ADVANCING THE USE OF INTEGRATED MEMBRANE BIOREACTOR-REVERSE OSMOSIS TECHNOLOGY TO RECLAIM WASTERWATER THRU PILOT TESTING

Benjamin Robert Freeman (Nitto Denko/Hydranautics, Oceanside, CA)
Steven Peck, Naomi Drossos, Toshiyuki Kawashima, Rich Franks (Nitto Denko/Hydranautics, Oceanside, CA), Dr. Takanori Itonaga, Yasao Oda (Mitsubishi Rayon Engineering, Toyohashi, Japan)

Abstract

In anticipation of the growing need to recharge local potable water supply (e.g. reservoirs, aquifers) with reuse water, Hydranautics has been working alongside wholesale water suppliers in testing the integration of membrane technologies to produce water that meets drinking water standards.

This paper reviews recent pilot projects conducted in Singapore where reverse osmosis is being used in conjunction with membrane bioreactor (MBR) technology to treat municipal wastewater for industrial processes and indirect potable reuse. MBR technology is capable of producing low TSS effluent suitable for reverse osmosis treatment. Specially-designed, low-fouling, energy-saving reverse osmosis membranes remove dissolved salts and organics from the MBR effluent as well as act as a secondary filter to remove viruses and bacteria.

In Singapore, where water resources are scarce, Hydranautics and Mitsubishi Rayon Engineering (MRE), under a joint venture, Kathyd, are working with the Public Utilities Board (PUB) to provide continued evidence in support of the PUB's NEWater program, in which municipal wastewater, treated with integrated MBR-RO technology, is being reused.

It is well known that a significant portion of membrane bio-reactor (MBR) operating cost comes from membrane air scour. In addition to demonstrating the viability of using MBR effluent as RO influent, the pilot study in Singapore is attempting to reduce MBR operating cost through optimizing membrane air scour intensity.

Additional testing to further support the viability of MBR-RO technology is underway in Las Vegas, Nevada in conjunction with the Southern Nevada Water Authority (SNWA) as part of WateReuse Foundation Tailored Collaboration #08-08.

Introduction

In 1998, the Singapore Public Utilities Board (PUB) and the Singapore Ministry of the Environment and Water Resources (MEWR), jointly started a water reclamation study, called the NEWater Study. The original objective of the NEWater study was to examine the suitability of using NEWater, which is wastewater that has gone through microfiltration, reverse osmosis, and ultraviolet treatment, to supplement Singapore's raw water supply. NEWater is used in different applications including industrial processes and indirect potable water use. Since the start of the NEWater study, four treatment plants have been commissioned and are currently producing NEWater. With the addition of the fifth NEWater treatment plant, 30% of Singapore's water demand will be met by NEWater [1].

Starting in February 2008, Hydranautics and Mitsubishi Rayon Engineering (MRE), under a joint venture, Kathyd, conducted a pilot study with PUB to investigate product water quality of and cost reduction methods for wastewater treated by an integrated membrane bioreactor (MBR) and reverse osmosis (RO) treatment system. The MBR system utilized Hydranautics' HYDRAsub®-MBR membranes, which are the same as Mitsubishi's Sterapore SADF®-MBR membranes. For the duration of this paper, the MBR membranes will be referred to as HYDRAsub®/Sterapore SADF®-MBR membranes. The RO system utilized Hydranautics' ESPA2 membranes.

A membrane bioreactor (MBR) utilizes a combination of activated sludge for biological treatment and membrane filtration for separation of solids. It is widely known that the main operating cost for a MBR is the energy consumption of aeration equipment to supply oxygen to the biological system for treatment of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) and to supply air to the membrane filtration system to create a scour effect on the membranes. This paper focuses on methods to decrease the overall aeration demand through flux optimization and reduction in membrane aeration intensity.

Materials and Methods

Pilot System Description

During testing, the feed water to the pilot system was effluent from the primary clarifier at the Bedok Water Reclamation Plant (WRP), located in Singapore. The Bedok WRP treats mostly municipal wastewater. Primary clarifier effluent was screened before entering the anoxic tank of the MBR pilot system. Screened primary clarifier effluent shall be referred to as MBR influent for the remainder of this document. Water quality for the MBR influent is given in Table 1.

Table 1: MBR Influent Water Quality

	BOD_5	COD	TOC	TSS	T-N	TKN	NH_4-N	T-P	Total Coliform Count	pH
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	cfu/100ml	-
AVG.	160	358	93	89	53	51	48	10	1.7E+07	7
MIN.	116	267	57.9	55	40.3	38.3	37.4	7.66	1.0E+05	6.8
MAX.	179	402	113	114	70	67.9	67.6	13.5	4.6E+07	7.4

The pilot system design was based on the Modified Ludzack-Ettinger (MLE) process for nitrogen removal, as shown in Figure 1. MBR influent was combined with return activated sludge (RAS) in the anoxic tank. The return activated sludge (RAS) contained nitrate and nitrite, which was mostly formed in the aeration tank. Nitrate and nitrite was converted to nitrogen gas (N_2) by heterotrophic bacteria, called denitrifiers, in the anoxic tank. The anoxic tank was equipped with a submersible mixer to keep the suspended solids well mixed. The activated sludge then overflowed to the aerobic tank, where heterotrophic bacteria, which use organic compounds as carbon sources, converted BOD to new bacterial cells and carbon dioxide in the presence of oxygen. Also in the aerobic tank, autotrophic bacteria, which use carbon dioxide as a carbon source, oxidized ammonia (NH_4^+) to nitrite (NO_2^-) and then to nitrate (NO_3^-) in the presence of oxygen. Following aerobic treatment, the mixed liquor overflowed to the membrane tank, where the membrane was used for liquid-solid separation. The separated suspended solids remained in the mixed liquor and continued to recirculate throughout the system, returning from the membrane tank to the anoxic tank.

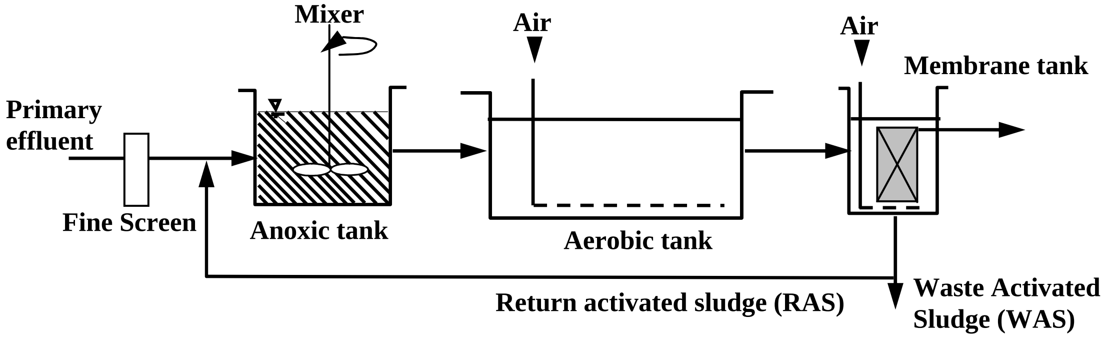

Figure 1: MBR Pilot System Flow Diagram

Specifications for the HYDRAsub®/Sterapore SADF®-MBR membranes utilized in the MBR system are listed in Table 2.

Table 2: MBR Module Specifications

Module Type	HYDRAsub®/Sterapore SADF®
Module Surface Area (m^2)	375
Element Surface Area (m^2)	25
Number of Elements	15
Membrane Material	Supported Polyvinylidene Flouride (PVDF)
Pore Size (µm)	0.4
Fiber Outer Diameter (mm)	2.8
Filtration Mode	Outside-In

MBR effluent, or filtrate, was collected in a tank, which served as the feed source for the RO system. As indicated by Figure 2, the RO system utilized six Hydranautics' ESPA2 4040 elements in a 2 x 1 array. Choloramines and anti-scalant were dosed continuously to prevent biofouling and scale formation of the RO elements.

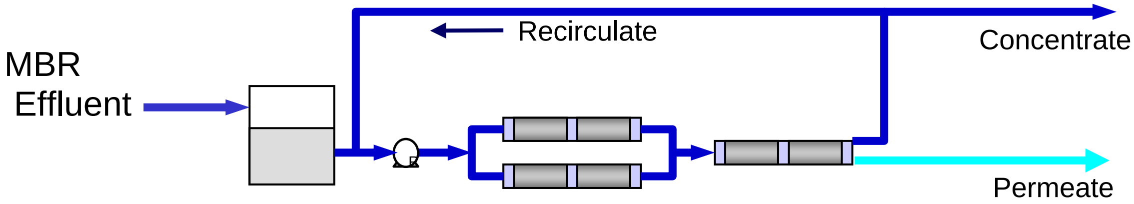

Figure 2: RO Pilot System Flow Diagram

Specifications for the ESPA2 membranes utilized in the RO system are listed in Table 3.

Table 3: RO Membrane Specifications

Element Type	Nitto Denko/Hydranautics ESPA2-4040
Material	Composite polyamide
Salt rejection (%)	99.6
Size (inches)	4
Number	6
Array	2 x 1

Operating Parameters

Pilot testing for the MBR was separated into 4 Phases, as shown in Table 4. The first phase was the startup phase. During the startup phase, the mixed liquor suspended solids (MLSS) concentration of the seeding sludge was about 1000 mg/L. The membrane flux during Phase 1 was set in order to maintain a Food to Microorganism (F:M) ratio approximately equal to 0.1 kg BOD/kg MLSS/day. The flux set points in Phases 2-4 were based on membrane performance.

Table 4: MBR Pilot Operating Parameters

	Phase 1	**Phase 2**	**Phase 3**	**Phase 4**
Duration (days)	0-49	50-66	67-110	111-165
Net Flux (LMH)	13-33	25	33	38-40
HRT (hours)	6-14	8	6	3
MLSS (mg/L)	1000-9000	6000-8000		
RAS (Q)	2-5	2		
Aerobic Tank Dissolved Oxygen (mg/L)	1~2			

The RO pilot system operated at a constant flux of 20.8 LMH and a recovery of 75% for the duration of the pilot study. The feed to the system was typically 23 L/min.

MBR Operating Sequence

Throughout testing, the MBR membrane system had three operational modes: filtration, relaxation, and chemically enhanced backwash. During filtration and relaxation, coarse bubbles, generated by a diffuser below the membranes, continuously rise through the membrane fiber bundles, creating a scouring effect which limits the amount of solids deposition on the outer membrane surface. During the relaxation step, filtration stops while coarse air bubbles continue to create a scouring effect to remove extraneous particulate matter from the feed side of the membrane which may have been accumulated during filtration. During operation, some accumulated particulate matter (or foulants) on the membrane and in the pores may not be removed by the relaxation step. To remove this portion of foulants, a weekly chemically enhanced backwash is utilized.

Analytical Methods

MBR Performance Analysis

The filtrate flux can be calculated as the volume of filtrate produced per unit time per membrane surface area. The flux at which a MBR membrane system can stably operate will contribute to the capital and operating cost of a system. The membrane flux will determine the amount of membrane required to meet the flow requirements of a project and will establish the size of the membrane tank. The membrane flux will also affect the operating cost through energy consumption, as shown by Equation 1 and Equation 2, and chemical consumption.

The transmembrane pressure, or TMP, is the main measurement used to determine membrane fouling. The rate of increase of TMP determines the maximum flux of the membranes. TMP can be calculated by subtracting the pressure on the filtrate side of the membrane from the pressure on the feed side of the membrane (with a correction for the elevation difference between the pressure gauge and the average membrane tank water level).

Membrane performance is also determined by the filtrate turbidity and total suspended solids (TSS). Filtrate turbidity was measured using a Hach FilterTrak660 Laser Turbidimeter.

MBR Energy Consumption

The specific energy demand for the entire MBR can be described as shown in Equation 1. A meter on the power supply to the MBR system was used to monitor the energy consumption of all associated equipment (including all pumps, blowers, instrumentation, mixers, automatic screen, etc.).

$$\text{Specific Energy Demand}_{\text{MBR}} = \frac{\text{Power consumption of all equipment (blowers, pumps, mixers, etc.)}}{\text{Volume of treated water}}$$

Equation 1

As mentioned above, the majority of the energy requirement in an MBR system comes from the biological aeration and the membrane scour aeration. The amount of aeration required by the biological system is dependent upon the MLSS, oxygen transfer efficiency (OTE), and the strength of various constituents in the wastewater, such as

BOD/COD, ammonia, etc., which will vary throughout the day and month due to normal peaking experienced at municipal wastewater treatment plants. Although the flow rate to the MBR pilot was held constant in each Phase (except Phase 1), the concentrations of the various constituents in the MBR influent changed as the feed water quality to the Bedok WRP changed. In order to ensure that the effluent water quality was maintained, the dissolved oxygen in the aeration tank was maintained at approximately between 1-2 mg/L. As a result of the varying MLSS, OTE, and feed water quality, the biological aeration demand varied throughout the day and month. Because there is no way to control the feed water quality, it is difficult to control the energy demand of the biological system.

However, the membrane aeration requirement is determined by the membrane manufacturer to maintain flux and to minimize the fouling rate of the membranes. Therefore, the membrane aeration flow rate can be easily controlled. Equation 2 was used to quantify the specific aeration demand of the membrane system only (SAD_P).

$$SAD_P = \frac{\text{Membrane Aeration Volume}}{\text{Volume of Treated Water}} = \frac{\text{Membrane Aeration Volume}}{\text{Flux} * \text{Membrane Area}}, \left(\frac{m^3 \text{air}}{m^3 \text{filtrate}} \right)$$

Equation 2

Biological System Performance Analysis

Samples of the MBR influent and effluent were sent to an outside lab to measure total organic carbon (TOC), biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammonia (NH4), total nitrogen (TN), and total phosphorus (TP) using Standard Methods [2].

RO Performance Analysis

Normalized permeability and operating pressure were recorded to quantify the performance of the RO membranes.

To verify the suitability of the ESPA2 permeate for water reuse, samples were analyzed by an outside lab using Standard Methods [2] for conductivity, total dissolved solids (TDS), TOC, chlorine, sulfate (SO4), aluminum (Al), calcium (Ca), iron (Fe), and manganese (Mn).

Results

MBR Performance

Figure 3 below displays the specific aeration demand of the membrane system, MLSS in the membrane tank, net flux, TMP, and specific energy demand of the entire MBR system. Table 4 describes the net flux set points for each Phase of testing. Because the TMP, which is represented by green triangles in Figure 3, remained fairly constant at approximately 11-13 kPa during Phase 2, the flux was increased and the membrane aeration intensity was decreased in Phase 3. In the final 10 days of Phase 3, the membrane aeration intensity was again decreased because of stable TMP. The TMP remained constant between 12-15 kPa throughout Phase 3, so the flux was again increased in Phase 4. As a result of these changes, the SAD_p was highest in Phase 2, lowest in Phase 4 and decreased in each phase of the testing.

In general, the specific energy demand of the entire MBR system, which is represented by the gray diamonds in Figure 3, followed the SAD_p trend, but not exactly. The specific energy demand was highest in Phase 2, when the flux was the lowest and the membrane aeration intensity was the highest. However, the specific energy demand of the MBR was lowest at the end of Phase 3 (0.57 kWh/m^3 filtrate). As defined by Equation 1, the specific energy demand is dependent upon all MBR equipment. Therefore, although the flux is highest and the membrane aeration is lowest in Phase 4, the specific energy demand of the remaining MBR equipment must have been higher, resulting in approximately the same MBR system specific energy demand as in Phases 3.

The MLSS is also shown on Figure 3. For Phases 3 and 4, the specific energy demand generally follows the MLSS. This may be a result of the changes in oxygen transfer efficiency (OTE) at varying MLSS concentrations. As MLSS increases, the viscosity of the activated sludge also increases, and the OTE decreases. Therefore, more air must be supplied to the biological system to maintain a DO between 1-2 mg/L in the aerobic tank. The average viscosity during Phase 3 was 20.8 cP and 23.2 cP in Phase 4. The F:M ratio may also be the reason for similar specific energy demand in Phases 3 and 4. As shown in Table 4, the average F:M ratio in Phase 3 was 0.11 kg_{BOD}/kg_{MLSS}/day and 0.14 kg_{BOD}/kg_{MLSS}/day in Phase 4. Therefore, although the flux was higher in Phase 4, the BOD load was also higher, which required more energy for biological aeration. Finally, although of lesser significance, the RAS and permeate pumps required more energy due to the higher flow rates required in Phase 4.

As shown in light blue on the graph, the temperature remained slightly less than 30° C for the majority of testing.

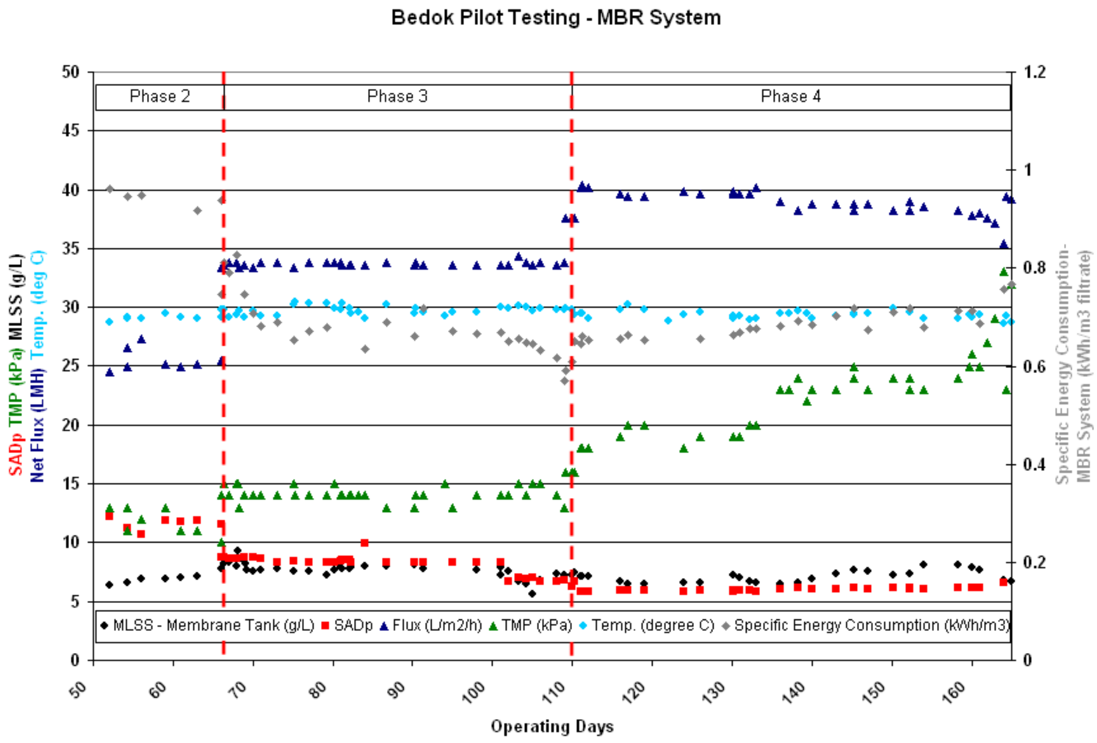

Figure 3: MBR Energy Consumption, Flux, SAD$_p$, and Net Flux

Table 5 below summarizes the MBR influent and effluent water quality. In all samples analyzed, the effluent levels of BOD, TSS, and Total Coliform Count were below the minimum detection limits (MDL) of 2 mg/L, 10 mg/L, and 1 cfu/100 mL, respectively. Consistent filtrate turbidity less than 0.1 NTU indicates that no damage occurred to the membranes.

Table 5: MBR Influent and Effluent Water Quality

	Phase 2		**Phase 3**		**Phase 4**	
	F:M Ratio = 0.09		F:M Ratio = 0.11		F:M Ratio = 0.14	
	Influent	**Effluent**	**Influent**	**Effluent**	**Influent**	**Effluent**
SS, mg/L	70.0	< 10	74.7	< 10	79.4	< 10
TOC, mg/L	76.5	6.2	88.1	4.9	89.6	4.9
COD, mg/L	308.5	14.4	323.6	24.0	347.9	17.9
BOD, mg/L	167.0	< 2	144.7	< 2	156.3	< 2
Total Nitrogen, mg/L	51.2	13.3	47.3	12.6	51.7	12.7
Ammonia, mg/L	46	0.9	42	0.8	48	0.3
Total Phosphorus, mg/L	10.0	7.5	8.8	3.0	9.8	3.2
Total Coliforms, cfu/100mL	1.7x107	< 1	1.9x107	< 1	1.2x107	< 1
Turbidity (NTU)	-	< 0.1	-	< 0.1	-	< 0.1

RO Performance

Figure 4 below displays the A value (normalized flux/net driving pressure), temperature, and feed conductivity for the RO system. In the middle of August, the antiscalant dosing pump failed. Apart from this mechanical failure and a spike in the feed conductivity in the middle of November, the ESPA2 membranes maintained an A value of slightly more than 0.6 throughout testing. The feed pressure was 0.65 to 0.67 MPa over a temperature range of 29.9 to 32.3 °C. The results indicate that the RO membrane permeability was stable for 165 days of operation without CIP.

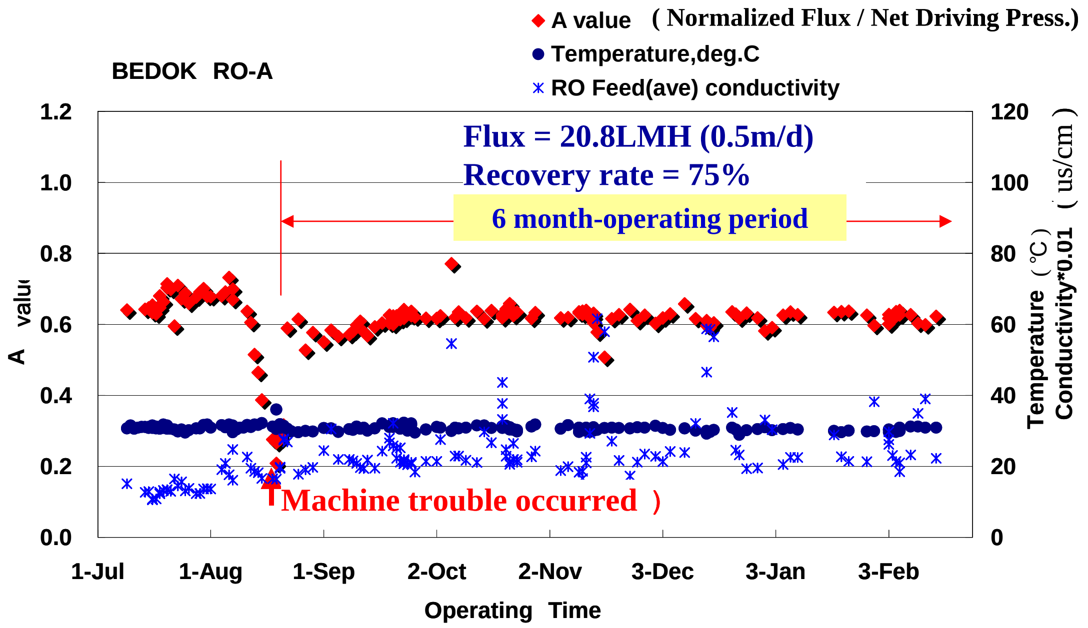

Figure 4: RO Permeability and Feed Water Conductivity

Figure 5 displays the TOC rejection for the RO for the testing period. The rejection rate varied between 99.5% and 99.9%. The rejection is shown in red and the TOC concentration is shown in blue.

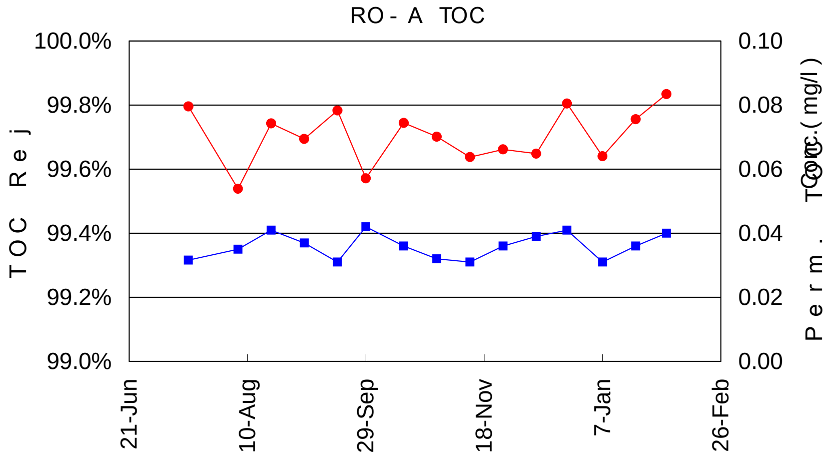

Figure 5: RO TOC Rejection

Table 6 shows the water quality results for the RO permeate. The RO permeate water quality met the Singapore PUB NEWater quality requirements throughout testing [1].

Table 6: RO Permeate Quality

	RO Permeate	**NEWater Requirement**
Conductivity (mS/cm)	23.6	< 250
TDS (mg/L)	13.7	< 150
TOC (mg/L)	0.036	< 0.5
Cl (mg/L)	0.87	< 20
SO_4 (mg/L)	< 0.1	< 5
AL (mg/L)	< 0.015	< 0.1
Ca (mg/L)	< 0.01	4 - 20
Fe (mg/L)	< 0.02	< 0.04
Mn (mg/L)	< 0.0009	< 0.05

Conclusions

MBR-RO pilot testing conducted by Hydranautics and MRE, under the joint venture, Kathyd, in cooperation with Singapore PUB, provided strong evidence in support of the applicability of integrated membrane solutions for wastewater reuse. Low fouling rates at high fluxes were observed for both HYDRAsub®/ Sterapore SADF®- MBR membranes and ESPA2- RO membranes.

HYDRAsub®/ Sterapore SADF®- MBR membranes operated under constant net flux of 33 LMH suffered no irreversible fouling, as indicated by constant TMP. The MBR membranes were able to sustain a net flux of 40 LMH for over 50 days before requiring a chemical clean in place. The minimum specific energy demand of the MBR pilot of 0.57 kWh/m^3 filtrate was achieved through sustainable high flux operation and decreased membrane aeration intensity. In full scale applications, with more efficient equipment than was available for the pilot testing, it is believed that lower specific energy demand can be achieved. MBR filtrate turbidity averaged 0.1 NTU and the filtrate TSS was below the minimum detection limit of 10 mg/L for the duration of the test, which made it well-suited for RO treatment.

Hydranautics' ESPA2®- RO membranes in the MBR-RO system demonstrated stable performance at a flux of 20.8 LMH without the need for a CIP for over 5 months of continuous operation. The RO permeate quality was well below the Singapore PUB NEWater requirements, demonstrating that the combination of MBR-RO is capable of producing high-quality water that meets the requirements for reuse.

Further testing in Singapore with PUB and in Las Vegas, NV with SNWA is being conducted to continue to minimize the energy consumption of the MBR system and to provide more support to the viability of MBR-RO integrated membrane solutions for wastewater reuse.

References

[1] Public Utilities Board of Singapore, Internet: www.pub.gov.sg/newater, 2008.

[2] American Public Health Association (APHA) (1998) *Standard Methods for the Examination of Water and Wastewater Methods,* 20th ed.; APHA, Washington, D.C.