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First year performance review of Magong UF/RO Seawater Desalination Plant

Verónica García-Molina[a*], Ronald Chang[b], Markus Busch[a]

[a]*Dow Water Solutions – Dow Deutschland Anlagengesellschaft mbH*
Tel. +49 7227 91 3775; email: vgarciamolina@dow.com
[b]*Dow Water Solutions – Dow Chemical Taiwan*

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ABSTRACT

The aim of this article is to describe the long term performance of one of the first Seawater Reverse Osmosis desalination plants with Ultrafiltration as pre-treatment. The plant in question is located in Magong (Taiwan) and has a current capacity of 5,500 m^3/day. In the near future this current capacity will be increased up to 13,000 m^3/day. The Magong desalination plant is an important example of how Ultrafiltration is a key component in seawater desalination plants to ensure sustainable and reliable operation of the downstream reverse osmosis installation. When the Magong desalination plant was initially started-up in 2002 it had a conventional pre-treatment. After six years of less than satisfactory performance, the conventional pre-treatment was replaced by a Ultrafiltration system. Nowadays the plant consists of a self-cleaning Filter, the Ultrafiltration units, Cartridge Filter and Reverse Osmosis lines. The Ultrafiltration system contains 7 racks, each with 60 modules DOW™ Ultrafiltration SFP2860. The Reverse Osmosis installation consists of a first pass using FILMTEC™ SW30HRLE-400 membranes and a second pass using FILMTEC™ LE-400 membranes.

During the first year of operation of the integrated system (UF + RO), the modus operandi of the Ultrafiltration has been optimized in order to ensure smooth operation and low chemical consumption. Thanks to this optimization the filtrate produced is of extremely good quality in terms of turbidity and the measured values of SDI_{15} and $MFI_{0.45\text{-}15}$ have been constantly below 2.1. Additionally, as a result of this optimization and of the stable performance of the Ultrafiltration, the Reverse Osmosis units have been operating according to the expectations, i.e., very low permeate flow loss over the first twelve months and perfectly achieved quality requirements. More in detail, the current Fouling Factor in all three Reverse Osmosis lines is around 0.85 and the salt content in the permeate is approximately 40% lower than the predicted value. It should be also emphasized that the Reverse Osmosis installation has been successfully run at a flux of 17–18 L/m^2h, which is much higher than the flux that a conventional pretreatment would have permitted.

1. Introduction

Integrated systems consisting of Ultrafiltration and Reverse Osmosis have been widely and successfully employed for the treatment of challenging waters such as polluted surface waters or municipal wastewaters. The application of such combination of technologies in seawater is however still limited to few plants, even though the general perception is that Ultrafiltration will soon be a key technology in seawater desalination. Two of the main aspects that have been conditioning the implementation of Ultrafiltration as a pretreatment

*Corresponding author

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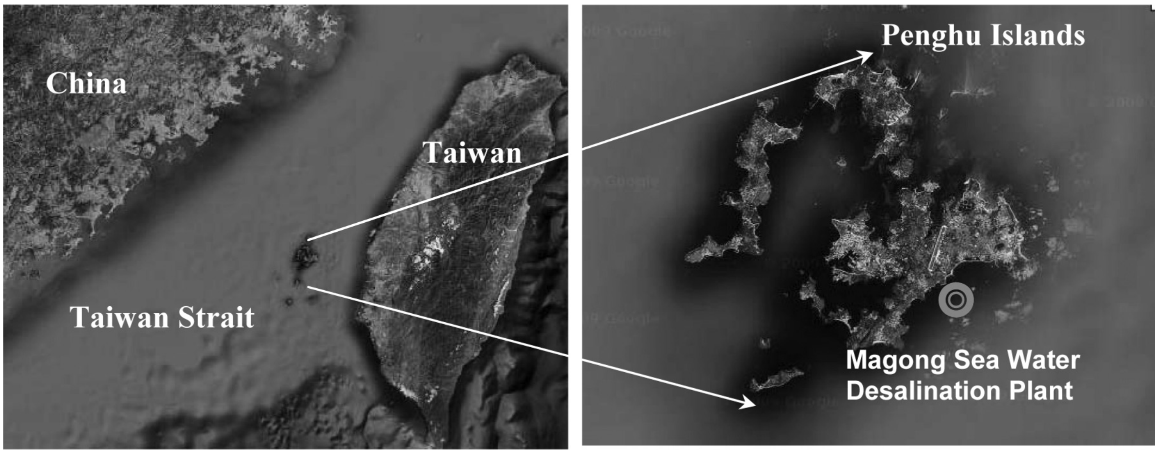

Fig. 1. Geographic location of Magong sea water desalination plant (from Google maps).

in seawater installations, despite the well-known benefits in terms of reliability and filtrate quality, are on one hand the traditional higher cost of Ultrafiltration compared to conventional pretreatment and secondly, the lack of combined systems key references. Regarding the costs, latest developments in membrane filtration systems have allowed higher permeability without compromising general performance, allowing thus, an important reduction in the capital costs. Literature data reveals that back in 2003 the cost of water of a seawater desalination plant with a capacity of 90,000 m^3/day and with a conventional pretreatment was 51.23 UScents/m^3 whereas with a membrane filtration pretreatment ranged between 52 and 53.85 UScents/m^3 [1]. The same publication however stated that the future projected cost for the membrane filtration system could decrease down to 47.23 UScents/m^3. More recent cost estimations [2] show an economical benefit in using a membrane filtration system and some authors have reported a decrease between 2 and 7% in the cost of ownership of a seawater desalination plant when operated with such pretreatment [3]. Estimating the economical benefits of a membrane filtration system as a pretreatment can be challenging, in the sense that some aspects such as longer reverse osmosis membrane life or lower fouling potential are difficult to quantify and to incorporate in any cost calculation. As pointed out by Busch and coauthors [4], a realistic and objective assessment, ideally based on side-by-side comparison with a conventional pretreatment, is needed to evaluate the potential advantage of an integrated system.

Regarding the currently available operating data, large scale experiences of integrated seawater systems are still very limited. There are however some key publications showing the operating data of such combined systems [4–6]. The first one is of special interest since 1,000 days operational experience of an integrated UF – SWRO system in Wang Tan Power Plant is described. This installation, with a capacity close to 8,000 m^3/day is one of the longest running SWRO plants with ultrafiltration pretreatment.

2. Magong UF-RO desalination plant background

The Magong sea water desalination plant is the largest sea water desalination plant in Penghu County, Taiwan, which desalts seawater for municipal use via RO membranes for around 50,000 people and other visitors to Magong Township. The plant is located in the Penghu Islands, in the Taiwan Strait between China and Taiwan in Asia (shown in Fig. 1).

A sea water desalination plant with 7,000CMD capacity was built and put in service in 2002. Its main treatment units included a sea water balance tank, horizontal multi-media filter (with sand and anthracite), 5 μm cartridge filter and reverse osmosis (RO) membrane system. Due to corrosion on high-pressure stainless steel pipes and severe fouling in RO membranes, the production of water significantly decreased after 4 years in operation. In order to provide sufficient and high quality water, and reduce operating costs as well, Taiwan Water Corporation (TWC), an authority for city water supply in Taiwan, decided to rebuild the old system and have a new expanded system which capacity is 5,500CMD. The new installation has been in operation since June, 2008, while the old one is under reconstruction. Therefore, the paper is focusing on the first year performance review of the new sea water desalination system.

2.1. Treatment process design

Further to the above mentioned treatment process, the new expanded sea water desalination plant and the

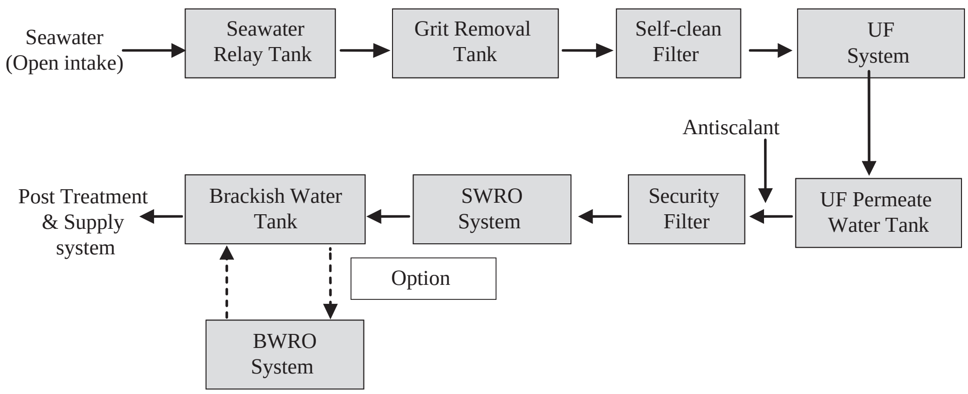

Fig. 2. Treatment process flow schematic.

old one after reconstruction will both employ ultrafiltration technology as pretreatment. A detailed scheme of the process flow is shown in Fig. 2.

The sea water is collected at 6 meters under sea level and channeled by gravity via a 300 meter pipe. After intake, the water is stored in a seawater relay tank and then pumped to a grit removal tank where coarse particles, sand and grit are removed by gravity. The water is then fed into self-clean filters with 130 μm screen to remove further impurities and safeguard downstream UF membranes from irreversible damage. The ultrafiltration system includes seven racks each with sixty DOW™ Ultrafiltration SFP 2860 modules. After the UF process, a break tank is used to store UF permeate water for backwash supply to the UF system and balance flow to the RO system.

Before SWRO unit operation, an antiscalant is added to prevent RO membrane from scaling. The security filters, with a 5 μm pore size, provide additional protection to the SWRO high pressure pumps and membranes. Most of the salt and undrinkable content in the seawater are removed in the first pass of the reverse osmosis installation. This first pass consists of 2 + 1 racks, each containing 29 pressure vessels with 7 modules FILMTEC™ SW30HRLE-400. Part of the permeate produced in this first pass is further treated in a second pass system to achieve the final content of Boron requirements (1.0 ppm). The second pass system includes two stages to achieve high recoveries. Eight pressure vessels are accounted for in the first stage and three in the second stage. Each pressure vessels consists of 6 FILMTEC™ LE-400 modules.

As described above the plant uses the separation component technology from Dow Water Solutions in the most critical unit operations of UF, SWRO and BWRO. The unit process design information is shown in Table 1.

Two photos of the UF and SWRO unit are shown in Fig. 3.

2.2. *Raw sea water quality*

According to the Environmental Impact Statement (EIS) and the Environmental Differential Impact Statement Analysis Report for the expansion project of Magong Sea Water Desalination plant, the feed water quality characterization is included in Table 2. This data was tested in the first quarter of 2005, in the first quarter of 2006 and the second quarter of 2007:

The quality of the seawater in the area where the plant is located has been also quarterly monitored from 2002 to 2008 by the Environmental Protection Administration (EPA), Taiwan. The results are summarized in Table 3.

Table 1
System information on unit operations in Magong

Unit operations	Total capacity (m^3/h)	Capacity per rack (m^3/h)	Number of racks	Component installed
Self-clean filter	960	320	3	
UF	960 (160)	160	6 (1)	DOW SFP-2860 UF, 60 modules/rack
SWRO system	230 (115)	115	2 (1)	FILMTEC SW30HR LE-400, 29V(7E)/rack
BWRO system	160	80	2	FILMTEC LE-400, 8V(6E): 3V(6E)/rack

Numbers in brackets indicate a standby capacity or rack.

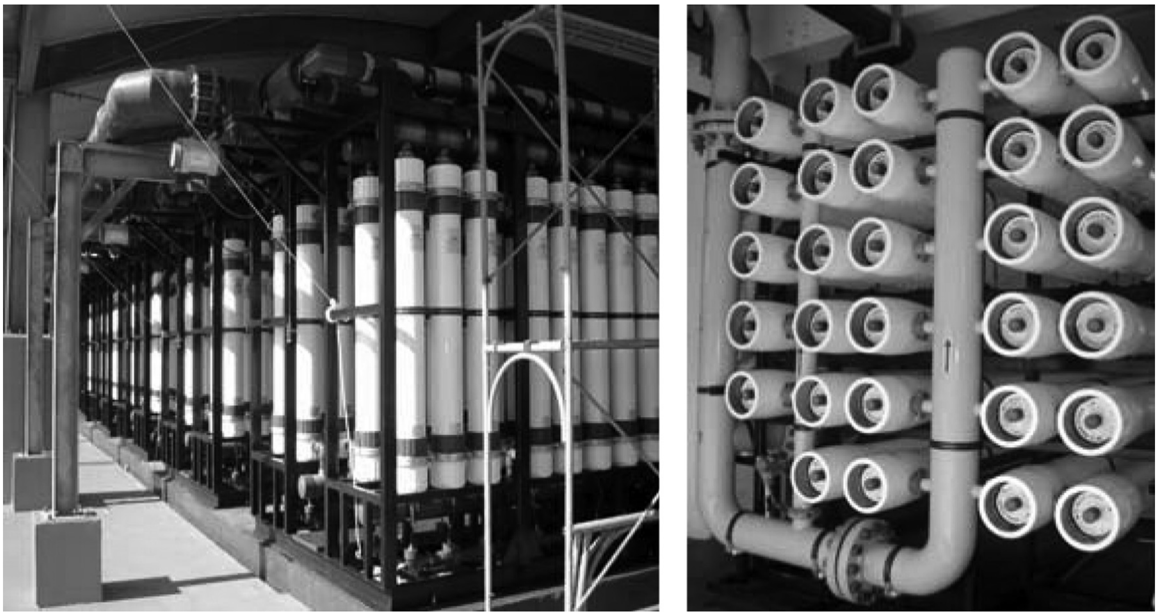

Fig. 3. UF (left) and SWRO trains (right).

A third feed water analysis carried out by Dow Water Solutions in October 2008 indicated a suspended solids content of 8.4mg/l and a TDS of 39,000 mg/l. SDI_5 was also tested in December 2008 and the result – 16.9 shows that the inlet water quality is very poor (the maximum SDI_5 is 20).

3. Operating Data Review

In this chapter the operating data since the start up of the UF + RO system is described. Data related to the quality of the UF filtrate produced in terms of SDI and MFI measurements is also included.

3.1. Ultrafiltration system

As previously indicated the UF installation consist of 7 racks with 60 modules DOW™ Ultrafiltration SPF2860 each. DOW™ Ultrafiltration SPF2860 module contains thousands of pressure driven outside-in hollow fiber membranes made from high-grade polymeric PVDF material and has a surface area of 51 m^2. The unit was designed so that one of the racks is in stand-by while the other six are in operation. The recovery of the unit is 90% and the design capacity of each rack is 160 m^3/h.

3.1.1. Operating protocol

The Ultrafiltration unit is operated without Chemical Enhanced Backwash (CEB) but with Backwash (BW) and Cleaning in Place (CIP). The BW is performed once every hour and consists of: 60 s air scrub, 20 s drainage, 40 s backwash top, 40 s backwash bottom and finally, 40 s of forward flush. The CIP protocols

Table 2
Sea water quality near Magong sea water desalination plant

Parameter	Unit	Water quality range
Temperature	°C	20.8–28.8
Salinity	(‰)	33.1–34.4
pH		7.9–8.2
BOD	mg/L	1.2–2.0
DO	mg/L	5.3–8.7
Coliform Group	CFU/100ml	10–35
pH		7.9–8.4
Hypochlorite	mg/L	<0.02

Table 3
Sea water quality near Magong Sea water desalination plant

Parameter	Unit	Avg. water quality	Water quality range
Temperature	°C	25.5	20.1–29.6
Salinity	(‰)	34.2	32.9–35.0
pH		8.2	8.1–8.3
DO	mg/L	6.6	7.7–7.3
SS	mg/L	–	<9.3

Remark: Data summarized from Taiwan's EPA web site.

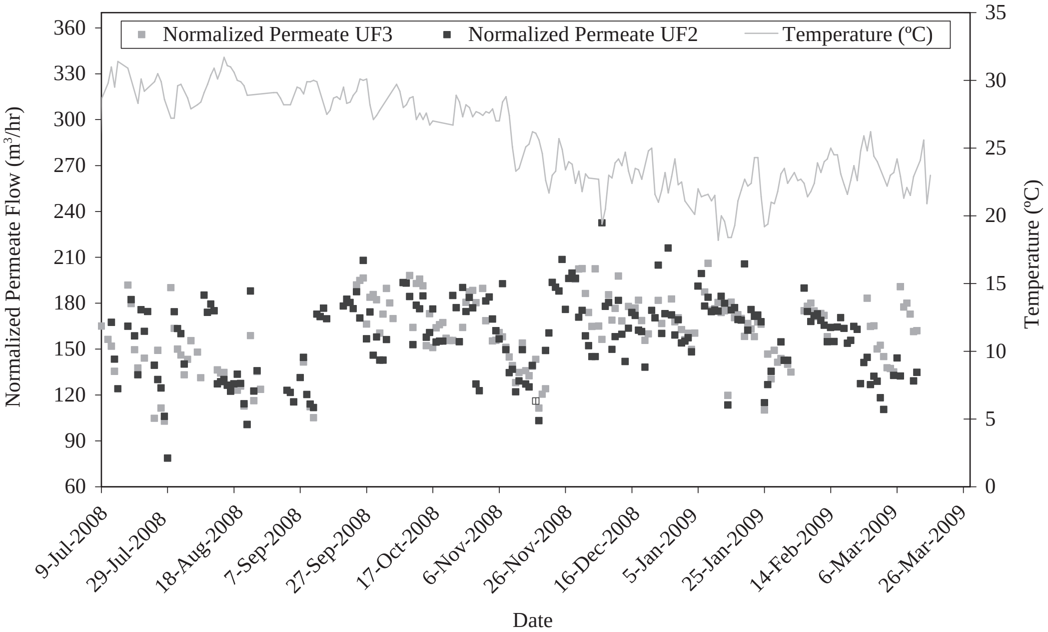

Fig. 4. Evolution of normalized UF permeate flow over time.

performed usually consisted of 1 h recirculation, 4 h soaking and 1 h flushing.

Regarding the CIP protocol, during the first months of operation, essentially from June to August 2008, the cleanings were performed with solutions containing HCl (0.4% w/w) followed by NaOH (0.1% w/w). Even though a certain improvement in terms of permeability was observed after each cleaning, the amount of flow restored was not sufficient and the values of the permeability of some of the units were fairly low (below 50 L/m^2hbar). It was then decided to try some alternatives, such as HCl (0.4% w/w) followed by NaOCl (0.2% w/w) and the combination of Oxalic Acid (2.0% w/w) followed by NaOCl (0.2% w/w). Applying cleanings consisting of HCl + NaOCl resulted in an increase in the permeability in those lines with low permeability up to approximately 80 L/m^2hbar. Additionally, the use of the third option, i.e. the combination of Oxalic acid and NaOCl resulted in an increase in the permeability of these specific UF lines up to 120 L/m^2hbar. When the UF system was started up the CIP frequency was high, i.e., once every two weeks on average, however, after the optimization of the cleaning protocol its frequency decreased to once per month.

Due to the high content in suspended solids and high SDI of the raw water, the Ultrafiltration is operated at a relatively low flux. During the first weeks of operation the flux was kept between 30 and 40 L/m^2h but after the optimization of the cleaning protocols, the flux was increased up to between 40 and 60 L/ m^2h under sustainable overall conditions.

3.1.2. Performance evaluation

In order to make a proper evaluation of the performance of the UF unit, a normalization has been applied to the recorded operating data. This is especially important to avoid a misinterpretation of the operating parameters, for example, due to the temperature fluctuations. In the case of Magong, the temperature of the feed water can oscillate between 20 and 30°C, depending on the season. Without a proper normalization, an increase in the temperature might be correlated with an increase in the permeability, which in reality remains constant.

In Fig. 4, the evolution of the normalized UF permeate flow of two of the UF lines is depicted. In this picture it can be observed that the normalized flow of both lines has been approximately constant between 150 and 180 m^3/h during this first year of operation. The normalized flow evolution gives an indication of the production of the lines but it does not reflect the feed pressure needed to maintain such UF permeate production, and thus does not reflect the real fouling tendency of the lines. In fact, the conclusion that can be reached from this figure is that the UF lines have been performing in a sustainable and reliable modus and that the required permeate production has been accomplished. Better information about the fouling

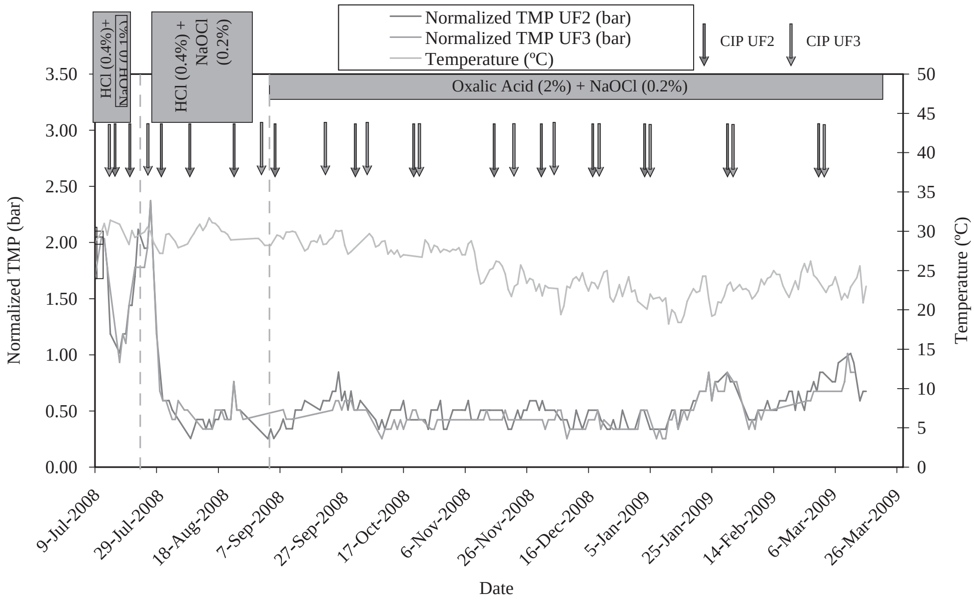

Fig. 5. Evolution of normalized TMP over time.

tendency should be evaluated from the evolution of parameters such as the normalized Transmembrane Pressure (TMP) and normalized permeability, shown in Figs. 5 and 6 respectively. It should be noted as well, that all normalized parameters (flow, TMP and Permeability) have been calculated using 20°C as a reference temperature. In the following plots, the evolution of the temperature is also depicted.

As previously indicated, in Fig. 5 the evolution of the TMP of two of the UF lines is shown. The figure also includes the CIP (cleaning in place) that have been applied to each one of these particular UF racks. In the figure it can be observed that the initial TMP was rather high and even though the CIP consisting of HCl and NaOH managed to substantially decrease the TMP from 2 to 1 bar, it rapidly increased back to 2 bar. Applying a CIP consisting of HCl and NaOCl

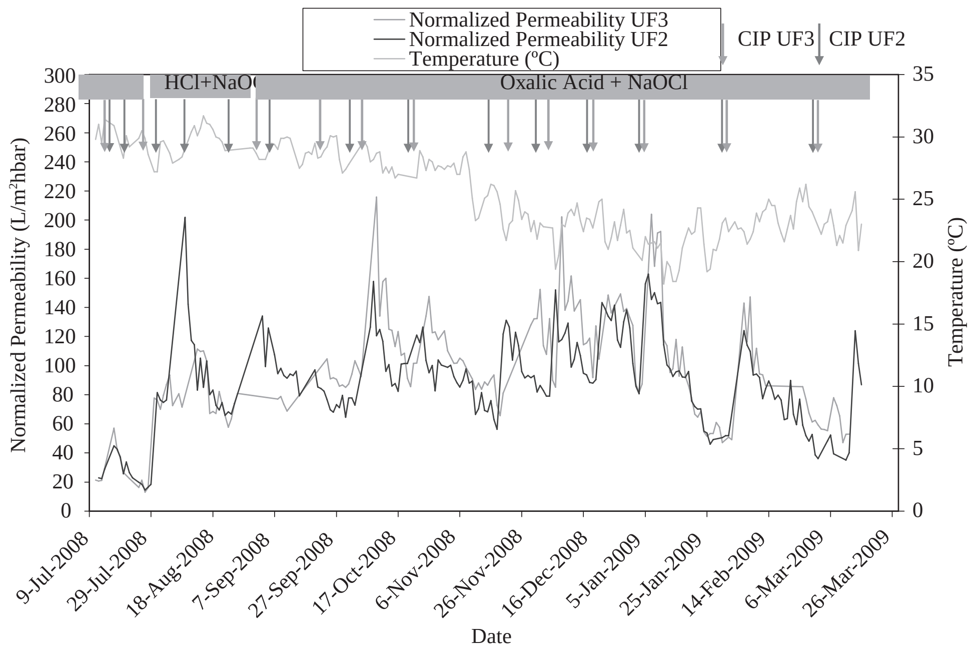

Fig. 6. Evolution of normalized permeability over time.

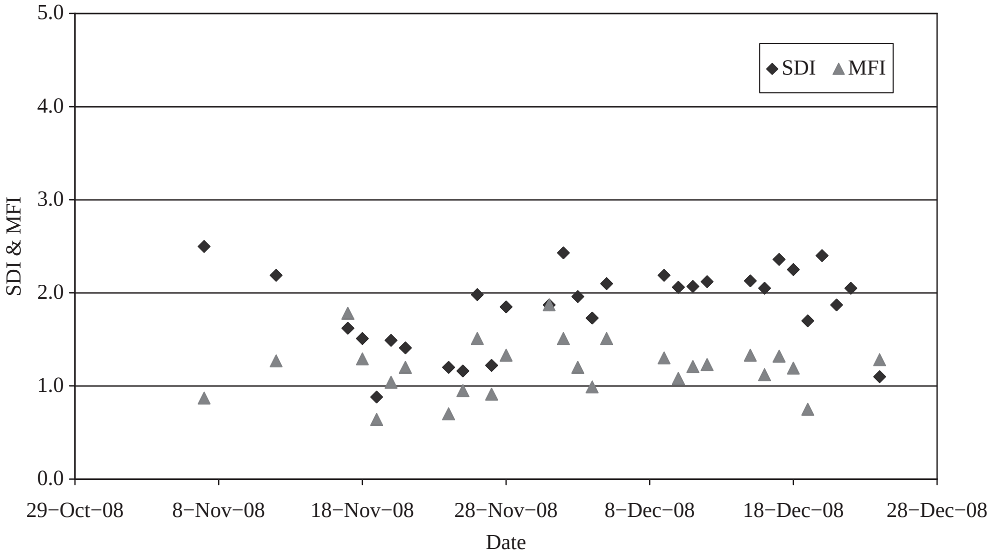

Fig. 7. SDI and $MFI_{0.45}$ at SWRO feed stream.

succeeded in decreasing the normalized TMP values from 2 bar to below 0.5 bar (31st July 2008). In September 2008, the CIP protocol was changed towards a combination of Oxalic Acid and NaOCl. Since then, the TMP of both lines has been properly maintained in values close to 0.5 bar. Since beginning of 2009, the frequency of the CIP applied have been decreased to once per month. As a result of this, slight increases of the TMP have been observed, however, the applied CIP have managed to restore the initial value of 0.5 bar.

In Fig. 6 the evolution of the normalized permeability over time is shown. This parameter is of special interest because it takes into account on one side the amount of UF filtrate produced and on the other hand the transmembrane pressures needed to achieve such production of permeate. As previously stated, during the first month of operation, i.e., July 2008, the required UF permeate production was attained but the transmembrane pressure was high. This fact can be also observed in terms of permeability in Fig. 6, where the permeability values during this period of time were fairly low. The cleanings applied based on acid and caustic solutions managed to increase the normalized permeability from 20 L/m^{2}hbar to 40 L/m^{2}hbar, but this improvement was insufficient. In the figure it can be observed that once the chemicals applied in the CIP were changed, the permeability significantly increased. More specifically, the combination of HCl and NaOCl succeeded in cleaning the fibers and an average permeability close to 100 L/m^{2}hbar was reached in each one of the two UF lines here evaluated during August-September 2008. The second change of the chemicals used in the CIPs, essentially resulted in a further increase of the permeability. In the figure it shown how after applying Oxalic Acid and NaOCl the permeability increased to an average value between 120 and 140 L/m^{2}hbar (period September 2008–January 2009). In January 2009 the frequency of the CIPs was decreased and consequently, the permeability dropped from initial values of 140 L/m^{2}hbar–60 L/m^{2}hbar before the next CIP was done. This figure provides significant information about the importance not only of the type of chemical to be used during the cleanings but also about the key role of the frequency of the cleanings. Optimization of these two parameters (chemicals and cleanings) can only be done with experience and having in-hand knowledge about the type of fouling affecting the UF fibers.

3.1.3. UF filtrate quality

The Ultrafiltration system has two goals to accomplish. On one hand it has to supply enough water to the downstream process, i.e., the RO lines, and on the other hand the quality of the filtrate produced has to be of good quality to ensure consistent and sustainable performance of the Reverse Osmosis.

Two of the commonly used parameters to asses the performance of the UF units are the SDI and $MFI_{0.45}$. In Magong desalination plant, these two parameters have been tested monthly at the permeate port of each UF rack since December, 2008. The SDI_{15} data has ranged from 0.7 to 2.1 with an average of 1.3 while the MFI $_{0.45\text{-}15}$ has ranged from 1.0 to 2.8 with an average of 1.9. These data show that all UF racks performed remarkable well.

Table 4
FILMTEC™ reverse osmosis modules specification at standard conditions

Element	Flow (gpd)	Rejection (%)	Standard conditions
SW30HRLE-400	7,500	99.75	32,000 ppm NaCl, 5 ppm boron, 800 psi, 25 °C, pH 8 and 8% recovery.
LE-400	11,500	99.3	2000 ppm NaCl, 150 psi, 25 °C, pH 8, and 15% recovery.

In addition to the above mentioned performance check, SDI and MFI $_{0.45}$ were daily monitored in November and December 2008. In Fig. 7 the SDI_{15} and MFI $_{0.45\text{-}15}$ of the RO feed stream are shown. These data reveal that the feed water quality of SWRO has been kept stable and good.

3.2 Reverse osmosis system

The Reverse Osmosis installation consists of two passes to ensure appropriate quality of the produced water. The first pass or seawater pass consists of three independent racks whereas the second pass or brackish water pass includes 2 racks. Each one of the seawater racks contains 29 pressure vessels with 7 FILMTEC™ SW30HRLE-400i elements. The brackish water unit has two stages to achieve high recoveries and contains 8 pressure vessels in the first stage and 3 in the second one. In each pressure vessel there are 6 elements FILMTEC™ LE-400 installed. In Table 4 the specification of the reverse osmosis elements operated in the plant is included.

3.2.1. Seawater reverse osmosis operation

The first pass of the reverse osmosis installation has been operating at a recovery between 44 and 45% and a flux close to 17–18 L/m^{2}h over the first year of operation. The evolution of the performance will be discussed in detail in the following chapter; however, it is remarkable that the three lines have been operated at a high flux in a sustainable way for many months. It should be then emphasized as well that the high flux operation has been possible thanks to the high quality of the UF filtrate.

3.2.2 Seawater reverse osmosis performance evaluation

The operating data of the seawater pass in the Magong desalination plant has been properly normalized in order to take into account possible fluctuations of external factors such as temperature or different recoveries rates that could lead to a misinterpretation of the results. In addition to the normalization, the operating data has been compared to Dow Water Solutions ROSA software projections to be able to complement the information extracted from the normalization with a comparison between real and predicted performance.

The comparison with ROSA has been made as follows: the operating data has been introduced in the software and the fouling factor has been iterated until the feed pressure predicted by ROSA coincides with the measured (real) values. This process provides then information not only of the fouling situation of the membranes but also about the performance of the membranes in terms of salt rejection. According to this evaluation, the fouling factor of the RO lines is approximately 0.85, which is actually a good indication of sustainable operation despite the high operating fluxes (between 17 and 18 l/m^{2}h). It is also important to emphasize that the salt content in the permeate produced is on average between 20 and 30% lower than predicted.

In Figs. 8 and 9 the normalized permeate flow and salt rejection of the three seawater reverse osmosis lines are shown. In Fig. 8 it can be observed how the normalized production of the three lines have been approximately stable over time and only a slight decrease of approximately 15% in the normalized permeate flow occurred during this first year of operation. After start-up, all three lines were producing between 130 and 140 m^3/h of normalized permeate flow. This value corresponds with a Fouling Factor of approximately 1. In January 2009, i.e., after 8 months of operation without having performed any cleaning, the normalized permeate flow of the lines had decreased to 100–120 m^3/h. A cleaning of the line A based on a caustic and acid treatment was subsequently carried out. The normalized permeate flow after the cleaning was close to 140 m^3/h, which indicates the CIP managed to restore initial conditions. The other two lines, i.e. B and C were cleaned with an acid solution (HCl) one month later. Even though, the normalized permeate flow slightly increased after applying the cleaning, the initial conditions were not restored. The results of the different cleaning protocols applied to the lines provide information about the existing type of fouling. Since the combination of NaOH followed by HCl restored the initial conditions in line A while the acidic cleaning was not too successful in lines B and C, the fouling of the lines might be of biological nature. A second cleaning based on a caustic and acid combination was applied to lines B and C at

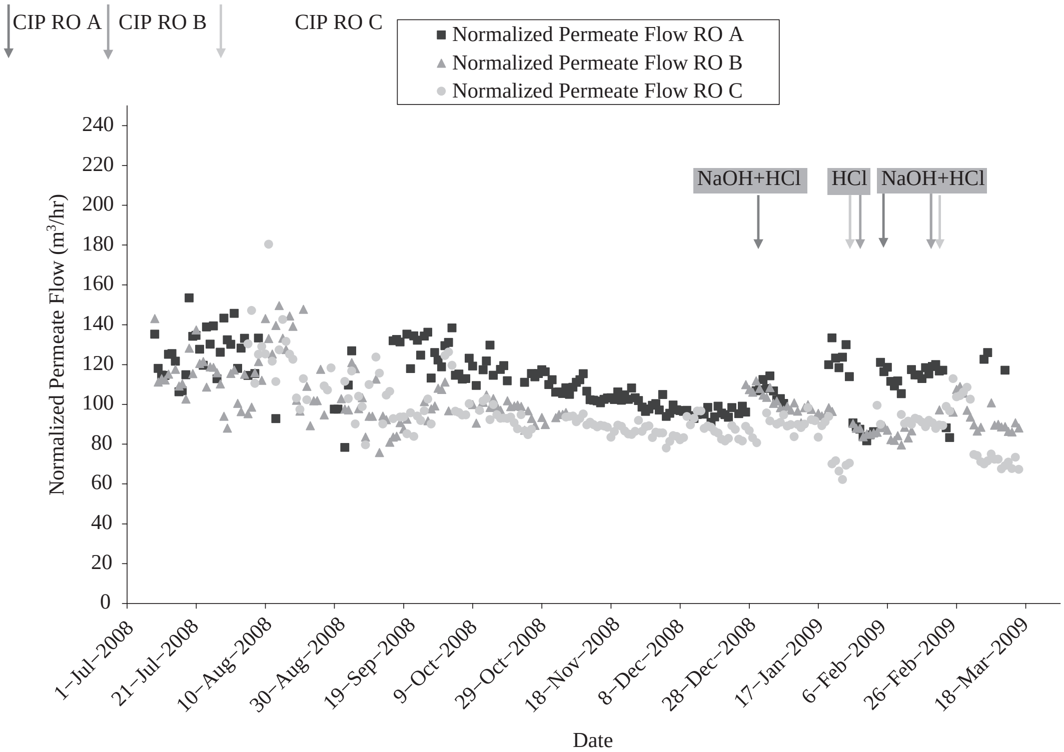

Fig. 8. Evolution of RO lines normalized permeate flow over time.

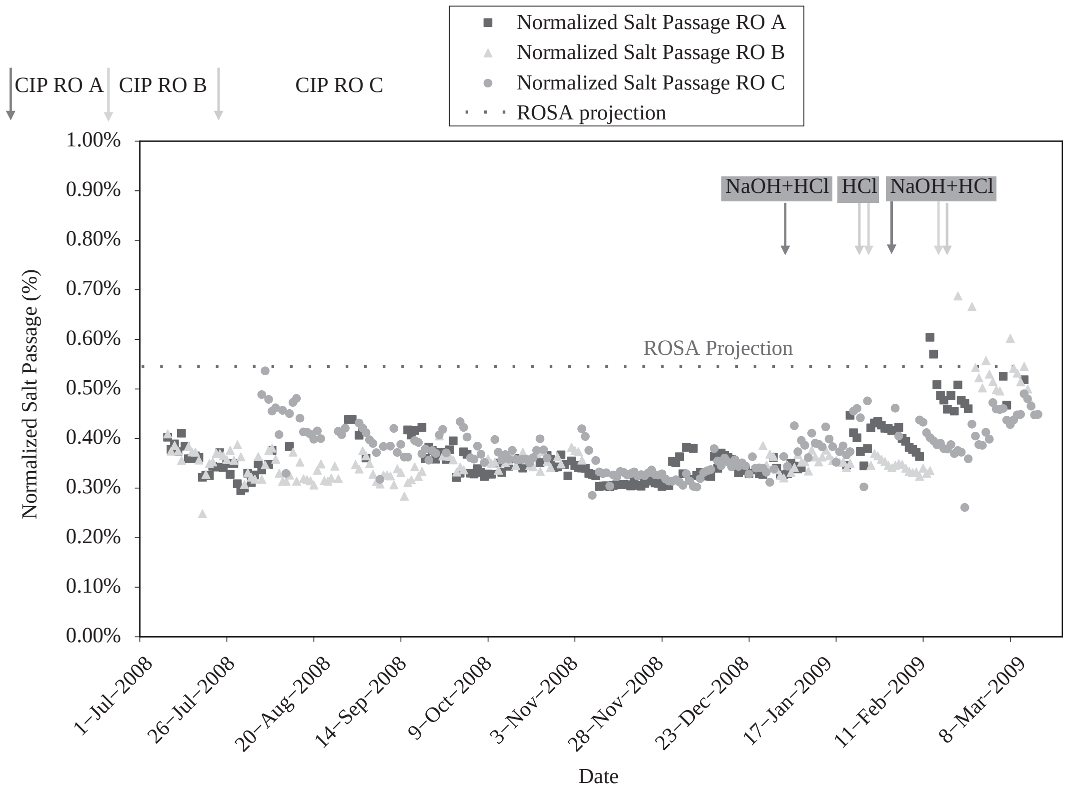

Fig. 9. Evolution of RO lines normalized salt passage over time.

the end of February 2009. After the cleaning, the initial normalized permeate flow values were attained.

All the cleanings performed in the Reverse Osmosis lines were performed at room temperature and included 1 h of recycling, 4 h of soaking and 1 h of recycling. Caustic cleanings were done at pH between 11.5 and 12 and acid cleanings reached a pH between 1 and 2.

In Fig. 9 the evolution of the normalized salt passage of the three reverse osmosis racks is shown. From this figure it can be concluded that the performance of the three racks in terms of salt rejection has been stable since the start-up of the units. In the figure, the normalized salt passage according to a ROSA projection is shown as well. Comparing the normalized ROSA projection salt passage and the normalized values from the three RO lines, it can be stated that the real salt passage through the membranes is approximately 40% lower than predicted. It should be pointed out, though, that after each one of the cleanings performed the salt passage experienced a slight increase. This is however expected since it usually takes sometime for the membranes to stabilize.

4. Conclusions

In this paper the successful performance of one of the largest desalination plants with UF pretreatment has been described. The plant was started up in June 2008 and consists of a Ultrafiltration system with 7 racks, each containing 60 modules DOW™ Ultrafiltration SFP2860 and a Reverse Osmosis installation consisting of a first pass with FILMTEC™ SW30HRLE-400 membranes and a second pass with FILMTEC™ LE-400 membranes. The current production of the plant is 5,500 m^3/day.

The operating process of the Ultrafiltration was optimized during the first months of operation, allowing a minimization of the cleanings performed and a subsequent operating expenses reductions in terms of chemicals used. It was proved that a cleaning protocol based on an initial oxalic acid cycle followed by a NaClO cycle attained the highest efficiency and managed to restore the initial conditions in terms of transmembrane pressure and permeability. Such cleanings also allowed the reduction of the CIP (cleaning in place) frequency down to once per month. It should be noted that the UF installation is operated with 1 backwash every hour but without CEB (chemically enhanced backwash). During this first year of operation the Ultrafiltration lines attained the established filtrate production, working at a permeability level between 120 and 140 L/m^2hbar and with a transmembrane pressure of 0.5 bar.

The constant good quality of the UF filtrate (SDI_{15} and $MFI_{0.45\text{-}15}$ below 2.1) has allowed to operate the first pass of the reverse osmosis installation at a consistent flux of 17–18 L/m^2h. In addition to the low fouling tendency of reverse osmosis, which currently present a fouling factor higher than 0.8, the salt content in the permeate produced by this first pass is on average 40% lower than the predicted value. Conventional cleanings based on an initial caustic cycle followed by an acidic protocol have proved to be successful in completely restoring the initial conditions in terms of permeate flow production.

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