Design, Operating and Research Experience at the Penneshaw Seawater Desalination Plant, South Australia

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Abstract

This paper provides a historical perspective of the plant, including performance problems and how they were overcome, as well as key learnings from selected process R&D studies. The South Australian Water Corporation (SA Water) is a wholly-owned public water utility, responsible for the management of water and wastewater supply, treatment and distribution infrastructure, for more than 90% of the state's population (~ 1.1 million people). Amongst its infrastructure, SA Water operates a 300 m^3/day seawater reverse osmosis (SWRO) desalination plant for the island coastal community of Penneshaw. Desalination was established as the most cost-effective supply option, when the existing source water, an open dam on a farmer's property, was deemed a very high microbiological risk to humans, particularly with respect to *Cryptosporidium* and trihalomethane disinfection by-product formation. SWRO was determined to provide lower cost water than constructing a new 60 kilometre pipeline to connect with treated water from an existing conventional water treatment plant in the mid-west of the island.

Built in 1998, the SWRO plant has provided an opportunity to develop a knowledge base for the design and operation of seawater desalination issues. Driven by the environmentally sensitive nature of the local marine environment, the requirement for the plant to be 'chemical-free' has resulted in numerous challenges for process design. The current operating recovery of the RO membrane system is low (by world standards), at 28%, in an attempt to mitigate calcium carbonate scaling. Mechanical integrity issues with the use of 15" diameter pressure vessels resulted in a shift to established conventional 8" RO membrane elements, with significant improvements in plant operation. An improved understanding of seawater corrosion issues and the critical importance of reliable and robust pre-treatment filtration and post-treatment conditioning systems have been positive outcomes from the various upgrades to the plant undertaken from 2001-2005.

In 2005 a research program was initiated to improve our understanding of the relevant fouling mechanisms of the open intake feed water on the RO membranes. The results confirmed significant biofouling activity, even with a pre-treatment system incorporating two stages of high intensity ultraviolet disinfection of the feed water. Pre-treatment efficacy was found to be reasonable, especially in light of the absence of coagulant addition. Most SDI measurements were below 4, with more than 50% below 3. Heterotrophic plate count analysis using marine agar yielded a removal efficiency near 90%. However, the removal of transparent exocellular particles was relatively poor for bacteria (< 5%). Removal of clumps was far more efficient (>85%). In relation to inorganic fouling, quantitative mass balances for key chemical species across the membrane system did not adequately predict the dominant inorganic foulants, when compared with the analysis of spent chemical cleaning solutions. An acid dosing trial to assess operational, water quality and environmental impacts from operating at a higher recovery (40%) revealed significant benefits.

I. INTRODUCTION

1.1. Site and Process Selection

Kangaroo Island is located approximately 120 kilometres south of Adelaide, separated by a 14 kilometre stretch of ocean at its nearest point (Figure 1). Penneshaw is located on the eastern side of the island (Figure 2). Historically, the potable water supply for the township of Penneshaw was sourced from a local, privately owned catchment reservoir. No treatment was provided, other than chlorine disinfection. Increased frequency of contamination from local farms, high concentrations of trihalomethanes (due to high levels of dissolved organic material), along with insufficient quantities of water, resulted in an urgent need to develop an alternative water resource. In 1996, a water supply investigation found that seawater desalination was the most cost-effective option for the provision of a safe and reliable source of drinking water. Four sites were investigated and the current site was chosen on the basis of the best access commensurate with deep water close to shore, good dispersion (based on plume modelling studies) and land availability.

During the project tender call and evaluation period, SA Water became aware of an innovative system developed by an overseas technology provider. The process was promoted as chemical-free, utilising an oscillating electromagnetic field (EMF) to mitigate scale formation and bio-fouling. In light of the pristine nature of Kangaroo Island and the promotion of the Island as an eco-tourism showcase, SA Water saw great potential for a chemical-free plant and this was supported by the state environmental protection agency (EPA). In the context of this project, 'chemical-free' is defined as no foreign chemicals being discharged to the marine environment in either the waste RO concentrate or the dirty filter backwash water.

1.2. Construction

Three Design & Construct contracts were let for the project:

- A civil construction contract for the site earthworks, road construction, seawater intake main and seawater pumping station, the concentrate outfall pipeline, and part of the rising main from the plant;
- The mechanical and electrical contract for the plant, plant building, tanks and associated pipe-work. The overseas EMF technology provider were to assist the Principal Contractor with plant installation and commissioning; and
- A final civil construction contract for earthworks to construct two 32 ML bulk storages, one of which was to be provided with a polyethylene liner and cover, and construction of the remainder of the rising main to the storage. The second storage may be lined and covered for future use if the desalinated water supply is extended to the township of American River (20 km west of Penneshaw).

1.3. Project Risks

The following risks were associated with employing chemical-free desalination technology, including:

- overseas manufacturer;
- anti-scaling device based on electromagnetic fields (minimal documented field experience); and
- corporate decision to 'break new ground' in this area.

Some level of comfort was gained by visiting several plants operating overseas with the EMF technology for seawater desalination. The project risk was mitigated to some degree by partnering of the technology provider with an Adelaide-based engineering firm (Principal Contractor). This would provide an opportunity to jointly develop and optimise process integration methods with the EMF technology.

Figure 1. Map showing Kangaroo Island in proximity to mainland and Adelaide (1: 1614008 @ A4)

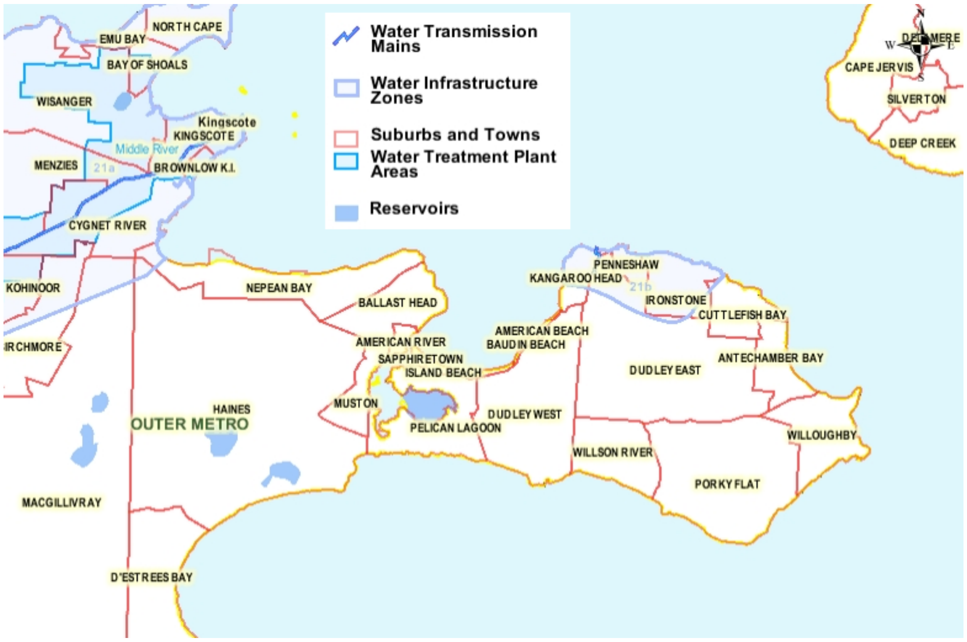

Figure 2. Map showing location of Penneshaw

There were some known but unqualified risks, including:

- seawater contamination;
- pre-treatment requirements;
- corrosion potential; and
- post-treatment requirements.

These risks were considered and plant design and construction proceeded on a capital expenditure versus risk basis. This was done with the knowledge that optimisation would be undertaken as learning history developed with site-specific conditions.

2. Plant Upgrade Design Experience

2.1. History

The initial installed plant utilised a close-coupled motor and pump-set, installed on the end of each pressure vessel (Figure 3). Although this configuration provided a modular design, the system suffered continual mechanical failures, including sheared keys, broken shafts, melted fans, high-pressure pump failures and significant leaks from the flexible pipe-work connecting the pumps to the feed and discharge manifolds. In addition, the pre-filtration equipment, which comprised a proprietary particulate filtration unit, did not perform as proposed. These problems were progressively addressed by the Principal Contractor. However, even with some plant modifications, ongoing reliability and product water quality requirements were not being achieved.

Figure 3. Initial RO plant skid showing close-coupled motors on each pressure vessel.

In May 2000, the RO skid was replaced with a new system, based on 15-inch vessels and membranes (Figure 4). The new plant required only 3 x 15-inch vessels instead of the 13 x 8-inch vessels in the original plant to achieve the same output capacity of 250 m^3/day. The pre-treatment system was simultaneously upgraded; comprising two multi-media filter vessels and two cartridge filters. System reliability continued to be low, with the following events contributing to plant downtime:

- pressure vessel failure;
- buckling of vessel end-plates and subsequent telescoping of the membrane elements;
- rapid head-loss build-up across the cartridge filters; and
- corrosion of the high-pressure pump units (primarily associated with 316 stainless steel pipe-work and pump components).

Figure 4. 15-inch RO skid

Following failure of the 15-inch pressure vessels, vessels with greater wall thickness were installed. However, within a few months problems also developed with these units. At this time, SA Water and the Principal Contractor jointly decided to completely replace the plant with a conventional RO system, employing 8-inch membrane elements. To ensure 'chemical-free' operation of the plant continued, the recovery rate was reduced from the original 40 percent in order to minimise membrane scaling. The new plant was sized for a slightly higher nominal output of 300 m^3/day, at a nominal RO recovery of 28 percent. The revised value was established, based on the flow-pressure operating limitations of the high-pressure pumping system.

The feed water was found to be supersaturated, with respect to calcium carbonate, based on calculation of the Stiff & Davis Saturation Index, SDSI (0.1-0.3). At 28% recovery, the range of SDSI in the RO concentrate was estimated in the range of 0.43-0.65. Hence, some degree of calcium carbonate scaling would be expected, particularly during summer. The objective of the pre-treatment filtration upgrade was to ensure compatibility with the higher feed flow within the available land area and endeavour to produce RO feed water of an acceptable quality (i.e. Silt Density Index, SDI < 5). Given the continuing low mechanical reliability, SA Water and the Principal Contractor applied the learnings to date to the design of a robust and reliable conventional RO plant, operating in a chemical-free manner, through the implementation of additional pre-treatment processes.

2.2. The Current RO Plant

The desalination plant (Figures 5a,b,c) consists of the following system components:

- Seawater Intake Main and Pump Station
- Seawater Filtration and Pre-treatment
- RO Plant & Energy Recovery
- Permeate Post-Treatment
- Concentrate Disposal.

A process schematic is illustrated in Figure 6.

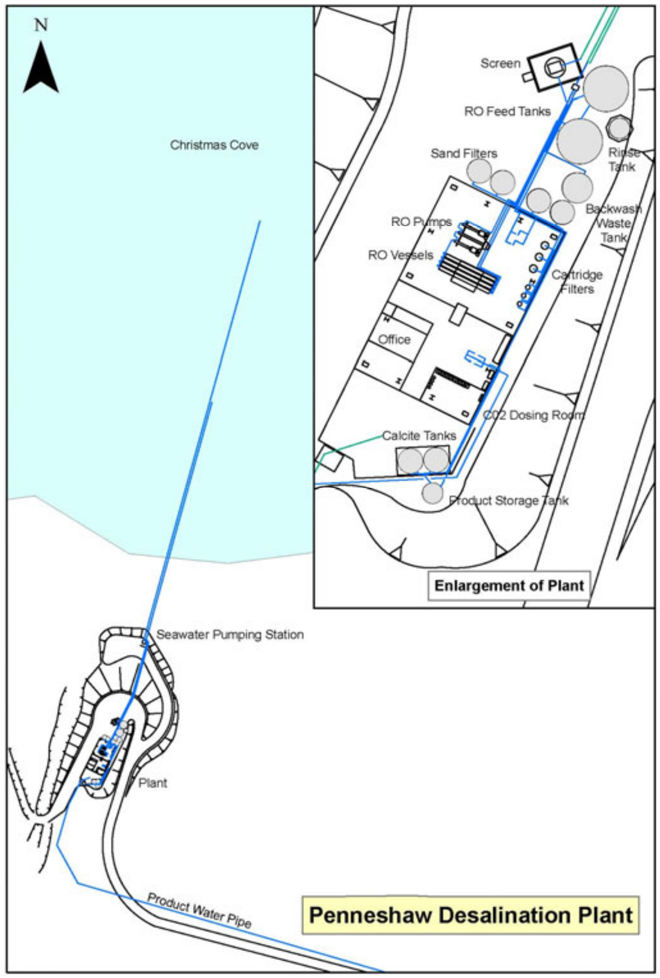

Figure 5a. Spatial view of main plant components

Figure 5b. Aerial photograph of Penneshaw desalination plant - 1

Figure 5c. Aerial photograph of Penneshaw desalination plant - 2

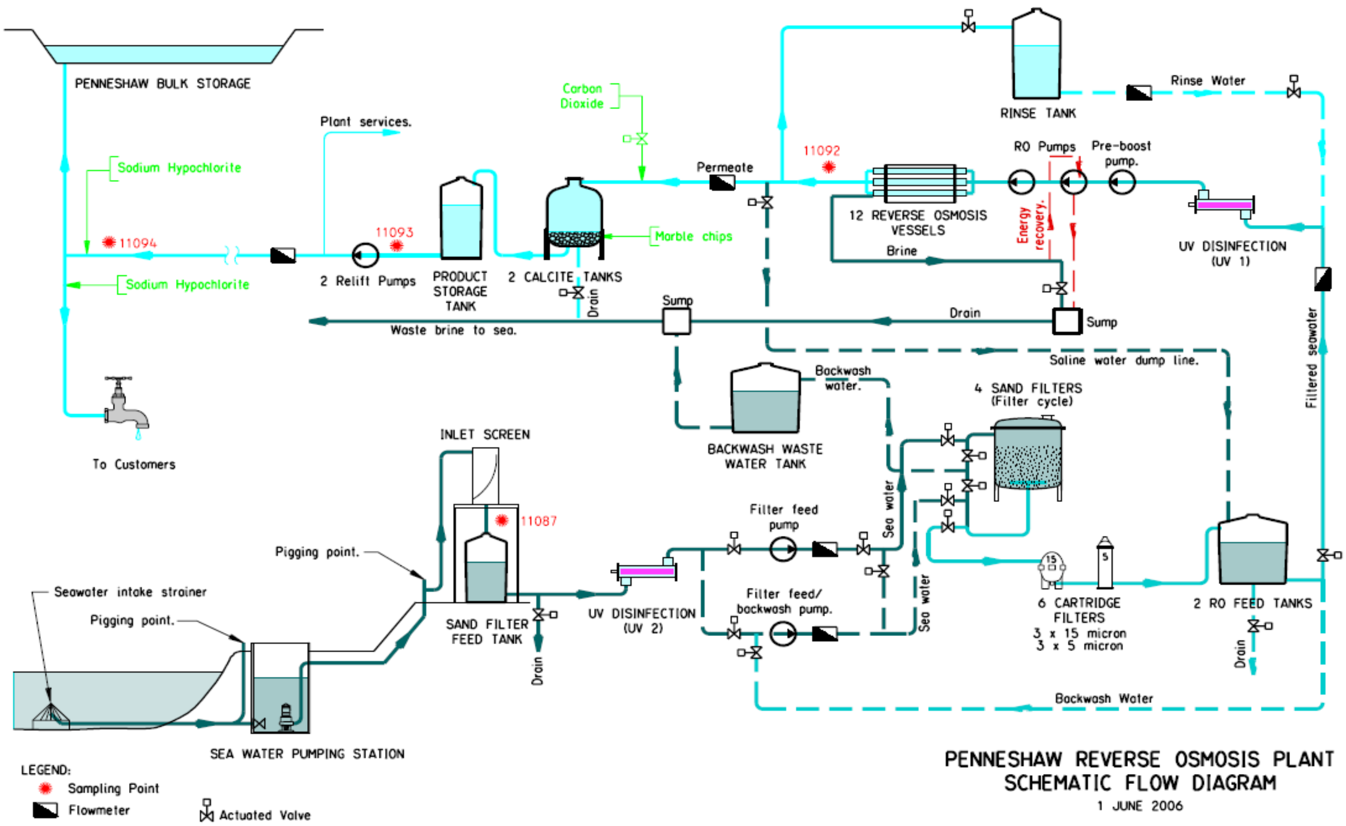

Figure 6. RO plant process flow sheet

2.2.1. Seawater Intake Main and Pump Station

The Seawater Intake Main extends 220 metres offshore with a coarse intake screen at a depth of approximately 8 metres (at low tide). The coarse screen prevents most fish and larger weed clumps entering the intake pipeline. The Intake Main is a DN280 high-density polyethylene pipe, weighed down by concrete rings at regular intervals. The main is laid on the seabed for part of the distance and then buried in the sand until reaching the Pump Chamber. Pigging facilities are provided for the Intake Main. This activity occurs every ~ 18 months, with a significant amount of biological material and suspended solids removed. The Seawater Pump Chamber is a vertical concrete pipe approximately 7 metres deep with a standard submersible sewage pump. The pump lifts the raw seawater to an overhead Contrashear™ wedgewire screen with an aperture size of 0.5mm. The screen removes small fish, seaweed and crustaceans. The variable speed drive maintains a set-point level in the Sand Filter Feed Tank.

2.2.2. Seawater Filtration and Pre-treatment

Following the screen, seawater is disinfected by a medium-pressure ultraviolet (UV) unit to minimise algal and microbiological growth in the media filters (Hanovia, UK). The disinfected seawater is filtered through four parallel multimedia pressure filters (1.5m diameter), each containing filter coal (0.9-1.1mm; 300mm depth), quartz sand (0.45-0.55mm; 500mm depth), garnet sand (0.3mm; 200mm depth) and graded gravel (500mm depth). The media was selected to ensure minimal mixing of the sand and filter coal media during filter backwashing. The media configuration was established in-house and has proven to be very effective, reflected in the significant reduction in head-loss build-up across the downstream cartridge filtration stage. No coagulant is dosed into the filters. Four filters were employed to reduce the filter loading rate and thus improve the quality of the filtered seawater. The design filtration rate is 6.3 m/hr, increasing to 8.4 m/hr when a filter is off-line for backwashing. Adopting as low as practicable filtration rate (based on available space) was considered the best method to produce an improved and more consistent filtered water quality. Filter backwashing is normally triggered by time (typically 48 hours). This set-point can be adjusted depending upon raw water quality.

The seawater is further filtered through 2x 15µm cartridge filters and 3x 5µm cartridge filters. The 5µm cartridge filter vessels each contain 7x 40-inch cartridges. The filtered seawater is stored in 2x 22m^3 closed feed tanks. The 15µm filters were in the original plant, but the need for finer filtration was identified as a key requirement for the plant upgrade. RO feed water is used for backwashing the multimedia filters. The backwash pump has a variable speed drive and flow meter to ensure that the correct backwash rate is achieved. Differential pressure transducers monitor the head-loss across the multimedia filters and each cartridge filter bank. Alarms are raised if the head-loss exceeds the set-point value. The multimedia filters are backwashed on a time basis, with an override for head-loss. Dirty backwash water is returned back to sea via the concentrate disposal outfall. In addition to being diluted by the waste concentrate, the dirty backwash water is discharged over an extended period of time, thus minimising the turbidity load at the outfall discharge point. Due to the absence of foreign chemicals in the dirty backwash water, this stream could be returned to the sea with the RO concentrate, through the open outfall.

2.2.3. RO Plant & Energy Recovery

The RO feed water is disinfected by a second medium pressure UV disinfection unit, located on the suction end of the high-pressure pumping station. At the time, in keeping with the theme of ‘chemical-free’ desalination, it was thought that UV disinfection would help control biofouling in the RO system. The high-pressure pump station consists of three pumps in series (Grundfos borehole pumps – 37kW rating), in order to achieve the required operating pressure for the RO skid. The pump drive systems were designed by the Principal Contractor to include an oil-lubricated thrust assembly, instead of a seawater lubricated system. The first pump operates under variable speed control to maintain the correct operating flow and pressure for the RO membranes, since the water temperature can vary from 12^{o}C (winter) to 23^{o}C (summer). The second pump is driven by an energy recovery turbine (i.e. Pelton

Wheel), which is fed by the pressurised concentrate stream from the RO membrane skid. The third pump is operated at fixed speed by an electric motor. To ensure smooth start-up, the fixed speed pump starts first, followed by the energy recovery turbine. The VSD-operated pump starts up last, whose function is to modulate the pressure of the feed stream to achieve the required permeate flow.

Energy recovery is critical to minimising the electrical power requirements of the plant. The Pelton wheel turbine typically recovers 28-30 kW of power (based on calculations using the speed of the Pelton Wheel and its characteristics). The net input power to the high-pressure pumping station is approximately 78 kW, yielding a normalised RO power consumption of 6.2 kWh/m^3 permeate.

The RO membrane skid consists of 12x 8-inch pressure vessels (Codeline, USA), each containing 4 membranes (TFC2822SS-Premium, Koch Membrane Systems, USA). Each membrane has a surface area of 300 ft^2 (27.9 m^2). These membranes were specifically selected since they are capable of producing a low salt permeate in a single pass (< 500 mg/L). Furthermore, the elements have larger feed spacer channels, which assist in reducing the rate of plugging (with particles in the filtered seawater) and maximising turbulence (for scale formation control). The vessels are arranged in an array 3 high by 4 wide, utilising the original skid frame.

Upon plant start-up, RO permeate is diverted to waste until the conductivity is less than 1,000 μS/cm. Following this, the RO permeate is diverted to the 5m^3 Rinse Tank, which is used for automatic rinsing of the RO membrane skid upon plant shutdown.

Following learnings from operational experience, in particular crevice corrosion of the original 316SS pipe-work, all high-pressure pipe-work was replaced with high corrosion resistant material. Corrosion was limited to weld zones, with 316SS machined components not found to have any problems. eg. valve bodies. These components were retained as 316SS. There was still some residual evidence of crevice corrosion under the rubber seals of the Victaulic style fittings used for pipe assembly. As a result, all 316SS fittings (with welded components) have been removed and replaced by either fully welded joints or SAF2205. Where such fittings are necessary for removal of membranes from the pressure vessels, special care is taken to ensure the metal and rubber surfaces are clear of imperfections that will allow seawater to enter a crevice. The fittings are also inspected after a membrane change-out and repaired if necessary. SAF2205 is becoming increasingly cost-competitive with 316SS, especially since thinner walled pipework is required to achieve the same strength. Together with the small quantities required, the cost of employing SAF2205 machined components was not prohibitive. Based on the critical importance of good welding practice to mitigate crevice corrosion, SA Water developed improved quality control on welds as well as welding qualifications and procedures.

2.2.4. Waste Disposal and Chemical Cleaning

The concentrate outfall pipe is a DN200 polyethylene pipe that extends 120 metres off shore, where tidal movement is sufficient for dispersal (based on an independent desktop dispersion modelling study prior to plant construction). Since the plant did not add chemicals to the feed water, a discharge license (with agreed monitoring and reporting requirements) from the EPA was not required.

There are no on-site membrane cleaning facilities. Off-site cleaning was considered more appropriate, for several reasons:

- eliminated the need for on-site chemical storage and waste disposal; and
- limited on-site space availability.

Two sets of membranes are employed, with one set stored in preservative (2%w/v sodium metabisulfite), while the other is in operation. Early during the plant upgrade project phase, membranes were cleaned on a quarterly basis, as a preventative measure. This practice ceased in 2004, with chemical cleaning frequency reduced to less than once per year, once an improved understanding of the system was acquired. Off-site cleaning is performed on the mainland, by a specialist membrane manufacturer, with access to trade waste disposal (via sewer) facilities. Off-site cleaning is significantly more expensive than on-site cleaning (nominally 10 times), but the specific site conditions at Penneshaw precluded the latter option. Based on early testing of spent cleaning solutions, calcium carbonate was identified as the predominant foulant, with evidence of biofouling.

2.2.5. Post-Treatment, Storage and Distribution

Due to almost complete removal of alkalinity and hardness, the RO permeate is highly corrosive. To mitigate corrosion in the reticulation system, as well as improve the taste of the water, alkalinity and hardness need to be added. The target pH range and alkalinity are 7.5-8.5 and 40-60 mg/L as $CaCO_3$, respectively. The post-treatment system consists of CO_2 dosing and filtration through 2x 1.9m diameter filters containing limestone (*calcite*). Flow through the filters is downward, with a maximum contact time of 40 minutes. The filters are slightly pressurised to minimise degassing, as a result of the supersaturated CO_2 permeate (0.5 bar gauge). The dissolved CO_2 reacts with the limestone to produce highly soluble calcium bicarbonate. The reaction simultaneously results in pH stabilisation of the permeate. The typical pH of the filter effluent is 8.2-8.3, with a Langelier Index of approximately -0.1. The limestone media is of high purity (>99%), having been washed, de-dusted, dried and packaged into 500kg bags prior to delivery. The major impurity is iron. Over time, the iron impurity accumulates at the base of each filter (as ferric hydroxide sludge). As a preventative maintenance strategy, an automated filter-to-waste mode is employed on a weekly basis during plant start-up to remove the accumulated impurity, which shows itself as a reddish-orange, turbid permeate stream.

The calcite filter effluent is stored in a 5m3 tank, which provides the suction head for the high-lift (14 bar) transfer pumps (duty/standby arrangement). These pumps transfer the conditioned permeate either direct to the distribution system or to the 32 ML lined (HDPE), in-ground covered storage tank (located ~ 600 metres from the plant), depending upon consumer demand. The water is disinfected using liquid sodium hypochlorite at two locations, depending upon the direction of flow: to the bulk storage, or combined storage water and plant water (when demand is greater than plant output). The target chlorine residual is 0.9 mg/L, for microbiological control.

3. Acid Dosing Trial

During April-May 2006, an acid dosing trial was undertaken to establish the overall impact (process, energy, environmental) of operating at a higher recovery (40%). Acid dosing is required to reduce the scaling potential associated with $CaCO_3$. The pH of the feed water was reduced from 8.1 to 7.3 using 67%w/w sulfuric acid (~22 mg/L). Acid was dosed upstream of the multimedia filters using an injection sparge, designed to effect rapid dissolution and minimise heat generation in the dosing zone. The membranes were replaced with a cleaned set prior to commencement of the trial. pH adjustment resulted in a lower CO_2 dosing requirement for the RO permeate (5 mg/L instead of ~ 20 mg/L) for post-treatment. This was a direct consequence of the increased concentration of dissolved CO_2 gas in the RO feed stream, which easily permeates through the membrane. Routine chemical analyses of the RO concentrate stream revealed no elevated levels of heavy metals (it was initially thought that a lowered pH could increase corrosion of metallic pump and pipework components within the plant) and a small increase in sulfate, consistent with the dosed acid. The pH of the waste concentrate was approximately 0.1 units higher than the RO feed stream, dissolved oxygen concentration was near saturation, approximately ~ 6 mg/L (indicative of no measurable reduction through biofilm contact in the RO membranes) and turbidity below 0.5 NTU (except during discharge of dirty filter backwash water). The EPA concurred that the chemical quality of the RO concentrate would not in itself result in observable environmental impacts. The outfall was designed for 45% recovery and product water production capacity of 500 m^3/day. The early dispersion modelling, based on an initial production capacity of 250 m^3/day, did not indicate that the low flow, higher salinity waste stream would cause problems, due to the high energy environment of the discharge zone and the absence of sensitive sea grass colonies (sandy sea floor).

During the acid dosing trial, the plant was operated continuously. It was clear that this mode of operation resulted in slightly lower permeate salinity, compared with start-stop operation. Operating continuously at the higher recovery resulted in a better water quality than a start-stop sequence coupled with the low recovery mode (28%).

Analysis of process performance data was performed using a proprietary software package, MASAR®, procured from MASAR Technologies, USA (www.masar.com). The software was custom-designed for the Penneshaw plant, based upon its configuration. MASAR® is able to predict the onset of long-term fouling more quickly than standard data-normalisation methods. e.g. ASTM D-4516 Standard Practice for Standardising Reverse Osmosis Performance Data. Critical model inputs include feed/permeate pressure, RO differential pressure, water temperature, feed/permeate flow rates and feed/permeate salinities. The model uses the data inputs to calculate a fouling monitor (FM) for each data set. According to the software developer, an FM of 0-3% indicates no significant fouling is occurring, 3-10% indicates low to moderate fouling may be starting to develop, 10-20% indicates moderate to heavy fouling is occurring, and over 20% indicates that heavy to irreversible fouling is occurring. The MASAR® fouling monitor trend throughout the acid dosing trial is shown in Figure 7. The following observations can be made:

- The FM ratio is always high when the plant is initially restarted. However, improvement occurs over time as the membrane operation stabilises. This equilibration period typically takes at least several days. There were two occasions during the acid dosing trial when the plant was restarted, and these can be clearly seen at around 14,600 and 14,775 hours, respectively, when the FM exceeded 100%.
- During the acid dosing trial, the average FM was about 27%. However, once the plant had stabilised following up to a week of continuous operation, the average FM was usually considerably lower than this, dropping below 10% quite frequently. This rarely, if ever, occurs under normal intermittent operating conditions, when the average FM is typically >40%.
- The erratic spikes in FM between 14,600 and 14,700 hours coincided with episodes of erratic variation in feed pH and flow rate. The results supports the theory that the membranes are adversely affected by variations in feed flow conditions, performing best when operated continuously. i.e. with minimal starts/stops.

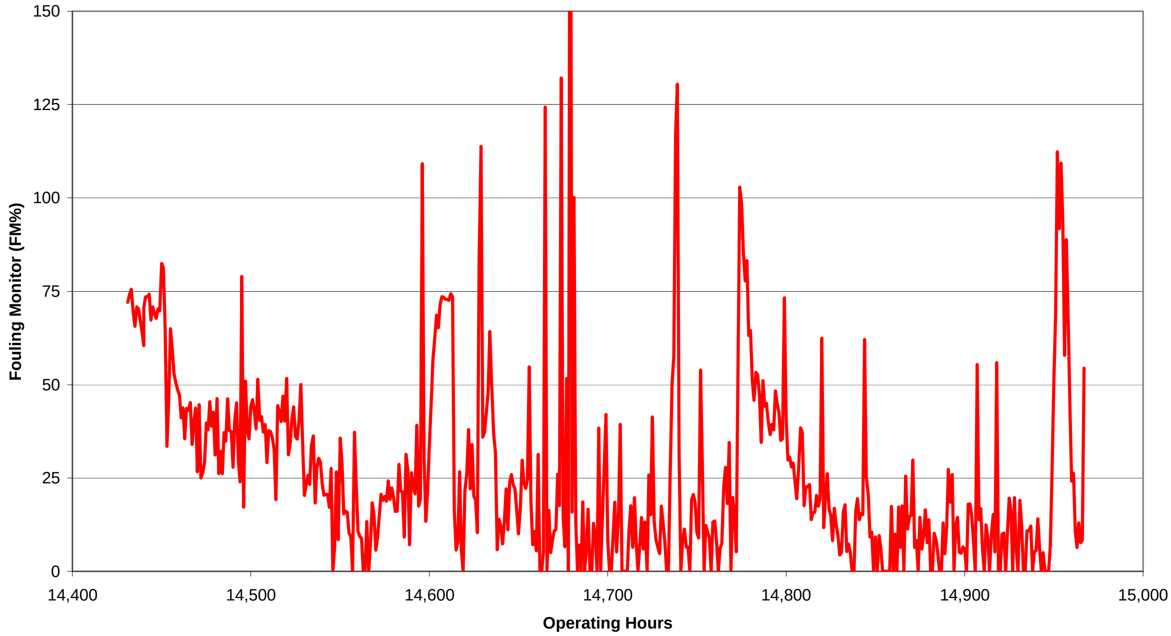

Figure 7. MASAR® Fouling Monitor during the acid dosing trial

A net reduction in energy consumption is one of the most important drivers for instigating acid dosing at Penneshaw. During normal operation total energy consumption (including sea water pumping, pre-treatment, RO processing, relift and electrics/electronics) has averaged about 8 kWh/m^3. During the acid dosing trial, this was reduced by at least 1 kWh/m^3. The actual energy saving was difficult to determine with high accuracy because the efficiencies of the RO feed pumps have been variable.

Based on an analysis of process energy efficiency, chemical cost consumption (H_2SO_4 versus CO_2) and an estimated 33% reduction in membrane cleaning frequency (due to reduced scaling potential), the estimated annual cost saving, based on 75 ML production was AUD$11,000. Increasing the acid dose to effect a pH of 7.0 in the RO feed water would eliminate the need for downstream CO_2 dosing of the RO permeate, potentially reducing the complexity of plant operation.

Intermittent plant operation was found to yield poorer overall water quality, with respect to salinity. However, significant power cost savings were obtained through this sub-optimal operating mode. This is a direct result of the lower off-peak power tariffs, which were approximately 65% lower than peak power costs (AUD$0.07 versus $0.20 per kWh). A high level economic analysis, based on the summer period, where warmer water temperatures result in increasing product water salinity and membrane fouling rates, revealed that despite its negative impact on product water quality, operating intermittently was more economical than continuous operation. Exceeding the product water conductivity limit for a short period (1-3 weeks) was possible during the summer-early autumn period, but not sufficient to override the energy cost savings. The analysis did not include the effect of intermittent operation on life cycle costs for key mechanical equipment, such as high pressure pumps.

4. Water Quality & Membrane Fouling Research Study

In June 2005, a 15-month R&D performance monitoring and evaluation program was initiated to evaluate plant performance and identify potential strategies to improve system operation. The study consisted of comprehensive monthly water sampling and detailed analyses to characterise water quality of key process streams (feed, after pre-treatment, waste concentrate, RO permeate and product). The data was used to perform mass balances across the RO unit and identify, if any, chemical or biological constituents were fouling or accumulating in the membrane system. A critical aspect of this program was to gain knowledge of membrane fouling issues.

4.1. General Water Quality

Table 1 summarises the water quality monitoring parameters, while Table 2 summarises the average and range of seawater quality. The relative proportion of the major ions (based on charge equivalent concentrations) is illustrated in the pie chart in Figure 8. Chloride and sodium are the dominant ions, followed by magnesium, sulphate, calcium and potassium.

Ion rejection across the single stage-single pass RO train was excellent (Table 3). However, as expected, boron rejection was significantly lower, at 72%. Unlike many other parts of the world where strict limits are placed on boron in the product water, here, the primary use of the desalinated water is drinking and not irrigation of boron-susceptible crops. e.g. citrus. The 2004 Australian drinking water guideline for boron is considerably higher than that in Europe and Japan (4mg/L versus < 1mg/L). As a result, there is no requirement (at present) to modify the RO plant to achieve a higher rejection of boron.

4.2. Pre-treatment System Performance

Pre-filtration performance was assessed as very good, with RO feed water turbidity observed to be consistently low despite varying raw seawater turbidity (0.3-10 NTU; normally < 1 NTU) and temperature (12-23^{o}C). Measured filtered water SDI results (Figure 9) have always been below the maximum allowable membrane manufacturer limit of 5, and less than 3 in approximately 50% of samples (average of duplicate analyses; 19 sampling events). Cartridge filtration had a small beneficial effect upon SDI (< 10%). The 5μm cartridge filters are typically replaced after 12-14 weeks of operation, which is very good, given that prior to the media filter upgrade, cartridge replacement frequency was 2-3 weeks.

With respect to microbiological quality, a variety of methods were adopted for characterisation. These included heterotrophic plate count (HPC), marine agar plate count and flow cytometry. Of these analytical tools, flow cytometry is the most sensitive, being able to detect culturable and non-culturable live bacteria. HPC results were generally '0' and not very useful. The Australian Water Quality Centre (www.awqc.com.au), a wholly owned business unit of SA Water, developed a different agar broth that was more suitable for saline water systems, since HPC analysis is normally confined to fresh drinking and municipal wastewater. The modified agar was able to detect measurable amounts of bacterial colonies in both the raw seawater and filtered seawater samples (Table 4). As expected, very large numbers of viable organisms were detected by flow cytometry, both in the raw and filtered seawater samples. The analyses confirm the limited information available from agar plate counts, since most bacteria (in fresh and seawater) are not culturable. Media filtration achieved approximately 75% removal. The observed increase following cartridge filtration is likely due to the 30 minute holding time within the RO feed tank, from which post-cartridge filtration samples are collected and where there is an increased potential for microbial regrowth. The cartridge filters themselves were not considered a significant source of microbial contamination, with the plant operator not observing slime or detecting septic odours during maintenance activities.

The presence of significant and measurable marine agar counts in the RO filtered water suggests that the raw water UV disinfection unit, which is designed to deliver a dose of 60 mJ/cm^2 (600 J/m^2), is not particularly effective. A review of the literature reveals a significant variation in the UV resistance of marine micro-organisms. For example, based on data from a study by Joux *et. al* [1] using a wide range of bacteria, inactivation rates for the range of raw water doses used at the Penneshaw plant ranged from 0-99%. Much higher UV doses (> 100-200 mJ/cm^2) are likely to be required to achieve an efficient biocidal effect. Even so, the reality is that only one micro-organism is required to pass through the pre-treatment system unaffected, and then attach and multiply within the RO membranes. UV irradiation may change the ecology of the microcosm that establishes on the membrane surface, but whether this results in a controlled biofilm or an out-of-control biofilm is not known. Further research is required in this area.

In May 2005, a review of the literature identified an additional parameter that could be used to establish the efficacy of the seawater pre-treatment system for removal of particles of biological origin. Termed transparent exocellular particles (TEP), they were discovered in 1993 when seawater was stained with Alcian Blue, a dye specific for acid mucopolysaccharides [2,3]. The particles ranged in size from 2-200 μm. TEP have been found in high concentrations in most marine and fresh water environments. TEP appear in many forms, including amorphous blobs, clouds, sheets, filaments or clumps. It is thought that TEP is an important initiator of biofilm formation on membrane surfaces. TEP are negatively charged polysaccharide particles. Being small and sticky, many of them carry resident bacterial populations.
In June 2006, following discussions with our senior microbiologist about the published methods for TEP measurement, it was agreed to undertake an initial TEP scan of various process streams from the Penneshaw plant. The TEP analysis was modified from the published method, with DNA-binding dyes employed instead of DAPI. The selected dyes allowed a differential count of live (membrane intact) and dead (membrane damaged) cells. Using these dyes, microbial counts could be performed by microscopy (as described in the referenced literature) or by flow cytometry (which is faster and has greater capacity for throughput). DAPI cannot be used for flow cytometry because it requires UV light for excitation and the flow laser operates at 488 nm. The initial TEP scan yielded the following observations:

- Post raw water UV (before media filtration) – live and dead bacteria present, with some clumps of cells and some large filaments (probably algae – not cyanobacteria).
- RO concentrate – live and dead bacteria, as well as some diatoms.
- Post multimedia filtrate – similar to the RO concentrate sample.
- RO permeate – a few dead bacterial cells.
- Distribution system – some dead cells (bacteria and diatoms).
- Product water storage – some dead cells (more than RO permeate).
- Raw seawater – many live bacteria, some clumps of cells, as well as algal filaments (with live and dead cells) and some big organisms (possibly worms or small arthropods).
- Filtered seawater (post-UV) – similar to Product Water Storage sample.

Based on these findings and the relatively low turbidity of all samples, it was agreed to collect samples for numerical TEP analysis. The calculated limit of detection was 1.1×10^7 cells per mL. Samples were collected in early July 2006 and the results are illustrated in Figure 10. Measured counts include both live and dead bacteria. i.e. total. It was reported that it was too difficult to do the live/dead count because the time it was taking to count was allowing the sample to quench, making it difficult to spot the cells. In future, one could use the flow cytometer to obtain a more accurate live/dead count, although this would be at the expense of not being able to measure clumps of cells. The removal of free bacteria across the pre-treatment system (multimedia filters, 2-stage cartridge filtration and two-stage UV disinfection) was poor, being approximately 10%. In contrast the removal of filaments and possibly green algae (designated 'other') and clumps (containing more than 5 cells) was greater than 90%. UV disinfection of the raw water (before filtration) did not reduce free bacteria or clump concentrations, but did yield 70% reduction in the filament concentration. The result is unusual and would require additional testing to confirm the initial findings. It is important to note that the analysis method measures membrane integrity only, so unless very high UV doses are applied, one would not expect UV exposure to change the integrity of the cell membranes. The findings confirm that the pre-treatment system is not very effective for the removal of TEP.

4.3. Chemical Mass Balances and Membrane Fouling

Macroscopic mass balance analyses across the RO skid was found to be an unreliable predictor of the predominant foulants, when the results were compared to the analytical data of the spent membrane cleaning solutions. Foulants, in decreasing order of prevalence (mass basis), are summarised below:

- Dissolved organic carbon (DOC)
    - much higher concentration in the lead element, consistent with biofouling
    - the DOC concentration of the feed water was very low (< 0.3 mg/L)
- Iron
    - accumulation was very significant, despite the very low concentrations of iron in the raw seawater (< 0.1 mg/L). This may indicate that corrosion of the plant infrastructure is presenting an added foulant loading to the RO membranes.
- Sulfate
- Calcium
- Magnesium
- Silica (reactive)
- Aluminium
- Manganese, and
- Strontium.

Table 1. Summary of monthly R&D sampling schedule

Analysis	Raw Seawater	Raw Water UV Inlet	Raw Water UV Outlet	Between MM & Cartridge Filters	Filtered Seawater	RO UV Inlet	RO UV Outlet	RO Permeate	RO Brine Concentrate	Product Water
pH	✓								✓	✓
TOC	✓									
DOC					✓				✓	
TDS (by evap.)	✓				✓			✓	✓	
Conductivity	✓							✓	✓	✓
Turbidity	✓									✓
Total Alkalinity	✓							✓	✓	✓
Total Hardness	✓							✓	✓	✓
TDS (by EC)	✓				✓				✓	
Langelier Index	✓								✓	
Chloride	✓							✓	✓	
Bicarbonate	✓							✓	✓	✓
Fluoride	✓							✓	✓	
Sulfate	✓							✓	✓	
Sodium	✓							✓	✓	
Potassium	✓							✓	✓	
Calcium	✓							✓	✓	✓
Magnesium	✓							✓	✓	✓
Barium	✓								✓	
Strontium	✓								✓	
Aluminium	✓				✓				✓	
Boron	✓							✓	✓	
Copper	✓				✓				✓	
Zinc	✓				✓				✓	
Iron	✓				✓				✓	
HPC (20ºC)		✓	✓	✓		✓	✓		✓	
BRP							✓		✓	
Nitrogen TKN	✓				✓				✓	
Phosphorus	✓				✓				✓	

Table 2. Summary of raw seawater ionic composition

ION		AVERAGE CONCENTRATION (mg/L)	RANGE (mg/L)
MAJOR ANIONS	Chloride (Cl^-)	20,900	20,300 – 21, 200
	Bicarbonate (HCO_3^{2-})	146	121 – 151
	Fluoride (F^-)	0.92	0.83 – 1.3
	Sulfate (SO_4^{2-})	2,890	2,740 – 3,040
MAJOR CATIONS	Sodium (Na^+)	11,400	11,000 – 12,300
	Potassium (K^+)	419	402 – 430
	Calcium (Ca^{2+})	420	406 – 449
	Magnesium (Mg^{2+})	1,390	1,320 – 1,490
TRACE METALS	Barium (Ba^{2+})	~ 0.005	<0.005 – 0.007
	Strontium (Sr^{2+})	7.3	5.91 – 8.76
	Aluminium (Al^{3+})	~ 0.08	<0.01 – 0.654
	Boron (H_3BO_3)	4.5	4.35 – 4.82
	Copper ($Cu^{2+/3+}$)	~ 0.02	<0.01 – 0.03
	Zinc (Zn^{2+})	~ 0.03	<0.03 – 0.05
	Iron ($Fe^{2+/3+}$)	~ 0.03	<0.005 – 0.136

[1] Boron is present in the un-dissociated boric acid form indicated here, rather than ionic form. However, the actual concentration of boron rather than boric acid is shown.

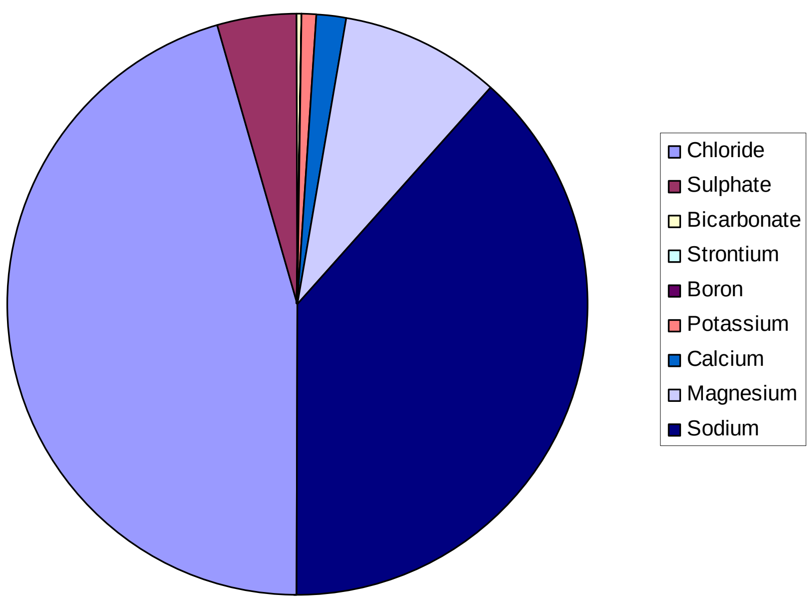

Figure 8. Relative ion charge composition of seawater

Table 3. Average rejection of major seawater ions by RO membranes

Component	*Raw seawater concentration (mg/L)*	*RO permeate concentration (mg/L)*	*Ion rejection (average %)*
Calcium	420	0.91	99.8
Magnesium	1,390	3	99.8
Sodium	11,400	119	98.9
Potassium	419	5	98.8
Sulfate	2,890	5	99.8
Chloride	20,900	192	99.0
Bicarbonate	146	7.9	94.6
Fluoride	0.92	<0.1	unknown
Boron	4.51	1.20	72.5
TDS (by calculation)	37,487	426	98.86

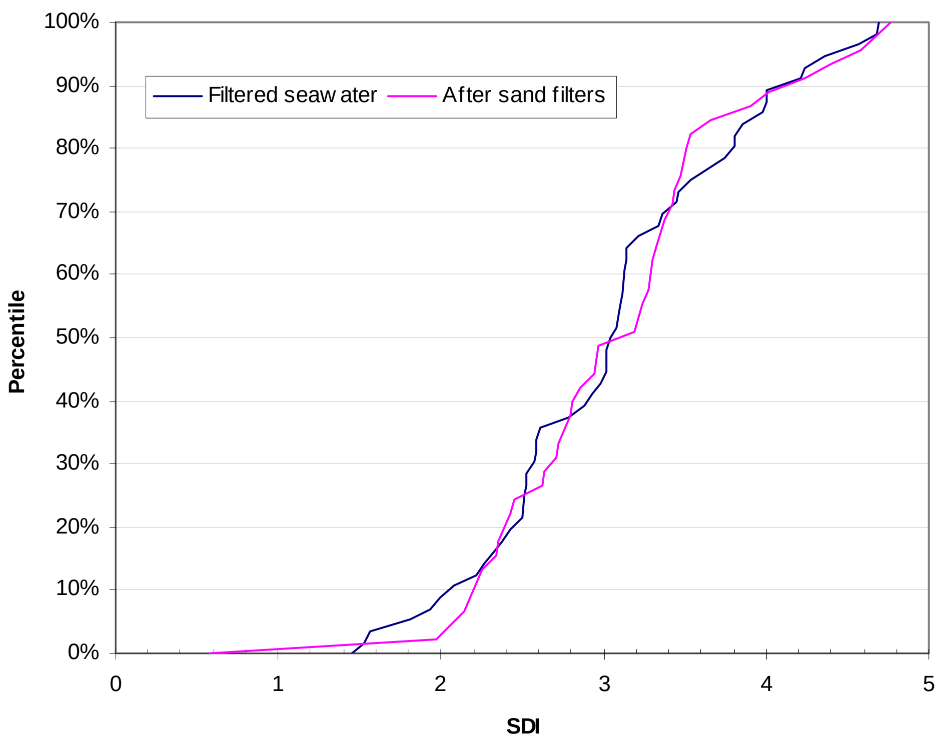

Figure 9. Frequency distribution plot of silt density index data (after media filters and after cartridge filtration)

Table 4. Microbiological analysis results (grab sample – 5 December 2006)

Location	*Flow cytometry bacterial count*	*Heterotrophic plate count (HPC 25ºC)*	*Marine agar plate count*
Raw Seawater	671,866	70.5	78.5
Post media filtration	176,057	0	26
Post cartridge filtration	183,409	1	10

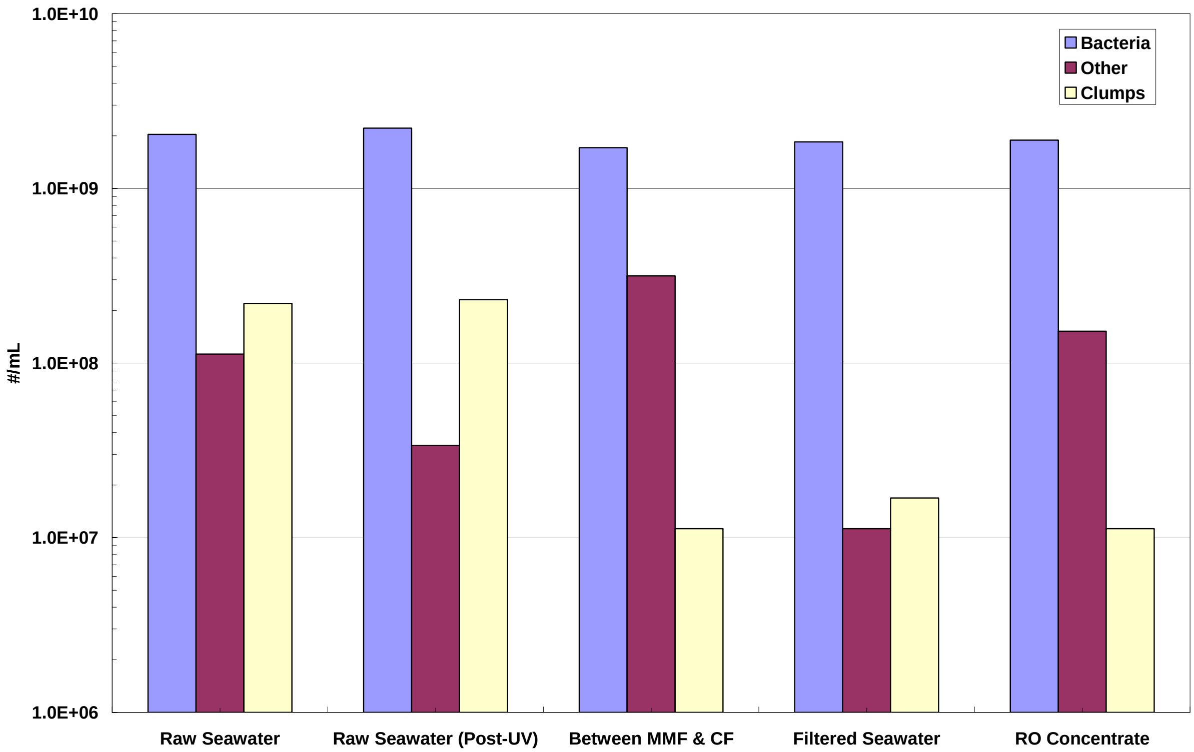

Figure 10. TEP concentration profile across the desalination process

Based on the inorganic ions in the bulk seawater feed, calcium sulphate and calcium carbonate were found to be the dominant inorganic scaling species.

Bacterial regrowth potential (BRP) analyses were performed during the study period in an attempt to confirm the presence and extent of bio-fouling. BRP analysis is normally used to study the effect of dissolved organic carbon on regrowth in drinking water distribution systems, based on fresh surface or groundwater sources. The focus of the test is the assimilable component of the dissolved organic carbon in the sample, using the indigenous bacteria present in the water sample of interest. This is the first application to examination of seawater samples. The initial hypothesis was that if biofouling is significant, the concentration of assimilable organic carbon should decrease through the membrane system, resulting in a lower BRP result for the waste concentrate (or brine) stream, even though the solution becomes progressively more concentrated as it flows through the feed side of the membrane elements. The RO permeate DOC concentration was negligible (<0.1 mg/L) confirming almost complete rejection and therefore accumulation on the feed side of the membrane.

BRP analyses were routinely carried out on RO feed water (post-UV) and RO concentrate. BRP results are reported as acetate carbon equivalents (µg Ac-C/L), derived from bacterial growth rates and changes in turbidity as a result of bacterial growth in test cultures, using sodium acetate-spiked clean water samples to generate a calibration curve. A water with a BRP of <40 µg/L is typically regarded as being biologically stable. i.e. not supporting bacterial regrowth. All tests were carried out in duplicate, with average results reported. Nutrients required for growth, other than DOC, including nitrogen, phosphorus and trace metals are enriched to excess. Water samples, filtered with 0.1µm polycarbonate filters are re-inoculated with a saline solution containing bacteria removed from the polycarbonate filter, to achieve a target starting turbidity of 0.02-0.04 ppm as SiO_2. Turbidity is monitored in real-time over a period of 5-7 days. Details of the BRP method are documented elsewhere [4].

Figure 11 illustrates the BRP results before (UV0001 out) and in the RO concentrate (brine). For most samples, the 'brine' BRP results were very similar to, or less than, the RO feed BRP. This observation lends support to the aforementioned hypothesis that biofouling is active in this system. Slight inhibition of growth due to the elevated salinity is confirmed by the slightly longer lag phase in the 'brine' samples (Figure 12). This illustration shows the turbidity growth profiles of a selected set of samples. B5 and B6 represent the RO feed water duplicate samples, while B7 and B8 represent the RO concentrate or 'brine' stream. The BRP of both the feed water and brine appears to have been higher during the warmer months (November – February). This may be due to changes in the character (e.g. molecular weight distribution) of the dissolved organic material, during the year, associated with changes in ocean currents between autumn and spring. This observation suggests that biogrowth is more prevalent during the summer months, not only due to the warmer water conditions, but also as a result of higher concentrations of bio-available organic carbon.

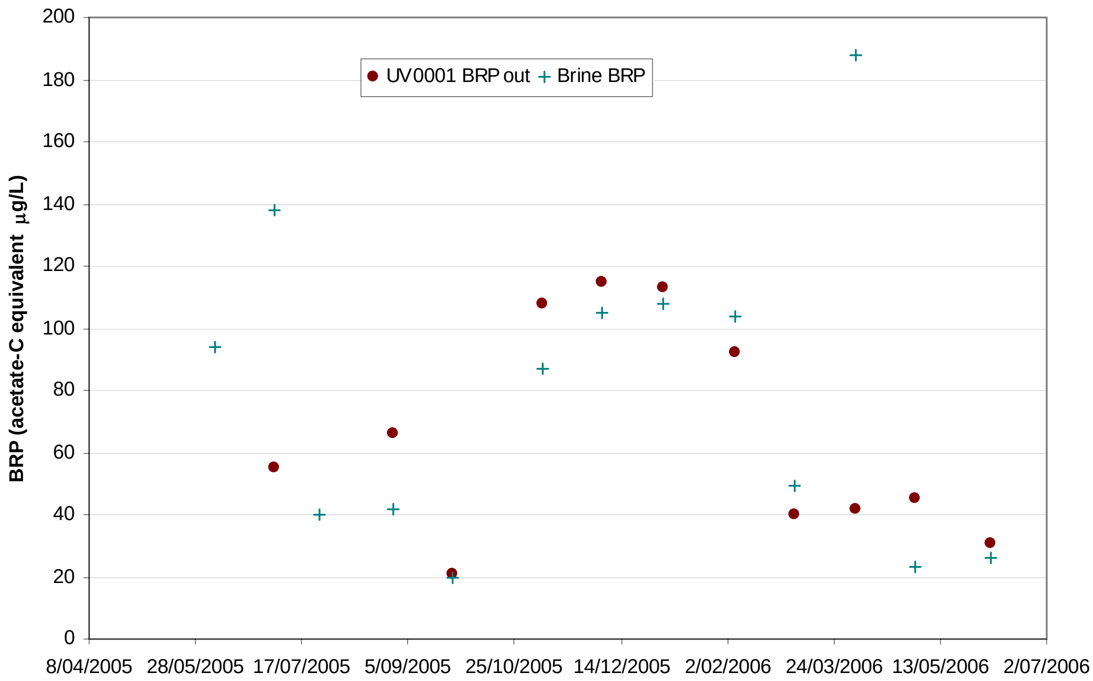

Figure 11. BRP profile (before and after RO)

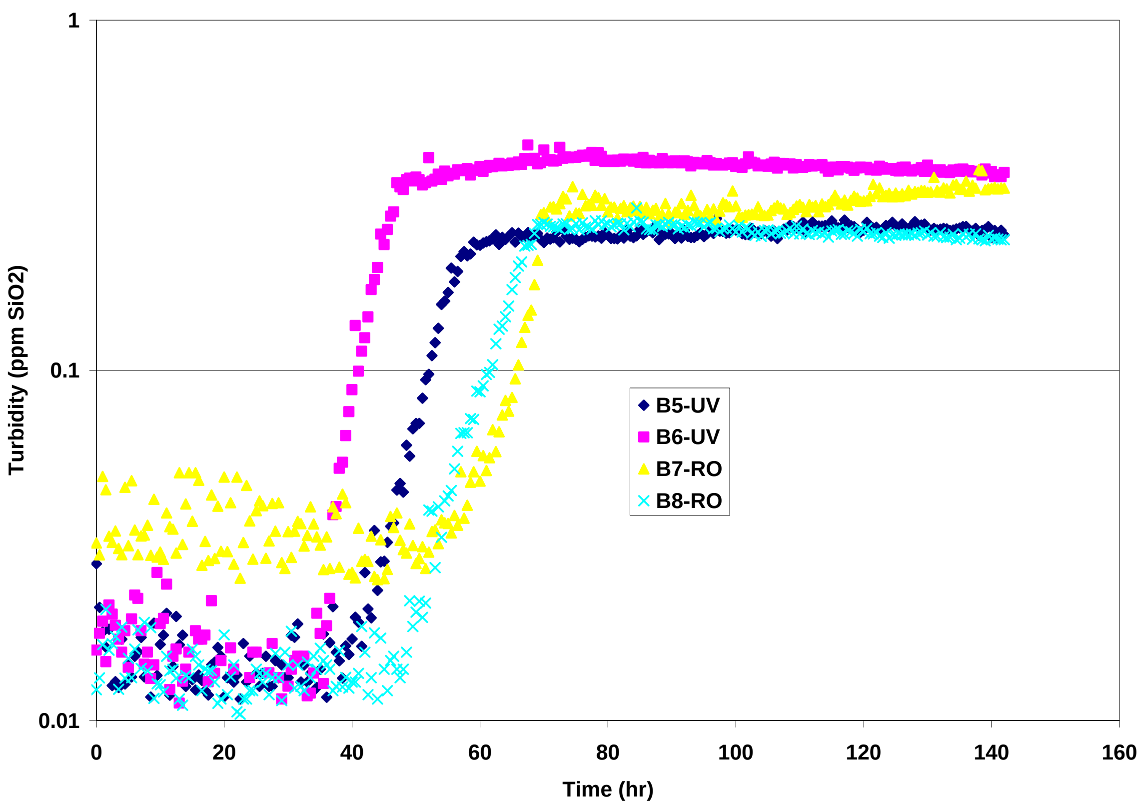

Figure 12. BRP turbidity profiles for a selected sample set (December 2005)

V. SUMMARY

The Penneshaw SWRO plant has provided SA Water with an excellent learning basis for the design and operation of a membrane plant. The 'chemical-free' nature of the process (with respect to pre-treatment) presented numerous challenges for process design. Although operating at relatively low recovery (28-30%), inorganic scaling by calcium sulphate and calcium carbonate, as well as iron were found to be significant. Biological fouling was prevalent in the system, and was indirectly verified through BRP measurements. Pre-treatment is critical to the performance of the system, with respect to achieving a reliable and consistent product water quality. It was found that although chemical-free pre-treatment yielded acceptable SDI results, very high concentrations of non-culturable bacteria still penetrate the filtration system. It is likely that cartridge filtration to less than 1μm would be required to effect any significant reduction in biological particles being fed into the RO membrane system. Although fouling was prevalent, chemical cleaning has only been required on a 12-month or 18-month basis, based on achieving product water quality requirements, particularly during the summer period. This suggests that there is an acceptable fouling tolerance for all systems, depending upon treatment requirements. Mass balance analysis across the RO skid did not reliably correlate with the characterised foulant material, as determined from the chemical cleaning solutions. Process monitoring, via the use of the proprietary MASAR software package for RO data normalisation is a useful tool for system performance assessment. Although intermittent operation yielded higher salinity product water than continuous operation, significant savings in energy cost were realised due to the much lower cost of off-peak power.

VI. REFERENCES

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