Pilot Plant Research For Sydney's Drinking Water Program Project

Pre-treatment Prior To RO for Seawater Desalination: Sydney Pilot-Scale Study

Authors: Sophie Rapenne, Catherine L. Port, Stephen J. Roddy, Jean-Philippe Croué

Presenter: Sophie Rapenne

Laboratoire Chimie Eau et Environnement – University of Poitiers – France

Abstract

Sydney Water will be constructing a desalination plant due to the prolonged drought conditions and to provide for growth. The plant will be a two-pass reverse osmosis desalination plant with a capacity of 250ML/d, upscaleable to 500ML/d.

Sydney Water Corporation has conducted a pilot-testing program to determine the most appropriate process to be used for the RO pre-treatment. This program tested conventional granular media filtration (GMF) and ultrafiltration (UF), an emerging alternative pre-treatment technology.

Two conventional pre-treatment plants were operated in parallel, providing five separate GMF trains. The process involved ferric chloride coagulation followed by granular media filtration (GMF). A ZeeWeed® 1000 submerged membrane from GE Water and Process Technologies was tested. It consisted of PVDF hollow fibres (out/in) with a nominal pore size of 0.02 µm.

The performances of both pre-treatment technologies were assessed by the monitoring of fouling potential and micro-organism content. The fouling potential was evaluated by Silt Density Index (SDI) measurements. Micro-organism content was measured by flow cytometry.

For the period of testing, optimisation and continued operation of the GMF pilot plant demonstrated that reliable performance with a filtered water SDI15 of 3 or less is able to be achieved with granular media pre-treatment using single stage filtration.

Ultrafiltration produced mixed results, producing permeate of SDI15 above 3 for a period of two months. The theory of micro-bubbles forming in the permeate, obstructing the pores of the SDI membrane, resulting in a falsely high SDI result, was investigated. Despite a range of methods used to eliminate micro-bubbles from the permeate water tested, only a marginal improvement in SDI was demonstrated. Therefore this theory could not be substantiated.

It was found that the quality of the UF permeate was strongly linked to the quality of the feed. The feed and permeate of the UF plant trended similarly over the 9 month testing period, and, tests feeding the UF plant with GMF filtered water showed that the SDI of the permeate significantly improved with improved feed quality.

In terms of micro-organism removal, the UF plant performed better, however the GMF removed more TOC. The GMF produced filtered seawater with low and reasonably consistent SDI15 while the UF also had a low average SDI15, albeit with a wider standard deviation. This is in contradiction to the expectation that UF would produce more consistent filtered water quality than GMF.

I. INTRODUCTION

Reverse osmosis has become the major technology used for new seawater desalination plants. Although there have been continuous improvements in various aspects of membrane performance including energy consumption, biofouling on the surface of the RO membrane is still a major problem to overcome. Seawater is a complex matrix of micro-organisms, organics and minerals making biofouling difficult to understand and prevent [1]. The maintenance of a high quality RO feed water is crucial to ensure the long-term performance of the RO membranes. Therefore, it is necessary to identify the type of pretreatment required to reliably produce high quality RO feed water.

Sydney Water is conducting a pilot study to determine the most appropriate pre-treatment process to produce filtered seawater suitable to be fed to the reverse osmosis plant. Many membrane manufacturers require the SDI15 (Silt Density Index – 15 mins) of the filtered seawater (RO feed) to be below 3.5. The aim of the pre-treatment testing was to develop a pre-treatment process to reliably produce filtered seawater with a SDI15 of 3 or below.

Currently, most operating seawater reverse osmosis plants use a conventional pretreatment process (disinfection Æ coagulation Æ granular media filtration) prior to RO desalination. Conventional pretreatment significantly reduces the SDI and the turbidity of the feed water, however micro-organisms and particles are not totally removed [2, 3]. More recently, membrane filtration (UF and MF) has been considered as an alternative to conventional pre-treatment, with the potential to provide RO feed water with low particles and micro-organism counts independent of the feed seawater quality [4, 5, 6, 7]. Hence, Sydney Water included GMF and UF as part of the pre-treatment pilot-testing program. A comparison of pre-treatment by Granular Media Filters (GMF) and Ultrafiltration (UF) was conducted between September 2006 and June 2007.

The pilot plant is fed with seawater from the proposed seawater intake point for the future plant, located off the Kurnell peninsula. In this area, the EAC (East Australian Current) plays an important role in the nutrient enrichment of the oligotrophic coastal waters of New South Wales. This leads to phytoplankton blooms and associated swarms of zooplankton on the continental shelf off Sydney in spring. These sudden blooms are due to short-lived diatoms that evolve in a predictable sequence from small chain-forming species to large centric species and eventually to large dinoflagellates. Efficient pre-treatment is necessary during these bloom events to prevent excessive fouling and to ensure successful long-term performance of reverse osmosis membranes.

The optimum treatment conditions for both conventional pre-treatment and UF were determined and the ongoing performances of the optimum treatment processes for the GMF and UF were then compared.

II. MATERIAL AND METHODS

2.1 Seawater Supply

The seawater intake for the pilot plant is located at the proposed intake point for the full-scale plant off the Kurnell peninsula, south of Sydney, 25 m below the sea surface, 400 m offshore and some 2.3 km from the pilot plant site. The seawater feed pump operates continuously to provide a constant supply of fresh seawater to the 30 kL seawater feed tank, which feeds to the two granular media filtration pilot plants and an ultrafiltration pilot plant.

2.2 Pilot Plant Configuration

2.2.1 Granular Media Filters

Two separate granular media pilot plants, each built into shipping containers, are located on the site. Table 1 gives the characteristics of the two GMF pilot plant units.

Table 1: Characteristics of the two GMF pilot plant units

Pilot Plant Characteristics	GMF Unit 1	GMF Unit 2
Number of Process Trains	2	3
Filter train Configuration	1 x Single Stage, 1 x 2 Stage	3 x 2 stage
Filter Diameter	0.4 m, 0.4 + 0.3 (2nd stage)	0.5 m
Type of filter	Closed - operating in gravity mode	Open gravity
Max Head loss	3m	3m
Graded Gravel (layer depth / size)		

100 mm / 6 -12 mm (bottom) 100 mm / 3 – 6 mm (mid) 100 mm / 0.8 – 1.8 mm (top)

100 mm / 6 -12 mm (bottom) 100 mm / 3 – 6 mm (mid) 100 mm / 0.8 – 1.8 mm (top)

Sand (depth / ES /UC)

800 mm / 0.65 mm / 1.4

800 mm / 0.65 mm / 1.4

Coal (depth/ ES /UC)

800 mm / 1.5 mm / 1.3

800 mm / 1.5 mm / 1.3

ES = effective size, UC = uniformity coefficient

Each of the granular media pilot plants has a flocculation tank with a variable speed mixer feeding each train. The flocculation configuration allows the testing of different contact times and G values. All chemicals were dosed prior to a static mixer.

2.2.2 Ultrafiltration Pilot

The ultrafiltration pilot plant is a submerged hollow fibre membrane Zenon Zeeweed 1000, supplied by GE Water and Process Technologies. Table 2 gives the characteristics of the UF plant.

Prior to ultrafiltration the feed water is filtered through fine screens to remove any gross solids which could harm the UF membrane fibres. After screening, the seawater flows to the membrane tank, containing the membrane modules. Each module contains immersed hollow fibre membranes. Filtration operates in dead-end mode without aeration. During filtration, permeate is drawn through the membranes by the negative pressure applied from a pump on the permeate side.

Table 2: Zeeweed® 1000 membrane characteristics

Pilot Plant Characteristic

Zeeweed 1000

Membrane type

Outside-in hollow fibres

Membrane material	Polyvinylidene fluoride (PVDF)
Membrane surface properties	Non-ionic and hydrophilic
Nominal pore diameter (µm)	0.02
Total membrane area (m2)	111.4

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2.2.3 On-line Equipment

For all pilot plants (GMF and UF), on-line equipment including, pressure sensors, flow meters, flow controllers and level sensors, were used to control and monitor the process via a PLC. The suspended solid content of feed and filtered water was measured with in-line turbidimeters (Hach 1720E and Lange Ultraturb sc) and a particle counter (Hach 2200 PCX). Due to technical difficulties, particle counts on the granular media filter plant were not obtained.

2.3 Sampling and Analysis

Bench pH measurements were conducted hourly on GMF filtrate, with some samples also subjected to iron analysis. The turbidity of the filtrate was monitored with on-line turbidimeters. Raw seawater was tested daily or twice daily for pH, turbidity, temperature, conductivity, dissolved oxygen and Silt Density Index (SDI3). SDI measurements were made twice a day for the raw seawater and ultrafiltration permeate and every two hours during the day for each GMF filtrate stream.

Raw seawater samples were analysed for Total Suspended Solids (TSS), Total Dissolved Solids (TDS), heavy metals, various chemicals, algae and bacteria at Sydney Water’s laboratories in West Ryde every 18 days. For most of the parameters tested, the levels in the raw seawater were very low and close to the detection limit. Therefore, other analytical tools were used to determine the efficiency of the pretreatment.

2.3.1 Silt Density Index (SDI) Test

SDI measurements were performed according to the ASTM method D4189-95. Water was passed through a cellulose acetate 0.45 µm membrane filter (Millipore type HAWP 47 mm) at a constant pressure of 30 psi. The initial time to collect

500 mL of permeate was measured (t0) and the same measurement was performed after 15 min of filtration (t15). The SDI was calculated using the following formula:

15 −t0 100

SDI =x (1)

t 15

15

2.3.2 Flow Cytometric Analysis

Samples were divided into two aliquots and fixed with formaldehyde (2% final concentration) and then frozen at – 196 °C in liquid nitrogen for delayed analysis. Samples were analysed using a Facsort flow cytometer (Becton Dickinson) [8]. The flow cytometer allows counting heterotrophic bacteria and picophytoplanktonic cells. The method used has been described in a previous article [9]. Sampling on pretreated seawater was performed after maturation of the filters, usually at least 8 hours after the beginning of the run at least. Raw seawater was sampled at the same time.

2.3.3 DOC and TDN Analysis

Samples were stored in brown glass bottles with Teflon lined screw caps after acidification to pH 2 with HCl. Total organic carbon (TOC) and total nitrogen (TN) analyses were performed using a Shimadzu TOC-Vcsh (high-temperature catalytic oxidation) equipped with the TNM-1 unit. Each sample was bubbled for 4 minutes to eliminate all the inorganic carbon. After CO2 elimination, a 80 µL aliquot was

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directly injected into the vertical furnace, filled with platinum coated silica and oxidised at 720°C. The CO2 formed was analysed with a non-dispersive infrared detector. Total dissolved nitrogen was analysed as NOx by chemiluminescence detection using the TNM-1 unit. The accuracy of measurements was verified using deep Sargasso Seawater (Certified Reference Material provided by the University of Miami) with 44-47µM C and 21µM N.

2.4 Pilot testing program

In order to obtain a valid comparison of the two pre-treatment processes, both needed to be optimised.

2.4.1 GMF Optimisation

The optimization of the GMF process was conducted in stages, focusing on each process parameter as follows:

-
Coagulation pH

-
Primary Coagulant and Dose

-
Secondary Coagulant and Dose

-
Flocculant and Dose

-
Flocculation Time

-
Flocculation G value

-
Filter Media

-
Filtration Rate

• 2-stage Filtration The optimum treatment condition for each parameter was determined by identifying the condition that resulted in the shortest filter ‘ripening’ time and lowest steady state SDI and permitted the longest filter run time.

The filter ‘ripening’ time was defined as the time elapsed from placing a filter on-line after a backwash to the time the filterate reached an SDI of 3.

Filter run time was defined as the time elapsed from placing a filter on-line after a backwash to the time for a filter to reach a head loss of 3 m, or, when the SDI exceeded 3 or the effluent turbidity exceeded

0.1 NTU.

The optimum treatment condition from a tested parameter was then carried forward for the testing of the next parameter.

2.4.2 UF Optimisation

The ultrafiltration process was optimised by monitoring trans-membrane pressure (TMP) and SDI of the permeate. The following parameters were adjusted in the optimisation process:

Backwash frequency and flux

Filtration flux (increased gradually from 30 L.m-2.h-1 to 42.5 L.m-2.h-1)

Chemically assisted cleaning

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The optimum treatment condition was determined based on SDI measurement and trans-membrane pressure monitoring. The daily chemical cleaning was adjusted to ensure the flux could be maintained.

III. RESULTS AND DISCUSSION

3.1 Physical & Chemical Characteristics of the Raw Seawater

Several physical and chemical parameters of the raw seawater have been monitored on a monthly basis since January 2006. Table 3 shows the results obtained on some of the parameters analysed.

Table 3: Physical Chemical composition of the raw seawater

Parameter	Concentration Range Detected	Long term average
Total Suspended Solids (TSS) (mg/L)	<2 – 5 (usually not detected)	<2
Silt Density Index (SDI3)	9.37 – 24.32	14.63
Turbidity (NTU)	0.07 – 4.70	0.16

Temperature (oC)
16.2 – 21.5
18

Conductivity (mS/cm)
52.4 – 54.6
53.7

Dissolved oxygen (mg/L)
5.35 – 7.80
6.66

pH
7.75 – 8.33
8.10

Total Dissolved Solids (TDS) (mg/L)
35370 – 37850
36580

TOC (mg C /L)
0.71 – 0.80
0.75

TN (μg N/L)
100 - 280
180

Silica (μg/L)
<100 - 300
<100

Chlorophyll a (μg/L)
<0.2 – 1.3
0.3

Phaeophytin a (μg/L)
< 0.2 – 0.9
<0.2

In addition to these parameters, sampling and monitoring for algae and bacteria has been conducted regularly, with particular attention to picophytoplankton monitored between October and December 2006 (Table 4).

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In general, over the testing period, the seawater has been of very good quality, with low turbidity and suspended solids content and relatively low SDI3 (Table 3). No simple relationship could be established between turbidity and raw water SDI. Turbidity was around 0.15 NTU most of the time, even on days when high SDIs were recorded (Figure 1). On some days of high turbidity (above 4.5 NTU) there were similar peaks in the SDI3 recorded. Slightly higher SDI values were obtained during events characterized by high micro-organism content, i.e. December (summer) 2006 (Figures 2 and 3). Prochlorococcus have been detected on only few days during the period of analysis (Figure 2).

Table 4: Micro-organism content of the raw seawater.

Algae / Bacteria Monitored	Concentration Range Detected	Long term average
Total picophytoplankton (count/mL)*	3 x 102 – 4.4 x 104	1.0 x 104
Synechococcus (count/mL)*	1.7 x 102 – 4.4 x 104	5.8 x 103

Picoeukaryotes (count/mL)*
1.3 x 102 – 1.0 x 104
2.4 x 103

Prochlorococcus (count/mL)*

Detected only for few samples
1.3 x 103 – 1.8 x 104
5.7 x 103

Total Coliforms (cfu/100ml)
0 – 550
-

Faecal Coliforms (cfu/100ml)
0 – 87
-

E Coli (cfu/100ml)
0 – 87
-

Enterococci (cfu/100ml)
0 –17
-

Total heterotrophic bacteria (count/mL)
3.7 x 105 – 1.8 x 106
7.9 x 105

* monitored between October and December 2006

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3/10/06 12/10/06 19/10/06 26/10/06 2/11/06 17/11/06 27/11/06 4/12/06 11/12/06 18/12/06 4/01/07 10/01/07

Figure 2: Variations of the picoplankton content versus SDI3 of the raw seawater

3/10/06 12/10/06 19/10/06 26/10/06 2/11/06 17/11/06 27/11/06 4/12/06 11/12/06 18/12/06 4/01/07 10/01/07

Figure 3: Variations of the bacteria content versus SDI3 of the raw seawater

During summer, sporadic increases of the bacteria content appeared to coincide with a significant increase in the SDI3. These increases correspond to an inversion of the proportion ratio between active

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bacteria (HNA bacteria for High Nucleic Acid Content) and dormant bacteria (LNA bacteria for Low Nucleic Acid content).

3.2 GMF optimisation

The objective of the GMF pre-treatment program was to determine the optimum conditions for each of the parameters to enable a comparison of the effectiveness of the GMF process to that of UF.

3.2.1 Coagulant and Flocculant Doses

Initial tests were conducted comparing the performance of varying doses of ferric chloride. Doses of 2, 4, 6, 8 and 10 mg/L of $FeCl_3$ were tested concurrently in the 5 process trains (Figure 4), under a ‘base case’ condition of 10 m/h filtration rate and pH 7.

Using an initial coagulation pH of 7 and dose of 6 mg/L of ferric chloride, a filtered seawater SDI_{15} of below 3 was consistently achieved, usually within 3-6 hours from the start of the run (the ‘filter ripening time’).

Samples collected after 8 hours of operation showed that the removal of heterotrophic bacteria and picoplankton increased with increasing $FeCl_3$ dose. Results obtained for Synechococcus followed the same trend as the one observed for SDI (Figures 4 a and b), exhibiting higher removal with higher $FeCl_3$ dose.

A number of secondary polymeric coagulants, including various polyDADMACs, were tested. Of those tested, LT425 (CIBA product) provided the best performances. The testing showed that 3 mg/L of ferric chloride with 0.2 mg/L of LT425 would provide equivalent performance to coagulation with 6 mg/L of ferric chloride alone (Figure 8 see experiments conducted at 10 m/h). Additional dosing of various polymeric flocculants (acrylamide polymers) was compared. Preliminary results showed that use of

0.04 mg/L of LT22 (CIBA product) provides a reduction in filter ripening time of up to 25%, compared with 6 mg/L of ferric chloride alone. However, further testing of flocculants showed that they were not effective when dosed in conjunction with LT425.

024 6810 12

2 mg/L 4 mg/L 6 mg/L 8 mg/L 10 mg/L $FeCl_3$ $FeCl_3$ $FeCl_3$ $FeCl_3$ $FeCl_3$

Filtration time (h)

Figure 4: Effect of coagulant dose on (a) SDI and (b) micro-organism removal after 8h filtration

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(pH 7, filter rate 8 m/h))

3.2.2 Coagulation pH

The coagulation pH was adjusted by the dosing of sulphuric acid. Tests were conducted at coagulation pHs of 6, 6.5, 7, 7.5 as well as with natural pH (pH ~ 8.1).

The SDI_{15} of the filtered seawater was significantly affected by the coagulation pH. It was found that the lower the coagulation pH, the lower the SDI_{15} of the filtered seawater delivered. Also, a clear difference was often observed (both for average raw seawater quality ($SDI_3 = 14$) and relatively poor seawater quality ($SDI_3 = 21$)) between the performances of trains at pH 6 or 6.5 and the others. An example is given in Figure 5a with an optimum $FeCl_3$ dose of 4 mg/L. In each test, the trains at pH 6 and 6.5 performed similarly with filter ripening times of around 2 hours, compared to a filter ripening time of around 4 hours for higher pHs.

This was reflected in the removal of micro-organisms, especially Synechococcus, as can be seen on Figure 5b. The ‘steady state’ SDI15 of the filtered water was generally higher for higher pHs, but was still quite low, at around 2.5.

Taking into account the increased acid requirement of the various coagulation pHs, pH 6.5 was selected as the optimum coagulation pH and was incorporated into the treatment regime as the basis for the further testing phases.

3.2.3 Filtration Rate

Once the optimum coagulants, doses and coagulation pH were established, it became obvious that the pilot plant could operate at filtration rates higher than 8 m/h while still achieving reasonable filter ripening times and a “steady state” filtered water SDI15 of well below 3. Filtration rates of 8, 10, 12 and 14 m/h were tested and compared using the optimum coagulation conditions previously found. Test durations were extended to at least 24 hours in order to obtain a picture of the performance over a longer run.

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Figure 6: Effect of filter rate on SDI15 (pH 6.5)

Among the different tests conducted with the differing water qualities, it was difficult to establish with precision the best filter operating conditions. The performance of the system was not as sensitive to filtration rate as other parameters. Generally, as expected, the filter operating at 8 m/h was found to have the shortest filter ripening time (Figure 6) and the difference between filtration rates was highlighted over longer operation times (e.g. up to 20 hours).

The micro-organism content analysis also shows that removal is fairly constant between 8-12 m/h, with a slight worsening of removal at 14 m/h (not shown). A filtration rate of 10 m/h has been determined to be the optimum and incorporated into the basis for further tests.

Over the testing period, the optimum treatment process for the GMF was determined to be as described in Table 5. Two sets of optimum coagulation conditions performed in a similar way in many cases and are shown in Table 5. Further tests were conducted and confirmed the similar behaviour of both coagulation conditions.

Table 5: Optimum Pre-treatment conditions

Parameter	Optimum conditions 1	Optimum conditions 2
Coagulation pH	6.5	6.5
Primary Coagulant and Dose (mg/L)	6 mg/L as $FeCl_3$	

3 mg/L as FeCl3

Secondary Coagulant and Dose (mg/L)

0

0.2 mg/L LT425

Flocculant and Dose (mg/L)

0

0

Flocculation Time (min)

0

0

Flocculation G value (s-1)

N/A

N/A

Stages of Filtration

1

1

Filter Media

Dual media - coal 1.7 mm

Dual media - coal 1.7 mm

ES with sand 0.65 mm ES

ES with sand 0.65 mm ES

Filtration Rate (m/h)

10

10

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3.3 Ultrafiltration Optimisation

3.3.1 Screening

Initially, the UF was preceded by 0.5 mm basket stainless steel strainers. The strainers were later replaced by plastic Arkal® filters with an opening of 0.1 mm for greater protection of the membranes. During the summer period where there was a higher concentration of micro-organisms in the raw seawater, the Arkal filters blocked frequently, requiring manual cleaning every 2-3 days. Analysis performed on the screenings showed that it mainly consisted of gastropods.

3.3.2 Operation

Initially the system ran only during the day to ensure the treated water storage tank would not overflow. Once level protection was available in the treated water storage tank, the UF pilot was operated 24 hours per day.

A chemical free membrane backwash (with permeate and air injection) was programmed every 30 to 45 min. A maintenance clean was performed once a day with a 100 ppm chlorine solution. The chlorinated solution was recirculated for 15 min at a flux of 30 L.m-2.h-1. In addition, four further cleaning steps (recovery cleans) were performed over the testing period to restore membrane permeability. Membranes were soaked overnight in a chlorinated solution at 500 mg/L Cl2 or a citric solution at pH 2.2.

Table 6 shows the main operating parameters of the Zeeweed system.

Table 6: Zeeweed® 1000 operating parameters

Operating transmembrane pressure (kPa)	Flux (lmh)	Backwash duration (min)	Backwash frequency (min)	Backwash flux (lmh)	Recovery (%)
-9 to -35	30 – 44	5-6	30-45	42	93

3.3.3 Permeability

The permeability of the membrane declined progressively over the first six weeks of operation. After mid October 2006 the permeability appeared to stabilise at approximately 200 L.m-2.h-1.bar-1. This phenomenon was expected for a new set of membranes due to pore compaction. A recovery clean was performed on the 30th October 2006 using sodium hypochlorite and citric acid, which provided only a limited improvement to the permeability. After this period the flux was set at 30 L.m-2.h-1 and later 40 L.m-2.h-1 .

Throughout November the permeability of the membrane continued to decline, which was suspected to be due to the accumulation of irreversible foulants on the membrane surface. At the beginning of December the permeabilty stabilized at 160 L.m-2.h-1.bar-1. A recovery clean using sodium hypochorite alone was performed on the 13th December and the flux set at 42.5 L.m-2.h-1. A severe drop of permeability followed, which was attributed to the significant increase in the algae content of the raw

seawater at the time. The permeability was restored after this event and stabilised to approximately 170 L.m-2.h-1.bar-1.

During the Christmas break the UF pilot was turned off and the membranes soaked in a 50 mg/L NaOCl solution. When restarted the permeability of the unit increased to 180 L.m-2.h-1.bar-1 (cleaning effect) that slowly decreased to 160 L.m-2.h-1.bar-1 with time.

3.3.4 UF Permeate SDI

One of the perceived advantages of UF as a pre-treatment technology is that the permeate is of constant quality whatever the quality of the feed water. However, Figure 7 shows that for approximately two months of the testing period (between mid-December 2006 and mid January 2007) the SDI15 of the permeate was consistently above 3.   Two hypotheses were considered to explain this result. The first hypothesis is that the presence of micro-bubbles produced at high vacuum conditions (the stronger the vacuum, the more abundant the micro-bubbles), that could lead to premature blockage of the pores 0.45 µm filter, resulting in higher SDI15 readings. The second hypothesis is that permeate quality is dependent on the feed seawater quality. Additional experiments were conducted in order to explore the two hypotheses.

Figure 7: Variations of Raw water SDI3 and UF permeate SDI15

Higher particle counts in the permeate and a drop in the TMP were observed at the time of higher permeate SDI readings. Membrane integrity tests were regularly performed, with the first failure registered at the end of January 2007. When the unit was repaired in early April 2007, it was found that only two hollow fibres were broken in the whole unit. Between the time of membrane integrity failure and repair, the SDIs measured were below 2.5. The fact that SDI dropped before repair, when raw seawater conditions remained quite similar, indicated that the fibre breakage was not the cause of the high SDIs recorded.

Considering the first hypothesis, that micro-bubbles could be responsible for the SDI15 increase, a range of laboratory tests were performed to tentatively eliminate any possible micro-bubbles from the UF

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permeate prior to an SDI test. These tests were performed when the UF pilot was operating at 42.5 L.m2.h-1 with a TMP of about – 26 kPa. For all SDI tests, after sampling, the SDI pressure vessel was pressurised at 30 psi for 30 minutes before measurement.

Table 8: UF SDIs with several methods of preparation of the sample (operating conditions when sampling : 42.5 L.m-2.h-1; TMP = – 26 kPa)

Method	SDI15
Sampled and pressurized for 30 min	3.35
Sampled after the degassing column	3.46
Set overnight	3.12
Vacuum filtration on 8 µm filters	3.05
Sonication (15 min)	

3.45

Heating at 70°C

3.43

Back to lower flux (30 L.m-2.h-1) before MIT* failure

3.52

Back to lower flux (30 L.m-2.h-1) after MIT failure (lower TMP)

2.31

* Membrane Integrity Test

Results given in Table 8 show that the SDI value remained relatively unchanged whatever the nature of the test performed. Hence, the presence of micro-bubbles (if any) was not considered to significantly interfere with the SDI test. Figure 7 shows that the permeate SDI generally follows the same trend as the raw seawater SDI, in support of the second hypothesis.

In addition, the permeate quality in terms of SDI15 and the membrane permeability loss were found to be clearly related, following the same trend as shown by Figure 8.

1/9/06 1/11/06 1/1/07 1/3/07 1/5/07 Operation Time

Figure 8: Evolution of UF Permeate SDI15 and Membrane Permeability loss (calculated from the initial permeability i.e. before membrane compaction)

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It is noted that these are lines of best fit, and that fluctuations in permeability due to maintenance and recovery cleans, whilst present, are relatively small and do not significantly affect the overall trend. The permeability loss represents the extent of fouling of the UF membranes, caused by the raw water quality. Looking at Figures 7 and 8, it can be seen that from January to July 2007, raw water SDI and hence permeate SDI steadily decreased. With the regular maintenance and recovery cleaning regimes, over time, it can be seen that the improvement in water quality is also reflected in a steady increase in permeability (decrease in permeability loss) over the period.

Therefore, as the raw water SDI influences the permeate SDI, and the loss of membrane permeability has been shown to closely correspond with the permeate SDI (Figure 8), it can be concluded that both the permeate SDI and loss of permeability of the membrane are mostly influenced by the raw water quality.

In a final attempt to test both hypotheses, the UF plant, while operating at 42.5 L.m-2.h-1, was fed with filtered water from the GMF plant. The results can be seen in Table 9.

Table 9: Modification of UF Permeate SDI with the quality of the feed water

Test	UF Permeate SDI15 Test 1	UF Permeate SDI15 Test 2
UF Permeate SDI15 with raw seawater feed	2.65	3.12
UF Permeate SDI15 with GMF filtered water feed	1.95	1.98
UF Permeate SDI15 with raw seawater feed (after GMF feed trial)	2.73	2.84

The results show that the SDI of the permeate dropped significantly when fed with GMF filtered water. If micro-bubbles were responsible for the higher SDI, it would be purely dependent on the TMP. It would therefore be expected that the SDI of filtered water would be equally high as when using raw seawater. However, since the SDI of the permeate dropped when using a better quality feed, the test indicates again that the SDI of the permeate can be attributed to the better quality of the feed water.

3.4 Comparison of UF and GMF

3.4.1 UF Permeate and GMF Filtered Water Quality

The qualities of UF permeate and GMF filtered water have been compared throughout the study based on several parameters. The UF pilot plant has produced water of very good quality with respect to turbidity, particle counts and micro-organism content. The results are summarised and are compared with the results obtained from the GMF treated water in Table 7.

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Table 7: Water quality: UF Permeate vs GMF filtrate (October to December 2006)

Parameter	UF permeate		GMF filtrate	
	Concentration Range Detected	Long term average	Concentration Range Detected	Long term average
Permeate turbidity (NTU)	0.01 – 0.05	0.02	0.02 – 0.07	0.03
TOC (mg/L)	0.70 – 0.79	0.75	0.59 – 0.71	0.65
Total particle counts > 2 µm (nb/mL)	0 – 21	< 1	n.a.	n.a.

Heterotrophic bacteria (count/mL)

2 – 600

< QL

3.8 x 104 - 8.1 x 105

1.9 x 105

Total picophytoplankton (count/mL)

0 – 70

< QL

2.1 x 101 -2.5 x 104

2.4 x 103

Synechococcus (count/mL)

0 – 45

< QL

1.7 x 101 -2.5 x 104

1.9 x 103

Picoeukaryotes (count/mL)

0 – 2

< QL

0.5 x 101 -3.0 x 103

3.4 x 102

Prochlorococcus (count/mL)

0 – 55

< QL

2.0 x 101 - 3.7 x 103

4.7 x 102

The results show that the UF unit was significantly more efficient in the removal of bacteria and picoplankton compared to the GMF unit. However, no removal of TOC was observed with the UF membranes, whereas, on average, about 15 % of TOC was removed by the granular media filters. This is not unexpected since no coagulant was dosed prior to the UF.

3.4.2 UF Permeate and GMF Filtered Water SDIs

To compare the performance of the GMF with the UF, the SDIs from the UF were compared with those of GMF filtered water for the period when the base case GMF treatment regime was followed (October to December) (Figure 9).

16/10/2006 30/10/2006 13/11/2006 27/11/2006 11/12/2006

Figure 9: Evolution of SDIs of UF permeate and GMF filtered water

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The SDI values of GMF correspond to the steady state for the base case (pH 6.5, $FeCl_3$ = 6 mg/L, 10 m/h). The results show that the variations of UF permeate SDI are close to the ones from GMF. This finding indicates that the change in the raw sea water quality that probably impacted the performance of the GMF unit also affected the performance of the UF membrane. This graph further reinforces the hypothesis that the variation of the SDI of the UF permeate was really due to a change in the quality of the water produced, rather than micro-bubbles.

The GMF produced filtered seawater with reasonably consistent low SDI15 with an average over the period of 2.57 with a standard deviation of 0.35. The UF plant also produced a low average SDI15 of

2.10 with a wider standard deviation of 0.58. This is in contradiction to the expectation that UF would produce more consistent filtered water quality than GMF.

IV. CONCLUSION

For the period of testing, the following conclusions can be drawn:

Optimisation and continued operation of the GMF pilot plant demonstrated that reliable performance with a filtered water SDI15 of 3 or less is able to be achieved with granular media pre-treatment using single stage filtration.

Ultrafiltration produced mixed results, producing permeate of SDI15 above 3 for a period of two months. The theory of micro-bubbles forming in the permeate, obstructing the pores of the SDI membrane, resulting in a falsely high SDI result was investigated. Despite a range of methods used to eliminate micro-bubbles from the permeate water tested, only a marginal improvement in SDI was demonstrated. Therefore this theory is not supported.

It was found that the quality of the UF permeate was strongly linked to the quality of the feed. The feed and permeate of the UF plant trended similarly over the 9 month testing period, and tests feeding the UF plant with GMF filtered water showed that the SDI of the permeate significantly improved with improved feed quality.

In terms of micro-organism removal, the UF plant performed better, however the GMF plant removed more TOC, about 15% due to the coagulation step. The GMF plant produced filtered seawater with low and reasonably consistent SDI15 while the UF plant also produced a low average SDI15, albeit with a wider standard deviation. This is in contradiction to the expectation that UF would produce more consistent filtered water quality than GMF.

V. ACKNOWLEDGMENTS

The authors thank Myo Min Cho, Alejandro De Eguiluz, Sarah Loder and Christian Sanders for their technical support in operating the pilot plant. The authors thank also GE Water & Process Technologies Australia.

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