

R.O. pretreatment design & performance under challenging conditions in the Arabian Gulf.

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Abstract

In early 2006 ACWA Services received a contract from Palm Water to design, install and commission 2 x 32,000m³/d seawater desalination plants on the Crescent of Palm Jumeirah.

The probability of high Silt Density Index (or SDI) figures (a full explanation of the term SDI is given at the end of this paper), the lack of space available for treatment equipment and the client's preference for minimal use of coagulants (to minimize environmental impact), along with the fact that the raw water was not expected to be highly fouling in nature led to the selection of membrane pretreatment rather than more traditional routes involving coagulation, flocculation and media filtration.

This paper focuses on the performance of the UF stage of the process in treating raw seawater with SDI (2.5) averaging 32 and occasionally peaking at around 38 and suggests certain considerations to be borne in mind by other designers working with variable, poor quality feedwater.

I. INTRODUCTION

In early 2006 ACWA Services received a contract from Palm Water to design, install and commission 2 x 32,000m³/d seawater desalination plants on the Crescent of Palm Jumeirah. Each plant is completely independent of the other and is in a separate location on the Crescent approximately 2km apart

Fig 1 Palm Jumeirah Aerial Views



It is well known that the key to successful reverse osmosis plant operation is appropriate pretreatment design and it was apparent to ACWA that with the massive amount of construction due to take place in the Gulf during the early part of the 21st century (Palm Jumeirah, Palm Jebel Ali, Palm Deira, Dubai Waterfront, The World etc) this maxim would hold particularly true to this project.

There are several possible solutions to the pretreatment of seawater prior to reverse osmosis (RO) and these include:-

- Conventional chemical coagulation, settlement and direct filtration.
- Beach well extraction followed by multimedia and / or cartridge filtration.
- Membrane microfiltration using in-to-out or out-to-in membranes.
- Ultrafiltration.

It is not the purpose of this paper to discuss the economics of pretreatment as the cost effectiveness of the various types of treatment has been discussed widely in the past with a variety of conclusions. Several studies have suggested that overall savings in total water cost of 10% might be achievable using membrane pretreatment rather than conventional pretreatment [1], [2], [3].

In this case, the probability of high Silt Density Index (or SDI) figures (a full explanation of the term SDI is given at the end of this paper), the lack of space available for treatment equipment and the client's preference for minimal use of coagulants (to minimize environmental impact), along with the fact that the raw water was not expected to be highly fouling in nature led to the selection of membrane pretreatment rather than more traditional routes involving coagulation, flocculation and media filtration.

Even after narrowing down the options to membrane filtration there is still a wide range of technologies and manufacturers to choose from. These include:-

- Zenon, Memcor and Puron who all offer 'submerged' systems.
- Pall, Norit, Hydranautics who all offer 'encased' systems.

Norit's Seaguard Ultrafiltration (UF) product was chosen after due consideration of the various options available.

This paper focuses on the performance of the UF stage of the process in treating raw seawater with SDI (2.5) averaging 32 and occasionally peaking at around 38 and suggests certain considerations to be borne in mind by other designers working with variable, poor quality feedwater.

1.1 Early Design Considerations

The client specified the raw water source as the inner side of the crescent in order that spillages of oil from the busy Gulf sea-traffic was excluded. Consequently, one of the major concerns for ACWA was the high level of very fine particles present in the raw seawater within the crescent of Palm Jumeirah. It is well known that high turbidity and Silt Density index (SDI), impact adversely on the pretreatment stages of the desalination process.

For efficient operation of the UF stage it is necessary to dose a mineral coagulant such as Ferric Chloride. This coagulant and the silt removed by the UF stage is backwashed out of the UF streams regularly and combined with the the RO reject stream (and all other waste streams including CIP chemicals) before discharge back to the open sea outside the Crescent.

Strict limits were imposed on the amount and type of chemical discharges from the works and it was therefore imperative to strike a balance between the necessity to dose coagulant and the need to minimise discharges to the Arabian Gulf whilst optimising the operation of the desalination facility. One of the main considerations was to minimise the possibility of polluting the seawater with the distinctive red colour of the chosen coagulant.

In fact the average iron concentration in the outfall is <1.0 mg/l which is well within the consent value of 2.0 mg/l.

The contractual design envelope is summarised in Figure 2.

Fig 2 Contractual Raw Water Envelope and Discharge Limitations			
Parameter	Unit	Threshold Level in raw water (for guarantee purposes)	Discharge limits
Ammonia	ppm	No limit defined	2.0 mg/l
Barium	ppm	0.02	No limit defined
BOD	ppm	No limit defined	20.0 mg/l
Calcium	ppm	560.00	No limit defined
Chloride	mg/L	24,674.00	No limit defined
Chlorine	mg/L	No limit defined	1.0 mg/l
Copper (Cu)	mg/L	0.02	0.5 mg/l
COD	mg/L	No limit defined	25.0 mg/l
Fluoride	mg/L	1.30	No limit defined
Iron	ppm	0.02	2.0 mg/l
Magnesium	ppm	1,798.00	No limit defined
Nitrates/ Nitrogen	mg/L	11.50	No limit defined
Silica	ppm	2.00	No limit defined
Sulphate	mg/L	3,439.00	No limit defined
Phosphate	mg/L	0.17	No limit defined
pH	pH unit	8.35	6 – 9 pH units
Temperature	°C	40.00	AT of 10°C
TDS at 180°C	mg/L	45,100.00	No limit defined
Oil & Grease	ppm	0.50	No limit defined
Silt Density Index (SDI)	2.5min	17.00	No limit defined
Boron	mg/L	5.40	No limit defined
Strontium	ppm	9.00	No limit defined
Total Organic Carbon (TOC)	mg/L	2.70	No limit defined
Turbidity	NTU	18.00	75 NTU
Giardia	counts/100 ml	5.00	No limit defined
Cryptosporidium	counts/100 ml	5.00	No limit defined

In addition to the list there are discharge concentration limits for several trace metals and for the quantity of coliforms as per JAFZA standards for discharge of wastewater to open sea.

1.2 Design Overview

Each 32MLD output site consists of the following process steps:-

- Shock Chlorination using Chlorine Dioxide (Occasional use),
- Coarse Screening (Travelling band screens),
- 200 micron self backwashing strainers,
- Coagulation (Ferric Chloride),
- Ultrafiltration (0.01 micron pore size),
- Acidification (H₂SO₄)
- Antiscalant dosing,
- 1st pass seawater Reverse Osmosis (TDS Reduction),
- pH Elevation and 2nd pass Reverse Osmosis (Boron removal),
- CO₂ injection
- Remineralisation by Limestone Contactors,
- Disinfection using Chlorine Dioxide,
- Storage,
- Distribution.

Each major treatment stage is designed to protect or enhance the next stage which is generally more expensive and more susceptible to physical damage.

Hence the coarse screens and self backwashing strainers are important and relatively inexpensive process steps designed to protect the UF membranes from physical damage by gross particles. The

UF stage is a more expensive process step (in terms of both capital and operating costs) whose sole purpose is to protect the most expensive and sensitive part of the process – the Seawater Reverse Osmosis stage.

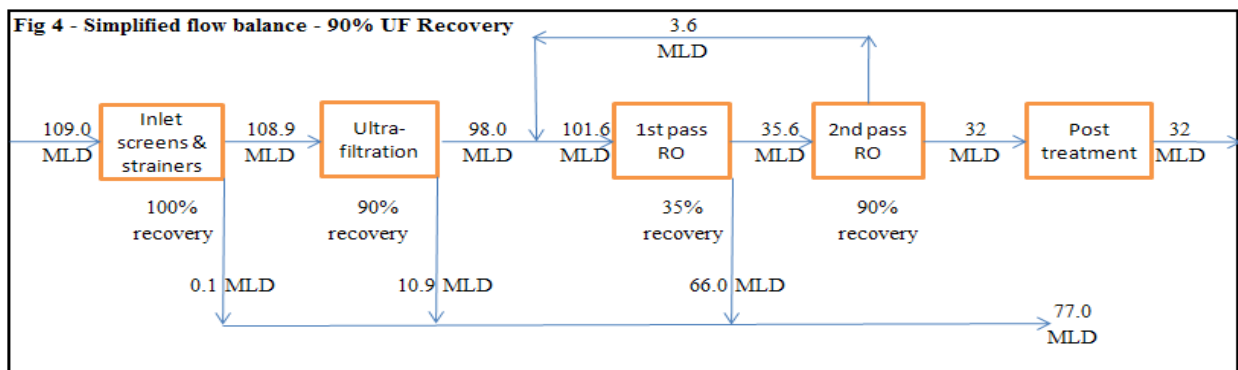
To combat the high SDI and Turbidity it was considered essential to employ a proven UF system and after careful consideration of the products available Norit's Seaguard membrane was selected due to its record of success elsewhere in the Arabian Gulf. The membranes are 8" diameter x 60" long modules designed to fit (4 per vessel) into standard RO pressure vessels.

Fig 3 Norit Seaguard Membrane and some of ACWA's 12 UF Skids per site



1.3 Overall System recovery and waste generation

Each stage of the treatment process up to the 1st pass R.O. generates a certain volume of waste. All waste streams (other than foul waste) across the site are collected and disposed of via a waste buffer tank which discharges into a buried outfall connection to a dispersal point 80m outside the crescent. At the design stage it was expected that the UF plant would operate around 90% recovery and that the total amount of waste to outfall per day would amount to 77,000m³/day.



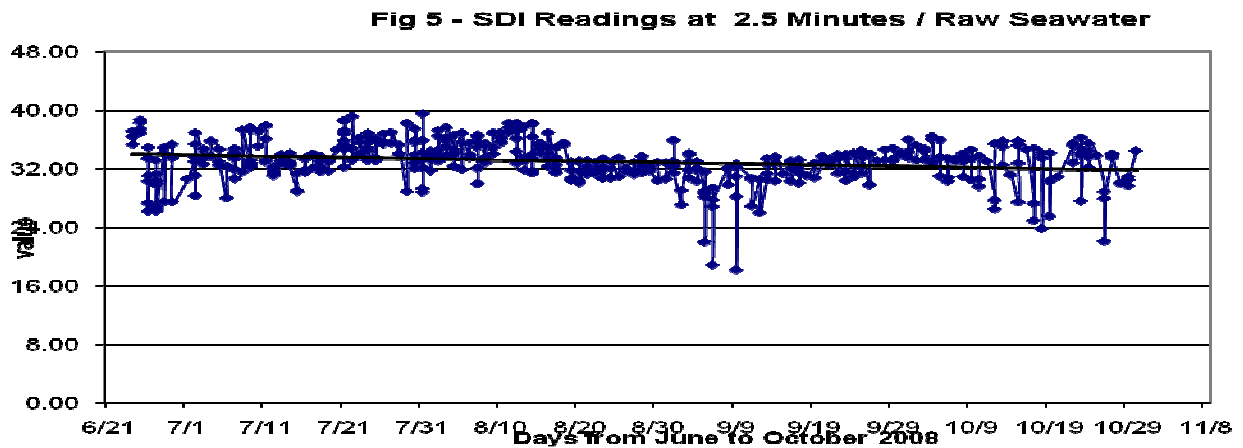
II. RAW WATER QUALITY

During the commissioning of the plant, the levels of very fine particles (and consequent high SDI) present in the seawater were found to be much above the design envelope and, to date, have remained consistently high.

2.1 Silt Density Index (SDI)

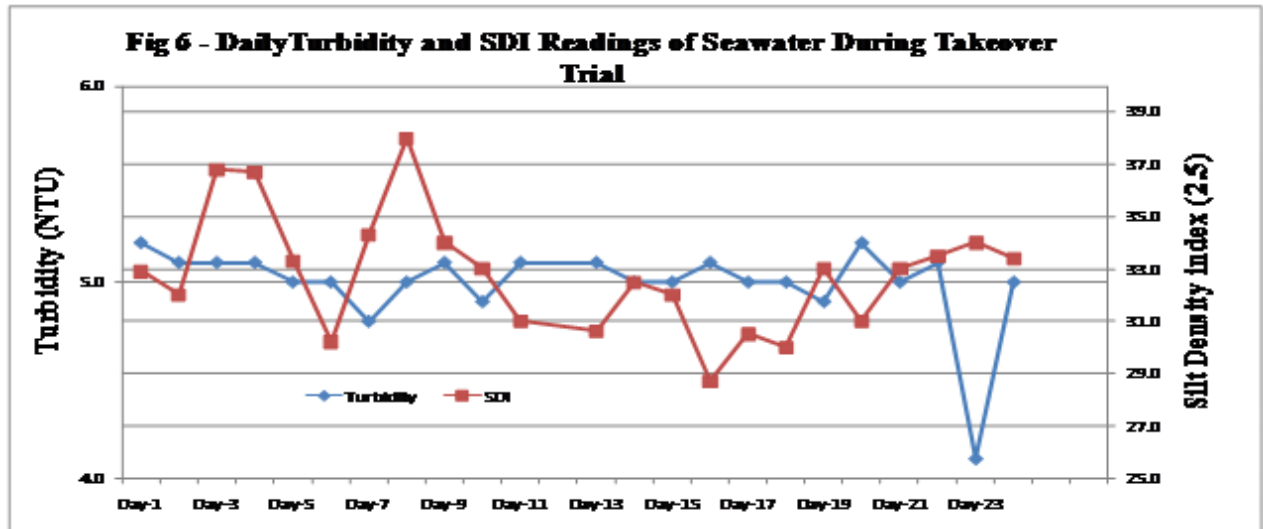
As expected it was impossible to complete the traditional 15 minute SDI tests (or even 10 or 5 minute SDIs) and therefore SDI tests of only very short durations were possible. Although SDI 2.5 tests are generally less than accurate than the longer SDI procedures, the tests in this case proved relatively repeatable on the lagoon water and were therefore be considered to be a good indicator of trends in the water quality.

As can be seen in Figure 5 the trend over the period June to October 2008 shows a gradual decrease in SDI, although it remains very high. It is not known whether the trend will continue due to the massive downturn in construction activities in the area or whether it is a seasonal variation which will reverse as time passes towards the summer of 2009 (By the time the paper is presented in November 2009 this issue should be clearer).



2.2 Turbidity

As can be seen in the figure below the turbidity of the raw seawater is consistently in the region of 5 NTU which is well within the 'Threshold Level' envisaged in the design envelope.



2.3 Particle Size

Experiments were performed on site using 10 μ , 5 μ , 1 μ and 0.47 μ test filter papers. It was found that the 10 μ and 5 μ filter papers removed almost no particles at all; the 1 micron filter paper was able to remove around 10% of the particles; a further 45% of particles were removed by the 0.47 μ filter and the remaining 50% had a particle size of less than 0.47 μ .

It is possible that some of the particles would be small enough to pass even the UF membrane (or migrate through faulty seals). For this reason a small amount of Ferric Chloride is dosed as a coagulant filtration aid (~ 0.25 mg/l as Total Iron was found to be optimal).

III. UF PERFORMANCE AND CLEANING REQUIREMENTS

When there are no leaks within the system and the UF membranes are new and unfouled the plants will produce water with an SDI of less than 1.5.

However as the membranes become fouled and operating pressures increases, leaking O-rings and broken fibres result in increased SDI figures. Even so, following optimization of the coagulation and cleaning regimes in the period after commissioning, the UF produces filtrate consistently below 3.0 SDI

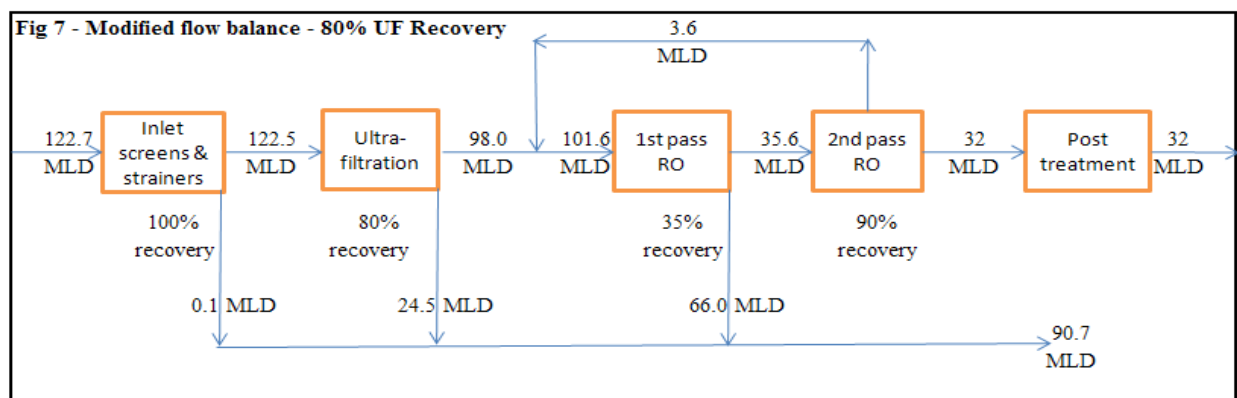
The normal cleaning regime on the UF plant is regular backwashing with filtered water, supplemented by 2 or 3 chemically enhanced backwashes (CEB) per day. During a CEB the backwash water is dosed with acid (or caustic and/or sodium hypochlorite to act on any persistent inorganic (or organic) fouling present.

As a consequence of the high level of silt (indicated by the high SDI) and the need for ferric chloride dosing, two changes to the operating original philosophy had to be made.

3.1 Changes to operating philosophy – reduced recovery

Firstly the UF skids need to be backwashed far more frequently in order to maintain the required flux. The overall recovery had to be dropped to around 80% (See Fig 7 below) from the 90% originally envisaged (See Fig 4). This means that 20% of all the filtrate produced by the UF stage is consumed in backwashing the accumulated silt out of the system. As a consequence the overall waste stream has increased from 77,000 to 90,700 MLD at full system output.

$$\text{Overall UF Recovery} = \frac{\text{Net filtrate flow to RO stage}}{\text{Feed flow to UF stage}}$$



The obvious result of a decrease in UF recovery is an increase in pumping costs and / or a loss of production. The increased energy costs are marginal compared to the costs of operating the RO

system but do need to be considered when developing models for future designs. It is particularly important to optimise coagulant addition as overdosing can be as detrimental to operation as is underdosing.

3.2 Changes to operating philosophy – Introduction of Clean-in-place (CIP)

The high volume of very small particle size silt and the consequent necessity to dose ferric chloride led to deposits forming on the membrane surface and to escalating operating pressure of the UF units as backwashing and CEB could not fully restore the trans-membrane pressure differential. A 'clean-in-place' (CIP) regime was implemented to restore the membranes to their original performance levels.

The selected cleaning chemical was a mixture of oxalic acid (a relatively strong organic acid, being about 10,000 times stronger than acetic acid and with a chemical formula of $\text{H}_2\text{C}_2\text{O}_4$) and ascorbic acid (a sugar acid with antioxidant properties and a chemical formula of $\text{C}_6\text{H}_8\text{O}_6$, and also known as 'synthetic vitamin C').

The cleaning solution consisted of RO permeate containing 1% oxalic acid and ¼% ascorbic acid heated to 36°C and the procedure was a series of soak and recirculation stages followed by rinsing with fresh, warm RO permeate. The results were immediate and dramatic as illustrated in the photos and table which follow.

Figure 8 – UF membrane before CIP



Figure 9 – UF membrane after CIP



3.3 Cleaning results

The original design flux was 67LMH and the system is able to achieve this without any problem. The slightly lower fluxes in the table above are due to the fact that at the time the final treated water demand was such that at the time only 2 RO skids were running and all 12 UF plants were on line. At full output the flux would rise to 67LMH with a DP of around 0.1 Bar.

	Flux	Permeability	TMP				Flux	Permeability	TMP
UF No.1	59 lmh	251 lmh/bar	0.18 bar	Before CIP	UF No.2	55 lmh	266 lmh/bar	0.13 bar	
	59 lmh	656 lmh/bar	0.06 bar	After CIP		60 lmh	599 lmh/bar	0.06 bar	
UF No.3	59 lmh	318 lmh/bar	0.15 bar	Before CIP	UF No.4	58 lmh	328 lmh/bar	0.13 bar	
	59 lmh	812 lmh/bar	0.05 bar	After CIP		60 lmh	657 lmh/bar	0.07 bar	
UF No.5	57 lmh	367 lmh/bar	0.12 bar	Before CIP	UF No.6	53 lmh	385 lmh/bar	0.10 bar	
	62 lmh	648 lmh/bar	0.07 bar	After CIP		59 lmh	807 lmh/bar	0.05 bar	
UF No.7	54 lmh	133 lmh/bar	0.29 bar	Before CIP	UF No.8	55 lmh	149 lmh/bar	0.26 bar	
	61 lmh	658 lmh/bar	0.07 bar	After CIP		60 lmh	543 lmh/bar	0.08 bar	
UF No.9	59 lmh	110 lmh/bar	0.39 bar	Before CIP	UF No.10	59 lmh	114 lmh/bar	0.37 bar	
	67 lmh	628 lmh/bar	0.07 bar	After CIP		62 lmh	522 lmh/bar	0.09 bar	
UF No.11	59 lmh	216 lmh/bar	0.20 bar	Before CIP	UF No.12	60 lmh	200 lmh/bar	0.21 bar	
	57 lmh	603 lmh/bar	0.07 bar	After CIP		57 lmh	532 lmh/bar	0.07 bar	

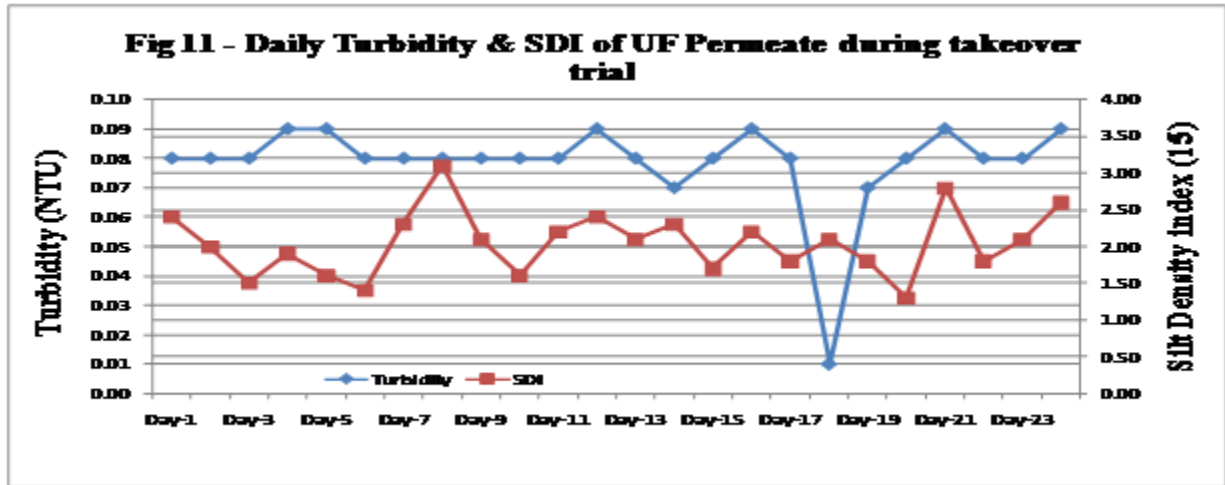
Figure 10 – UF performance before/after cleaning

The UF skids are quite large and therefore a fully automatic ‘CIP’ cleaning procedure is not as effective as one run manually ensuring the cleaning chemicals reach all parts of the skid.

It is anticipated that CIP will be implemented twice a year or as dictated by rising trans-membrane pressure. This will be kept under review and trans-membrane pressure monitored carefully.

IV. PERFORMANCE OF R.O. STAGES AND FINAL WATER QUALITY

The 1st and 2nd pass RO membranes are supplied by Toray who specified a maximum feed SDI of 5 with an average of less than 3. As can be seen in the graph below this level of filtration is consistently achieved by the UF plant.



As a consequence of the highly reliable quality of water leaving the UF stage, RO performance has exceeded all expectations of reliability and water quality. During the performance tests all contractual criteria, including water quality and power consumption per m3 were continuously and easily achieved.

Fig 12 - Reverse Osmosis performance

First pass R.O. Permeate quality				Second pass R.O. Permeate quality			
Parameter	Unit	Specified threshold level	Average over trial period	Parameter	Unit	Threshold level for guarantee purposes	Average over trial period
Bicarbonate	mg/L	< 50	12.47	Bicarbonate	mg/L	< 20	3.84
Calcium	ppm	< 20	0.71	Calcium	ppm	<20	LT 0.1
Chloride	mg/L	< 250	146.09	Chloride	mg/L	< 50	3.03
Magnesium	ppm	< 26	2.05	Magnesium	ppm	< 10	LT 0.1
Sulphate	mg/L	< 40	6.95	Sulphate	mg/L	< 10	LT 1
Boron as 'B'	mg/L	< 1	0.52	Boron	mg/L	< 0.6	0.19
pH	pH unit	< 8.0	6.45	ph	pH unit	< 9.0	7.17
TDS at 180°C	mg/L	< 400	367.05	TDS 180°C	mg/L	< 50	8.73
Total hardness	mg/L	< 50	15.43	Total hardness	mg/L	< 10	LT 1

The second pass is employed to ensure Boron is brought below 0.5mg/l. This treats a variable portion of the first pass permeate with the remainder by-passing this stage of treatment.

The water now has such a high purity that it has an unpalatable taste and is corrosive and aggressive to water storage and distribution systems.

The blended permeate is therefore remineralised by the injection of Carbon dioxide (CO₂) followed by passing through Limestone (CaCO₃) Contactors. This adds hardness (Calcium ions) and Alkalinity (HCO₃ ions) to the water as well as raising the pH up into a palatable (and non corrosive) range.

Fig 13 - Final (Potable) water quality after remineralisation

Parameter	Unit	Range as per the Contract	Threshold Level as per contract	Average over trial period
Bicarbonate as HCO ₃	mg/L	50 to 75	75	65.7
Calcium	ppm	15 to 25	25	18.7
Chloride	mg/L	N/A	250	76.7
Magnesium	ppm	N/A	20	1.7
Sulphate	mg/L	N/A	< 20	5.5
Boron as 'B'	mg/L	< 0.50	< 0.50	0.1
pH		7.5 to 9.0	7.5 to 9.0	8.1
Langelier Index	ppm	-0.5 to +0.5	-0.5 to +0.5	-0.1
TDS at 180°C	mg/L	100 to 450	450	181.4
Total hardness	mg/L	50 to 120	120	53.4
Turbidity	ntu	---	---	0.1
Total Alkalinity	mg/L	---	---	53.9
ClO ₂	C ⁰	---	---	0.2
Temperature	mg/l	---	---	32.5

V. CONCLUSIONS

If there is any doubt about the long term quality of the feedwater then the following should be considered when designing a desalination plant....

- UF will provide effective treatment of the raw water, producing the equivalent of a good quality borehole supply. Therefore the RO stages can therefore be designed quite aggressively, saving money on the most expensive equipment area.
- Turbidity alone is not a good predictor of fouling potential.
- The UF system should be designed using conservative flux and net recovery assumptions. Physical space should be left for additional UF plant in case anticipated flux values and net recovery are difficult to achieve. Additional capacity should be designed into the screening and straining stage. This will not be expensive if incorporated in the design at an early stage.
- A CIP system should be installed as well as the conventional backwash and CEB systems for the UF stage. This is inexpensive to add to the design but may be crucial to the long term economics of the plant
- The outfall should be designed taking into account potential reduced recovery over the UF Stage. This is relatively inexpensive when compared to constructing an additional outfall at a later date.

VI. ACKNOWLEDGEMENTS

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1. F. Knops, S. van Hoof, H. Futselaar, L. Broens. "Economic evaluation of a new ultrafiltration membrane for pretreatment of seawater reverse osmosis". Desalination 203 (2007) 300–306
2. Lisa Henthorne, "Evaluation of Membrane Pretreatment for Seawater Reverse Osmosis Desalination", Desalination and Water Purification Research and Development Program Report No. 106, U.S. Department of the Interior, Bureau of Reclamation, October 2007
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VII. EXPLANATION OF SILT DENSITY INDEX (SDI)

The 'Silt Density Index' was developed as a measure for the fouling capacity of water in Reverse Osmosis systems and is now widely used as a factor in the design of other membrane based treatment systems.

This test is defined by its specific procedure (ASTM D-4189). The ASTM procedure should be referenced for a more detailed description of the procedure.

The full SDI test passes the feedwater at a constant pressure through a 0.47 micron filter paper. The tester will measure and record the times to collect additional 500 ml volumes of sample, starting the collection at 5, 10, 15 minutes of total elapsed flow time. This value is recorded as (tf) with f being the time used. Measure the water temperature and check the pressure as each sample is collected. The pressure must remain constant at 30 psig (+/- 1 psig) and the temperature must remain constant +/-1°C.

Calculation of SDIT = $[1 - (t_i / t_f)] * 100 / T$

Where:

T = total elapsed flow time in minutes (e.g., 15 minutes for an SDI15).

t_i = initial time to collect 500 ml sample.

t_f = final time to collect 500 ml sample after test time T (15 minutes for an SDI15).

Ie if an initial sample took 20 seconds to collect and the 15-minute sample 60 seconds then the SDI would = $[1 - (20/60)] * 100 / 15 = 4.44$.

The expression $[1 - t_i / t_f]$ should not exceed 75%. If it does exceed this value, then a shorter time for T must be used.

Reference: - The Silt Density Index (SDI)(ASTM D-4189 -7)

Retrieved from "http://en.wikipedia.org/wiki/Silt_Density_Index"