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# Pilot study for reclamation of the secondary effluent at Changi water reclamation plant

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ABSTRACT

The objective of this study was to use an ultrafiltration (UF)-reverse osmosis (RO) pilot plant to assess the RO permeate quality using the secondary effluent as feedstock on a continuous basis at Changi Water Reclamation Plant (CWRP) in Singapore. Pilot trials were conducted over three months. The RO plant was in 2:1 configuration with two stages and was operated at 75% recovery during the study. The RO plant was also operated at different membrane fluxes to study the effect of RO membrane flux on permeate quality. An on-line total organic carbon (TOC) analyzer was installed to monitor the TOC of RO permeate. The results of the pilot study showed that TOC of RO permeate with G3 effluent as raw feed generally ranged from 65 to 95 μg/L at membrane flux of 8.5 L/m$^2$/h (LMH) or 5 gallon/ft$^2$/day (gfd). TOC of RO permeate at 17 LMH or 10 gfd was 45–60 μg/L which was about 30% lower than that at 8.5 LMH on the same days. Feed conductivity normally varied between 600 and 850 μS/cm and was around 1000 μS/cm during the week of 8–12 March 2008. Permeate conductivity was less than 40 μS/cm, most of time. It was concluded that most parameters of RO permeate met the requirement of NEWater quality. UF cleaning regime was generally effective to recover the membrane flux and the selected anti-scalant F for RO process was potentially suitable for the specific wastewater containing fluoride.

***Keywords**:* Secondary effluent; Reclamation; Reverse osmosis; Total organic carbon; NEWater

## 1. Introduction

A dual membrane microfiltration (MF) or UF-RO process has become increasingly attractive for the reclamation of municipal wastewater [1–17] since it was demonstrated at Water Factory 21 as it is highly efficient, easy and economical to operate. Kim et al. [1,2] tried to treat a secondary effluent generated from a mixed domestic and industrial sewage wastewater using a UF-RO process in laboratory. A challenge was faced in their study because the RO membrane showed an unsatisfied performance on conductivity and TOC rejections of 81–89% and 70–80%, respectively. Pino and Durham conducted pilot MF-RO studies to treat an effluent from municipal wastewater treatment plant for irrigation. They reported that rejections of conductivity, TOC and ammonium in the RO process were 95%, 91% and 91% in average, respectively [3].

After a successful demonstration for production of High Grade Water (so-called NEWater) from the secondary treated domestic sewage effluent [4], four factories with the total capacity of over 200,000 m$^3$/day have been commenced to supply NEWater to the wafer fab industry, cooling towers and indirect potable use in Singapore [5]. NEWater is one of four national water taps in Singapore. The current NEWater

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factories use UF/MF followed by RO and UV to treat the final effluent at different Water Reclamation Plants (WRP) where the source used water is predominantly of domestic nature with little industrial used water (trade effluent). As NEWater demand increases, the fifth NEWater factory is being built at Changi WRP. The used water is from catchments with more industries. There was need to check the feedstock for the suitability for NEWater production in particular with respect to TOC and the fluoride and ammonium contaminants in the RO permeate.

To assess this, there was a need to characterize the trade effluent in Changi WRP catchment in terms of the substances of concern for NEWater production, particularly in TOC. This required a sampling protocol. However, any sampling protocol can only provide snapshots of the water quality, and may miss some substances of concern. For a rigorous identification of such substances, a study with a pilot UF-RO plant similar to the NEWater process with water quality analysis along the whole flow stream—from trade effluent samples at factories, strategic manholes, influent and effluent samples at the WRP and pilot plant samples—was conducted. The pilot plant treated the final effluent and RO permeate water quality was monitored for on-line TOC and conductivity. The data obtained from the pilot study was used to a part of an integrated database which would be build-up to service NEWater production.

## 2. Materials and methods

### 2.1. Pilot system description

A combination of UF and RO pilot plants was used in this study. Schematic diagrams of the UF and RO pilot plant are shown in Figs. 1 and 2 [10], respectively.

For the UF plant as shown in Fig. 1, the process was as follows. The feed went through a multimedia filter (MMF). Then the filtrate passed a 100-μm bag filter and UF modules. After that, the UF permeate was collected in the product tank. NaClO was dosed before MMF. Eight newly purchased polyacrylnitrile hollow fiber modules (KOCH UF Membranes, MWCO: 50,000 Da, Model: HF66-45-XM50 P) were used for the study. Dosage of NaClO to backwash of UF had been added to control biofouling of the UF membranes. The UF plant was operated in a cross flow mode and its capacity was 2.4–3.0 $m^3/h$ depending on the quality of the secondary effluent. For the RO plant as shown in Fig. 2, 18 of 4-inch polyamide RO membrane elements were used. The RO plant was in 2:1 configuration with two stages and was operated at 75% recovery during the study. The capacity of the RO plant could be 2.4 $m^3/h$ at the membrane flux of 17 LMH. However, unless specified elsewhere, it was operated at 8.5 LMH due to the limited output of UF. Anti-scalant F, an aqueous solution of a specialized polycarboxylic acid, was continuously dosed to the RO feed line to control scaling in RO plant during the plant operation.

### 2.2. Pilot trials

The pilot plant was operated with the secondary effluent as the raw feed from one of the modules (named as G3) at CWRP in Singapore. The raw feed flow rate to MMF was 4–5 $m^3/h$ while the UF feed flow rate was less at 3–4 $m^3/h$. MMF was automatically backwashed once per day over 20 min while UF backwash interval was 30 min and the backwash duration was 2 min. UF system recovery was 75–80% and trans-membrane pressure (TMP) of UF membranes ranged of 14–26 psi. To ensure a constant 75% recovery, RO feed and permeate flow rates were remained at 1.6 and 1.2 $m^3/h$, respectively

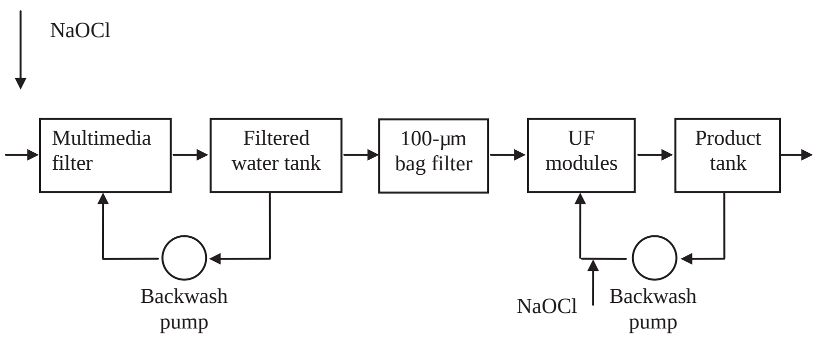


Fig. 1. Schematic diagram of the UF pilot plant.

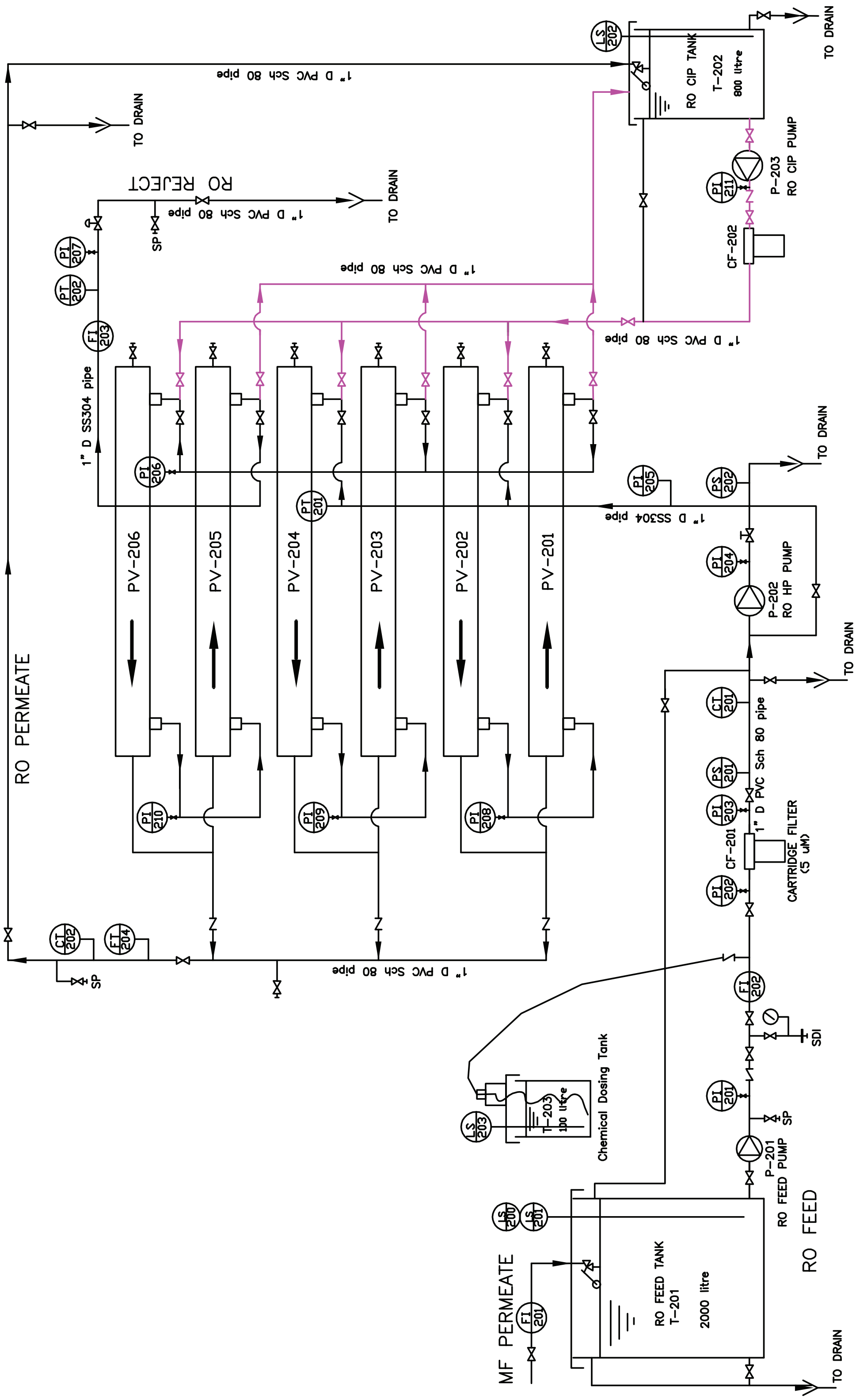


Fig. 2. P&ID of the RO pilot plant.

Table 1
Operating conditions of the pilot system.

| Parameters | Unit | Values |
|---|---|---|
| Raw feed to MMF | ($m^3$/h) | 4–5 |
| Hypo dosage to raw feed | (mg/L) | 3.5–4 |
| UF feed flow | ($m^3$/h) | 3.0–4.0 |
| UF permeate flow | ($m^3$/h) | 2.4–3.0 |
| UF recovery | (%) | 75–80 |
| Average TMP of UF | (psi) | 14–26 |
| RO feed flow | ($m^3$/h) | 1.6 |
| RO permeate flow | ($m^3$/h) | 1.2 |
| RO recovery | (%) | 75 |
| Dosage of antiscalant F | (mg/L) | 6.5 |

while operating pressure was adjusted. The antiscalant dosage was constant at 6.5 mg/L . The general operating conditions of the pilot system during the study are summarized in Table 1.

The RO plant was operated once a week at 10 gfd over 1 h for sampling purpose after 13 Feb 2008 to study the RO permeate quality at a realistic RO flux in NEWater production.

Cleaning-in-place (CIP) on UF membranes was conducted with Koch liquid *detergent* (a proprietary alkaline surfactant) and 200 mg/L NaClO at pH 10. No CIP on RO membranes was carried out during the period of this study.

### *2.3. Sample analysis*

During the continuous operation of the pilot plant over three months, RO feed and filtrate samples were collected twice per week for full analysis of water quality. An on-line TOC analyser was installed to monitor the quality of RO permeate. Other process parameters measured were RO feed flow rate, RO permeate flow rate, pressure of RO feed and concentrate. All the parameters as well as on-line conductivity of RO feed and permeate were recorded.

Turbidity was measured according to APHA 2130B. Cation analysis was performed according to APHA 3120B using a Perkin Elmer model DB3000 Inductively Coupled Plasma Emission Spectrometer. Ammonium analysis followed APHA 4500N standard method. Anion was analyzed using a Dionex DX-120 Ion Chromatograph following APHA 4110B standard. TOC measurements were done as per APHA 5310B standard. On-line TOC was monitored using a portable TOC analyzer model 820. Analysis of silica followed APHA 4500-Si C standard. Total alkalinity and total trihalomethanes were analyzed according to APHA 2320B and USEPA 8260 B standard.

Membrane performance refers to the normalized flux as defined in equation (1):

$$\text{Normalized flux} = Q/(A \times \Delta p) \quad (1)$$

where $Q$ is volume flow rate of permeate (L/h), A is effective membrane area (m2), $\Delta P$ is transmembrane pressure (MPa) which is the average of feed and reject pressure minus permeate pressure.

Membrane performance in terms of the percentage rejection of a particular component is defined as per equation (2):

$$\text{Rejection} = (1 - C_p/C_f) \times 100\% \quad (2)$$

where $C_f$ and $C_p$ are the component concentration in the feed and permeate, respectively.

## 3. Results and discussion

### *3.1. TOC of RO permeate*

The daily recorded on-line TOC of RO permeate as a function of time during the study is shown in Fig. 3. It can be seen that TOC was high up to 245 µg/L (ppb) at the beginning of January (which could be due to illegal

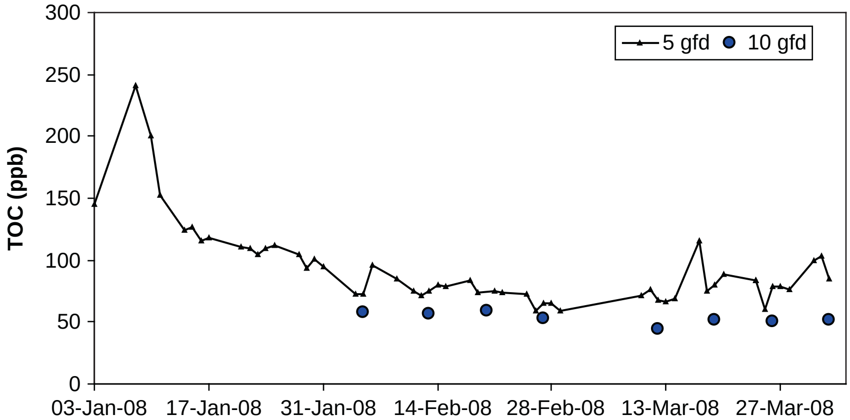


Fig. 3. RO permeate TOC versus time.

discharge to sewage) then gradually decreased to below 100 μg/L in February 2008. After that, most of the time, the RO permeate TOC was in the range of 65–95 μg/L. It should be pointed out that on-line TOC of RO permeate at 10 gfd had been recorded weekly (when samples for analysis were taken) since 13 Feb 2008, which are shown by solid circles. TOC of RO permeate at 10 gfd was 45–60 μg/L which was about 30% lower than that at 5 gfd on the same days.

### 3.2. Conductivity of RO feed and permeate

On-line conductivity of RO feed and permeate as a function of time during the study is shown in Figs. 4 and 5. It should be pointed out that thick lines are real data and other dots are stray data caused by disturbed signals. Feed conductivity normally varied between 600 and 850 μS/cm and was around 1000 μS/cm during the week of 8–12 March 2008, which was most probably because more upstream catchments from industry were diverted to CWRP. Permeate conductivity was in the range of 40–65 μS/cm before mid Jan 2008 and was 25–40 μS/cm from mid Jan to mid Mar 2008. Fluctuation of permeate conductivity after mid Mar 2008 was mainly due to unstable RO operation caused by the fiber breakage of UF membranes.

### 3.3. Quality of RO feed and permeate

Table 2 shows the quality of RO feed with ten data points and permeate (at 10 gfd) with eight data points during the study with G3 second effluent as raw feed.

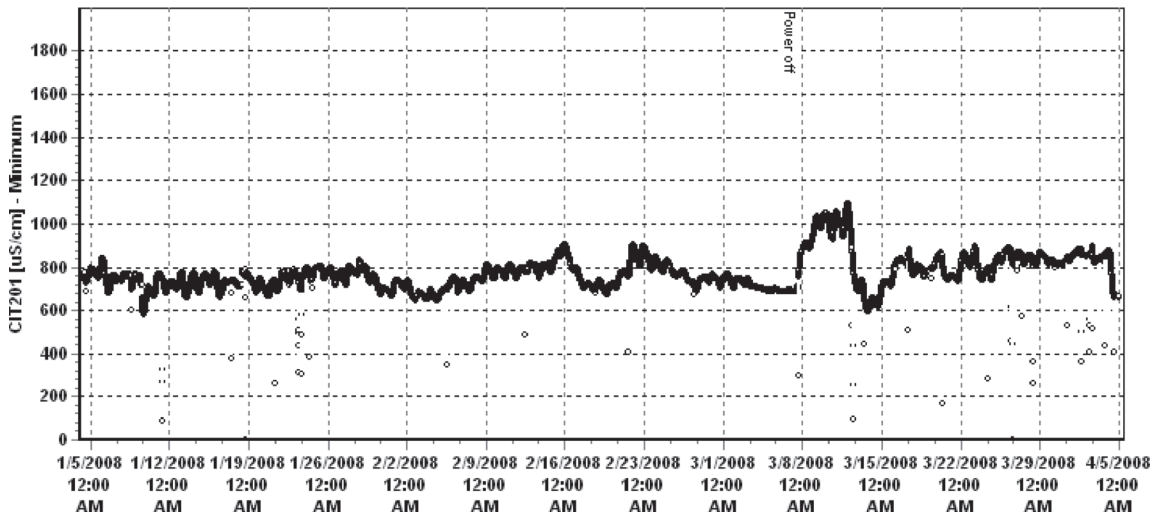


Fig. 4. Conductivity of RO feed versus time.

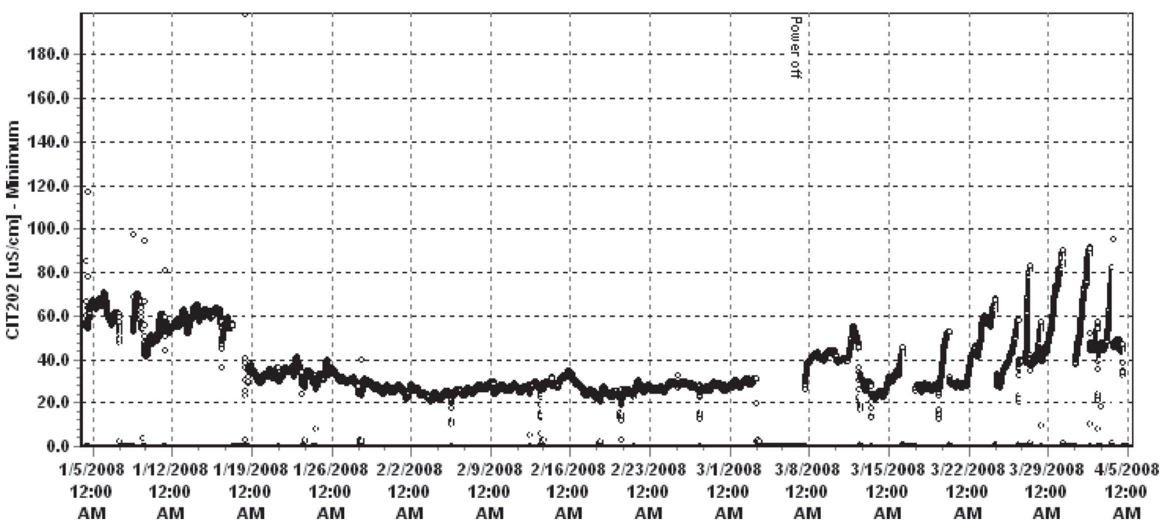


Fig. 5. Conductivity of RO permeate versus time.

Table 2
Quality of RO feed and permeate (G3 second effluent as the raw feed).

| Parameter | RO feed | RO permeate | NEWater |
|---|---|---|---|
| Aluminium | 0.02–0.16 | <0.02 | <0.1 |
| Ammonium as N | 1.4–32 | 0.08–1.5 | <1.0 |
| Barium | 0.004–0.006 | <0.003 | <0.1 |
| Boron | 0.05–0.16 | 0.02–0.04 | <0.5 |
| Calcium | 19–23 | 0.02–0.03 | 4–20 |
| Chloride | 87–138 | 0.42–1.7 | <20 |
| Conductivity (μS/cm) | 659–918 | 15–21 | <250 |
| Copper | NA | <0.002 | <0.05 |
| Fluoride | 3.5–5.2 | 0.08–0.2 | <0.5 |
| Iron | 0.04–0.07 | <0.003 | <0.04 |
| Manganese | NA | <0.002 | <0.05 |
| Magnesium | 3.4–6.0 | 0.005–0.03 | – |
| Nitrate | 0.62–4.87 | 0.09–0.22 | <15 |
| pH | 6.8–7.3 | 6.1–6.6 | 7.0–8.5 |
| Ortho phosphate (as $PO_4$) | 4.5–24 | – | – |
| Potassium | 12–16 | 0.1–0.48 | – |
| Silica as $SiO_2$ | 10–12 | <0.1 | <3.0 |
| Sodium | 69–168 | 2.0–6.9 | <20 |
| Strontium | 0.05–0.08 | <0.01 | <0.1 |
| Sulphate | 52–74 | 0.05–0.06 | <5 |
| TDS | 335–404 | 1–11 | <150 |
| TOC | 6.2–8.6 | 0.044–0.073** | <0.5 |
| Total alkalinity as $CaCO_3$ | 76–141 | 6–12 | – |
| Total hardness as $CaCO_3$ | – | <1 | <50 |
| Total THMs (μg/L) | – | <20 | <80 |
| Turbidity (NTU) | 0.1–0.3 | <0.1 | <2 |
| Zinc | 0.01–0.05 | <0.005 | <0.1 |

*All units are in mg/L unless specified.
**On-line data.

RO feed quality was well within the standard limits for most parameters. But, spikes of ammonium ranged of 17–32 mg/L in the feed could be major concern for the wafer fab industry. Ortho-phosphate of 24 mg/L and fluoride of 5.2 mg/L could be the other concerns for RO fouling.

Fig. 6 illustrates RO feed quality in terms of fluoride, nitrate, TOC and ammonium as a function of time during the study. Fluoride and TOC concentrations in RO feed were stable. However, ammonium concentration fluctuated in a wide range of 1.7–31 mg/L (as ammonia), indicating the nitrification process at WRP was not stable yet while nitrate concentration was low during the same period. As a result, RO permeate quality was in general within the limit of NEWater quality, however, ammonium may be a concern if the nitrification process at WRP is incomplete.

### 3.4. Effect of membrane flux on RO rejection

Rejections of the RO membranes at different fluxes were calculated from the analytical results of RO feed and permeate and compared in Table 3. For those parameters in permeate showing low detected limits, rejections are not compared. It can be seen that RO rejections at 10 gfd were in general improved compared to that at 5 gfd. This could be explained as follows. Concentration of solutes in the permeate was lower (or better quality of RO permeate was produced) at a higher water flux while the concentration of solutes in the feed was same for both fluxes as shown in Table 3. Especially, the rejections on ammonium, conductivity, fluoride, nitrate and TOC were more than 96%, 97%, 98%, 97% and 99%, respectively, indicating the separation performance of the RO membranes are satisfied.

### 3.5. Normalized fluxes of UF and RO

Fig. 7 illustrates the normalized flux of UF membranes as a function of time during the study. The flux was in the range of 20–40 LMH, most of the time. When few fibers in the UF modules were broken, off-line cleanings (indicated as 'clean') were conducted together with the repair of modules by the supplier. Immediately after cleaning,

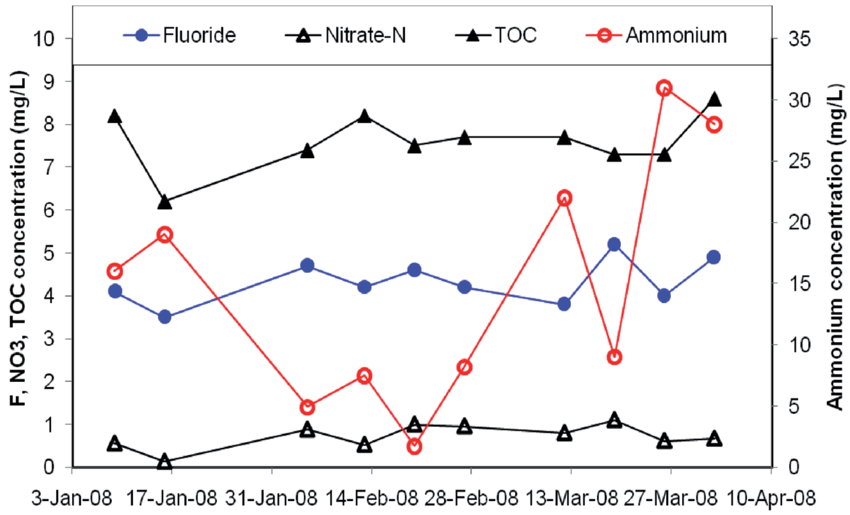


Fig. 6. RO feed quality vs. time.

Table 3
Rejection of the RO membranes at different fluxes.

| Parameter | Feed (mg/L) | Permeate at 5 gfd (mg/L) | Permeate at 10 gfd (mg/L) | Rejection at 5 gfd (%) | Rejection at 10 gfd (%) |
|---|---|---|---|---|---|
| **Ammonium as N** | 3.1 | 0.13 | 0.12 | 95.8 | 96.1 |
| Calcium | 20 | 0.04 | 0.02 | 99.8 | 99.9 |
| Chloride | 120 | 1.1 | 0.48 | 99.1 | 99.6 |
| **Conductivity** | 900 | 35.1 | 19.8 | 96.1 | 97.8 |
| **Fluoride** | 5.0 | 0.4 | 0.1 | 92.0 | 98.0 |
| Magnesium | 5.3 | 0.016 | 0.004 | 99.7 | >99.9 |
| **Nitrate as N** | 3.8 | 0.17 | 0.11 | 95.5 | 97.0 |
| Potassium | 14 | 0.87 | 0.11 | 93.8 | 99.2 |
| Silica as $SiO_2$ | 12 | 0.12 | 0.10 | 99.0 | 99.2 |
| Sodium | 118 | 12 | 2.5 | 89.8 | 97.9 |
| Sulphate | 70 | 0.07 | 0.07 | 99.9 | 99.9 |
| **TOC** | 7.4 | 0.074* | 0.044* | 99.0 | 99.4 |
| Total alkalinity as $CaCO_3$ | 81 | 12 | 6 | 85.2 | 92.6 |

*On-line data.

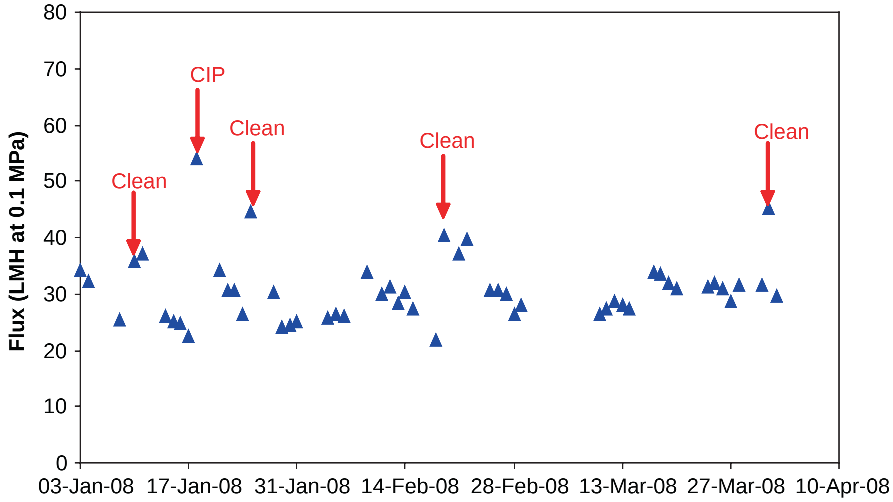


Fig. 7. Normalized flux of UF versus time.

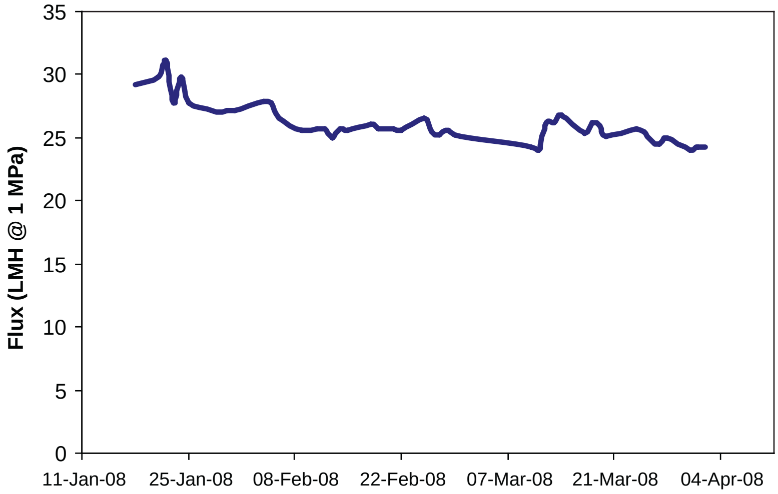


Fig. 8. Normalized flux of RO versus time.

the flux was recovered to 35–45 LMH. CIP on UF was conducted once and the flux was recovered to 53 LMH.

Colloidal fouling, scaling, biofouling and organic fouling are common in a RO process [18,19]. In presence of UF as a pre-treatment and appropriate dosage of hypochlorite prior to RO in reclamation of the secondary effluent, the colloidal fouling and biofouling might be mitigated [9]. Therefore, scaling and organic fouling could be major concerns in this study. Fig. 8 illustrates the normalized flux of RO membranes as a function of time during the study. It can be seen that the flux started at around 30 LMH and declined to 28 LMH in the first few days, and then was stable at around 25 LMH. No CIP on RO membranes was carried out during the period of this study, which indicated that the selected antiscalant F for RO process was potentially suitable for the specific wastewater containing fluoride. It should be pointed out that antiscalant F was dosed at a high rate of 6.5 mg/L during the study. A cost-effective antiscalant and its optimum dosage should be further investigated as the antiscalant F is expensive. It was noted that the net pressure drop increased from 12 psi to 15 psi during the study. This could be mainly attributed to the fact that the UF integrity problems occurred for four times as shown in Fig. 7. There might be a certain scaling/organic fouling that should be further explored in next study although the RO fouling rate was acceptable under the conductions tested.

## 4. Conclusion

From the results of the pilot trials, the conclusions can be drawn as follows:

(1) TOC of RO permeate with G3 secondary effluent as raw feed was in the range of 65–95 µg/L, most of the time.
(2) Most parameters of RO permeate quality met the requirement of NEWater quality.
(3) Fluctuation of ammonium concentration in RO feed could be the major concern.
(4) RO permeate quality and rejections were improved when the membrane flux was increased from 8.5 to 17 LMH. TOC of RO permeate at 17 LMH was 45–60 µg/L which was about 30% lower than that at 8.5 LMH on the same days.
(5) The separation performance of the RO membranes were satisfied with rejections on Ammonium, Boron, Conductivity, Fluoride, Nitrate and TOC being more than 96%, 75%, 97%, 98%, 97% and 99%, respectively.
(6) The antiscalant F for RO process was found to be potentially suitable for the specific wastewater containing fluoride.

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## References

[1] S.L. Kim, J. Paul Chen and Y.P. Ting, Study on feed pretreatment for membrane filtration of secondary effluent, Separation and Purification Technology, 29 (2002) 171.

[2] J.P. Chen, S.L. Kim and Y.P. Ting. Optimization of membrane physical and chemical cleaning by a statistically designed approach, J. Membr. Sci., 219 (2003) 27.

[3] M.P. del Pino and B. Durham, Wastewater reuse through dual-membrane processes: Opportunities for sustainable water resources, Desalination, 124 (1999) 271.

[4] J.Y. Tan and M.F. Lee, NEWater—an alternative source of water for the wafer fab industry in Singapore, In Proc. of Recycling and Alternate Sources for the Wafer/PCB Industries Conference, 11–12 July 2001, Singapore.

[5] Public Utilities Board of Singapore, NEWater quality, Internet: www.pub.gov.sg/NEWater, October 20, 2008.

[6] J.J. Qin, M.H. Oo, M.N. Wai and H. Lee, Pilot study for reclamation of the secondary treated sewage effluent, Desalination, 161 (2004) 155.

[7] J.J. Qin, M.H. Oo, H. Lee, and R. Kolkman, Dead-end ultrafiltration for pretreatment of RO in reclamation of municipal wastewater effluent, J. Membr. Sci., 243 (2004) 107.

[8] J.A.L. Ramirez, S.Sahuquillo, D.Sales and J.M. Quiroga, Pretreatment optimization studies for secondary effluent reclamation with reverse osmosis, Water Res., 37 (2003) 1177.

[9] J.J. Qin, M.H. Oo, M.N. Wai, H. Lee, Y.J. Xing and M.C. Zhang, Pilot study for reclamation of the secondary treated sewage effluent, Desalination, 171 (2005) 299.

[10] K. Kekre, J.J. Qin and H. Seah, Pilot study: Dual membrane process for water reclamation in Singapore, Water Today, l(November–December) (2008) 66.

[11] P. Lawrence, S. Adham and L. Barrott, Ensuring water re-use projects succeed-institutional and technical issues for treated water re-use, Desalination, 152 (2002) 291.

[12] J.J. Qin, B. Liberman and K.A. Kekre, Direct osmosis for reverse osmosis fouling control: Principles, applications and recent developments, The Open Chem. Eng. J., 3 (2009) 8.

[13] J.J. Qin, M.N. Wai, M.H. Oo, H.Lee, K.A. Kekre and H. Seah, Feasibility study for reclamation of a secondary treated sewage effluent mainly from industrial sources using a dual membrane process, Separation & Purification Technology, 5 (2006) 380.

[14] J.J. Qin, M.H. Oo, M.N. Wai and K.A. Kekre, TOC removal in reclamation of municipal wastewater by RO, Separation and Purification Technology, 46 (2005) 125.

[15] C. Reith and B.Birkenhead, Membranes enabling the affordable and cost effective reuse of wastewater as an alternative water source, Desalination, 117 (1998) 203.

[16] E.R. Cornelissen, J.S. Vrouwenvelder, S.G.J. Heijman, X.D. Viallefont, D. Van Der Kooij and L.P. Wessels, Periodical air/water cleaning for control of biofouling in spiral wound membrane elements, J. Membr. Sci., 287 (2007) 94.

[17] M. Wilf and S. Alt, Application of low fouling RO membrane elements for reclamation of municipal wastewater, Desalination, 132 (2000) 11.

[18] G. Singh and L. Song, Quantifying the effect of ionic strength on colloidal fouling potential in membrane filtration, J. Colloid Interface Sci., 284 (2005) 630.

[19] T. Tran, B. Bolto, S. Gray, M. Hoang and E. Ostarcevic, An autopsy study of a fouled reverse osmosis membrane element used in a brackish water treatment plant, Water Res., 41 (2007) 3915.