WATER RECLAMATION - THE JURONG ISLAND EXPERIENCE - SUT SERAYA (SINGAPORE) USING FOULING RESISTANT RO MEMBRANES TO RECLAIM WASTEWATER

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ABSTRACT

Water is a strategic resource for Singapore, a small island-state with few natural resources of its own. About half of the country's potable water supply currently comes from neighboring Malaysia, through two supply agreements that expire in 2011 and 2061, respectively. With industry booming, demand for water has also increased. This has prompted the Government of Singapore and industry to investigate creative ways to supply water and make the country more self-reliant in its water resources.

A reverse osmosis plant supplied by Aquatech International Corporation (AIC) equipped with fouling resistant DOW FILMTEC® BW30-365-FR2 membranes is currently being used to process tertiary treated effluent and convert it to high-grade industrial water for consumption by Singapore's thriving petrochemical industry. SUT Seraya (SUT), a subsidiary of SembCorp Utilities Pte Ltd, has installed a single pass RO unit with six trains of equal size producing 6 x 5000 m^3/day permeate with a total of 30,000 m^3/d. Each of these trains comprises three arrays in an 28:16:8 configuration with 52 (seven element) pressure vessels equipped with 352 FILMTEC BW30-365 FR2 RO elements. The design flux is 10 GFD and the design feed TDS is ~1300 mg/l.

By exploiting RO technology and the economies of scale derived from its 30,000m^3/day capacity, SUT can sell the reclaimed water at a price cheaper than potable water currently supplied to Jurong Island by the Public Utilities Board of Singapore. The high-grade industrial water SUT supplies offers further savings on demineralization as most of the dissolved solids in the reclaimed water are removed by the membrane.

To make the project economically viable an aggressive recovery was required and thus the SUT plant was designed to recover 85% of the treated tertiary effluent and turn it into reusable high-grade industrial water. Aquatech's proprietary conventional pretreatment process reduces the silt density index (SDI) of the biologically active water to normally less than 4. SUT and Aquatech engineers have found the FILMTEC FR membranes to be easy to clean. Generic chemicals are found to be adequate for cleaning, keeping the cost of cleaning low.

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1. Introduction:

1.1 Formation of Jurong Island

When Singapore embarked on its ambitious plan to develop a world-class chemicals hub in the Asia-Pacific Region in 1994, it chose to amalgamate seven southern islands by reclaiming the channels between the islands to form one large island with an ultimate land area of 2650ha. This island is now known as Jurong Island (JI).

In parallel with the planning and development of JI, SembCorp Utilities Pte Ltd - through its subsidiaries SUT Sakra Pte Ltd and SUT Seraya Pte Ltd - put a Centralized Utilities Concept into place. It would provide a range of utilities such as the supply of steam, waste water treatment, de-mineralized water supply, cooling water supply, product storage facilities, and terminalling facilities to the cluster of petrochemical, chemical plants and refineries that were targeted to be located on JI.

1.2 Water, a strategic resource

Due to Singapore's small size of 660 sq km and a relatively high population of 4 million, the water catchments on Singapore Island alone cannot yield enough water to meet all its needs. About half of the water supply for Singapore comes from neighboring Malaysia, through two supply agreements expiring in 2011 and 2061, respectively.

Due to its strategic importance, as early as the 1970s, the industrial area of Jurong in Singapore was provided with Industrial Water (IW) as an alternative source of water for industrial use. This IW is basically tertiary treated sewage effluent reclaimed from the effluent discharged from the Ulu Pandan Water Reclamation Plant. (The effluents from plants in Singapore are treated to a 20ppm BOD, 30ppm SS standard). IW which typically has a BOD <3 ppm, SS <5 ppm and TDS <1300 ppm is sold at a much cheaper price than potable water to encourage its use and make it attractive to industries for either direct use or for further treatment to meet their requirements.

As the consumption of water by the chemical and petrochemical sector was mainly for non-potable purposes (and this amounted to some 5% of the total potable water consumed in Singapore), SUT together with the Government was prompted to explore innovative alternatives to supply such water in place of potable water.

2. Project Planning & Development:

2.1 Planning an alternative water supply source for JI

During the planning stages of JI, it was envisaged that the industrial water reticulation system already in place in the Jurong industrial area would be extended to serve industries on JI. Taking advantage of the supply of IW to JI, it was conceived that it would be economically feasible to have a plant employing RO/EDR, or equivalent technology, to further process IW in order to produce a higher-grade industrial (HGIW) water.

2.1.1 HGIW (high-grade industrial water) specification

To make it more attractive to industries it was decided that the HGIW should have a quality that is slightly better than the potable water supplied by the Public Utilities Board (PUB). A conductivity of less than 250 µS/cm was targeted (in comparison PUB water in the JI area had a conductivity between 350 to 650 µS/cm).
Via surveys conducted in 1996 and 1997, it was projected that an estimated 50,000m3/day of potable grade water would be required by the petrochemical, chemical plants and refineries planning to invest in Singapore on JI. It was thus projected that a plant producing 30,000m3/d of higher-grade water, when commissioned, could easily substitute PUB potable water, if supplied at a somewhat lower price.

Consequently in 1997 and 1998, SUT undertook the planning and development of an alternative source of water by using IW as feedstock. It was envisaged that IW could be further processed to produce a product comparable to potable water, but for industrial use. This water was named high-grade industrial water (HGIW) to differentiate it from IW, and is sold to industries on JI through a separate supply system.

2.2 Raw water specification

The starting point in the design of the HGIW plant was the quality of the industrial water. By that point of time the Public Utilities Board of Singapore (PUB) had been operating their Jurong Industrial Water Works (JIWW) - the Tertiary Treatment plant treating the effluent from the Ulu Pandan Water Reclamation Plant (UPWRP) - for about 20 years and had a wealth of data on the quality of IW over time.

However, like many coastal cities with old sewers and a high water table, the phenomena of intrusion of seawater had caused water composition of the IW to vary with tidal levels. Chloride levels can vary between 100 and 500 mg/l, but are normally found to be in the range of 250 ppm +/- 100 ppm.

It was observed that over an extended period of time, the conductivity of the IW could fluctuate from a low of 800µS/cm to as high as 1800µS/cm and sometimes even rise above 2000µS/cm. A safety margin was therefore prudently provided for and a maximum conductivity corresponding to a TDS of 1300 mg/l was adopted in the raw water specification for the RO design. The high safety margin was also provided to allow for a gradual aging of RO membranes and an increase in salt passage over time.

2.3 Tenders and evaluation of technologies

Tenders were called in early 1997 for the construction of a 30,000 m^3/d industrial water polishing plant and proposals from more than ten reputable international water companies were received. The bids were evaluated on the basis of the net present value of each proposal (incorporating the effect of both capital and long term operating costs) and in consideration of the best reliable technology available at that time.

For the most part, the various proposals submitted could be categorized into three basically different processes:

a) EDR technology
b) Reverse Osmosis (RO) with MF (micro filtration) pretreatment
c) RO with traditional media filtration pretreatment

The EDR technology that was offered was not accepted, as it did not have the high salt rejection required when compared to RO.

The MF membranes suffered from two drawbacks to project economics in comparison to traditional media filters as pretreatment process. One had to allow for replacement of MF modules over a five-year life, and the MF membranes could only provide a recovery of 90 to 95%. In comparison, traditional dual media filters (DMFs) do not require such expensive replacement of media (sand and anthracite are relatively cheap), and more importantly, the DMFs give a recovery as high as 99% since RO concentrate is used for back-washing DMFs.

SUT took comfort that at the Madras Fertilizer Ltd (MFL) plant in Chennai (India), traditional dual media filters with RO membranes were successfully employed to produce 12,250 m^3/d of permeate.

Hence RO with traditional dual media filter (DMF) pretreatment was selected.

2.4 Plant recovery and project economics

As the PUB charges a tariff of Sing$ 0.43 for each m^3 of industrial water used in Singapore, it was realized that only a water reclamation plant with the highest possible recovery could make the project economically viable as consumers would also want a water at more competitive rates. Therefore short-listed proposals had to incorporate media filters as pretreatment to the RO stage with the recovery on the RO unit of 86%. The combined recovery of the RO stage at 86% and the pretreatment stage at 99% yielded a final overall plant recovery of 85%.

3. Pilot Testing and Plant Design

The contract to design and build the water reclamation plant was secured by Aquatech International (AIC) of the USA. At an early stage in the design, it was decided that two DMF pretreatment stages (primary: PDMF and secondary: SDMF) were required as pretreatment to achieve a target silt density index (SDI) level of 4 or less for the RO membranes. This was meant to provide a margin for any irregularities in the condition of the incoming JI water.

3.1 Pilot testing

A pilot plant designed to simulate the two stage DMFs was installed to select and optimize coagulation/ flocculation and also optimize media layers.

3.1.1 Coagulation and flocculation optimization:

Through a series of jar tests, various types of polymers in different concentrations were tested for the best process efficacy as observed through settling properties, floc formation and turbidity measurement. From this, two polymers were short-listed for further extensive testing in the pilot plant. Turbidity and SDI measurements were taken at various polymer concentrations. Based on the results the polymer and coagulant was selected.

3.1.2 Dual Media Filters (DMFs) – Optimization of media layers

As SDI breakthrough (>5) was observed in the pilot tests, fine sand was used in the secondary filter to add stability to SDI values (design target was an SDI of less than 4), based on very minimal carry over of sludge from the primary filters.

3.1.3 Polymer carry over study

Polymer carry over tests was conducted and found to be negative.

3.1.4 Study of pretreatment adequacy and the nature of fouling

After finding the optimum configuration of chemicals and media in the filters, a separate pilot plant consisting of a single eight inch DOW fouling resistant membrane FILMTEC BW30-365 FR2 was operated at 86% recovery in a closed loop re-circulation to simulate conditions in the last element in the third array of the RO plant. After operating for almost a month there was no evidence of any fouling and recovery was then raised to 90% to artificially generate some fouling. However, even this did not produce any substantial fouling. The pretreatment process was therefore concluded as adequate. The trials also had the benefit of reducing the time required for plant commissioning.

3.1.5 RO membrane element features and selection

SUT chose the FILMTEC BW30-365-FR2 membrane because of the product’s proven performance in cleaning biologically active water, and because of Dow’s reliable technical service and support. SUT was also reassured by Dow’s track record at the Madras Fertilizer Plant in Chennai. For nearly 10 years, Dow membranes have successfully been used at the Chennai plant to clean biologically active water high in organic compounds. Previously, membranes were not considered suitable for such difficult applications, due to the membranes’ rapid rate of fouling.

FILMTEC BW30-365FR2 is a thin film composite, spiral-wound membrane with fouling resistant properties. The benefits of FILMTEC FR elements include a wide range of performance and economic advantages: Superior automated element construction technology which results in a level of precision that is impossible to achieve with manually rolled elements. The higher number of shorter membrane leaves in a FILMTEC FR element results in reduced pressure loss on the permeate side, yielding higher efficiency, more uniform net driving pressure, and a more uniform permeate flux distribution. The element’s 34-mil spacer, which is 10-20% thicker than in competing elements, also makes it easier to clean. FILMTEC FR membranes have been shown to resist bacterial adhesion, thus extending the time between cleanings. A lower rate of biomass accumulation and biofouling on FILMTEC FR elements results in lower average feed pressure to operate a RO facility, thus substantially lowering energy costs.

3.2 Unique plant design features provided by AIC

3.2.1 Efficient filter design for getting consistently low SDI water

To maintain SDI values the plant incorporated the following features in the filter design:

a) A dual compartment filter design to enable efficient air scouring and back-washing by separating the bed area into half.

This allows for better control of flow distribution compared to the full area of filter. Extended stem strainers have been provided to further enhance flow distribution. The primary filter provides void spaces for particulate and sludge build-up. The secondary filters act as polishing filters. There is more than one filter on line of each primary and secondary filter at all times. This provides stability to SDI readings because at no point in time is the plant operating only on freshly back-washed filters.

b) Staggered back-washing of primary (PDMF) and secondary (SDMF) filters

Back-washing of primary and secondary filters is staggered by design so that they never coincide. The build-up of dP across the primary filter occurs more frequently than on the secondary filter and therefore, the frequency of primary filter back-wash is higher. The concept of staggering helps to ensure that the filtration is being done through compacted beds at all times, which is beneficial in attaining a stable SDI.

3.2.2 Energy conservation achieved by inter-stage booster pumps

One booster pump to operate the first and second stage together (with a restriction orifice in the first stage permeate line to control feed flow to the second stage) and an inter-stage booster pump for stage 3 to achieve the overall recovery of 86% was provided. This also allows for flushing of the third stage elements while stages one and two are operating.

3.2.3 Feature of third stage flushing

Due to the nature of the water treated and the high recovery conditions, the saturation levels reached in the third RO stage are extremely conducive to fouling and scaling. Third stage permeate flushing was incorporated using the dissolving potential of permeate water to flush out contaminants and remove precipitants before they become permanent. Once per shift the third stage is isolated for permeate flushing and the plant continues to produce water using the first two stages with 75% recovery. The regular flushing protocol is followed for start-up and shutdown sequence.

3.2.4 VFD (Variable Frequency Drive) and energy conservation

Variable frequency drives (VFD) were provided by AIC in the plant as an energy saving device. The high-pressure pump was designed with sufficient overhead capability to cater for higher pressures as the membranes age and foul, as the full life of the membrane-elements is reached.

The pump operates at a speed desired to produce the head required for un-fouled conditions of membranes using variable frequency drive. Therefore the margin in the head does not have to be killed by throttling the valve at the discharge of the pump. This saves substantial power in the first few years.

The VFD also enables a soft start and stop so that motor can ramp up and down to the desirable speed over a period of time. This prevents hydraulic hammering to the membranes, which can often result in compaction of the membrane pore size and loss of flux. The possibility of movement of the membrane elements inside the pressure vessel resulting in telescoping is also avoided with this feature.

3.2.5 Features to achieve high recovery

The following features were adopted by AIC to reduce water loss and improve recovery:

a) Recovery of drain down water

The water that is drained before the filter is backwashed is recovered and pumped back into the inlet tank through recycle lines. This feature has saved a considerable amount of water, which would otherwise be lost.

b) Back-wash of dual media filters with chlorinated RO reject water

Substantial water saving was also achieved using reject water for back-washing. The back-wash tank was kept in an agitated mode by allowing the full flow of reject through the back-wash tank so that the tank can be kept full and the tank volume can be replaced with fresh reject. This water is also chlorinated just before the back-wash process is started so that any contamination can be avoided at the bottom of the filters.

c) Recirculation of rinse water

The rinse step consumes a significant amount of water. After an initial dump to replace rejects at the bottom of the filter in the rinse cycle, the entire water is recycled to the inlet tank. This also allows the rinse step to be prolonged to achieve better filter bed compaction so that SDI values remain under control.

4. Plant Layout and Performance

4.1. Overview of layout of the complete SUT water treatment plant

Tertiary treated sewage feedwater (raw IW) goes through the pre-treatment process steps shown in figure 1.
NaOCl is dosed to keep biological and algae growth as low as possible. Free residual and combined chlorine levels are maintained throughout the pretreatment. Sodiumbisulfite (SBS) is dosed to ensure that no free residual chlorine comes in contact with the membrane elements. Antiscalants are always dosed in the RO feedwater to prevent scaling by sparingly soluble salts. The oxidizing reduction potential (ORP) is measured online in the pre-treated feedwater that leads to the RO elements. Once a week, a non-oxidizing biocide is added upstream of the RO elements to help prevent biological growth in the RO system. Chloramines are present in the feed at ~ 0.5 mg/l. The RO feed-pressure is 980 kPa (9.8 bar, 140 PSI).
The RO unit referred to as “MEMBRANE 1-6” in figure 1 consists of six trains of equal size.

4.2. Layout of the RO trains
Each of the RO trains comprises three stages, the layout of which is shown in figure 2.

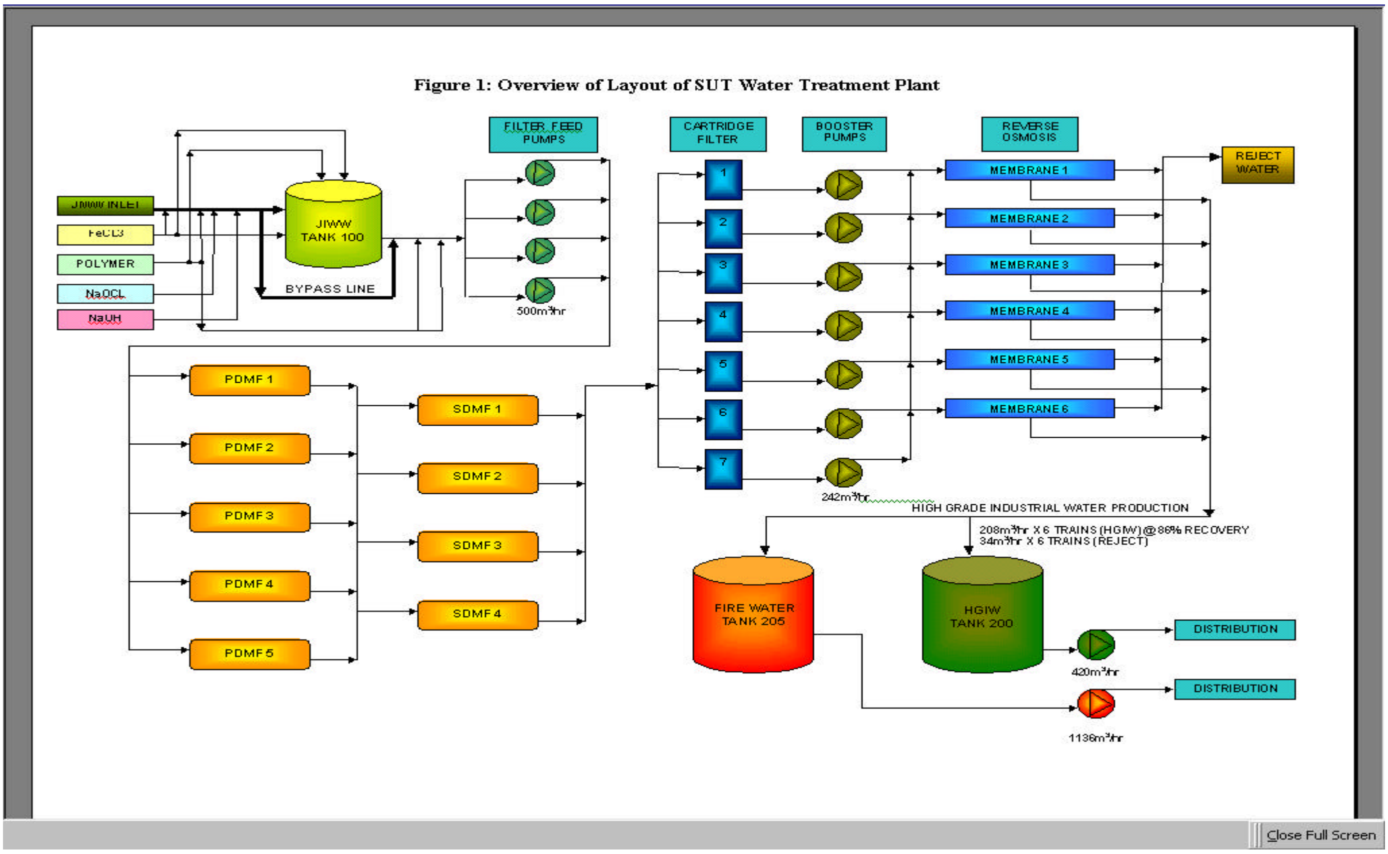


Figure 1: Overview of Layout of SUT Water Treatment Plant

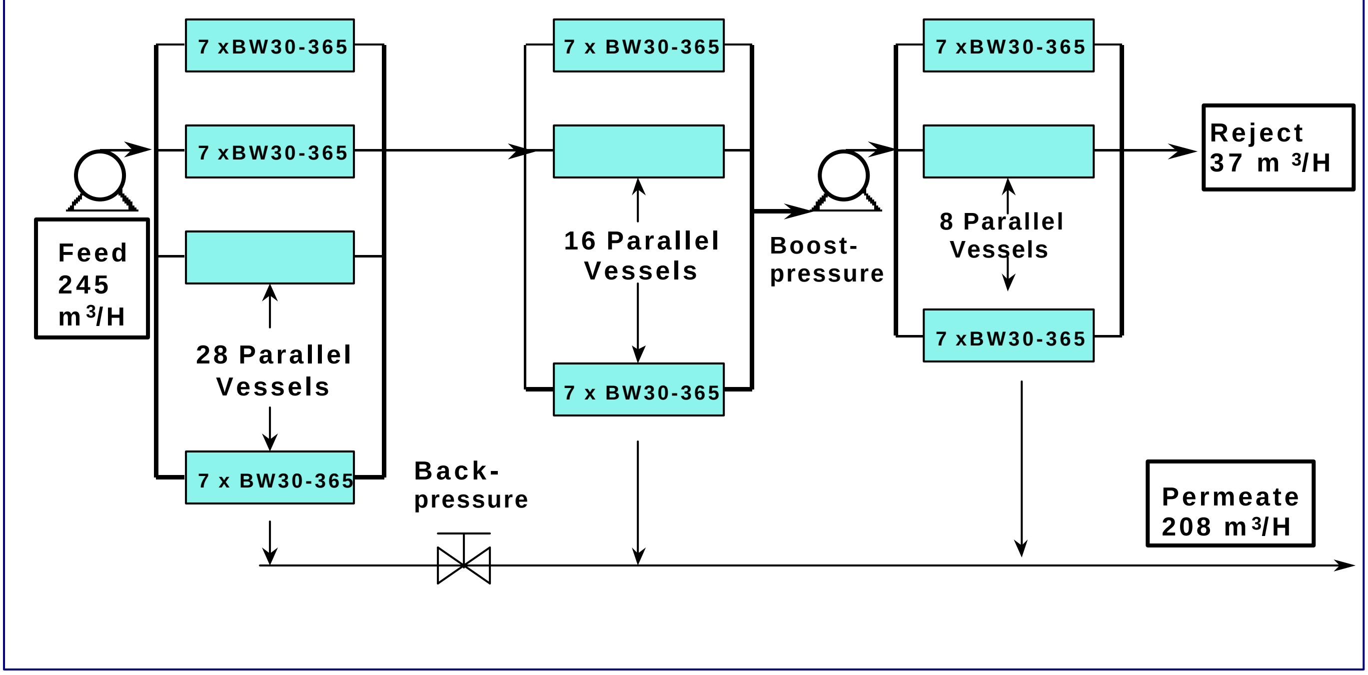


Figure 2:Configuration of One of Six Identical RO Trains

4.3. RO operational considerations, cleanings, membrane analysis

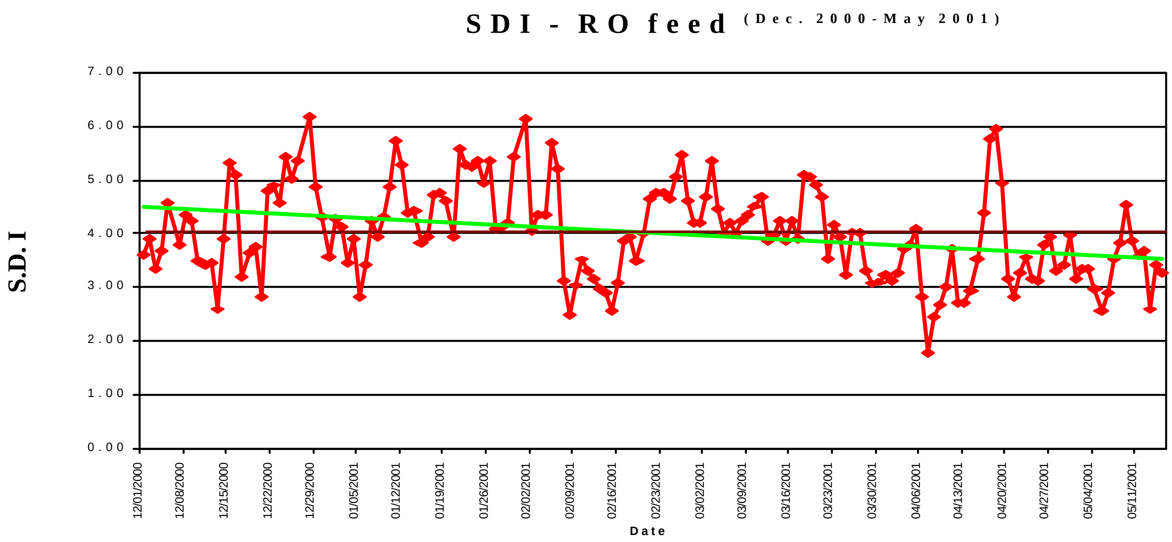
The RO permeate water quality is always well within the specifications for HGIW. See table “Comparison of Specification vs. actual values of raw JI IW and HGIW”.

Comparison of Design Specification vs. Actual values of Raw Jurong Industrial Water and High Grade Industrial Water

Parameters units are expressed in mg/l unless otherwise stated.	**Raw IW Specification**	**Raw IW actual (min.-max.)** operational range	**HGIW Spec.**	**HGIW –actual (min.-max.)** operat. range
pH	6.5 – 7.0	**6.6 – 7.4**	6.5 – 7.5	**6.8 – 7.2**
Conductivity (µS/cm)	700 – 2200	**700 – 2200**	< 250	**66 – 133**
Total Dissolved Solids (TDS)	350 – 1,300	**500 – 1300**	< 150	**33 – 70**
Turbidity (NTU)	0.5 – 2.0	**0.4 –1.7**	< 0.5	**0.1 – 0.4**
TSS-Total Suspended Solids	3.0 – 6.5	**1-2**	< 0.5	**0.07 – 0.13**
Color (Hazen Unit)	5 – 15	**13**	< 5	**<5**
Total Hardness (as $CaCO_3$)	100 – 250	**100 –160**	< 60	**1 – 3**
Total Alkalinity (as $CaCO_3$)	30 – 80	**40 – 80**	< 45	**16 – 22**
Sodium	65 – 300	**150 – 200**	< 50	**10 – 12**
Chloride	100 – 500	**150 – 500**	< 55	**6 – 21**
Sulphate (as SO_4)	80 – 145	**120 – 160**	< 30	**< 7**
Silica (as SiO_2)	1-10	**6 – 10**	<2.0	**0.1 – 0.4**
Ammonia-Nitrogen (as N)	3 – 18	**5 – 15**	< 3	**0.1 – 1.0**
PO_4-Phosphorus (as P)	1-4	**2 – 4**	< 0.5	**0.04 – 0.10**
Odour	U.O.	U.O.	U.O.	U.O.
BOD_5	<5	**<5**	< 3	**< 1**
COD	30 – 60	**20 – 30**	< 10	**2 – 4**
Bacteria CFU / 100 ml	< 0	**<1000**	<1000	**<1**
Fluoride	0.2-1.0	**0.2 - 0.7**	< 0.1	**< 0.02**
Strontium	N.M	**0.2 – 1**	N.M.	**N.M.**
Barium	N.M	**0.01 – 0.1**	N.M.	**N.M.**
Aluminum	0.09	**0.03**	< 1.0	**< 0.1**
Iron	0.09	**0.02 – 0.09**	< 0.04	**0.02 – 0.04**
Manganese	0.06	**< 0.05**	< 0.05	**< 0.05**
Copper	0.02	**< 0.05**	< 0.02	**< 0.05**
Zinc	0.06	**< 0.05**	< 0.05	**< 0.02**
As,Cd,Cr,Pb,Hg,Se	< 0.02	**50ppb max. each**	N.D.	**< 0.0001**
Cyanide & H2S	< 0.02	**N.D.**	N.D.	**CN - < 0.01**

Notes: N.D. means non detectable., N.M. means not measured, U.O. means unobjectionable.

Raw IW can be high in SDI (>6) and TSS (6-6.5 ppm) at times, which may occasionally lead to feed RO SDIs of > 4.



When SDI levels in the feed water to the RO exceed SDI 4 for an extended period of time the plant recovery is typically reduced from 86% down to 75%. Also during start-up in January 2000 and the following months the plant recovery was deliberately kept at 75% and slowly increased to 86% over a period of half a year.

The time between cleanings was predicted to be once per month at 86% recovery. Cleanings are done every 4 weeks during which time the normalized permeate flow decreases by typically 15-20%. After the cleanings, the normalized flow returns to the original values. The FILMTEC membrane chemistry allows cleaning to be carried out at higher pH levels (up to pH 12 at 30° C or pH 11.5 at 35° C) without negative impact on membrane performance. This is higher than for most other membrane elements available on the market. Generic cleaning chemicals (NaOH, Na-EDTA, HCl) are normally used. The acidic cleanings are done with HCl at pH 1-2.

After one year of operation a routine membrane analysis and autopsy was carried out to test for scaling and fouling residues and check element performance under standard conditions. As expected a slight biofouling was observed and minor residues of Ca, Si and Fe were detected indicating mild colloidal fouling. Salt rejection and flow was within specification as was expected from the plant performance, which has not shown signs of product water deterioration, flux loss or the need to increase feed and boost pressure.

5 Conclusion and outlook - helping preserve scarce water resources

Owing to the close cooperation between SUT, AIC and DOW and the numerous reviews during the various phases of the project stages the plant was commissioned on time and the resulting quality of product water exceeded specifications. Since start-up in January 2000 the RO plant has performed well and reliably within the design parameters.

The high recovery of 85% pioneered by this project is now considered to be an industry benchmark in tertiary effluent waste-water reclamation.

SUT and AIC engineers have found the FILMTEC FR membranes to perform well and as predicted under the stringent design and operating conditions imposed. Generic chemicals are found to be adequate for cleaning, keeping the cost of cleaning low. This results in a substantially lower operating cost for the plant, compared with some of the older plants using non-fouling resistant membranes.

The high-grade industrial water SUT supplies offers further savings on demineralization to its customers on JI because the membrane removes most of the dissolved solids in the reclaimed water. It is thus a true win-win situation as industries not only have access to a cheaper source of water, but it is also helping Singapore to conserve scarce fresh water.

The implications and future potential for RO technology and FILMTEC FR membranes reach far beyond the success this will bring SUT and its customers on Jurong Island. RO technology is a viable, affordable technology that enables water reuse and conservation, as well as the production of fresh water from seawater. An ongoing, affordable supply of water at consistent quality and quantity will save industry in Singapore millions of dollars and act as an incentive for others to locate there. Likewise, this technology can also be used to reclaim and recycle wastewater in other parts of the world where water is scarce, thus preserving vital natural resources.

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