Implementing Energy Saving RO Technology in Large Scale Wastewater Treatment Plants

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Abstract

In an effort to address increasing water demands, a growing number of municipalities throughout the world are employing membrane technology to reclaim their wastewaters. Pilot studies, demonstration plants, and the use of membrane pretreatment have increased confidence in RO membrane technology for wastewater reclamation and fostered the design and construction of larger systems. In 2007, two of the world's largest wastewater reclamation plants using similar energy saving RO membrane technology will be commissioned on opposite sides of the Pacific. One plant, Orange County Water District's (OCWD) Groundwater Replenishment System (GWRS) located in Southern California, is expanding to 265,000 m3/d (70 MGD), while the other, Ulu Pandan located in Singapore, is producing 148,000 m3/d (39 MGD).

OCWD's GWRS is being implemented in two phases over a three year period. Phase I, commissioned in April 2004, consists of a single 18,900 m3/d (5 MGD) system. Lessons learned during two years of Phase I operation are being implemented in the Phase II operation of an additional fourteen trains to be commissioned in mid 2007. Each train of the GWRS is equipped with energy saving membranes in three stages to achieve 85% recovery at a flux of 20.4 lmh (12 gfd). Water produced from the RO is further treated using UV with hydrogen peroxide and used for groundwater recharge and coastal injection to protect the existing freshwater basin from seawater intrusion. The stability of the energy saving RO membranes has been demonstrated at this site during extensive pilot testing.

Ulu Pandan, commissioned in early 2007, is Singapore's fourth and largest wastewater reclamation facility. Each of Ulu Pandan's 13 RO trains uses an enhanced version of the same energy saving membranes installed at OCWD. The RO trains use a two stage design to achieve a recovery of 80% and flux of 11 gfd with the flexibility to increase to 20.4 lmh (12 gfd). RO permeate from Ulu Pandan is further treated with UV and delivered for indirect potable reuse and industrial water applications.

This paper will discuss the evolution of the design of these large scale wastewater reclamation plants using energy saving RO membranes. Lessons learned from years of piloting, demonstration plants, and full scale plant experience at both OCWD and UP will be presented. RO performance data, including permeability, differential pressure, and salt passage will be presented as well as analysis of RO elements from each site after extended operating periods.

I. INTRODUCTION

In 2007, two large scale wastewater reclamation plants, utilizing energy saving RO membrane technology, will be commissioned on opposite sides of the Pacific Ocean. The design of these plants reflects years of experience gained from pilots, demonstration plants, and full scale plants. They are part of an increasing number of larger wastewater reclamation plants which reflect the growing demand for new, unconventional water sources to support growing populations and diminishing fresh water sources. A common solution for water shortages is imported water. In many cases, water is conveyed great distances (even across international borders) to alleviate supplement limited local supplies. Imported water has typically been one of the more cost effective methods for increasing the supply to a water taxed region. The island nation of Singapore and Orange County of Southern California are two regions which have traditionally relied heavily on imported water.

Orange County Water District (OCWD), as a member agency of the Metropolitan Water District (MWD) of Southern California, relies on imported water from the Colorado River located over 150 miles away on the California/Arizona border. The imported water serves to supplement Orange County's overdrawn groundwater supply. The groundwater level reduction has led to seawater intrusion from the Pacific Ocean, which further reduces the usable local groundwater supply. Orange County has, for many years, been a pioneer in wastewater reclamation. Orange County's Water Factory 21, commissioned in 1975, used lime clarification pretreatment and cellulose acetate RO membranes to treat secondary effluent to supply water for a seawater intrusion barrier.

Singapore finds itself in an even more precarious situation in terms of water supply. The only natural source of fresh water for Singapore's 4.5 million residents is the annual rainfall, most of which is lost as runoff to the surrounding ocean . For this reason, a majority of Singapore's fresh water is imported from its northern neighbor, Malaysia. In an effort to decrease its dependency on imported water, Singapore has sought to develop alternative water sources, including the reclamation of wastewater using RO membrane technology.[1]

The design and operation of Orange County Water Districts (OCWD) Ground Water Replenishment System and Singapore's Ulu Pandan (UP) Waste Water Reclamation Plant draw on lessons learned from years of pilot, demo, and full scale RO plant operation. The experience at both sites has resulted in optimized RO designs that minimize operating costs while maintaining stringent permeate quality requirements. One of the most significant discoveries has been the ability of the energy saving RO membranes to perform as well as the low fouling membranes when treating the challenging secondary wastewaters. The use of energy saving membranes along with the control of fouling and the implementation of other cost saving technologies such as energy recovery devices and improved chemical pretreatment has served to reduce operating cost of these recently commissioned RO reclamation plants on both sides of the Pacific.

II. Source

Both the OCWD and Singapore's UP RO systems treat secondary effluent from municipal wastewater treatment plants. UP takes its source from the South Works and Liquid Treatment Modules of Ulu Pandan Water Reclamation Plant. This water contains 677 ppm of TDS with average phosphate (PO4) concentrations of 15 ppm and TOC of 12 ppm. OCWD obtains its secondary effluent from the Orange County Sanitation District located adjacent to the reclamation plant. OCWD has similar TOC concentrations but a higher feed TDS due to the already high salinity of the region's imported water supply – the Colorado River. OCWD water quality objectives include the reduction of TOC to less than 0.5 ppm and Total Nitrogen to less than 5 ppm as N. The UP primary permeate targets include a TOC level less than 0.1 ppm and an Ammoniacal Nitrogen concentration of less than 1 ppm as N. **Table 1** below compares the feed water of the two sites. Differences that impact the design and operation of the two plants include temperatures and phosphate levels. Though OCWD has twice the calcium concentration as UP, the phosphate levels at UP can be nearly five times that of OCWD. The higher temperatures at UP also contribute to a lower solubility of CaPO4 which in turn results in a lower recovery of 80% at UP compared to 85% at OCWD. Studies at OCWD (discussed in more detail below) have sought to optimize chemical pretreatment to better control calcium phosphate precipitation.

Table 1. Comparison of Ulu Pandan and Orange County Water District feed water.

Parameter	units	UP	OCWD
pH raw		6.8	7.6
pH feed		6.7	6
Chloramine	mg/L	2-3	2-3
Temp	mg/L	28-32	19-27
SDI	mg/L	<3.0	<3.0
Turbidity	mg/L	0.1-0.5	0.1-0.5
Ca	mg/L	36	77
Mg	mg/L	5	23
Na	mg/L	170	213
NH4	mg/L N	8	20.1
PO4	mg/L	15	2.7
Alk	mg/L CaCO3	72	264
Cl	mg/L	271	219
Floride	mg/L	0.6	1.1
Sulfate	mg/L	70	254
Nitrate (NO3)	mg/L	43	4
SiO2	mg/L	8.4	21.9
TOC	mg/L	12	10.5
Iron (Fe^{2+})	mg/L		0.22
Manganese	mg/L	n/a	0.05
TDS	mg/L	677	1167

III. Pretreatment

3.1 Microfiltration to control colloidal fouling

Colloidal fouling is one of the primary mechanisms of RO fouling in wastewater treatment. The source of the colloids is both mineral (i.e. aluminum silicate) and organic. To address the problem of colloidal fouling at OCWD and UP, both sites employ the well established practice in wastewater reclamation of using UF or MF membrane pretreatment. It has been shown that the use of membrane pretreatment reduces fouling rates and extends the life the RO membrane [2]. Membrane pretreatment provides the finely porous barrier necessary for removing colloidal material and large organics. Stable operation can be maintained with these membrane systems by using regular backwashes, air scouring, and regular chemical cleanings. The MF or UF pretreatments can reduce SDIs to below 2.5 and as low as 0.5. This compared to conventional pretreatment SDIs in the range of 4.5 to 6.0. The improved water quality and reduced fouling rate also leads to a lower cleaning frequency; increases the duration between RO cleanings by as much as four times.

The OCWD system employs submerged CMF-S polypropylene (PP) hollow fiber membrane pretreatment manufactured by US Filter while UP system utilizes pressurized MF polyvinylidene fluoride (PVDF) hollow fiber membranes produced by Asahi Kasei. Both MF systems are configured for outside-in operation. The PP fibers have a nominal pore size of 0.2 microns with an inner diameter of 0.39 mm and an outer diameter of 0.65 mm. Every 22 minutes, the system undergoes reverse filtration and air scouring to remove particles accumulated on the fiber surface. Every 21 days, the system undergoes a clean in place, including a three hour soak, to remove foulants not removed during reverse filtration. Feed to the MF is dosed with chlorine to maintain a 2-3 ppm chloramines residual through the MF to the RO. The residual chloramine in the feed to the RO serves to control biofouling in the RO element's feed/brine channels and on the RO membrane surface.

3.2 Anti scalant and pH adjustment to control scaling

Scaling in a wastewater system is most often caused by silica, calcium carbonate, or calcium phosphate precipitation. The understanding and control of silica and calcium carbonate scaling is well established and straight forward.

Calcium phosphate scale has traditionally been more complicated and more difficult to control. PO4 is a trivalent anion also known as orthophosphate. It is the typical, inorganic form of phosphorus found in wastewaters at concentrations between 3 ppm and 15 ppm. Phosphate can be problematic for RO systems when it combines with calcium to form tricalcium phosphate ($Ca_3(PO_4)_2$) scale with a fifth order reaction:

$$3\,[Ca] + 2\,[PO4] \rightarrow Ca3(PO4)2$$

$$\text{Saturation level} = \frac{[Ca]^3[PO4]^2}{Kspc}$$

Because tricalcium phosphate saturation is fifth order, small changes in free phosphate concentration, or even smaller changes in calcium concentration, significantly affect the calculated saturation level. Studies have shown that scale inhibitors alone are insufficient to control calcium phosphate scaling when pH exceeds 7.0 [3]. However, a reduction in pH will decrease the saturation level to a point where calcium phosphate specific antiscalants can effective.

Due to the combination of high recovery (85%) and high calcium concentration, pH to the RO at OCWD is reduced to 6.0. To optimize the OCWD system, studies have been conducted with the goal of operating at higher pH levels. These studies were done comparing the current antiscalant with six other antiscalants that specifically control CaPO4 precipitation. One of the six antiscalants tested allowed the RO system to operate at a pH of 7 with no calcium phosphate scaling. The cost of the antiscalant tested was 43% lower than the antiscalant currently in use. This, combined with the savings in acid consumption, was calculated to reduce annual chemical consumption cost to the RO by 62%. [4].

3.3 Chloramines to control biofouling

Secondary effluent is contains a high concentration of organic material and bacteria. This combination is conducive to biofouling of the RO membranes. Biofouling reduces membrane permeability and increases pressure drop through the feed channels – both of which lead to higher feed pressures and higher energy consumption. Biofouling is controlled by the presence of chloramines. Chlorine dosed into the feed streams at OCWD and UP combines with the 3 to 5 ppm of ammoniacal nitrogen to produce chloramines. Chlorine is known to oxidize the polyamide membrane leading to a doubling of salt passage within 3000 ppm-hours of exposure. Chloramines, however, are less aggressive. Polyamide membranes can tolerate up to 100,000 ppm-hrs before a doubling of salt passage occurs. OCWD and UP maintain a continuous chloramine concentration of 2-3ppm.

IV. Lessons Learned from Pilot, Demonstration, and Full Scale Plant Experience

Since the 1990s, both OCWD and Singapore have accumulated a wealth of data and experience on the design and operation of polyamide RO membrane systems for wastewater reclamation. Several different membrane types from at least three different membrane manufactures have been operated in pilot, demonstration, or full scale plants. The characteristics of membranes tested at either of these two locations during the past are summarized in **Table 2** below.

Table 2. Characteristics of polyamide RO membranes tested at OCWD and/or Singapore based on membrane manufacture's specification.

Membrane	Manufacturer	Area (sq.ft.)	Test Pressure (psi)	Test NaCl (ppm)	Flow (gpd)	Flow (m3/h)	NaCl Rej (%)
TFC-HR	Koch	400	225	2000	11,200	42.4	99.5
BW30-400FR	Dow	400	225	2000	10,500	39.7	99.5
XLE-440	Dow	440	100	500	12,700	48.1	99.0
LFC1	Hydranautics	400	225	1500	11,000	41.6	99.5
LFC3	Hydranautics	400	225	1500	9,500	36.0	99.7
ESPA2	Hydranautics	400	150	1500	9,000	34.1	99.6
ESPA2+	Hydranautics	440	150	1500	12,000	45.4	99.6

4.1 Orange County Water District Experience

The design of the OCWD RO system is based on years of pilot testing and demonstration plant operation. Extensive pilot testing occurred in OCWD between 2001 and 2002. The studies involved three different pilot units and five different membrane types from three RO membrane manufactures. The testing aided in the determination of a number of important design characteristics of the final RO system, including maximum recovery, chemical pretreatment and element selection.

One of the pilot units operating in 2001 and 2002 used 8 inch ESPA2 membranes in a three stage 6:4:2 array with 7 elements per vessel. Within three weeks of startup, the third stage of the pilot unit began to lose permeability and increase in salt passage – both characteristic of scaling. The membranes underwent a successful citric acid cleaning, but scaled again after resuming operation. Scaling was found to be caused by calcium phosphate. Following a second citric cleaning, the feed pH was reduced from 6.5 to 6.0 and the recovery was reduced from 87% to 85%, after which the demonstration unit operated stably for 5000 hours.

In addition to determining operating parameters, membrane selection was another important objective of the OCWD pilot studies. Though the basic chemistry is the same, variations exist in the surface properties of different polyamide membranes. These variations in surface charge, hydrophilicity, or surface roughness influence the extent of organic and colloidal fouling. OCWD pilot tested several different polyamide membranes, including low fouling and energy saving membranes. The principal differences between the low fouling and energy saving membranes are surface charge and degree of hydrophilicity. The low fouling membrane contains an additional neutrally charged layer on the existing negatively charged polyamide layer. These neutrally charged, highly hydrophilic membranes have been shown to reduce fouling when treating certain waste streams [5]. However, when piloted at OCWD, both membrane types experienced a similar initial flux loss of 25% before stabilizing. This early loss of permeability, typical of RO membranes treating secondary effluent, is caused by the deposition of organic foulants on the membrane surface. Once the initial organic layer is deposited, subsequent fouling proceeds at a slower rate [6]. The similar flux loss in both membranes suggests that the relative difference between anionic and cationic foulants is negligible in the OCWD wastewater. This discovery was beneficial for OCWD since the energy saving membranes showed a 30% higher permeability than the low fouling membranes and produced a similar permeate quality.

Beginning in April 2004, a 19,000 m3/d (5 MGD) demonstration plant was operated at the OCWD to supply reclaimed water for injection wells before and during construction of the 265,000 m3/d (70 MGD) system. The demonstration plant provided valuable lessons for the operation of the full scale plant. Within the first four months of operation, the membranes experienced severe biofouling which lead to a 40% loss in permeability and a 30% increase in differential pressure (Figure 1 and 2). A high pH cleaning reduced differential pressure and recovered 80% of the original membrane flux, but performance continued to decline soon after restarting the system. Additional high pH cleanings produced a similar cycle of improved performance followed by rapid fouling [7].

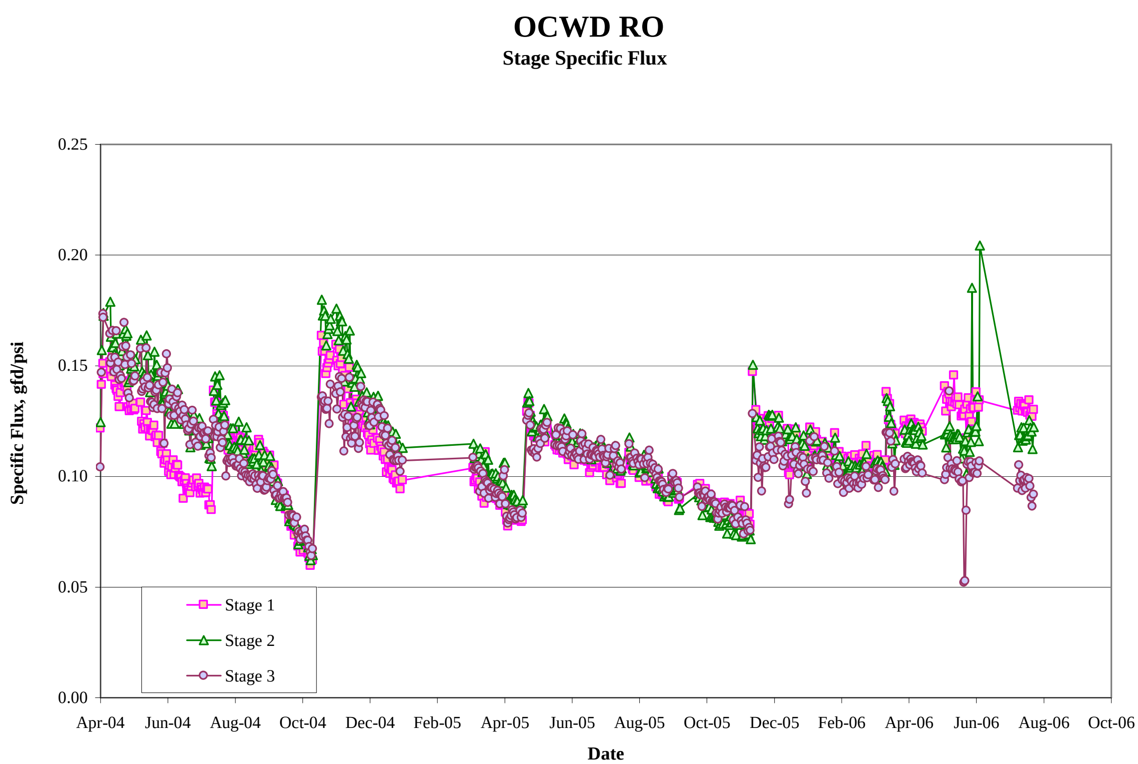


Figure 1. OCWD 5MGD RO Demonstration Plant – Stage Specific Flux.

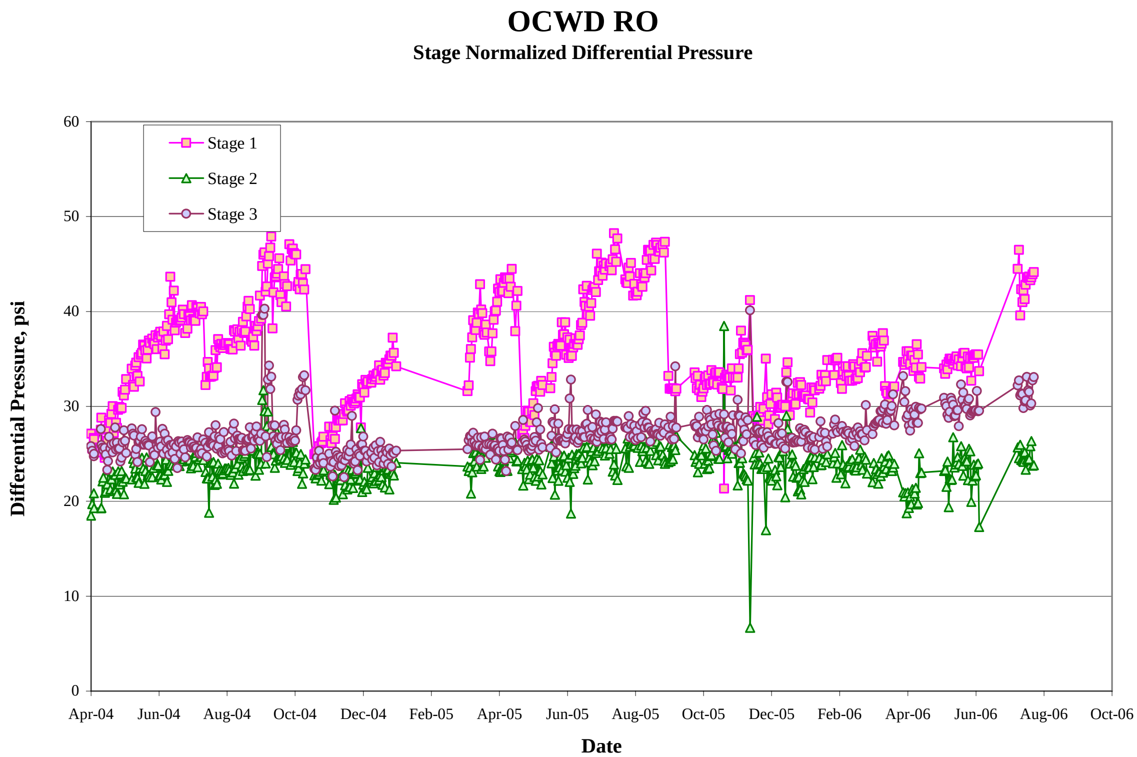


Figure 2. OCWD 5MGD RO Demonstration Plant – Stage Differential Pressures.

In 2005 and early 2006, several adjustments were made to the system to bring the rate of fouling under control. One modification involved eliminating an open air basin between the MF system and the RO system. Debris collected in the basin entered the RO system and plugged the lead elements. This was confirmed through lead element autopsies which revealed visible foulant embedded on the feed end of the element (Figure 3) and between the membrane leaves (Figure 4). [8]

Figure 3. Debris trapped between the seal carrier and the feed end of the lead element.

Figure 4. Debris trapped between the leaves of the lead element.

The pump station wet wells were also cleaned and disinfected. This reduced the high level of biological activity that was discovered in the RO feed through heterotrophic plate count testing. Before disinfection, plate counts in the feed were between 500 and 1000. The periodic failure of the chlorine injection system also contributed to the higher level of biofouling. Repair and closer monitoring of chlorine injection served to control the problem. By the end of the test period in August 2006, stable performance, comparable to early pilot studies, had been achieved.

4.2 Singapore Experience

Ulu Pandan draws on experience from two existing waste water reclamation plants in Singapore using RO membranes: Bedok (32,000 m3/d) and Kranji (40,000 m3/d). The Bedok demonstration plant, operated from 2000 to 2002, revealed the propensity of the three stage, 85% recovery design to fouling by calcium phosphate scaling [9]. Within the first ten days of operation, the system showed signs of scaling as evidenced by a loss of flux and an increase in salt passage in the third stage. Recovery was reduced to between 75% and 80% and a new anti scalant was tested. After these design changes, stable operation was achieved. First and second stages are cleaned twice a year while third stage cleanings are required three to four times per year. The findings from the Bedok demonstration led to the current UP design with a two stage array, seven elements per vessel and a recovery of 80%. Feed pH is reduced to 6.8.

Experience at Bedok and Kranji has demonstrated the successful performance of the low fouling membrane in treating secondary effluent. Similar to the OCWD pilots, the membranes lose about 25% of initial permeability before stabilizing within the first 1000 hours. Even with the successful results of the low fouling chemistry in Singapore, the Ulu Pandan RO uses energy saving membranes due to their lower pressures and proven performance at other wastewater reclamation sites such as OCWD.

Piloting for the UP site started on March 11, 2006, with a two stage, 4:2 array and seven elements per vessel. The pilot operated at conditions identical to that of the full scale system. However, unlike the full scale system, the pilot did not operate with the turbo booster. Approximately 30 psi of permeate throttling was applied to the first stage to simulate the presence of the booster. Seven months of specific flux and differential pressures can be seen in Figure 5 and Figure 6 respectively. As is typical of an RO treating secondary effluent, the first stage specific flux drops 20% during the first two months of operation and then stabilizes. This drop is caused by the deposition of an organic fouling layer on the surface of the membrane.

The differential pressure in stages one and two are stable during the first month of the study. However, a loss of chloramine dosing and subsequent biofouling caused the differential pressure in the first stage to increase rapidly. Without chloramines, the differential pressure in the first stage doubled in twenty days. When chloramine dosing was resumed, the differential pressure dropped slightly but stabilized 50% higher than the initial 1.7 bar (25 psi), suggesting that the chloramines hindered further growth but removed only a fraction of the existing biofilm. Because chloramines act as a biostat, not a biocide, they do not completely breakdown and remove the biofilm. Even a caustic cleaning in early August did very little to remove the biofilm.

A second increase in differential pressure over a period of four weeks occurred approximately 40 days after the first upset had been corrected and stabilized. This time, the increase was more pronounced in the second stage. This upset in the second stage differential pressure was accompanied by a drop in specific flux and an increase in salt passage; all signs characteristic of scaling. In early August, a caustic cleaning followed by citric acid cleaning returned the second stage differential pressure to less than 20 psi where it remained for the next three months of operation.

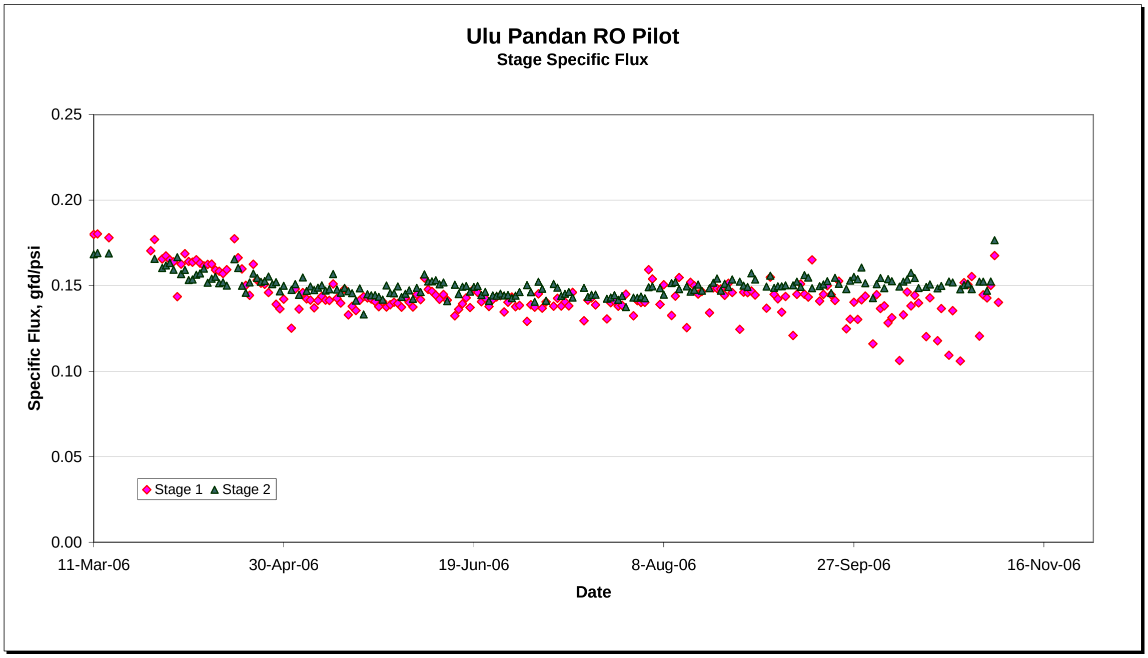


Figure 5. Ulu Pandan RO Pilot – Stage Specific Flux

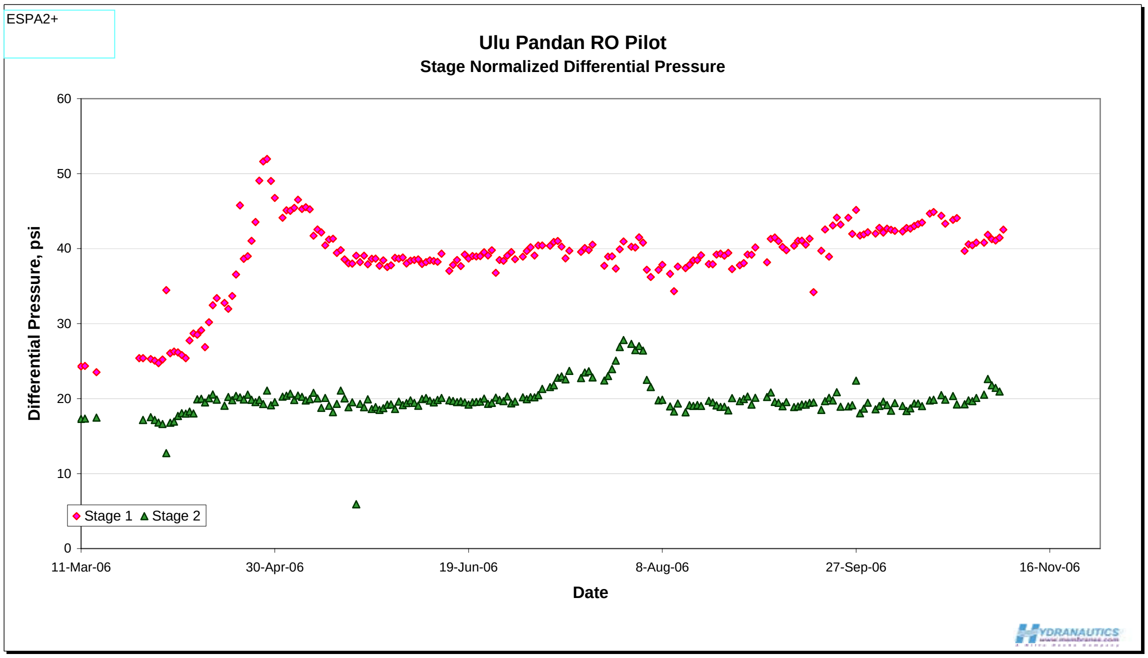


Figure 6. Ulu Pandan RO Pilot – Differential Pressure.

Two elements from the Ulu Pandan pilot were analyzed after eight months of operation. One element came from the lead position of the first stage while the second element was removed from the tail position of the second stage. Retesting the elements at standard test conditions showed both elements had lost some permeability and significant rejection relative to initial factory testing. The lead element had more than tripled in salt passage while the tail element showed an increase in salt passage of 57%. The high salt passage exhibited by each element agrees with a 25% overall increase in salt passage seen in stage 1 and stage 2 during the eights months of pilot operation. Testing of the membrane surface for oxidation damage (Fujiwara Test) was negative and very little scale was found on the membrane as discussed in more detail below.

The lead element had a greater differential pressure of 0.62 bar (9 psi) compared to the 0.46 bar (6.7 psi) of the tail element. A typical unfouled spiral element will have about 0.3 bar (5 psi) of differential pressure at standard test flows.

After retest, both elements were autopsied and examined. Both membranes were found to have a brown slimy/gritty film on the membrane surface caused by a combination of organics, polysaccharides excreted from bacteria cells that grow and adhere to the membrane, and particulate fouling. The denser film on the lead element explains its higher differential pressure. The presence of chloramines should hinder the growth of these cells, however, if chloramine dosing is stopped for a period as is the case for the UP pilot, cells will grow and a biofilm will form that is very difficult to remove.

A weight loss on ignition (WLOI) of foulant scrapped from the membrane's surface revealed that approximately 96% to 97% of the foulant on both the lead and tail was organic in nature.

As part of the autopsy, samples were extracted and imaged with a scanning electron microsope (SEM). As a reference, Figure 7 shows a clean membrane surface magnified 3000 times. Figure 8 and Figure 9 show the lead and tail elements respectively. Not surprising, the build up of foulant was heavier on the lead element than the tail. Membrane from the lead element is completely obscured by the thick, amorphous foulant layer while foulant only partially covers membrane from the tail element. Numerous bacteria were also found on the lead element (Figure 10)

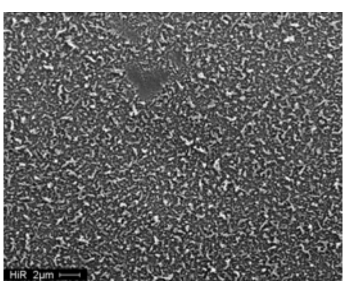


Figure 7. Control

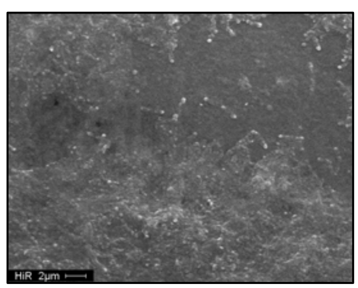


Figure 8. Lead Element

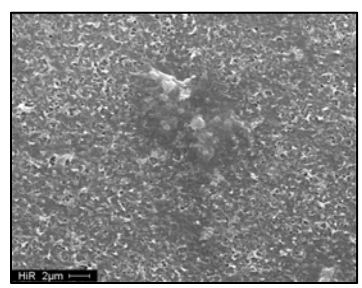


Figure 9. Tail Element

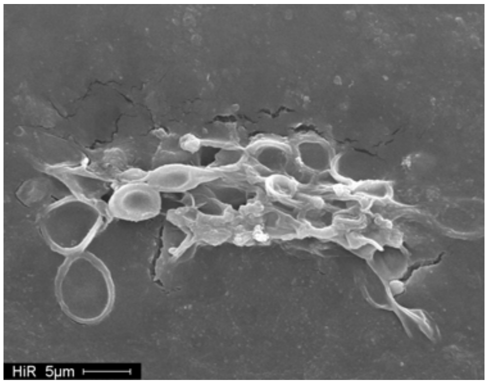


Figure 10. Isolated patch of cells on the lead element magnified 2000 times.

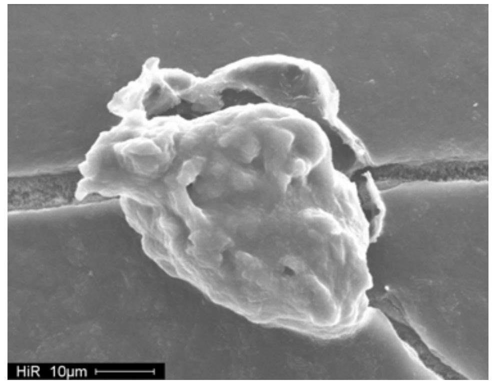
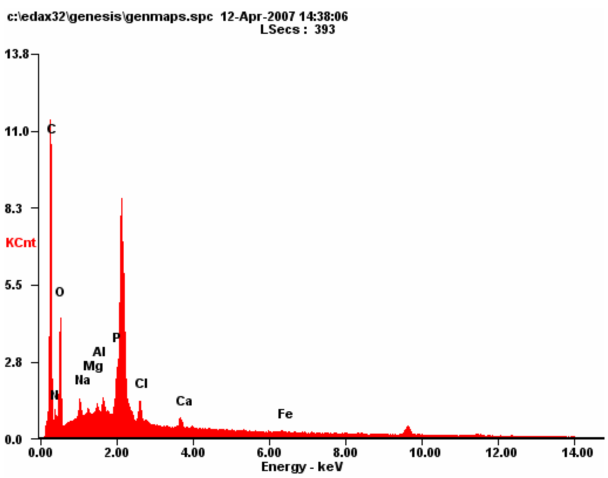


Figure 11. Particle, 40 um in diameter, found at the brine spacer line on lead membrane surface. Photo is magnified 1250 times.

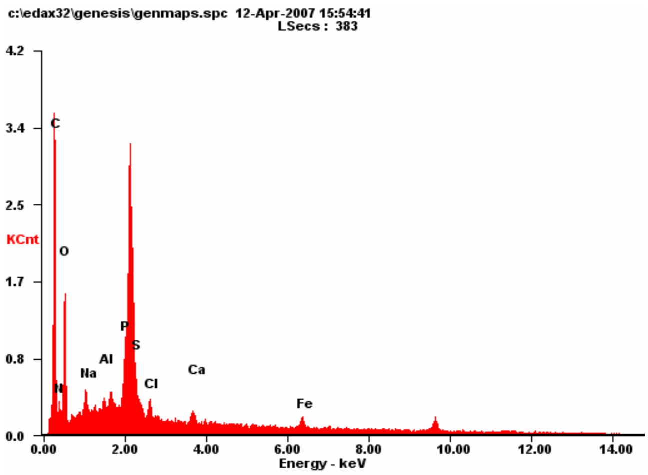
The SEM photos also revealed the presence of particulate fouling. Figure 11 shows a large particle, 40 um in diameter, embedded on the surface of the lead element membrane. These particles may have damaged the membrane and contributed to the lead element's low rejection.

Foulant scrapped from both lead (Figure 12) and tail (Figure 13) membranes were analyzed for their specific composition using EDAX. The composition of both foulant samples is very similar; the dominant constituents being carbon, nitrogen, and oxygen. This finding agrees with the high organic content as found in the WLOI test. In addition to the organic foulant, both membranes contained a similar composition of inorganic constituents. Notably, both lead and tail membranes showed some CaPO4 scale. This is not surprising considering the 15 ppm maximum concentration of phosphate reported in the UP feed.



Element	Wt%	At%
CK	60.22	68.18
NK	10.73	10.42
OK	21.28	18.09
NaK	01.17	00.69
MgK	00.26	00.14
AlK	00.36	00.18
PK	02.81	01.23
ClK	01.40	00.54
CaK	01.02	00.35
FeK	00.75	00.18
Matrix	Correction	ZAF

Figure 12. EDAX analysis of foulant collected from membrane surface of lead element.



Element	*Wt%*	*At%*
CK	57.55	67.22
NK	10.01	10.03
OK	20.51	17.98
NaK	01.22	00.74
AlK	00.29	00.15
PK	03.25	01.47
SK	02.01	00.88
ClK	00.86	00.34
CaK	01.01	00.35
CrK	00.26	00.07
FeK	03.04	00.76
Matrix	Correction	ZAF

Figure 13. EDAX analysis of foulant collected from membrane surface of tail element.

The tail element, which treats the highly concentrated brine, contained a significantly greater amount of iron precipitation (3% by weight) than the lead which contained 0.75% by weight.

V. Current Wastewater RO System Design and Operation

Differences in pretreatment, feed water composition and production requirements influence subtle differences in the design and operation of the RO systems at OCWD and UP.

Each of the thirteen UP trains produces 12,300 m3/d (3.25 MGD) for a total of 148,000 m3/d (39 MGD). Twelve of the thirteen trains are in continuous operation with one as standby. The average system flux is 18 lmh (10.6 gfd) and system recovery is 80%. Each train is configured as a 64:36 two stage array with seven elements per vessel. A turbo booster is operated between the two stages. The turbo boost is an Energy Recovery Device (ERD) which employs a direct coupled impeller to transfer hydraulic energy from the concentrate stream of the second stage to the feed of the second stage. The turbo boost improves the flux balance between the two stages, improves permeate quality and reduces overall energy consumption. The booster is equipped with a flow bypass to control and balance the flow. The bypass is employed when the second stage brine flow exceeds the flow required for booster pressure. Figure 14 provides a process flow diagram of the OCWD system.

The OCWD plant consists of 15 trains (14 in operation with one train as standby) with a capacity of 18,900 m3/d (5 MGD) per train for a total plant capacity of 265,000 m3/d (70 MGD). The array for each train is three stages (78:48:24) with seven elements per vessel. The OCWD design has a higher flux at 20.4 lmh (12 gfd) and a higher recovery of 85%. Figure 15 provides a process flow diagram of the OCWD system.

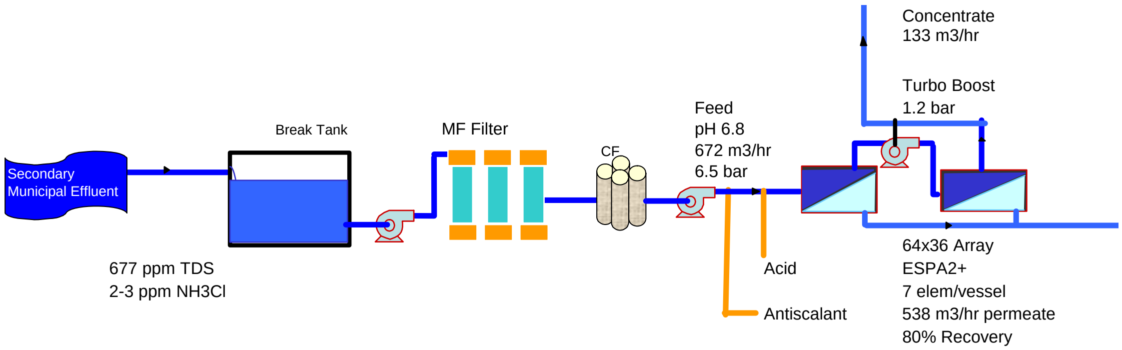


Figure 14. UP Single Train Process Flow Diagram

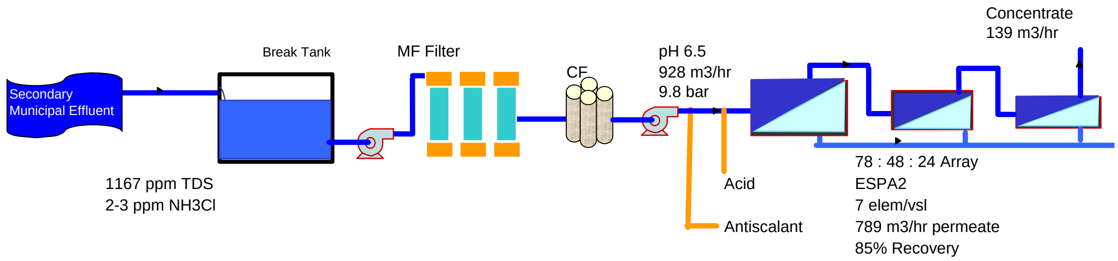


Figure 15. OCWD Single Train Process Flow Diagram

Comparing the design of the two RO plants shows the evolution in wastewater RO design toward greater savings in both capital and operation. In terms of capital savings, the UP two stage design reduces the cost of piping and pressure vessels compared to a three stage design. The two stage design, in combination with the lower feed salinity and turbo booster, also realizes a better flux distribution throughout the system.

In terms of operational savings, the use of the latest energy saving membranes with greater surface area results in lower power consumption. Both sites use the Energy Saving Polyamide (ESPA2) membrane technology. OCWD uses the standard ESPA2 while UP uses an enhanced version of the membrane, designated ESPA2+, which was not commercially available at the time OCWD finalized its membrane selection. Both membranes are based on the same high flow, high rejection polyamide chemistry to achieve 99.6% sodium chloride rejection at standard test conditions. The ESPA2+ produces a higher standard flow of 12,000 gpd compared to the 9000 gpd of the ESPA2. The ESPA2+ enhanced performance is due to a number of incremental improvements building on the existing technology. For example, the number of membrane leaves per element versus the leaf length has been optimized to reduce pressure losses as permeate travels the spiral path to the element core tube. Element productivity has also increased with an increase in membrane surface area. The 440 sq. ft. of membrane in the ESPA2+ is the direct result of the automated placement of glue lines in element manufacturing.

The higher surface area of the enhanced element has a number of advantages for the design of an RO system. The RO system using the 440 sq ft elements can be designed with an equivalent number of elements as a system with 400 sq ft to reduce average system flux and lower operating cost. The lower flux can reduce cleaning chemical consumption by decreasing the rate of fouling. The lower flux will also reduce energy consumption by reducing feed pressure. To illustrate the advantages of enhanced energy saving membrane, **Table 3** compares hypothetical designs with actual designs at OCWD and UP. Using the OCWD design as an example, a comparison can be made between the current design using ESPA2 (design 1) and an identical, hypothetical, design using ESPA2+ (design 2). In the hypothetical design 2, the use of the higher area membrane would reduce flux from 20.4 lmh (12 gfd) to 18.4 lmh (10.8 gfd) and reduce feed pressure from 9.8 bar (142 psi) to 8.3 bar (120 psi). Though it is difficult to project how much the lower flux would reduce cleaning frequency, the lower pressure can be calculated to reduce power consumption by 15%.

Alternatively, the higher area membranes can be used to maintain a similar average system flux while reducing the number of elements and pressure vessels by 9 %. Considering all 15 trains at OCWD, this would total approximately 1470 less elements and 210 less pressure vessels.

Another source of operational savings is the energy recovery device (ERD). To illustrate the energy savings obtained by the ERD, TABLE 3 compares the UP design with ERD (design 3) with a hypothetical UP design using a standard booster pump (design 4). All other design parameters, including feed salinity, recovery, and fluxes, are held constant. The comparison shows that 0.31 kwhr/m3 is required from the standard booster pump design 4 whereas 0.29 kWhr/m3 is required from the EDR design 3. This difference is relatively small due to the already low pressure requirement of the system. However, over the 20 year life of the plant, assuming rising energy cost, the savings could be significant.

A disadvantage of the ERD is the narrow operating window required to achieve maximum efficiency. Like a regular pump, the EDR is designed for an optimal flow/pressure point. An RO system, however, rarely operates at a constant combination of flow and pressure throughout its operating life, especially an RO system treating secondary effluent. As the initial organic fouling occurs in the first stage, pressure increases and more flow is produced from the less fouled second stage. Similarly, the combination of compaction, fouling, and cleaning, shifts the flow distribution between the two stages throughout the operating life of the system. For this reason, the ERD will operate at less than optimum efficiency during the majority of the system's operating life.

Also displayed in **Table 3** is the calculated power consumption of the OCWD system. Comparing this with the UP power consumptions illustrates the energy savings at UP that comes from a combination of ERD, low feed salinity, and higher productivity RO membranes.

Table 3. Wastewater RO System Design Comparison at 30 C.

System Design	1 OCWD w ESPA2 (Actual Design)	2 OCWD w ESPA2+ (Hypothetical)	3 UP with ERD Booster (Actual Design)	4 UP with Standard Booster (Hypothetical)
Feed Salinity (mg/L)	1167	1167	677	677
RO Element	ESPA2	ESPA2+	ESPA2+	ESPA2+
Feed Pressure (bar)	9.8	8.3	6.5	6.5
Concentrate Pressure (bar)	4.7	3.7	4.8	4.8
Permeate Flow (m3/h)	788.6	788.6	12900	12900
Recovery (%)	85	85	80	80
Feed Pump Efficiency (%)	83	83	83	83
Feed Motor Efficiency (%)	93	93	93	93
Boost Pressure (bar)	0	0	1.2	1.2
ERD Efficiency (%)	n/a	n/a	58.1	n/a
Pumping Energy (kWhr/m3)	0.41	0.35	0.29	0.31

VI. Conclusions

The different RO designs at Orange County Water District in Southern California and the Ulu Pandan Waste Water Reclamation Plant in Singapore are influenced by years of experience and their respective feed waters, pretreatments, and permeate targets. The following lessons can be learned from the experience and designs at the two sites:

- In terms of fouling, experience has shown that the energy saving membranes perform as well as low fouling membranes on some municipal feeds. The use of energy saving membranes over low fouling membranes leads to capital savings (due to the lower element cost) and operational savings (due to lower pressure requirements).
- The enhanced performance of the higher area ESPA2+ elements contribute to a 25% reduction in feed pressure. The higher surface area and higher productivity of the latest generation of energy saving elements used in the UP design requires less elements, less pressure vessels, lower capital cost, lower feed pressure, and lower operating cost.
- Both sites experienced $CaPO_4$ scaling during demonstration studies. The problems with scaling led to the lower recovery rates and higher acid dosing than was originally anticipated. Based on studies done at Orange County Water District, wastewater reclamation system may be able to further optimize performance and increase recovery or reduce acid dosing if the proper antiscalant, targeting $CaPO_4$ precipitation, is selected.
- The higher phosphate levels of 15 ppm and higher feed pH of 6.8 at Ulu Pandan limit system recovery to 80% versus 85% at Orange County Water District which reduces feed pH to 6.0.
- Proper operation of membrane pretreatment and chemical dosing can ensure the stable operation of the RO and reduce chemical cleaning frequency.
- The lower feed salinity, flux, and recovery, as well as the use of a turbo charger and ERD leads to lower power consumption at Ulu Pandan.
- The use of an ERD instead of a booster pump reduces pumping energy by 6.5% at Ulu Pandan.

VII. References

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