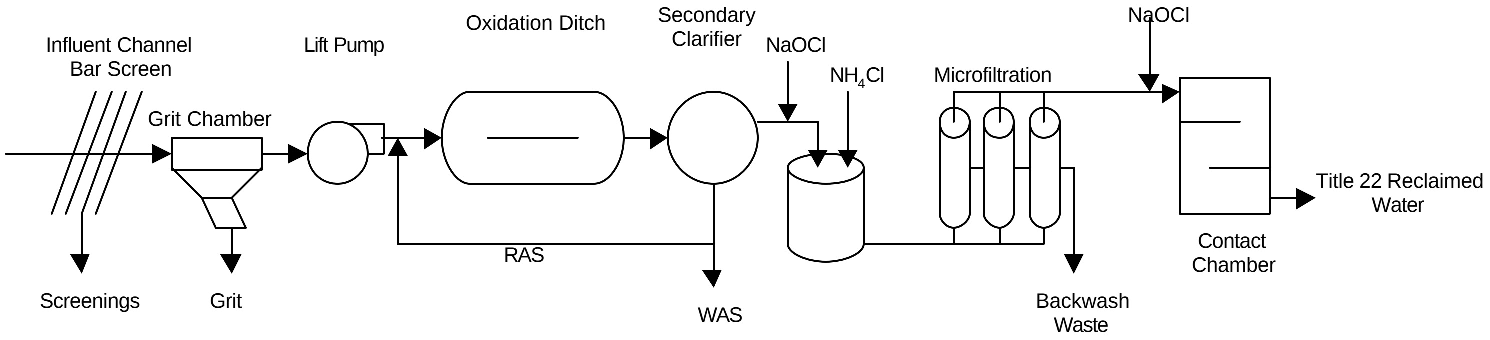


Figure 8-1 Wastewater Installations Producing Secondary Effluent Water

Oxidation Ditch with Filtration and Chlorination



Oxidation Ditch with Microfiltration and Chlorination



Membrane Bioreactor with Chlorination

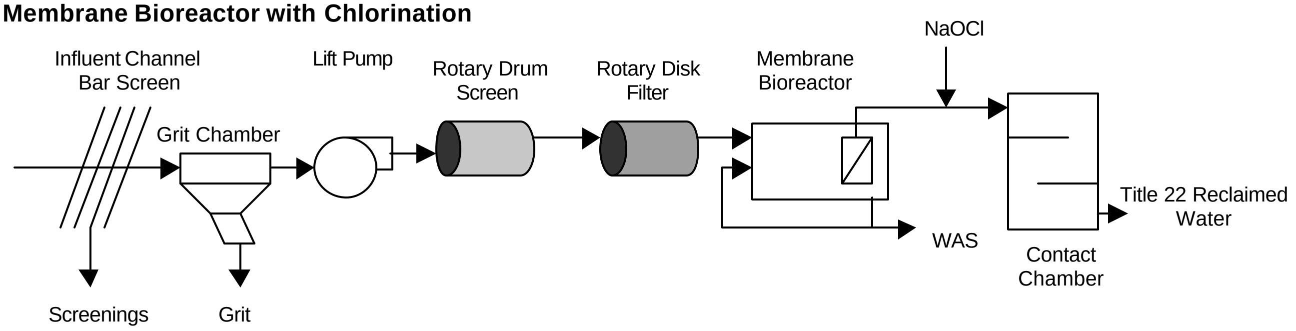
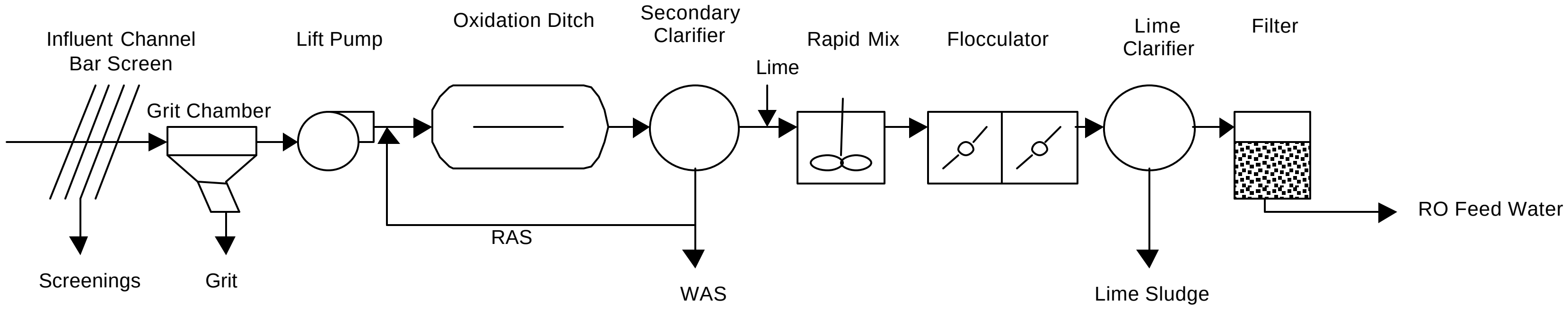
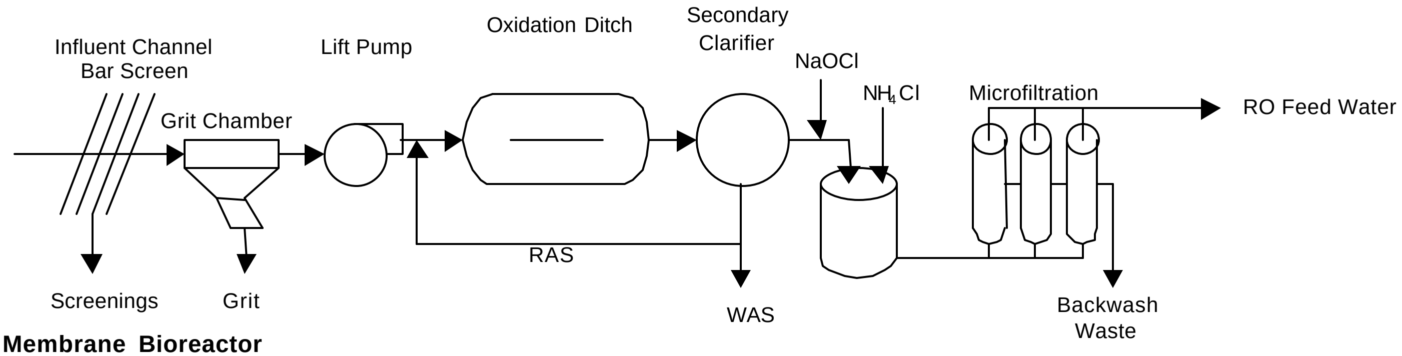


Figure 8-2 Wastewater Installations Producing Title 22 Reclaimed Water

Oxidation Ditch with Lime Flocculation, Coagulation, Sedimentation and Filtration



Oxidation Ditch with Microfiltration



Membrane Bioreactor

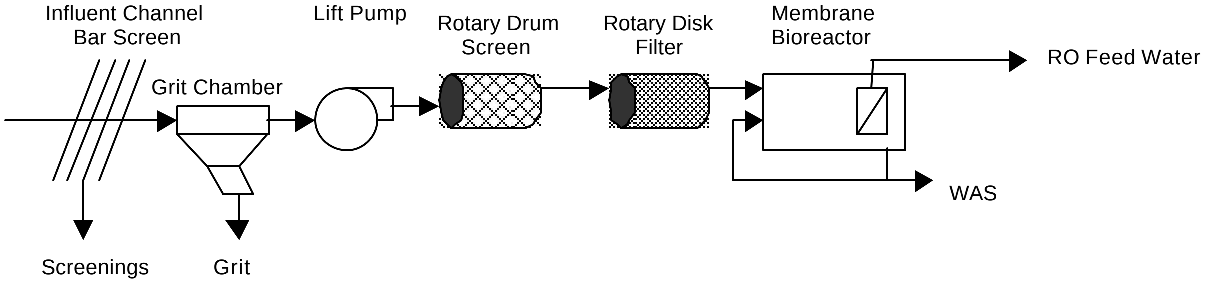


Figure 8-3 Wastewater Installations Producing Pre-RO Water

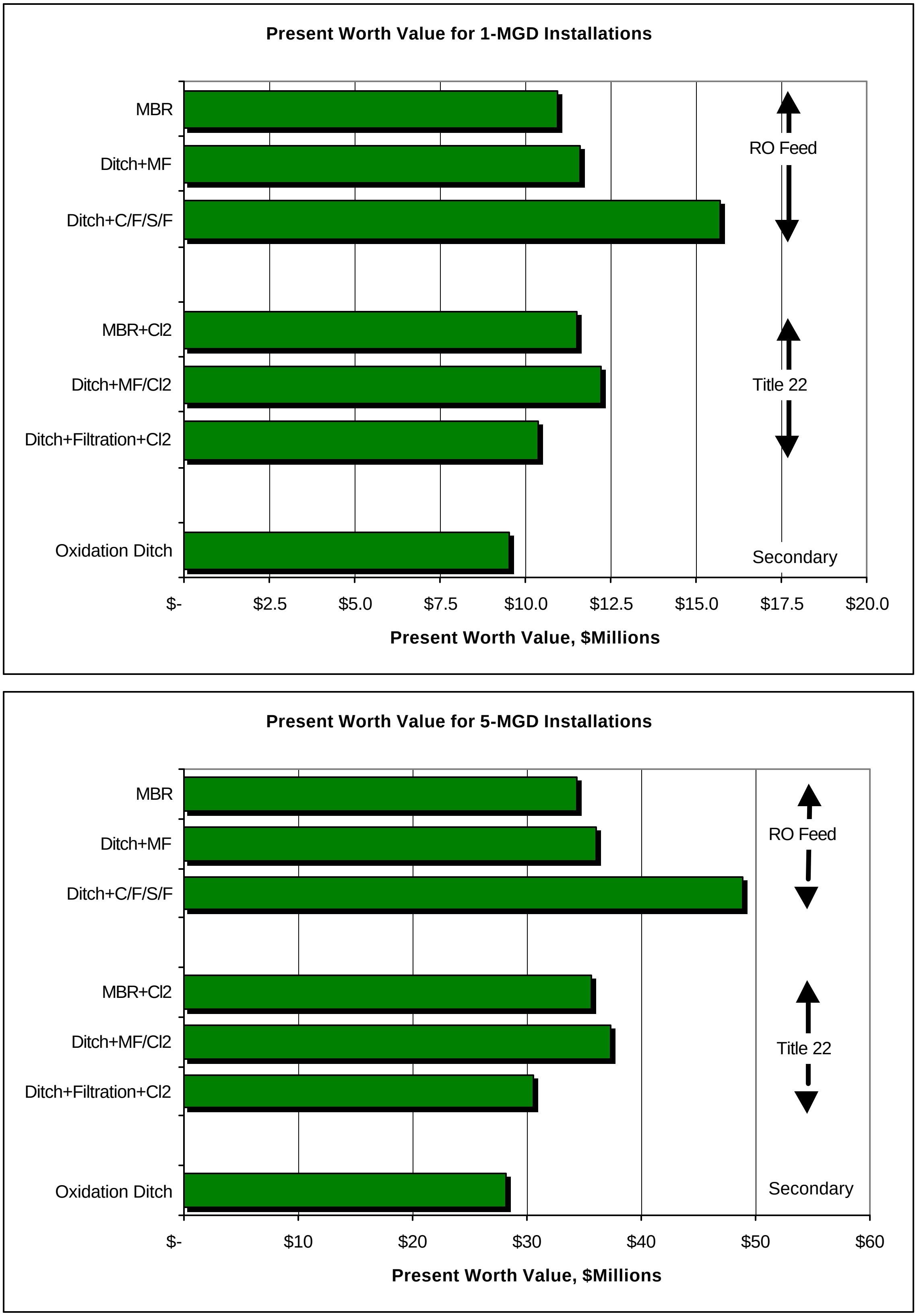


Figure 8-4 Present Worth Value for 1 and 5-MGD Installations Producing Secondary Effluent, Title 22 Water and RO Feed Wate

APPENDIX B

MEMBRANE CHEMICAL CLEANING PROTOCOLS

Mitsubishi MBR In-Line Chemical Cleaning Protocol

Chemical Reagent: NaOCl (effective chlorine concentration: 3,700 mg/L)
Volume of Chemical Reagent: 0.186 L/ft^2 of membrane area

1. Stop the vacuum pump.
2. Place the chemical tank 1 m above the membrane injection port.
3. Connect the chemical tank to the chemical injection port.
4. Open the valve of the chemical tank and chemical injection port, and operate the vacuum pump for 30 s.
5. Stop the vacuum pump.
6. Inject 30 L reagent for 10 min (this was changed to 45 L for 15 min for all cleanings after the initial cleaning).
7. Inject 70 L reagent for 2 h (this was changed to 105 L for 3 h for all cleanings after the initial cleaning).
8. Place the system in normal operation.

Zenon Chlorine Cleaning Protocol

Chemical Reagent: NaOCl (effective chlorine concentration: 2,000 mg/L)
Volume of Chemical Reagent: 1.35 L/ft^2 of membrane area

1. Isolate the ZenoGem tank
2. Drain tank, and hose down until water appears clear
3. Fill with tap water
4. Add chlorine solution to the ZenoGem tank
5. Circulate the cleaning solution through the membrane
6. Close appropriate valves to prevent water from siphoning out through the membrane
7. Allow to soak overnight
8. Drain tank and hose down until there is no chlorine present
9. Put back into service

Zenon Citric Acid Cleaning Protocol

Chemical Reagent: Citric Acid (effective pH = 2.5)

1. Isolate the ZenoGem tank
2. Drain tank, and hose down until water appears clear
3. Fill with tap water
4. Add citric acid solution to the ZenoGem tank
5. Circulate the cleaning solution through the membrane
6. Close appropriate valves to prevent water from siphoning out through the membrane
7. Allow to soak overnight
8. Drain tank and hose down until there is no citric acid present
9. Put back into service

Zenon Maintenance Cleaning Protocol

Chemical Reagent: NaOCl (effective concentration: 200 mg/L)

1. Shut down pilot unit
2. Let the system relax for 5 min
3. Fill the CIP (clean in place) tank with the cleaning solution
4. Put the system in CIP mode
5. Backpulse the system for 2 min at a flow rate of 2 gpm
6. Relax for 3 min
7. Backpulse the system for 1 min
8. Relax for 3 min
9. Repeat steps 7 and 8, 8 times
10. Turn on blower for 10 min
11. Put system back into service

Cleaning Protocol for FilmTec/Dow BW30HP-4040 Reverse Osmosis Membranes

Chemical Reagent: 0.1 gal of NaOH, 0.025 gal of sodium lauryl dodecyl sulfate, pH 11 – 12,

Temperature 30°C

Volume of Chemical Reagent: 0.81 L/ft^2 of membrane area

1. Flush pressure vessels at 5 gpm with RO permeate for several minutes.
2. Circulate the cleaning solution at 5 gpm for 30 min. If the cleaning solution colors becomes turbid, restart with freshly prepared cleaning solution.
3. Check pH of cleaning solution while in circulation. If pH increase by more than 0.5 pH units, add acid (HCl).
4. Turn recirculation pump off and allow the membranes to soak for 1 hour.
5. Circulate the cleaning solution again at 10 gpm for 30 - 60 minutes.
6. Drain and flush cleaning tank.
7. Rinse pressure vessels with RO permeate whose pH has been adjusted to 4.5 - 5.5 using hydrochloric acid (HCl) for several min. The minimum temperature of the rinse water should be 68°F (20°C). Have both permeate and concentrate valves open during flushing. Flushing should be once-through step.
8. Operate the system as normal.

APPENDIX C

Aqua 2000

Aqua 2000 Research Center
14103 Highland Valley Road
Escondido, California 92025

Tel: 619 538 8194
Fax: 619 538 8199

To:	Samer Adham, Ph.D.	**Date:**	June 8, 1999
From:	Rion P. Merlo	**Reference:**	MBR project
Subject:	Bureau of Reclamation QA/ QC		

The Bureau of Reclamation project, Membrane Bioreactors for Water Reclamation, was begun in March of 1999 and is in progress at the Aqua 2000-Research Center in San Pasqual, California. To ensure the accuracy and integrity of data collected, a number of quality assurance and quality control procedures were followed. These procedures are described in this memorandum and represent the quality assurance and quality control checks for the beginning of the project. A subsequent memo will be drafted at the conclusion of the study.

ON-LINE TURBIDIMETERS

Hach 1720C online turbidimeters were used during testing to acquire MBR permeate turbidities at 1 minute intervals. The following procedures were followed to ensure the integrity and accuracy of this data:

- a primary calibration of the on-line turbidimeters was performed at the beginning of the test period and as needed during testing.
- Aquaview + data acquisition software was used to acquire and store turbidity data. Data was stored to the computer database each minute.
- the manufacturer’s specified acceptable flow range for these turbidimeters is 250 to 750 mL/min. On-line turbidimeter flows were verified manually with a graduated cylinder and stopwatch once per day (5 times per week).
- on-line turbidities were compared to desktop turbidities when turbidity samples were collected.
- Approximately 50ppm free chlorine solution was pumped through turbidity and particle counter sample lines as needed to clean potential buildup from these lines.

ON-LINE PARTICLE COUNTERS

Hach 1900 WPC light blocking particle counters were used to monitor particles in raw and filtrate waters. These counters enumerate particles in the range 2 to 800 microns.

The particle counters were factory calibrated. Factory calibrations took place in June of 1999. The manufacturer recommends factory calibration on a yearly basis. The following procedures were followed to ensure the integrity and accuracy of the on-line particle data collected:

- the Aquaview software was configured to store particle counts in the following size ranges (2-5 um, 5-10um, 10-15um and >15um). NIST traceable monospheres were purchased from Duke Scientific in the following sizes (2um, 4um, 10um and 20um). Duke monospheres were pumped to the constant head flow controller of each particle counter using a peristaltic pump. The same solution was used for each particle counter.

  The following approximate concentration of each monosphere were present:

2um	10,000/mL
4um	1,000/mL
10um	50/mL
20um	10/mL

  A typical response of the particle counters to this monosphere solution is presented in the attached figure. The figure shows the response of each particle counter with particles grouped into the size ranges of interest.

  - flows through the particle counters were maintained at 200+/- 10 mL/min with constant head devices. Flows were verified on a daily (5 times per week) basis with a graduated cylinder and stop watch. Flows were observed to be extremely consistent (typically within 2 mL/min of the target flow rate).
  - 50 ppm free chlorine was run through particle counters for on an as needed basis to to remove potential buildup.

ONSITE LABORATORY DESKTOP TURBIDIMETER

A Hach 2100N desktop turbidimeter was used to perform onsite turbidity analyses of feed and permeate samples. Readings were recorded in non-ratio operating mode. The following quality assurance and quality control procedures were followed to ensure the integrity and accuracy of onsite laboratory turbidity data:

- weekly primary calibration of turbidimeter according to manufacturer's specification.
- daily secondary standard calibration verification. Three secondary standards (approx. 0.8 NTU, 1.8 NTU and 20 NTU) were recorded after primary calibration and on a daily basis for the remaining 6 days until the next primary calibration.

- Proficiency samples with a turbidty of 0.8 NTU were purchased from a commercial supplier. Two of these samples were analyzed during testing with results of 0.74 and 0.80 NTU.

ONSITE LABORATORY pH METER

An Hach EC20 pH/ISE meter was used to conduct routine pH readings at the pilot facility. The following procedures were followed to ensure the quality of the pH data collected:

- Daily (5 times per week) calibration of the pH meter using at least pH 7 and 10 buffers. The slope obtained after calibration was recorded.
- recording of the temperature of the sample when reading sample pH.

ONSITE LABORATORY CONDUCTIVITY METER

Two dedicated Fisher Scientific digital conductivity meters were used to check the conductivity of the MBR permeates and the RO permeate. One meter is used only for MBR permeate samples and calibrated using a conductivity standard of 951µmhos. The other conductivity meter is used for RO permeate and was calibrated using a 9.5 µmhos standard.

MEMBRANE BIOREACTOR THERMOMETERS

All thermometers that are used were verified at a normal operating temperature (25-30°C) using an NIST thermometer. The thermometers used to monitor the temperature of the MBRs were all within 5% error. The thermometers used to measure the RO influent water were also verified and within 5% error.

ONSITE PORTABLE DISSOLVED OXYGEN METER

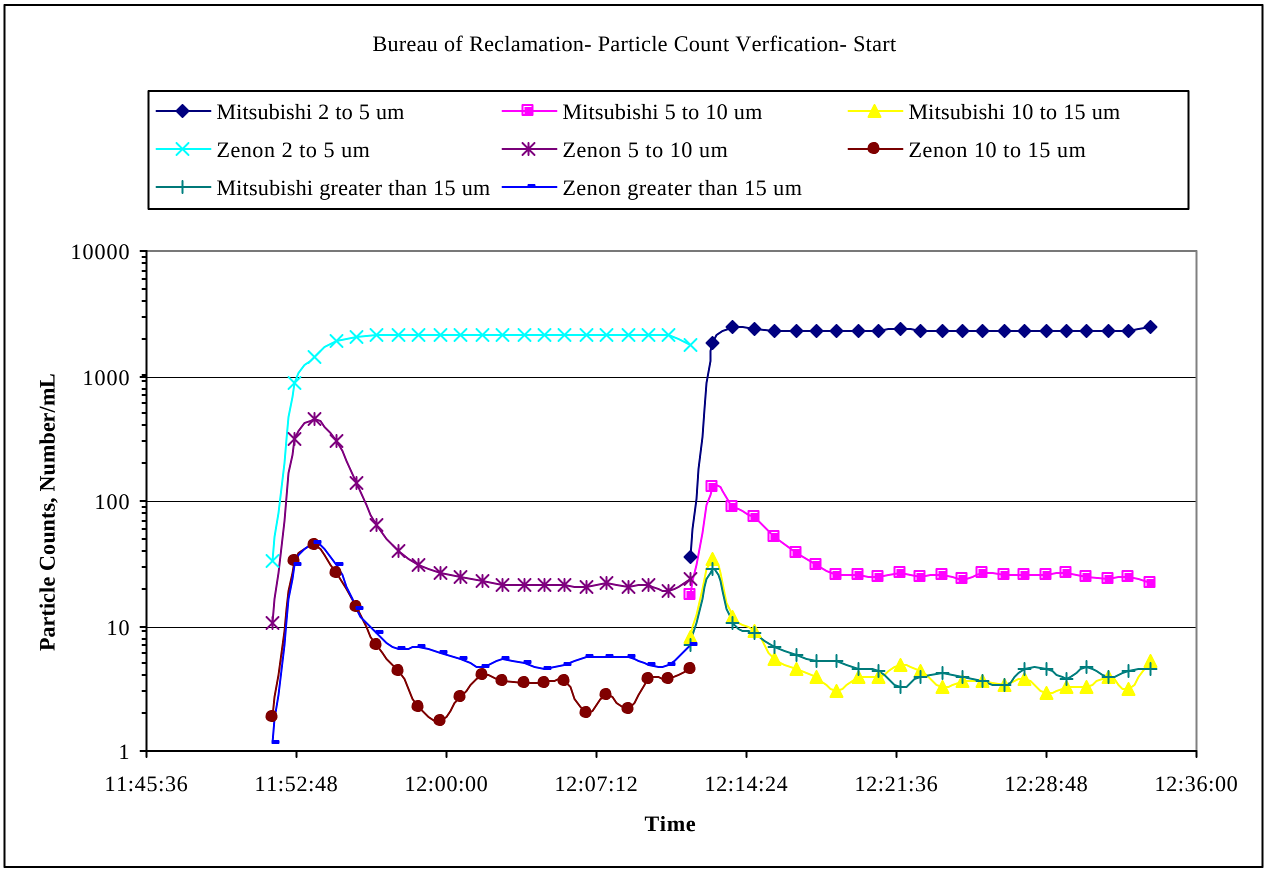
A YSI Model 58 dissolved oxygen meter is used for all DO readings. The DO meter is calibrated before every use according to manufacturer's directions. The membrane and electrolyte solution are replaced as needed.

MEMBRANE SYSTEM PRESSURE GUAGES

Pressure and vacuum gauges supplied with the membrane systems tested were verified against recently purchased grade 3A 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. The vacuum gauge for the Mitsubishi MBR is a pressure transmitter that has been factory calibrated to an accuracy of ±1%. The calibration report from the manufacturer is on file at the Aqua 2000 Research Center. The vacuum gauge for the Zenon system had an average error less than 5 % over the range of normal operating pressures. The pressure gauges for the RO skids were also within 5% error.

MEMBRANE SYSTEM FLOW RATES

Membrane system flow rates were verified volumetrically. The measured flow rate was compared with flows indicated on rotameters. Measured and indicated flow rates agreed to within 5% for both the Zenon MBR permeate and the Mitsubishi MBR permeate. However, it should be noted that the Mitsubishi MBR error was 4.57%. The combined flow rates, concentrate and permeate, of the two RO skids were checked volumetrically and were both within 5% error.


Bureau of Reclamation- Particle Count Verfication- Start
Mitsubishi 2 to 5 um
Mitsubishi 5 to 10 um
Mitsubishi 10 to 15 um
Zenon 2 to 5 um
Zenon 5 to 10 um
Zenon 10 to 15 um
Mitsubishi greater than 15 um
Zenon greater than 15 um
Particle Counts, Number/mL
10000
1000
100
10
1
11:45:36
11:52:48
12:00:00
12:07:12
12:14:24
12:21:36
12:28:48
12:36:00
Time

Aqua 2000

Aqua 2000 Research Center
14103 Highland Valley Road
Escondido, California 92025

Tel: 619 538 8194
Fax: 619 538 8199

To: Samer Adham, Ph.D.
Date: **June 8, 2000**

From: Rion P. Merlo
Reference:

Subject: Bureau of Reclamation QA/ QC

The pilot testing for the Bureau of Reclamation project, Membrane Bioreactors for Water Reclamation, was completed in March of 2000. To ensure the accuracy and integrity of data collected, a number of quality assurance and quality control procedures were followed as described in the previous memo drafted. This memorandum presents the quality assurance and quality control checks performed at the completion of the project.

ON-LINE PARTICLE COUNTERS

The Aquaview software was configured to store particle counts in the following size ranges (2-5 um, 5-10um, 10-15um and >15um). NIST traceable monospheres were purchased from Duke Scientific in the following sizes (2um, 4um, 10um and 20um). Duke monospheres were pumped to the constant head flow controller of each particle counter using a peristaltic pump. The same solution was used for each particle counter.

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MEMBRANE BIOREACTOR THERMOMETERS

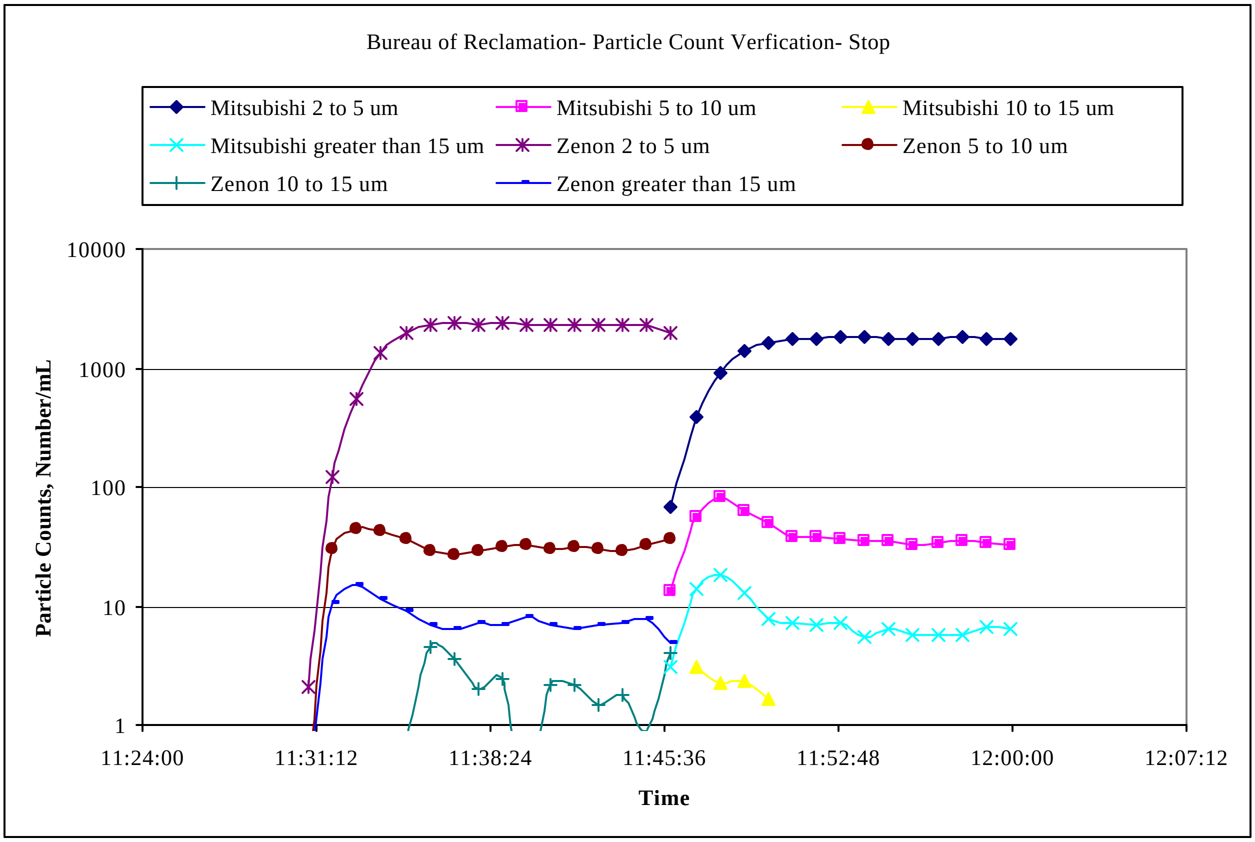
All thermometers that were used were verified at a normal operating temperature (25-30°C) using an NIST thermometer. The thermometers used to monitor the temperature of the MBRs were all within 5% error. The thermometers used to measure the RO influent water were also verified and within 5% error.

MEMBRANE SYSTEM PRESSURE GUAGES

Pressure and vacuum gauges supplied with the membrane systems tested were verified against recently purchased grade 3A 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. The vacuum gauge for the Mitsubishi MBR is a pressure transmitter that has been factory calibrated to an accuracy of ±1%. The calibration report from the manufacturer is on file at the Aqua 2000 Research Center. The vacuum gauge for the Zenon system had an average error less than 8 percent over the range of normal operating pressures. The pressure gauges for the RO skids were also within 5% error.

MEMBRANE SYSTEM FLOW RATES

Membrane system flow rates were verified volumetrically. The measured flow rate was compared with flows indicated on rotameters. Measured and indicated flow rates agreed to within 6% for both the Zenon MBR permeate and the Mitsubishi MBR permeate. The combined flow rates, concentrate and permeate, of the two RO skids were checked volumetrically and were both within 7% error.


Bureau of Reclamation- Particle Count Verfication- Stop
Mitsubishi 2 to 5 um
Mitsubishi 5 to 10 um
Mitsubishi 10 to 15 um
Mitsubishi greater than 15 um
Zenon 2 to 5 um
Zenon 5 to 10 um
Zenon 10 to 15 um
Zenon greater than 15 um
10000
1000
100
10
1
Particle Counts, Number/mL
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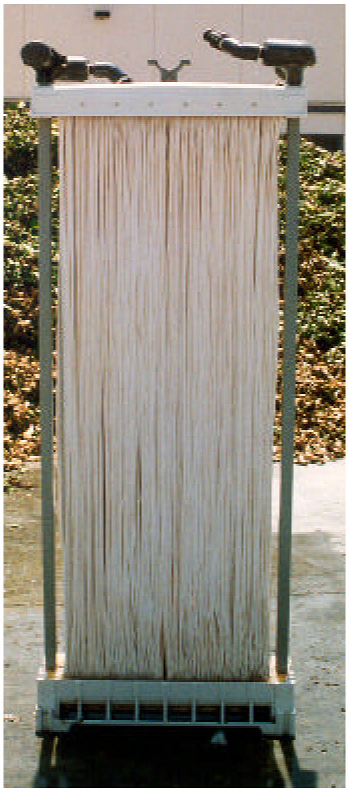
APPENDIX D

Mitsubishi MBR Pilot Unit

Mitsubishi Sterapore HF Microfilter (top view)

Zenon MBR System With Extra Reactors

Zenon MBR Pilot Unit



Zenon OCP Ultrafilter