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Long term experience in the operation of nanofiltration pretreatment unit for seawater desalination at SWCC SWRO plant

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ABSTRACT

Saline Water Conversion Corporation is the pioneer in developing applications and operation of nanofiltration (NF) pretreatment for seawater desalination which was developed by its research arm, namely, the Saline Water Desalination Research Institute. Initial work on a pilot plant scale, resulted in its application in one of the commercial seawater reverse osmosis (SWRO) plants at Ummlujj currently in operation since September 2000. During this long term of operation of NF–SWRO system, a number of improvements were made on the system operation based on operational experiences as well as research, which ultimately resulted in smooth operation of the same. This long-term operation revealed that it is possible to operate NF at 65% recovery at pH = 6 utilizing only low feed pressure of <25 bar. This led to increase in SWRO production by 42%. Also, no chemical cleaning or membrane replacement was required for SWRO membranes. These achievements make the NF–SWRO process economically attractive and feasible. This paper provides an overview of long-term operation of NF–SWRO plant as well as different research programs which were undertaken and results obtained following the application of the same. Major obstacles in the smooth operation of the NF pretreatment and future direction of improvement and research to be adopted are also addressed.

Keywords: Nanofiltration; Seawater desalination; Pretreatment

1. Introduction

With ever increasing population and rise in their living standard, there is always an increase in demand for good quality water throughout the world. To meet this rise in demand, water treatment, in all its form, is also on the rise. This tends to be the case also for water desalination market of which the capacity by the end of year 2011 stands at 71.9 million m^3/d [1]. However, one of the major impediments in widespread application of seawater desalination technology whether thermal or membrane is the relatively high cost associated with it. Recently, there were many advances that were made in seawater desalination technology which led to drastic decline in water production cost, especially in the seawater reverse osmosis (SWRO) technology. One such advancement is the breakthrough application of nanofiltration (NF) membrane pretreatment technique for both thermal and membrane process which was pioneered by Saline Water Conversion

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Corporation (SWCC), Saudi Arabia. This new NF pretreatment process produced a new, very clean, and partially desalinated seawater product, considerably different and superior to seawater in qualities and without the problems normally associated with seawater of high concentration of scale forming ions, high total dissolved solids (TDS), high turbidity, and high bacteria count. The mentioned desalination arrangements led to a significant improvement in the seawater desalination processes.

During the year 1996, for the first time ever, a new approach to seawater desalination processes by integrating the NF membrane process with one of the conventional desalination processes to form, for example, an NF–SWRO or NF–multistage flash distillation (MSF) was developed at SWCC, Saline Water Desalination Research Institute (SWDRI) and was successfully applied to those cases on a pilot plant scale with remarkable results. The seawater treatment first with the NF membrane removed from it turbidity and microorganisms, caused significant rejection of the scale forming hardness ions, and produced a new seawater product, considerably different and superior to seawater in qualities. The mentioned desalination arrangements led to a significant improvement in the seawater desalination processes by lowering their energy consumption and chemical consumption thereby making the process friendly to the marine environment, as well as by doubling their product water output and recovery ratio with the ultimate benefit of lowering the cost of fresh water production. The new concept was applied as a dihybrid process consisting of one fully integrated process system, the NF product constitutes the feed to SWRO plants or the makeup to other thermal, e.g. MSF, vapor compression, and multiple effect desalination plants. Alternatively, in a trihybrid system, the reject from SWRO of the NF–SWRO unit is used as the makeup to the MSF unit. This concept was evaluated successfully on a NF–SWRO, a NF–MSF, and a NF–$SWRO_{reject}$–MSF pilot plant units using Gulf seawater with remarkable results. This new process offers several advantages over the conventional seawater desalination processes [2–6].

Initially, the NF process was developed with one type NF membrane and all the work was performed on it. Later on, the study dealt with NF process optimization, where the performance behavior of different NF membranes, made by different membrane manufacturers was investigated along with their influence on SWRO performance when using NF permeate as their feed. To optimize the NF pretreatment of seawater feed to seawater desalination plants, the performance behavior of a total of 11 different NF membranes, made by different membrane manufacturers, size $4'' \times 40''$ and or $8'' \times 40''$, was investigated along with the influence of using NF permeate as feed on SWRO membrane performance. Although all NF membranes examined showed excellent rejection of $SO^{=}_4$ from 3,200 to less than 70 ppm, for a rejection of 98% or better, nevertheless, each of the membrane was found to differ from other membranes in performance behavior, which is measured by NF permeate flow, permeate recovery ratio, and hardness ions ($SO^{=}_4$, HCO^{-}_3, Ca^{++} and Mg^{++}) as well as TDS rejection. It was also found that at the same applied pressure, NF membranes with high rejection of Ca^{++} and Mg^{++} tend to have low flow and recovery, while the reverse is true, i.e. membranes with low rejection of Ca^{++} and Mg^{++} tend to have high flow and high permeate recovery [7]. All these works were done on a pilot plant scale by integrating NF spiral wound membrane elements in series, size $4'' \times 40''$, with a SWRO unit employing $2.5'' \times 40''$ membrane elements.

In view of the positive and encouraging results obtained on a pilot plant scale, trial on an NF–SWRO demonstration unit was not only logical but essential to determine the operating conditions as well as to establish plant performance parameters for commercial size NF–SWRO plants. The demonstration unit built for this purpose consisted of six NF spiral wound membrane elements, size $8'' \times 40''$ arranged in series followed by a SWRO unit comprising three hollow fine fiber SWRO elements of size $9'' \times 40''$ also arranged in series. Results obtained confirmed that findings from pilot plant trials and findings from both units allowed for the selection of NF membranes for use with SWRO or MSF plants as well as the determination of operation parameters for commercial large size seawater desalination plants [8].

Following the excellent and encouraging results obtained at the pilot and demonstration plant stages, this new dual desalination process was applied successfully to a commercial production plant. To evaluate this new NF–SWRO desalination process on a commercial plant scale, one SWRO Train 100, capacity 2,203 m^3/d (582,085 gpd) at the existing Ummlujj SWRO plant, which was commissioned in 1986 was converted from a single SWRO desalination process to the new dual NF–SWRO desalination process by the introduction of NF pretreatment of size semi-desalination unit ahead of the existing SWRO unit. The second Line, Train 200, at the same plant, which is identical in design and production to Train 100 was kept operational in the single SWRO mode. Prior to the conversion of the plant to the dual NF–SWRO process, the process was tested utilizing a demonstration unit simulating the new NF–SWRO plant in design and operation [9]. This paper describes the overall performance of Ummluj NF–SWRO plant during initial eight years of service.

2. Plant description

Schematic flow diagram of the Ummlujj SWRO plant modified after incorporating NF pretreatment is as shown in Fig. 1.

2.1. Seawater intake

The seawater supplied to the plant from an open intake enters through two 600 mm fiberglass pipes which are embedded in concrete in the coral reef. Copper sulfate solution is injected in each supply pipe, to prevent algae and marine growth in intake pipe and basin. After entering the seawater well, the water passes through a screening plant to prevent shells, fish, and debris from entering the seawater pumps.

2.2. Dual media filters

Three seawater pumps are used to pump water from the seawater intake sump to the Dual Media gravity filters. The purpose of the gravity filter is to remove fine suspended materials from the seawater. The filtered water from dual media filters flows by gravity into the filtered water sump. Filtered seawater is pumped to two banks of dual media pressure filters by the filter forward pumps. The purpose of the pressure filters is to further remove suspended solids so that the filter effluent will have an silt density index not exceeding 3.0.

2.3. Filtered water clear well

The effluent from the pressure filters is collected in the filtered water clear well from where it is pumped to the reverse osmosis (RO) train as well as NF train. Prior to entering the cartridge filters, the filtered water from clear well tank, is injected with sulfuric acid to decrease the pH to a level of about 6.0 along with 3–5 ppm of sodium hexametaphosphate $(NaPO_3)_6$ to prevent the formation of scale on the RO membranes. The cartridge filters are the final barrier to prevent suspended particles from entering the membranes. The cartridge elements have a pore size of 20 μm and are made of polypropylene.

2.4. RO system

There are two RO trains called Train 100 and Train 200. Each train is arranged in an array of 108 pressure vessels. All 108 pressure vessels are connected in parallel. Each pressure vessel contains six, 6″ × 40″ thin

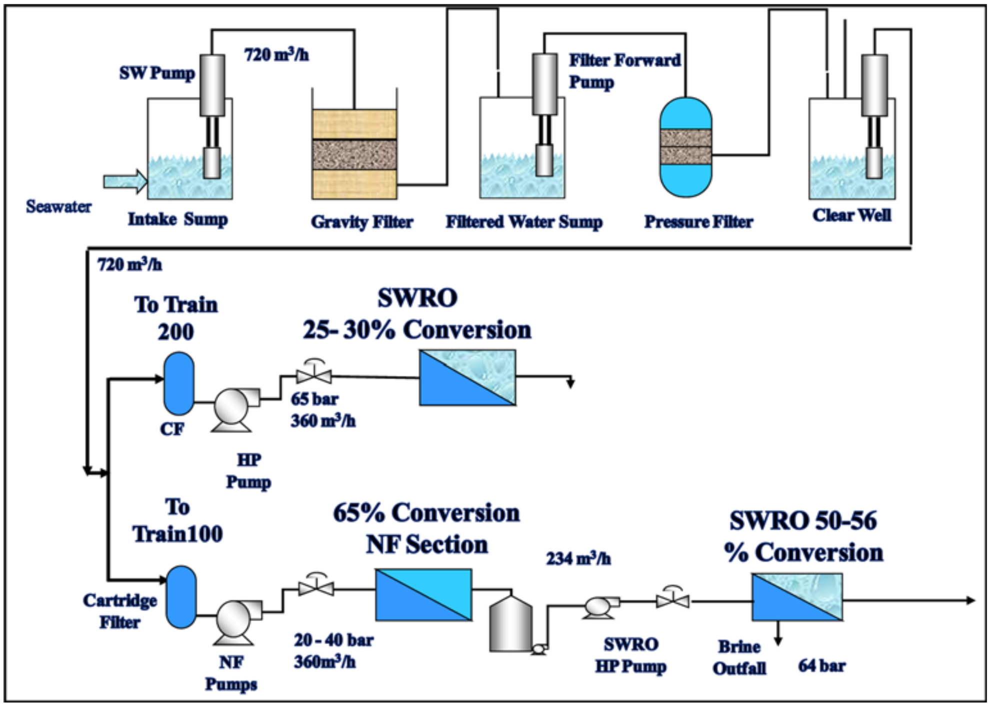

Fig. 1. Schematic flow diagram of Ummlujj SWRO plant after incorporating NF pretreatment.

film composite (TFC) spiral wound membrane elements. Both trains are fed with two high pressure of normal capacity of 360 m^3/h. Originally RO trains are designed to operate at 30% recovery. The first stage product water was collected for subsequent second stage reverse osmosis processing, which was later on abandoned due to utilization of high salt rejection membranes. The concentrated feed stream that leaves the unit is then allowed to flow through the energy recovery pelton impulse turbine to seawater outfall.

During February 1997 and January 2000, the old membranes in RO first stage trains were replaced by new model membranes in Train 200 and Train 100, respectively. The product water conductivity subsequently dropped from about 8,000 μS to about 370 μS and hence, the second stage RO was stopped and the product water from the first stage RO was directly sent to the product reservoir after posttreatment. A lime solution (slurry) is injected into the product water stream for pH adjustment to be between 7.5 and 8.0. An aqueous solution of calcium hypochlorite ($Ca(OCl)_2$) is injected into the final product water from the RO trains.

2.5. NF–RO system

In the year 2000, the Train 100 was converted to NF–SWRO system. This was done by installing an NF train upstream of Train 100 RO. The second stage RO high pressure feed pumps of capacity 360 m^3/h were utilized to pump the pretreated feed seawater to NF train. The NF train is arranged in an array of 108 pressure vessels. All 108 pressure vessels are connected in parallel. Initially, the NF train was designed to use a different NF membrane and hence had 108 pressure vessels. However, later for the NF membranes used, only 27 pressure vessels, each containing six, 8″ × 40″ spiral wound TFC NF membrane elements are required. Later on, 45 pressure vessels were in service which were added as needed to maintain rated product flow during operation. The NF is designed to operate at 65% recovery. The product water is collected for subsequent reverse osmosis processing in Train 100. The concentrated feed stream leaves the unit as the brine stream.

3. Plant performance

3.1. NF performance

The initial results obtained from the operation of SWRO train (RO 100) in the new dual NF–SWRO desalination hybrid showed vastly improved product output and recovery ratio over its operation in the conventional SWRO (RO 200) desalination process. The output of Train 100 operated in the NF–SWRO

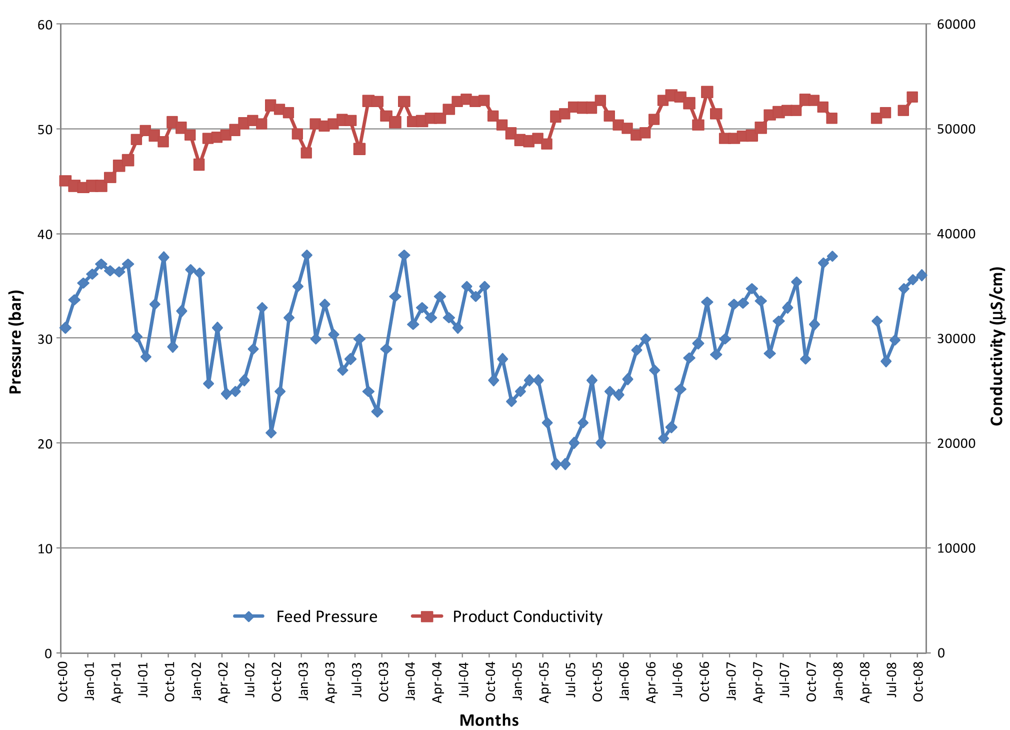

Fig. 2. Long-term performance of NF unit in terms feed pressure and product conductivity.

Table 1a
Chemical cleaning carried out on NF and its effect on NF and RO performance

Cleaning data	12 June 2001						7 October 2001						21 October 2001						27 January 2002					
	Before cleaning		24 h after cleaning		30 days after cleaning		Before cleaning		24 h after cleaning		30 days after cleaning		Before cleaning		24 h after cleaning		30 days after cleaning		Before cleaning		24 h after cleaning		30 days after cleaning	
	11 June 2001		13 June 2001		11 June 2001		6 October 2001		8 October 2001				20 October 2001		22 October 2001		21 October 2001		6 January 2002		28 January 2002		27 January 2002	
	NF	RO	NF	RO	NF	RO	NF	RO	NF	RO	NF	RO	NF	RO	NF	RO	NF	RO	NF	RO	NF	RO	NF	RO
Feed temp. C	30.6	31.6	31.4	32.4	33.6	34.6	31.37	32.37	31.22	32.22	Done chemical cleaning after 14 days		30.47	31.47	30.17	31.17	27.57	28.57	23.18	24.18	23.22	24.22	25.95	26.95
Feed press. bar	37.8	62	25.9	65	27.6	65	39	58.4	22.85	65			28.95	64	26.4	65	34.4	65	37.8	65	30.22	65	25.8	65
Δ Press. bar	2.88	0.6	3.27	0.7	3.2	0.6	3.37	0.4	3.58	0.6			3.72	0.5	3.3	0.5	3.42	0.6	2.58	0.5	2.82	0.7	1.92	0.6
Product flow. m^3/h	204.3	104.3	234	119	234	125	194	93	227.1	11.66			234	114.5	234	112	234	117	208.8	108	234	110.3	234	114
Brine flow	126	100	126	115	126	109	124	101	124	116.4			126	119.5	126	122	126	117	126	126	126	123.7	126	120
Product E.C. us/cm	47,400	613	49,900	608	49,800	735	48,600	777	52,300	736			50,900	643	51,000	683	49,800	544	46,200	468	48,400	478	49,100	540
Chemical used and procedure	*Low pH* 1% citric acid 45 min circulation *High pH* 1% solution (ethylene di amine tetra acetic acid, tri sodium phosphate and sodium tri poly phosphate) 45 min circulation						*High pH* 1% solution (ethylene di amine tetra acetic acid, tri sodium phosphate, sodium tri poly phosphate and sodium lauryl ether sulfate) 5 min circulation and 15 min soaking for 2 h						*Low pH* 1% citric acid 2 times 45 min circulation *High pH* 1% solution (ethylene di amine tetra acetic acid, tri sodium phosphate and sodium tri poly phosphate) 60 min circulation						*High pH* 0.5% solution (ethylene di amine tetra acetic acid, tri sodium phosphate, sodium tri poly phosphate and sodium lauryl ether sulfate) 5 min circulation and 15 min soaking for 2 h *Low pH* 1% citric acid 45 min circulation					

Table 1b
Chemical cleaning carried out on NF and its effect on NF and RO performance

Cleaning data	1 September 2002					
	Before cleaning		24 h after cleaning		30 days after cleaning	
	31 August 2002		2 September 2002		1 October 2002	
	NF	RO	NF	RO	NF	RO
Feed temp. C	32.8	33.8	32.9	33.9	32.01	33.01
Feed press. bar	36.8	65	18.65	65	22.4	65
Δ press. bar	2.88	0.69	2.66	0.98	2.77	0.88
Product flow. m^3/h	207.6	109.5	234	112.7	234	110
Brine flow	126	98.1	126	121.3	126	124
Product E.C. us/cm	50,450	825	52,750	811	52,000	757
Chemical used and procedure	*High pH* 0.5% solution (ethylene di amine tetra acetic acid, tri sodium phosphate and sodium tri poly phosphate) 5 min circulation and 15 min soaking for 2.5 h *Low pH* 1% citric acid 45 min circulation					

Cleaning data	3 February 2003					
	Before cleaning		24 h after cleaning		30 days after cleaning	
	2 February 2003		4 February 2003		3 March 2003	
	NF	RO	NF	RO	NF	RO
Feed temp. C	24.2	25.2	23.98	24.98	23.67	34.67
Feed press. bar	37.42	62.88	25.95	65	30.85	65
Δ press. bar	2.96	1.05	3.04	1.55	2.82	1.95
Product flow. m^3/h	189.4	96	234	104	234	110
Brine flow	126	93.36	126	130	126	124
Product E.C. us/cm	49,200	635	51,400	571	50,700	592
Chemical used and procedure	*High pH* 0.5% solution (ethylene di amine tetra acetic acid, tri sodium phosphate, sodium tri poly phosphate and sodium lauryl ether sulfate) 5 min circulation and 15 min soaking for 2 h *Low pH* 1% citric acid 45 min circulation					

Cleaning data	11 August 2003					
	Before cleaning		24 h after cleaning		30 days after cleaning	
	10 August 2003		12 October 2003		11 September 2003	
	NF	RO	NF	RO	NF	RO
Feed temp. C	34.03	35.03	34.35	35.35	32.78	33.78
Feed press. bar	36	65	18.4	65	22.05	65
Δ press. bar	2.9	0.86	2.64	0.98	2.95	0.92
Product flow. m^3/h	234	115	234	111	234	112
Brine flow	126	119	126	123	126	122
Product E.C. us/cm	50,900	880	53,900	970	52,800	864
Chemical used and procedure	*High pH* 0.5% solution (ethylene di amine tetra acetic acid, tri sodium phosphate, sodium tri poly phosphate and sodium lauryl ether sulfate) 5 min circulation and 15 min soaking for 2 h *Low pH* 1.1% citric acid 45 min circulation					

Cleaning data	13 January 2004					
	Before cleaning		24 h after cleaning		30 days after cleaning	
	10 January 2004		14 January 2004		13 February 2004	
	NF	RO	NF	RO	NF	RO
Feed temp. C	25.4	26.4	27.8	28.8	23.97	24.97
Feed press. bar	39.6	65	24.9	65	30.78	65
Δ press. bar	2.67	0.9	1.94	1.1	2.68	1.13
Product flow. m^3/h	234	114	234	106	234	108
Brine flow	126	120	126	128	126	126
Product E.C. us/cm	49,600	699	49,600	699	51,300	586
Chemical used and procedure	*High pH* 0.5% solution (ethylene di amine tetra acetic acid, tri sodium phosphate, sodium tri poly phosphate and sodium lauryl ether sulfate) 5 min circulation and 15 min soaking for 2 h *Low pH* 1% citric acid 45 min circulation					

Table 1c
Chemical cleaning carried out on NF and its effect on NF and RO performance

Cleaning data	18 May 2004						22 August 2004						18 April 2005						3 October 2005					
	Before cleaning		24 h after cleaning		30 days after cleaning		Before cleaning		24 h after cleaning		30 days after cleaning		Before cleaning		24 h after cleaning		30 days after cleaning		Before cleaning		24 h after cleaning		30 days after cleaning	
	18 May 2004		19 May 2004		17 June 2004		22 August 2004		23 August 2004		21 September 2004		17 April 2005		20 April 2005		17 May 2005		2 October 2005		3 October 2005		2 November 2005	
	NF	RO	NF	RO	NF	RO	NF	RO	NF	RO	NF	RO	NF	RO	NF	RO	NF	RO	NF	RO	NF	RO	NF	RO
Feed temp. C	29.5	28	29	27	32.5	33	31.5	32.5	31	32	30	31	26	26	26	26	28	29	30	30	30	30	28	29
Feed press. bar	37	65	25	65	30	65	38	65	25	65	37	65	26	65	17	65	18	65	34	65	16	65	23	65
Δ press. bar	2.75	1.08	2.87	1.11	2.95	1.1	3.1	1	3.12	1.1	3.17	1.02	1.74	1.19	1.71	1.2	1.78	1.2	3	1.39	2.75	1.36	2.76	1.52
Product flow. m^3/h	226	111	234	111	234	112	210	105	234	112	221	109	234	112	234	111	234	111	234	109	234	109	234	108
Brine flow	126	115	126	123	126	125	126	105	126	122	126	115	126	124	126	129	126	126	126	126	126	126	126	131
Product E.C. us/cm	51,200	736	53,100	775	52,900	787	52,200	986	53,800	869	52,500	805	49,400	569	52,000	622	51,000	660	51,100	980	53,300	965	52,300	805
Chemical used and procedure	*High pH* 0.5% solution (ethylene di amine tetra acetic acid, tri sodium phosphate, sodium tri poly phosphate and sodium lauryl ether sulfate) 5 min circulation and 15 min soaking for 2 h *Low pH* 1% citric acid 45 min circulation						*High pH* 0.5% solution (ethylene di amine tetra acetic acid, tri sodium phosphate, sodium tri poly phosphate and sodium lauryl ether sulfate) 5 min circulation and 15 min soaking for 2 h *Low pH* 1% citric acid 45 min circulation						*High pH mild cleaning* 0.5% solution (1- sodium hydroxide, 2- sodium dodecyl sulfate) 5 min circulation and 15 min soaking for 2 h						*Low pH* 1% sodium bi sulfite 45 min circulation and15 min soaking for 2 h *High pH mild cleaning* 0.5% solution (1- sodium hydroxide, 2- sodium dodecyl sulfate) 5 min circulation and 15 min soaking for 2 h					

Table 1d. Chemical cleaning carried out on NF and its effect on NF and RO performance

Cleaning data	18 April 2006						30 October 2006						24 April 2007						11 September 2007					
	Before cleaning		24 h after cleaning		30 days after cleaning		Before cleaning		24 h after cleaning		30 days after cleaning		Before cleaning		24 h after cleaning		30 days after cleaning		Before cleaning		24 h after cleaning		30 days after cleaning	
	17 April 2006		19 April 2006		17 May 2006		29 October 2006		31 October 2006		29 November 2006		23 April 2007		25 April 2007		23 May 2007		10 September 2007		12 September 2007		10 October 2007	
	NF	RO	NF	RO	NF	RO	NF	RO	NF	RO	NF	RO	NF	RO	NF	RO	NF	RO	NF	RO	NF	RO	NF	RO
Feed temp. C	25	26	25	26	28	29	29	29	29	29	26	26	26	26	26	26	29	29	31	31	31	31	29	29
Feed press. bar	34	65	16.41	65	21	65	36	63	21	63	30	63	35.28	63	29.1	63	29	63	38	63	17	64	29	63
Δ Press. bar	2.25	1.7	2.2	1.76	2.2	1.95	3.64	1.92	3.63	2.19	3.4	2.3	2.66	1.92	2.71	1.97	2.78	1.95	3.1	1.5	2.9	1.8	3.3	1.9
Product flow. m^3/h	251	115	254	109	265	115	226	103	245	105	250	106	228	104	234	104	234	106	204	99	234	103	234	102
Brine flow	126	139	126	151	126	156	126	128	126	146	126	151	126	136	126	136	126	134	126	110	126	137	126	137
Product E.C. us/cm	49,400	604	53,300	681	52,800	674	52,200	835	52,700	802	50,700	629	50,000	737	51,200	770	51,100	884	51,300	993	54,500	760	53,000	895
Chemical used and procedure	*Low pH* 1% sodium bi sulfite 45 min circulation and15 min soaking for 2 h *High pH mild cleaning* 0.5% Solution (1- sodium hydroxide, 2- sodium dodecyl sulfate) 5 min circulation and 15 min soaking for 2 h						*High pH mild cleaning* 0.5% solution (1- sodium hydroxide, 2- sodium dodecyl sulfate) 5 min circulation and 15 min soaking for 2 h						*Low pH* 1% sodium bi sulfite 45 min circulation and15 min soaking for 2 h *High pH mild cleaning* 0.5% solution (1- sodium hydroxide, 2- sodium dodecyl sulfate) 5 min circulation and 15 min soaking for 2 h						*Low pH* 1% sodium bi sulfite 45 min circulation &15 min soaking for 2 h *High pH mild cleaning* 0.5% Solution (1- sodium hydroxide, 2- sodium dodecyl sulfate) 5 min circulation and 15 min soaking for 2 h					

mode was 124 m^3/h as compared to an output of 86 m^3/h when it was operated in the singular, conventional SWRO operation (RO 200), for an increase in train productivity by 44%. However, the initial production increase could not be maintained due to fouling NF as well as decrease in NF salt rejection. As the NF recovery was maintained constant, the performance of NF was mainly monitored in terms of increase in feed pressure as well as product conductivity, which is shown in Fig. 2. Feed pressure was initially about 30 bar which increased steadily as high as 38 bar at which chemical cleanings were conducted after nine months of operation.

During entire operation period, the NF feed pressure varied between 18 bar to maximum 38 bar depending on feedwater temperature, NF fouling, chemical cleaning as well as membrane replacement. The NF product conductivity was initially about 44,400 μS/cm compared to feed seawater conductivity of about 58,000 μS/cm which gradually increased with time due to various reasons such as fouling, chemical cleaning, etc. and reached as high as 53,500 μS/cm.

Like most of the membrane processes, NF membranes are also prone to fouling which could lead to reduction in its performance. Moreover, since there was no prior experience with NF membrane performance restoration which was operated on seawater feed, it was a challenge to develop an appropriate chemical cleaning method for the NF performance restoration. With cooperation of membrane manufacture, chemical cleaning methods were evolved during the long-term operation which is dealt in a separate section. A total of 16 chemical cleanings were performed during the entire eight years of operation in order to restore the NF performance, the results of which are tabulated in Table 1. This amounts to a membrane cleaning frequency of six months interval which is quite acceptable in desalination industry.

Several membranes were also replaced during the course of eight years in the NF rack which was required to maintain the NF production. The details of membrane replacement is shown in Table 2. It is understood that a total of 567 NF membranes were used since the operation started, which amounted to an annual membrane replacement of about 25% which was significantly high compared to the desalination industry standard. Hence, new developments in NF operation which are recently achieved at SWDRI is to be adopted to increase the membrane life and eventually the membrane replacement ratio [10].

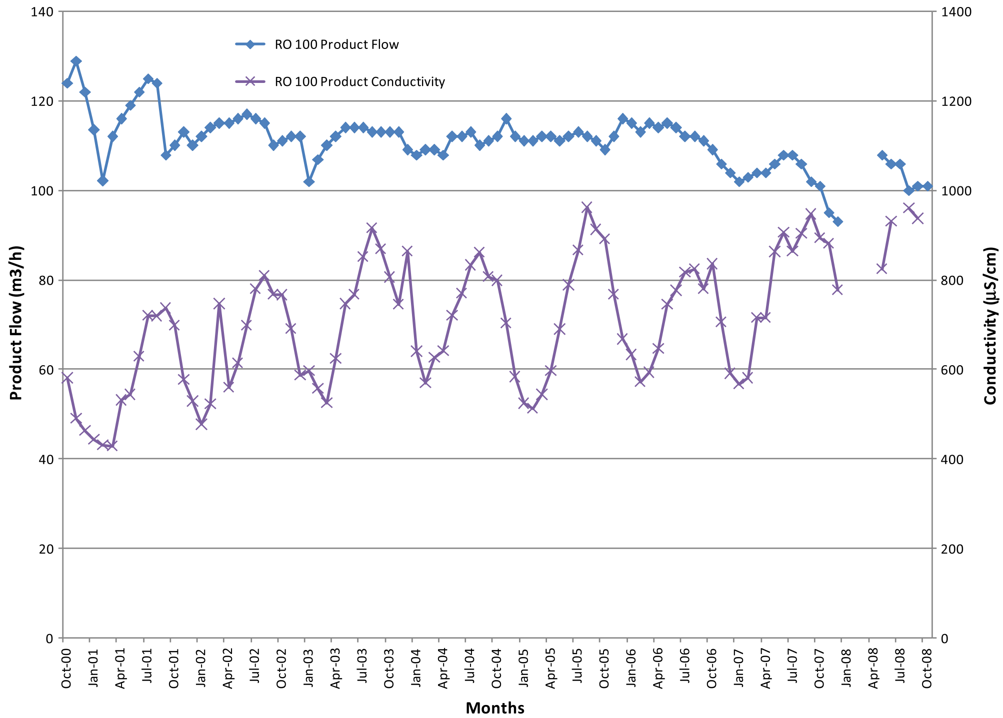

Fig. 3. Long-term performance of RO Train 100 which received NF product as feed showing product flow and conductivity.

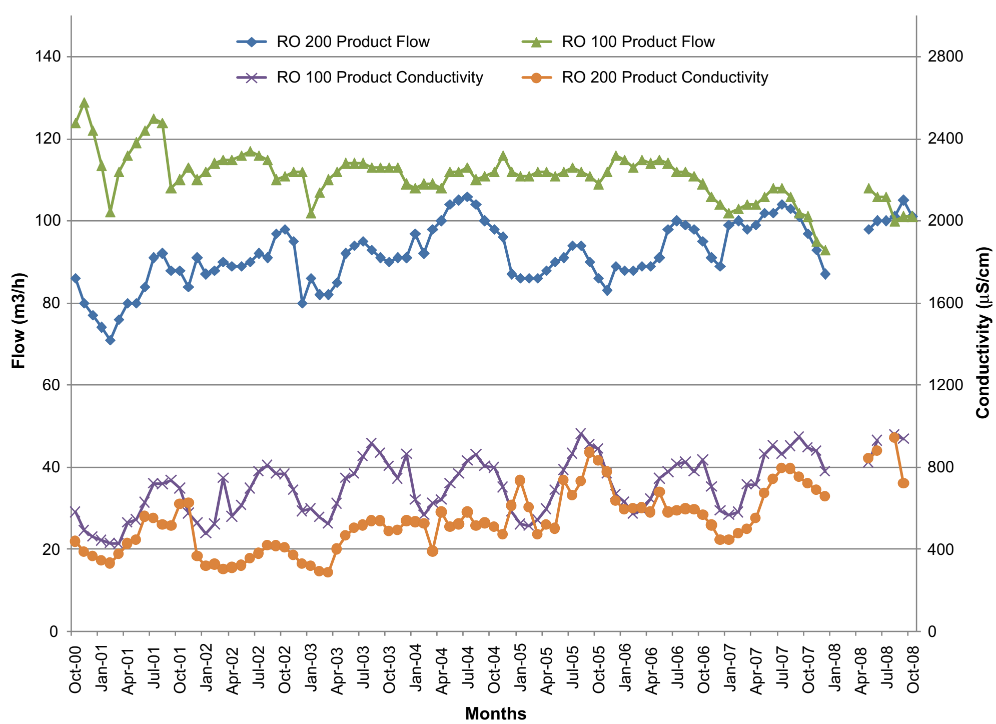

Fig. 4. Long-term performance comparison of RO Train 100 with NF product as feed and RO Train 200 without NF.

Table 2
Chronological data of membrane replacement in NF train

No.	Date	No. of vessels	No. of new element	Action
1	30 December 2001	27	54	33.3% elements replaced
2	3 February 2002	36	54	Added 9 new vessles
3	27 November 2002	36	36	16.6% elements replaced
4	16 September 2003	36	36	16.6% elements replaced
5	10 October 2004	45	162	*50% elements replaced *Added 9 new vessels
6	13 November 2005	45	90	33.3% elements replaced
7	2 August 2006	45	45	16.6% elements replaced
8	10 February 2008	45	90	33.3% elements replaced

Table 3
Chronological data of membrane replacement in RO Train 200

No.	Date	No. of vessels	No. of new element	Action
1	26 November 2001	66	264	66.7% element replaced
2	30 December 2002	66	132	33.3% element replaced
3	15 November 2005	66	132	33.3% element replaced
4	1 January 2004	72	36	Added 6 new vessels
5	24 December 2006	72	288	66.7% element replaced

3.2. SWRO performance

As stated earlier, following application of NF to RO 100, the production increase by about 44% compared to RO 200 which could not be maintained later mainly due to increase in the NF product TDS. This is especially due to the fact that the RO trains operated at constant feed pressure of about 65 bar. Hence, the RO 100 production was affected by the feed temperature as well as NF product conductivity. The RO 100 performance for eight years which was monitored by product flow rate as well as product conductivity is shown in Fig. 3. The product flow varied from 93 m^3/h to as high as 129 m^3/h during the course of eight years of operation. Similarly, the RO 100 product conductivity varied from 430 μS/cm to as high as 960 μS/cm. The RO product conductivity mainly varied with seasonal variation in feedwater temperature. However, there was very slight increase in the conductivity over the period of eight years as can be noticed from the Fig. 3. This exemplary performance of RO 100 is mainly due to the excellent quality of feed it received from NF. Moreover, this was achieved despite no membrane replacement during the entire eight years of service except towards the last three months (50% elements replacement) which did not significantly improve the performance indicating that the RO membrane replacement was not necessary in RO 100. Moreover, two chemical cleanings were also conducted which did not have any effect on the RO 100 performance further confirming the excellent condition of SWRO membrane in RO 100. This proves that utilization of NF product as feed to SWRO shall extent the life membrane beyond eight years.

The performance of RO 200 which was operated on pretreated seawater feed compared to the RO 100 which operated on NF product as feed is shown in Fig. 4. The RO 200 product flow varied between 71 and 106 m^3/h. The high flow rate was mainly due to the fact that during the course of study some additional pressure vessels of containing standard 8″ × 40″ size membranes were evaluated on the RO 200 train. The product conductivity ranged from 280 μS/cm to as high as 950 μS/cm. This was achieved by applying standard chemical cleaning on every six months interval and also by regular membrane replacement. The details of membrane replacement were given in Table 3, which indicate that an annual membrane replacement rate of 25% is relatively high compared to the industry standard.

3.3. NF membrane fouling and remediation measures

Following the application of NF pretreatment in Train100 at Ummlujj, the permeate flow from the RO

100 was increased to 124 m^3/h compared to 86 m^3/h permeate flow from single mode RO 200. However, after about nine months of continuous operation of NF unit, one pressure vessel was isolated from NF unit for chemical cleaning at low pH followed by high pH as the plant permeate flow was reduced from 234 to 200 m^3/h and the feed pressure increased from 30 bar to 38 bar as a result of decrease in feed temperature from 32 to 23 ℃ as well as suspected fouling. The chemical cleaning test resulted in improvement of the NF permeate flow, i.e. 100% recovery of the permeate flow, but with slight reduction in hardness rejection. Thereafter, low and high pH cleaning was successfully carried out on entire NF unit to restore its performance. After about three months from the first cleaning of NF unit, the permeate flow was again gradually reduced to 190 from 234 m^3/h. Only a high pH cleaning in presence of sodium dodecyl sulfate surfactant, in addition to other components was carried out to the NF unit to restore its performance in the second occasion. The permeate flow of NF unit was recovered back to 234 m^3/h whereas the rejection of hardness ions of NF unit was reduced as in the first cleaning. Hence, autopsy of two NF membranes was carried out to find out the reason for decline in permeate flow. Before doing autopsy, both lead element and end element membranes were subjected to performance evaluation and it was found that the performance of the end element was much better than the performance of the lead element. Autopsy and analyses results showed that the lead element surface was covered with thick reddish brown slimy deposits whereas the end element was relatively clean, with slight deposits only. The deposits constitute mainly the primary organic matter, iron, chromium, and fungus in addition to the chemical constituents usually found in the seawater. Even though few diatoms could be seen on both membrane surfaces, bacteriological analyses and the amount of primary organic matter indicate that the membranes were not biofouled during the 12 months operation of NF unit. Moreover, the lead element was found to be more fouled than the end element, which is an indication of typical organic fouling. Based on the autopsy results, measures were taken to reduce fouling and chemical cleaning frequency which included replacement of the first two lead elements as well as addition of more NF membranes to the NF rack resulting in reduced feed flow to membranes while maintaining the same recovery. This resulted in lowering of flux rates (from 25 to 15 gfd), which ultimately improved the NF performance and lowered the chemical cleaning frequency during the rest of the operation period [11].

The operation of plant for the two years with lower flux rate resulted in a steady performance of the NF unit leading to lower chemical cleaning frequencies (from every three to six months), a typical indication of lower fouling rate. As the foulants are mainly deposited on the lead elements, only these (lead) elements were replaced during the regular annual membrane replacements and while end elements (which were less fouled) remained in pressure vessels during the initial five years of operation. However, at the end of five years of operation, the last two end elements that were in continuous operation for more than five years were removed and new replacement elements were placed as lead elements in each vessel. Out of the several NF elements removed, a total of six elements were subjected to autopsy and analyses [12]. The appearance and foulant contents on both membrane surfaces were the same and there was a remarkable reduction in their flux along with a significant increase in salt passage. Foulant deposits mainly consisted of organic matters that were easily scraped off from the membrane's surface, however, leaving stubborn stains that were difficult to clean even with strong chemical cleaning agents. Thus, leading to conclude that with long operation period, these foulants strongly adsorbed onto the membrane surface and became irreversible in nature. The existence of organic foulants suggests the urgent need and application of coagulation—filtration pretreatment process using coagulant such as $FeCl_3$. The foulant mainly consists of primary organic matter which is far higher than the previously found value for the lead element after one year of operation. This indicates slow accumulation of organic matter on the membrane surface. In short, it could be identified that organic fouling is one of the main cause that deteriorate the NF membrane performance in terms of both flux and salt rejection, especially specific salt rejection (Table 4). This was also confirmed by pilot study on NF membrane carried out with Gulf seawater, where both feed side element as well as end element were found to be fouled mainly by organic substances within a period of two years.

Unlike the RO membranes, the NF membrane's specificity to rejection makes it difficult to deal with, especially reduction in rejection of hardness ions such as Ca and Mg during the operation. Moreover, these ions are responsible for scaling which ultimately decide the recovery ratio of SWRO system. Membrane fouling tends to change the specific rejection properties of the membrane especially rejection of hardness ions like Ca and Mg ions and to some extend to TDS [11]. Fouling could be tackled by either prevention or by remediation. Remediation measure is usually carried out when fouling occurs on the membrane and is

Table 4
Results of autopsy of NF membranes and their individual performance

NF membrane details					
Feed seawater source	Red sea			Gulf sea	
Total operating period (years)	1		5	2	
Operating flux (gfd)	25		15	22	
Membrane position in the pressure vessel	Lead element	End element	End element	Lead element	End element
Foulant analyses results					
Foulant/membrane area (mg/cm^2)	0.52	0.15	0.7	0.82	0.22
Organic matter content in the foulant (%)	30.5	18.3	73.5	69	91
Protein and carbohydrate portion of organic matter (%)	–	–	10	3	37
Performance test results					
Normalized flow (m^3/h)	0.81	1.22	0.51	1.0	1.29
Product conductivity (μS/cm)	47,500	43,000	54,500	51,800	51,500
Product water analysis results					
Ca (ppm)	192	56	366	372	353
Mg (ppm)	224	39	933	642	688
SO_4 (ppm)	<2	<2	138	41	39
TDS (ppm)	32,100	28,120	36,600	35,100	34,880
Chloride (ppm)	18,832	17,362	21,422	–	–

done mostly by chemical cleaning. However, chemical cleaning also was found to change the rejection properties of NF membrane and ultimately deteriorates NF product quality which has significant effect on the operation conditions of the desalination unit, whether membrane or thermal. Although, it has been found that the sulfate rejection does not change much: the Ca, Mg, and TDS rejection do deteriorate with every chemical cleaning. Hence, efforts are to be made to avoid chemical cleaning or modify the membrane chemical characteristics to overcome this problem. In order to avoid cleaning, NF unit was operated in Gulf seawater at moderate flux of 12 gfd together with occasional flushing with pretreated seawater on monthly basis without chemical cleaning for more than a period of two years [13]. Hence, proper selection of membrane, pretreatment as well as operating conditions, especially flux may be adapted to control fouling in NF membranes.

4. Conclusions

Long-term operation results of NF-SWRO plant at Ummluj proves that NF pretreatment of seawater provides excellent feedwater SWRO which not only increased the production but also extended the RO membrane life. Also it avoided chemical cleaning of RO membrane. However, the operation of NF suffered initially due to fouling which was later on remedied to have an acceptable chemical cleaning frequency with slightly higher membrane replacement rate. It is recommended to apply latest finding in NF design and operation which shall not only reduce the chemical cleaning frequency but also the membrane replacement rate.

References

[1] IDA Desalination Yearbook 2011–2012, Water Desalination Report, Global Water Intelligence.

[2] A.M. Hassan, M.A. Al-Sofi, A. Al-Amoudi, A.T.M. Jamaluddin, A.M. Farooque, A. Rowaili, A.G.I. Dalvi, N.M. Kither, G. M. Mustafa, I.A. Al-Tisan, A new approach to membrane and thermal seawater desalination processes using nanofiltration membranes—part 1, Desalination 118 (1998) 35–51.

[3] A.M. Hassan, M. Ak, A. Al-Sofi, A.T.M. Al-Amoudi, A.G.I. Jamaluddin, N.M. Dalvi, G.M. Mustafa Kither, I.A. Al-Tisan, A new approach to membrane and thermal seawater desalination processes using nanofiltration membranes—part 1, Desalin. Water Reuse 8 (1998) 53–59.

[4] A.M. Hassan, M. Ak, A. Al-Sofi, A.T.M. Al-Amoudi, A.G.I. Jamaluddin, N.M. Dalvi, G.M. Mustafa Kither, I.A. Al-Tisan, A new approach to membrane and thermal seawater desalination processes using nanofiltration membranes—part 2, Desalin. Water Reuse 8 (1998) 39–45.

[5] A.M. Hassan, M.A. Al-Sofi, A. Al-Amoudi, A.T.M. Jamaluddin, A.M. Farooque, A. Rowaili, A.G.I. Dalvi, N.M. Kither, G. M. Mustafa, I.A. Al-Tisan, A new approach to membrane and thermal seawater desalination processes using nanofiltration membranes—part 2, in: Proceedings of the Fourth Gulf Water Conference, Water Science & Technology Association (WSTA), Bahrain, vol. 2, 1999, pp. 577–594.
[6] A.M. Hassan, Process for desalination of saline water, especially, water having increased product yield and quality. Saline Water Conversion Corporation, US Patent 6,508,936 B1, 2003.
[7] A.M. Hassan, A.M. Farooque, A.T.M. Jamaluddin, A.S. Al-Amoudi, M.A. Al-Sofi, A. Al-Rubian, M.M. Al-Gurashi, N.M. Kither, A.G.I. Dalvi, I.A.R. Al-Tisan, Optimization of NF pretreatment of feed to seawater desalination plants, in: Proceedings of International Desalination Association (IDA) World Congress on Desalination Water Reuse, vol. II, San Diego, CA, 1999, pp. 15–28.
[8] A.M. Hassan, A.M. Farooque, A.T.M. Jamaluddin, A.S. Al-Amoudi, M.A. Al-Sofi, A.F. Al-Rubaian, N.M. Kither, I.A.R. Al-Tisan, A. Al-Rowaili, A demonstration plant based on the new NF-SWRO process, Desalination 131 (2000) 157–171.
[9] A.M. Hassan, A.M. Farooque, A.T.M. Jamaluddin, A.S. Al-Amoudi, A.A. Al-Sofi, A. Al-Rubian, N.M. Kither, A.M., A.-A., I.A.R. Al-Tisan, A.A. Al-Azzaz, A. Abanmy, A. Al Badawi, A.S. Al-Mohammadi, A. Al-Hajouri, M.B. Fallata, Conversion and operation of the commercial Ummlujj SWRO plant from a single SWRO desalination process to the new dual NF-SWRO desalination process, in: Proceedings, International Desalination Association (IDA) World Congress on Desalination and Water Reuse, Bahrain, 2002.
[10] A.M. Farooque, Research Efforts by SWCC SWDRI Towards the Development of Nanofiltration Pretreatment for Seawater Desalination IDA World Congress on Desalination and Water Reuse, International Desalination Association, Dubai, 2009.
[11] A.S. Al-Amoudi, A.M. Farooque, Performance restoration and autopsy of NF membranes used in seawater pretreatment, Desalination 178 (2005) 261–271.
[12] A.M. Farooque, T.N. Green, N.K. Mohammed, F.A. Al-Muali, Autopsy of NF membranes after 5 years of operation at Ummlujj SWRO plant, Desalin. Water Treat. 3 (2009) 83–90.
[13] A.-E. Abdullatef, M. Farooque, G. Al-Otaibi, M. Kither, S.A. Khamis, Optimum nanofiltration membrane arrangements in seawater pretreatment—part-I, Desalin. Water Treat. 28 (2011) 270–286.