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Prospects for improving the performance of SWRO plants by implementing advanced NF/RO techniques: Part-I

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ABSTRACT

The Saline Water Conversion Corporation (SWCC) is responsible for desalting seawater and faces several challenges, such as high feed salinity with high feed temperature and very stringent permeate quality standards (TDS < 50 mg/l, chloride <25 mg/l, and boron < 2.4 mg/l). Most plants employ hollow fiber membrane technology, with smaller plants operating at 30–35% recovery rates, whereas larger plants operate at an approximately 42% recovery rate. The SWRO permeate boron concentration is between 2 and 3 mg/l. Finally, the Umm Lujj SWRO plant employs NF pretreatment and operates at approximately 32.5% overall recovery. This study focuses on designing high recovery SWRO operations by employing spiral wound membranes and recent design approaches. The study using Gulf seawater includes a performance comparison of five different SWRO elements, an examination of the performance of conventional 6-element arrays compared to 7- and 8-element arrays, a performance comparison of 5 hybrid and non-hybrid SWRO designs and an evaluation of the performance of two hybrid SWRO designs operated at 46.5 and 48% recovery and incorporating a split partial two pass approach over 6100 hours of operation. The results indicate that spiral wound membranes with recent design approaches succeed in maximizing the overall recovery up to 45–46.5% compared with existing plants, with an overall recovery of 33–38%.

Keywords: Spiral wound SWRO membranes; SWRO arrays; Hybrid and non-hybrid SWRO designs; Split partial two pass RO; Permeate TDS; boron

I. Introduction

The major force driving the use of membrane desalination technology is the recent technological advances made by industries, which not only enabled cost reduction of water produced by the SWRO process but also offered solutions to many problems initially faced by the membrane desalination industries. For decades, thermal processes dominated the seawater desalination market. In 1995, membrane processes formed 11% of the total installed/contracted seawater desalination capacity of 12.3 million m^3/d [1]. However, in the last few years, SWRO desalination technology has undergone a remarkable transformation and gained widespread acceptance, which is evident from the increased share of SWRO (65%) in the total installed/contracted seawater desalination capacity of 86.5 million m^3/d in 2015 [2]. The number and capacity of large SWRO plants have increased significantly, and plants with permeate capacity up to 624,000 m^3/d are currently in operation. The major reasons for the increase in popularity of the SWRO desalination process are improved manufacturing processes for membranes and cost reduction due to a very competitive market for the products. To make the process more economic, various approaches have been recently applied

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to many of the newly built SWRO plants. These new concepts introduced into the SWRO process design, equipment and operations during the last decade resulted in a sharp decrease in the unit water production cost to approximately US$ 1/m^3.

A typical example of the end product of new technologies for improving SWRO plant performance can be clearly seen in many different SWRO plants located on the Red Sea and Mediterranean Sea. Many SWCC satellite SWRO plants (5000 m^3/d), which are located on the Red Sea (commissioned during 1983–1989), employ conventional SWRO designs and operate at a 30–35% recovery rate, where the cost of water production varies between $ 2.5 and 3/m^3 [3]. Additionally, large SWRO plants (above 90,000 m^3/d) operate at 35–42% recovery [4]. Most SWCC SWRO plants mainly employ hollow fiber membrane technology. In contrast, some of the large SWRO plants located on the Mediterranean Sea (commissioned during 2000–2005) utilize spiral wound membrane technology with advanced RO design features and are operating at approximately 47–50% recovery, thus maintaining desalinated water costs at less than US$ 1/m^3 [5]. SWRO plants in both locations show large variation in terms of plant performance as well as water cost, although there is no significant difference in feed TDS, which is considered to be the most significant factor limiting SWRO process design, as shown in Table 1.

In addition, based on SWCC regulations, SWRO plants are designed to achieve very stringent permeate quality: the permeate water before re-mineralization has to exhibit <50 mg/l TDS and <25 mg/l chloride, whereas the boron concentration has to be <2.4 mg/l. After the re-mineralization process, the product water TDS should not exceed 130 mg/l. Consequently, a second pass RO is required, which results in a further reduction in overall recovery up to 33–38%, as practiced in two of the large SWCC SWRO plants. The first plant is a 240,000 m^3/d capacity Jeddah SWRO-III (commissioned in 2013) operating on the Red Sea at approximately 42% recovery and employs second pass RO at 92%, with an overall recovery of 38%; the second plant is the 91,000 m^3/d capacity Al-Jubail SWRO plant (commissioned in 2000) operating on the Gulf at approximately 35% recovery, and recently, the installation of a second pass is being installed to operate at a recovery of 93% thus leading to an overall recovery of 33%. Another challenge is the Umm Lujj NF/SWRO plant, which utilizes NF pretreatment and operates at an approximately overall recovery of 32.5% (the NF and SWRO stages operate at approximately 65% and 50% recoveries, respectively).

To make the NF/SWRO process economically more attractive, the process needs to be optimized at the highest possible recovery based on findings obtained from recent successful trials of NF pretreatment, which operated at 90% recovery [7–9]. Based on the above discussion, SWCC SWRO plants face many challenges, and to overcome these challenges, the present study aims to design a high recovery SWRO process by employing spiral wound membrane technology with recent design techniques. This paper presents the first part of the study, which focuses on Gulf seawater as one of the most challenging water sources with high feed TDS and temperature, whereas the second part will focus on NF pretreatment as a superior RO feed [10]. To achieve this target, the following different design approaches were considered.

Table 1
Comparison between Larnaca, Ashkelon, Fukuoka and SWCC Satellite SWRO Plants

SWRO Plants	Recovery %	Feed TDS mg/l	Water Cost $/$m^3$
SWCC Satellite Plants[3]	35	42500	2.5–3
Ashkelon Plant [5,12]	47.5	41000	0.78
Larnaca Plant [15]	50	40800	–
Fukuoka Plant [6]	60	35000	–

1.1. Eight SWRO elements in a single pressure vessel

In addition to flux and recovery rates, another significant parameter that can influence the cost reduction of the SWRO process is the membrane configuration. Over the years, membrane configurations have gone through different development steps due to advancements in membrane technology as a result of continuous improvement in membrane performance by membrane manufacturers.

The SWRO system can be adopted as a single- or two-stage (brine staging) system and as a single or two pass (permeate staging) system. In the past, a two-stage SWRO array (brine staging) was usually configured with six elements per pressure vessel to operate at a recovery rate of 35–40%. A two-stage design is usually adopted to maintain high feed-brine flow to reduce concentration polarization. A two-stage design is always accompanied by an increase in power consumption due to the increase in pressure drop across the RO array and by increases in the capital cost compared to a single-stage design due to the requirement of more pressure vessels and piping.

However, recent advances in membrane technology have resulted in the transition of plant design to the single-stage configuration, which enabled an increase in the number of elements per vessel up to 8 elements. From a technical point of view, this results in better membrane hydraulic performance due to the reduced number of pressure vessels at a given recovery rate, which leads to a higher feed-brine flow rate and a higher cross-flow velocity coupled with a lower concentration polarization. Consequently, an 8-element array is adopted for the high recovery operation in this study. From the cost effectiveness point of view, the SWRO system employing six elements per vessel requires 34% more pressure vessels than a system using the same membrane area but configured with eight elements per vessel [11,12]. It has also been shown that a significant savings in capital cost up to 24.7% can be achieved with longer pressure vessel configurations, as shown with an 8-element array compared to a conventional 6-element array [11,12]. Additionally, the same result was confirmed recently at SWCC DTRI for an NF system, where the study revealed that an 8-element array at 65% recovery is found to be the best choice for a single-stage NF seawater pretreatment process compared to the conventional array of six elements [13]. The study showed that productivity and feed flow increased by 25% with no increase in feed pressure or energy consumption and no drop in product quality coupled with better membrane hydraulic performance.

1.2. The split partial two pass SWRO design

Many plants utilize a second pass BWRO to meet the demand of low TDS, as well as boron content, in the final product. For this reason, instead of sending the entire product from the first pass SWRO, it has been the practice to split the permeate into two portions, one exiting from the feed side and the other from the brine side. The permeate collected from the feed end is of lower salinity and flows directly as product water. The fraction of permeate collected from the brine end has the highest salinity value and is therefore polished with second pass RO. This split partial two pass SWRO design is achieved by taking advantage of the intrinsic salinity gradient present inside the pressure vessel of the 1st pass SWRO. The utilization of this salinity gradient in RO arrays to produce permeates of different salinities was studied in 1975 [14]. Recently, this technique has been successfully applied in the Tampa, Larnaca and Ashkelon SWRO plants to reduce both the capital cost of the second pass and energy consumption coupled with improvements in RO permeate quality [15,16]. In Larnaca, 25% of the 1st pass is used as feed to the split partial two pass SWRO to maintain the concentrations of boron <1 ppm and chloride <200 mg/l, whereas in Ashkelon, 75% of the 1st pass is used to achieve stringent permeate quality with boron <0.35 ppm.

1.3. Internally staged designs

The concept of introducing internally staged designs into SWRO desalination plants is mainly to decrease the capital and operating costs of SWRO plants [16,17]. This hybrid design employs high energy consumption elements in the front of the vessel and lower energy elements in the back of the vessel. This approach results in a feed pressure and a permeate salinity value between those of the two membranes. The advantage of this design is that the low permeability lead elements will have a lower flux, resulting in a more balanced element flux distribution, especially at high feed temperatures and high recovery operations. Additionally, the concept of mixing lower flow elements and higher flow elements leads to improved operation and performance of SWRO plants in terms of feed pressure, recovery rate, flux rate and membrane fouling.

1.4. Second pass concentrate recirculation

The 2nd pass concentrate can be circulated to the main RO feed line of the 1st pass, resulting in reducing the operating feed pressure and improving the permeate TDS because the TDS of the 2nd pass concentrate is much less compared to seawater feed TDS. Additionally, the amount of feed for the 1st pass can be reduced with better SWRO economics [18,19].

1.5. Membrane pretreatment techniques

To obtain the best performance from the SWRO membrane and to operate SWRO at high flux and recovery, it is very essential to have extremely good quality pretreated feed, free from suspended solids and microbes. Conventional pretreatment cannot produce such high-quality RO feed because the coagulation-filtration process is not an absolute physical barrier. In this context, the application of microfiltration (MF), as well as ultrafiltration (UF), which emerged in the last decade as an efficient method for treating seawater feed, has become quite important. The nanofiltration (NF) membrane is another type of membrane that has mainly been used for the softening of water and was first introduced by SWCC DTRI for seawater pretreatment. Optimization of the NF process at the highest possible recovery to provide a superior RO feed with recent design modifications will be explored in the second part of this project [7–10].

2. Experimental work

The aim is to demonstrate a high recovery SWRO process operating on Gulf seawater while maintaining severe permeate quality based on SWCC regulations. To achieve this target, the following investigations were carried out: (1) testing five different SWRO elements in terms of permeate TDS and feed pressure; (2) evaluating the performance of conventional 6-element arrays compared to 7- and 8-element arrays to select the optimum arrangement; (3) comparing the performance of 5 different hybrid and non-hybrid SWRO designs with varying membrane characteristics in terms of salt rejection and productivity; and (4) based on the results obtained, adopting the optimum membrane arrangement and process design parameters for high recovery operation in a hybrid split partial two pass design for long-term operation and investigation.

2.1. Pilot plants

2.1.1. Seawater supply and pretreatment system

Seawater is fed from a non-chlorinated seawater intake. The pretreatment unit comprises a dual media filter followed by a fine sand filter with a capacity of 17 m^3/h. Ferric chloride was dosed as a coagulant at a concentration of 1–3 ppm as $FeCl_3$. The pretreated SDI was maintained between 2.5 and 4. There are three chemical dosing systems in the pretreatment for ferric chloride, the coagulant aid and sulfuric acid.

2.1.2. SWRO-1

The first experimental unit, SWRO-1, consists of 8 SWRO elements of size 8″ × 40″ connected in series. It employs a hybrid split partial design, where 2 very high rejection (VHR) SWRO elements followed by 6 high flow (MR) SWRO elements are arranged with an average element flow rate of 26.8 m^3/d. The product is split into rear and front permeates, and the rear product is further treated in a second pass BWRO unit. The front permeate is by-passed for blending with the second pass permeate,and the mixing ratio depends mainly on the requirement to maintain permeate TDS in accordance with SWCC guidelines. Based on preliminary results, SWRO-1 with an average element flow rate of 26.8 m^3/d was operated at 46.5% recovery and a 12.45 l/m^2/h flux rate. A proprietary antiscalant was dosed at a concentration in the range of 1–2 mg/l.

2.1.3. SWRO-2

The second unit (SWRO-2) consists of 8 SWRO elements of size 8″ × 40″ connected in series (2 higher rejection (HR) SWRO elements followed by 6 higher flow (HF) SWRO elements). This unit is designed to utilize a hybrid split partial technique with an average element flow rate of 31.8 m^3/d. Based on preliminary test results, this design option was operated at 48% recovery and a 12.85 l/m^2/h flux rate. Antiscalant was dosed at a concentration in the range of 1–2 mg/l. Fig. 1 shows a schematic flow diagram of an SWRO skid. Each skid consists of a booster pump (5 bar, 12 m^3/h), a high pressure pump (82 bar, 12 m^3/h), a 5 micron cartridge filter, a flushing pump and four pressure vessels connected in series, each containing two SWRO spiral wound elements of 8″ × 40″. There are three chemical dosing systems. Additionally, there is a provision to test single element performance.

SWRO-1 and SWRO-2 have different membrane characteristics in terms of production and salt rejection and employ the advantages of internally staged membrane design as well as the split partial technique.

2.1.4. BWRO unit

The BWRO unit would receive rear end products of both SWRO-1 and SWRO-2. The brine produced by the second stage, having lower salinity than seawater, is recycled upstream of both the SWRO-1 and SWRO-2 feed. Fig. 2 shows a schematic flow diagram of the BWRO skid. It consists of a booster pump (6 bar, 7 m^3/h), a high pressure pump (18 bar, 7 m^3/h), a 5 micron cartridge filter, a flushing pump (7 bar, 8 m^3/h), a brine recirculation pump (6 bar, 1 m^3/h) and 22 BWRO elements of 4″× 40″ (2×8 elements in the first stage and 6 elements in the second stage). The second pass high pressure pump motor is equipped with a variable frequency drive to operate the second pass at different fluxes/capacities. There are two chemical dosing systems for antiscalant and NaOH. The second pass has the flexibility to change the pH, feed flow, recovery, and other operational parameters to meet seasonal needs and research requirements.

2.2. Operating conditions of trials

2.2.1. Testing the performance of five different SWRO elements on Gulf seawater

SWRO membrane elements available in the market have different membrane characteristics in terms of salt rejection and flow rate. The five SWRO membranes tested are shown in Table 2. Testing of the performance of various SWRO membranes was carried out at ambient seawater temperature (29–30°C) and constant operating conditions to obtain a real comparison. The operating conditions used are a seawater feed flow of 8 m^3/h, 8% recovery, a 17 l/m^2/h flux rate and a feed pH of 8.1. The feed pressure ranged from 45 to 55 bar, whereas the seawater feed conductivity was in the range of 61000–62000 µS/cm. During the trial, operation and performance parameters were collected for each of the SWRO membrane elements.

2.2.2. Testing the performance of conventional 6-element arrays compared to 7- and 8-element arrays

To identify the optimum membrane arrangement for high recovery operation, 6-, 7- and 8-element SWRO arrays

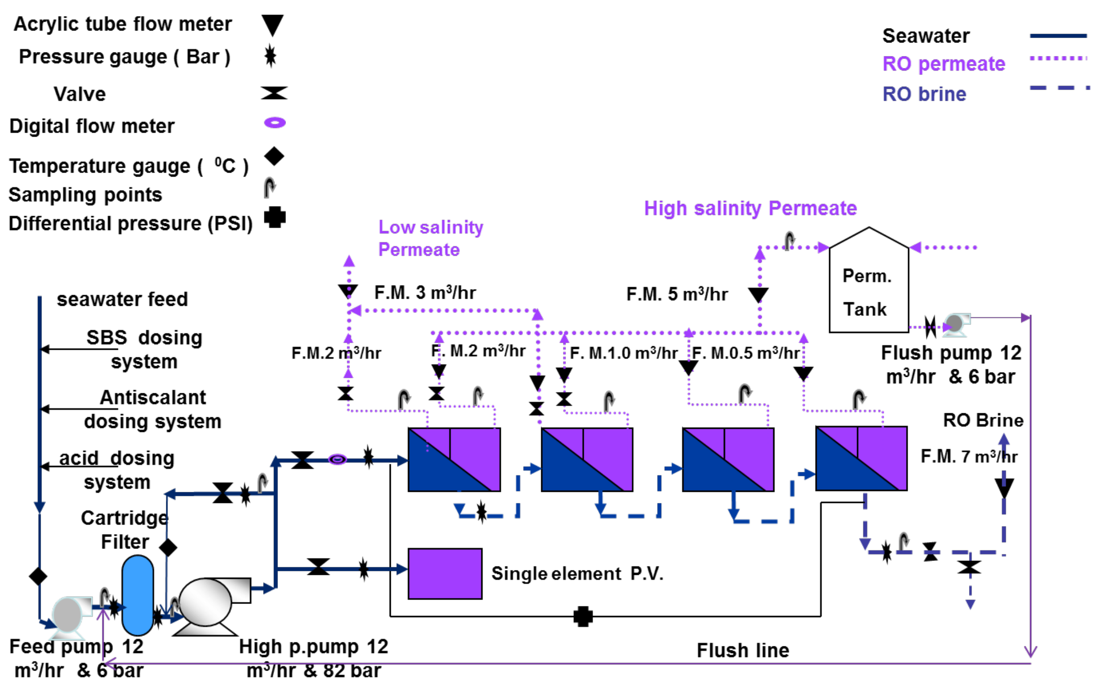


Fig. 1. SWRO unit (four pressure vessels connected in series, each containing two SWRO elements of 8″ × 40″).

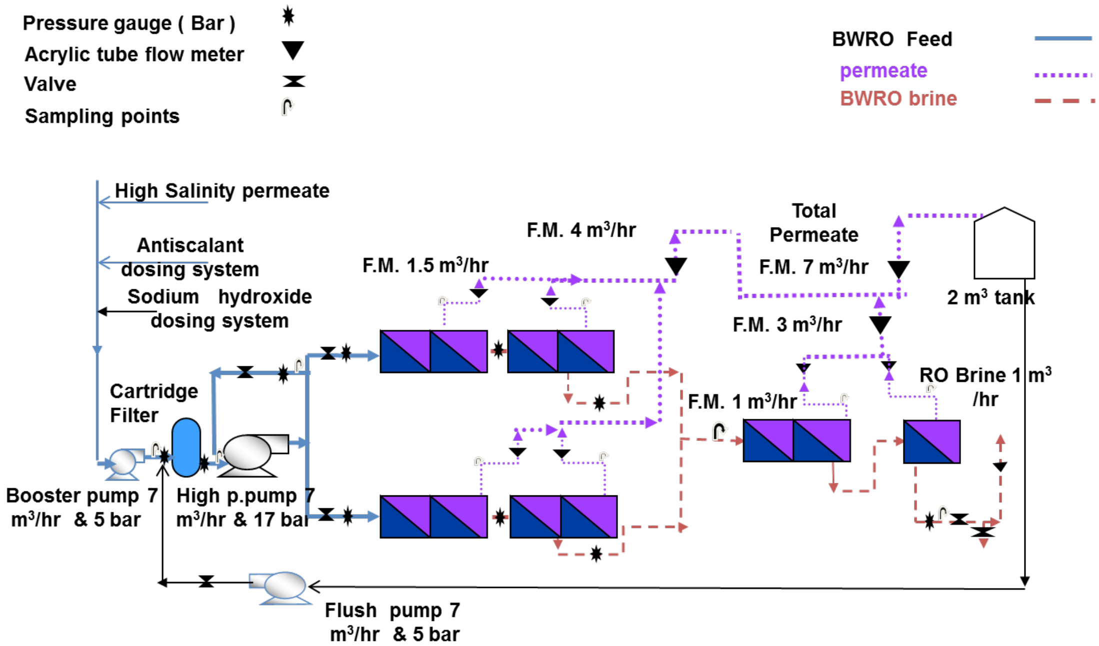


Fig. 2. BWRO unit (2×8 BWRO elements of 4″ × 40″ in the first stage and 6 elements in the second stage).

Table 2
Characteristics of various SWRO elements understandard test conditions

Element description	Area m^2	Flow rate m^3/d	Salt rejection %	Boron rejection %
Highest rejection VHR	37.1	23	99.85	93
High rejection HR	37.1	24.6	99.80	93
Moderate rejection MR	37.1	28	99.75	93
High flow HF	37.1	34.1	99.75	92
Highest flow XHF	37.1	45.5	99.7	91

Standard test conditions: (NaCl feed of 32000 mg/l, recovery of 8%, 25 °C, 55 bar, pH of 8).

were operated on Gulf seawater at constant operating conditions (45% recovery - 12.5 $l/m^2/h$ flux rate - 26–27°C ambient feed temperature). Operation and performance parameters were collected for each SWRO array. Additionally, the projected performance of the 6-, 7- and 8-element configurations at 26.5°C and 45% recovery was investigated using projection software.

2.2.3. Testing the performance of various hybrid and non-hybrid designs on Gulf seawater

Based on the results drawn from the previous trials, which confirmed that an 8-element array is the recommended configuration for a high recovery operation, five cases, including hybrid and non-hybrid designs, were investigated under constant operating conditions (46% recovery, 12.5 $l/m^2/h$ flux rate, 25–26°C ambient feed temperature) as per the following:

Non-hybrid designs:

This approach represents a standard design (basic design) in which only one type of SWRO membrane element is used. Three non-hybrid designs with different membrane characteristics in terms of salt rejection and productivity were examined as follows:

- Case # 1: An 8-element array utilizing a higher rejection (HR) membrane of 99.8% salt rejection with an average element flow rate of 24.6 m^3/d.
- Case # 2: An 8-element array employing a moderate rejection (MR) membrane of 99.75% salt rejection with an average element flow of 28 m^3/d.
- Case # 3: An 8-element array utilizing a high flow (HF) membrane of 99.70% salt rejection with an average element flow rate of 34.1 m^3/d.

Hybrid designs:

- Case # 4: The first hybrid (2VHR/6MR) utilizes 2 very high rejection VHR elements in the lead position and 6 MR elements in the rear positions with an average element flow rate of 26.8 m^3/d.
- Case # 5: The second hybrid (2HR/6HF) uses 2 HR elements in the lead position followed by 6 HF elements in the rear positions with an average element flow rate of 31.8 m^3/d.

2.2.4. Operating conditions of the BWRO unit

The BWRO unit received rear end permeates of SWRO-1 and SWRO-2 operated at an approximately 92% recovery rate to maintain the desired permeate quality. The BWRO membrane arrangement in the second pass was designed to maintain the necessary flux of 24 and 37 l/m²/h during winter and summer months, respectively.

3. Results and discussion

3.1. Performance of five different SWRO elements on Gulf seawater

There are a wide range of commercial SWRO elements available in the market, ranging between high rejection and high flow rate. Trade-offs between higher rejection and higher flow need to be made. Table 2 shows the performance of these elements under standard test conditions. Single element tests were carried out at an ambient seawater temperature of 29–30°C under constant operating conditions. Additionally, the projected performance was investigated at 14°C as the minimum feed temperature. Fig. 3 shows the comparison of the actual and projected performances of five SWRO elements operating on Gulf seawater in terms of feed pressure and permeate TDS.

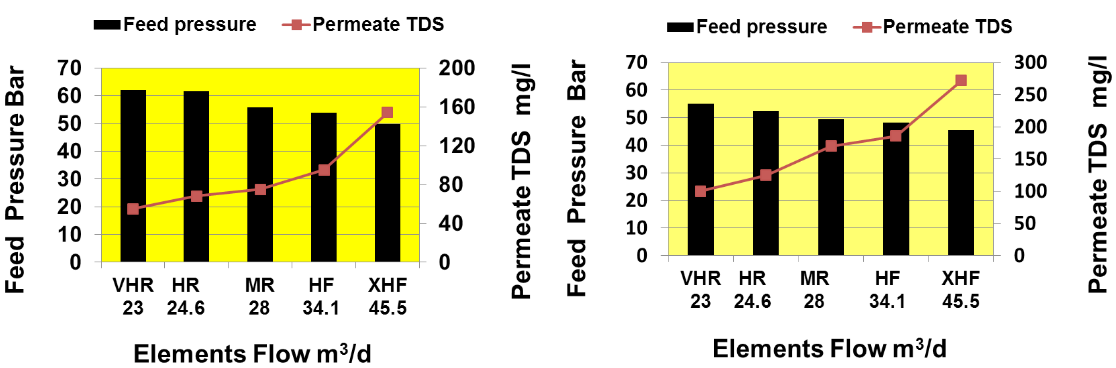
When SWRO elements are tested at the same flux rate and varying pressure, the relative change of permeate quality can be differentiated. Therefore, the SWRO elements were tested at constant operating conditions as discussed before. The highest rejection, lowest flow VHR element at ambient feed temperature showed the highest operating pressure and the lowest permeate TDS as expected, which were 55.2 bar and 100 mg/l, respectively. The VHR element had the lowest permeate salinity at the expense of energy consumption, especially during winter months, which reached approximately 62 bar and 55 mg/l TDS. Consequently, this element is not suitable for high feed salinity cases. In contrast, the highest flow XHF element exhibited the lowest feed pressure (45.5 bar) but at the expense of salt rejection, where the permeate TDS increased to a value of 272 mg/l.

The highest flow, lowest energy XHF element produces permeate that has 172% higher salinity than the highest rejection element VHR with a 9.7 bar lower operating pressure. The extra low energy XHF element will be useful for RO feed waters of lower salinity and temperature ranges. It will have limited use in high feed salinity and high temperature designs. The most economical way to use such a higher flow element is through hybrid design, including both the highest rejection VHR and highest flow XHF elements. The existing studies address two different feed waters (NF product and Gulf seawater), and therefore, the benefits of such higher flow elements in hybrid design will be investigated and optimized for both streams. In particular, the NF product, as a superior RO feed, has a lower fouling and scaling potential and can therefore be optimized at higher flux and recovery without worrying about lead element fouling. The typical high rejection HR element with a flow rate of approximately 24.7 m³/d and a salt rejection of 99.8% is considered a standard element among various membrane suppliers and is recommended for high salinity and temperature designs, for which a single pass RO employing this element at approximately 40% recovery produces the normal potable specification of TDS <400 ppm.

The moderate rejection MR and high flow HF elements represent low energy SWRO elements and result in a pressure midway between those of the typical rejection HR element and the extra high flow XHF element but only 36% and 49% higher permeate salinity than the typical rejection HR element, respectively. The potential use of low energy elements with an element flow range of 28–35 m³/d depends on the site conditions, operating conditions and permeate TDS requirements. These elements can be used across a wide range of feed salinities with decreased energy consumption compared to typical rejection HR elements. Therefore, in the existing trials, such low energy elements are investigated in hybrid designs with the aim of optimizing Gulf seawater at the maximum possible recovery with reduced feed pressure.

3.2 .Single-Stage SWRO 6-,7- and 8-element arrays

The configuration of the membrane arrays plays an important role in the performance of SWRO systems, especially in the recovery ratio, product quality, operation parameters and time-dependent phenomena such as fouling and scaling. Accordingly, preliminary tests were conducted at the pilot plant to determine the optimized SWRO membrane arrangement for high recovery operation. Trials were focused on the performance evaluation of conventional 6-element arrays compared to 7- and 8-element arrays. The



Actual performance at 29–30°C Projected performance at 14°C

Fig. 3. Comparison of the actual and projected performances of five different SWRO elements.

three different arrays were operated at constant operating conditions (recovery of 45%, flux rate of 12.5 l/m^2/h and ambient feed temperature in the range of 25–27°C). During the trial, feed conductivity was in the range of 61200–61700 µS/cm. The results of this trial are presented in Table 3. Fig. 4 displays the projected individual element flow, recovery, and flux and concentration polarization factor based on the element position for the three configurations at a feed water temperature of 26°C.

Analyzing the configurations based on Table 3, the hydraulics indicate that a configuration with 8 elements per vessel is preferable due to higher brine flow in the last element. The total permeate TDS for the three configurations remains relatively constant with a slight increase in operating feed pressure (0.7 bar) for the 8-element case compared to the conventional 6-element array. The pressure drop along the vessel increases as the number of elements increases. It is important to note that the recovery of 45% in the 6-element case is extremely high and exceeds the design manufacturer limits (first element recovery > 13%), whereas the 8-elements array is below these limits, as shown in Fig. 4. Additionally, the lead element of the 8-element array has the lowest concentration polarization factor compared to the 6- and 7-element arrays, as seen in Fig. 4. It is clear that an 8-element array is considered a suitable membrane arrangement for high recovery operations that allows the first pass to reach the nominal recovery of approximately 50%. Additionally, the introduction of higher rejection elements in the lead position of the 8-element array would result in significant improvements in lead element performance in terms of recovery and flux rate. Consequently, another set of experiments was carried out employing hybrid and non-hybrid designs of 8-element arrays with different membrane characteristics to select the optimum membranes and recommended design parameters for high recovery operation.

Table 3
Single-Stage Performance of 6-, 7- and 8-element arrays

No. Elements	Feed pressure (bar)	ΔP (bar)	Position			Total permeate TDS (mg/l)
			Lead element		Last element brine flow (m^3/h)	
			Recovery (%)	Flux (l/m^2-h)		
6	65.6	0.70	14.5	21.6	3.40	260
7	65.9	0.85	11.7	22.6	3.96	254
8	66.3	1.0	11.0	24.3	4.47	265

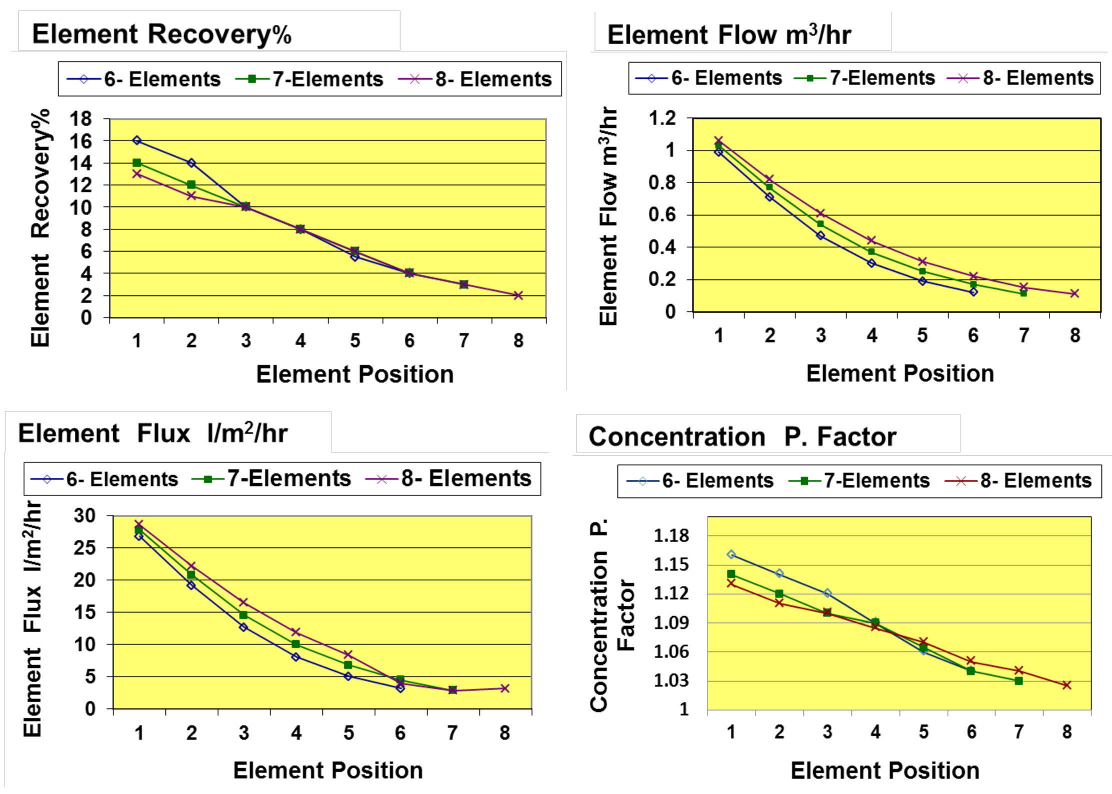


Fig. 4. Projected individual element flow, recovery, and flux and concentration polarization of 3 different configurations.

3.3. High recovery performance of hybrid and non-hybrid designs on Gulf seawater

The results from the previous trial indicate that an 8-element pressure vessel is the preferred configuration for high recovery operations. To investigate the optimal membrane arrangement for this configuration, an analysis was carried out to study the effect of element placement on the performance and operation parameters of the SWRO process. The goal was to maximize recovery from Gulf seawater while maintaining very severe permeate guidelines. The SWRO process design is challenged by high recovery operation, high feed TDS of 46,000 mg/l with high feed temperature up to 36°C, pretreated seawater produced from conventional seawater pretreatment and very stringent permeate qualities. Consequently, the permeate recovery and average permeate flux were determined to be 46% recovery and 12.5 l/m^2/h, respectively. Five different cases, including hybrid and non-hybrid designs of 8-element arrays, were investigated. Table 4 shows the actual performance of various hybrid and non-hybrid designs at temperatures of 25–26°C, 46% recovery and a flux rate of 12.5 l/m^2/h. In addition, the projected permeate TDS, feed pressure and lead element flux and recovery for various cases were investigated at the minimum and maximum feed temperatures of Gulf seawater (14°C and 36°C). Figs. 5 and 6 exhibit the actual performance at 25–26°C compared to the projected performance at 14 and 36°C for 8-element arrays.

The hybrid and non-hybrid arrangements have different membrane characteristics in terms of rejection and productivity. Table 3 shows the average element flow of each array, which ranged from 24.6 to 34.1 m^3/d and reflected the system performance in terms of feed pressure and permeate TDS. An array with 8 HR elements shows the lowest permeate TDS at the expense of energy, which were 222 mg/l TDS and 5.20 kWh/m^3. Employing higher rejection HR elements led to a significant increase in both feed pressure and energy consumption, especially during winter months, which reached approximately 71.7 bar and 5.48 kWh/m^{3,} respectively, as shown in Fig. 5. It should be noted that the 8 HR element array resulted in the highest operating feed pressure with a wide range of pressures in the range of 67.5–71.7 bar, corresponding to permeate TDS in the range of 130–300 mg/l at a feed temperature range of 14–36°C. Therefore, such higher rejection elements are not recommended for high recovery operation due to high feed pressure accompanied by higher energy consumption.

A higher flow HF element array (8 elements) with an average element flow of 34.1 m^3/d at 25°C led to a decrease in feed pressure and an increase in permeate TDS, which were 64.5 bar and 330 mg/l, respectively. This array had the lowest feed pressure, with a very narrow range of feed pressures of 64.5–65.6 bar, whereas the permeate TDS range was in the range of 185–428 mg/l at a feed temperature range of 14–36°C. In addition, this arrangement exhibited the highest lead element flux and recovery, especially during summer months, which reached approximately 39 l/m^2/h and 18.5%, respectively, resulting in unbalanced flux with a higher fouling rate in lead elements. It is clear that higher flow elements cannot be used alone, especially at higher feed temperature and salinity. Hybrid design is the recommended option in such cases to take advantage of higher flow elements in terms of lower feed pressure and higher productivity while optimizing the flux rate in lead elements.

An MR element array (8 elements) with an average element flow of 28 m^2/d showed moderate performance between the two previous arrays (8 HR elements and 8 HF elements) in terms of feed pressure and permeate TDS, as

Table 4
Performance of hybrid and non-hybrid 8 elements arrays at 46% recovery

Case	SWRO array	Element flow (m^3/d)	Feed pressure (bar)	TDS (mg/l)	Energy (kWh/m^3)
Non-hybrid-1	8 HR elements	24.6	68.2	222	5.20
Hybrid-1	2 VHR / 6 MR elements	26.8	66.9	269	5.11
Non-hybrid-2	8 MR elements	28	66.2	280	5.05
Hybrid-2	2 HR / 6 HF elements	31.7	65	290	4.97
Non-hybrid-3	8 HF elements	34.1	64.5	330	4.93

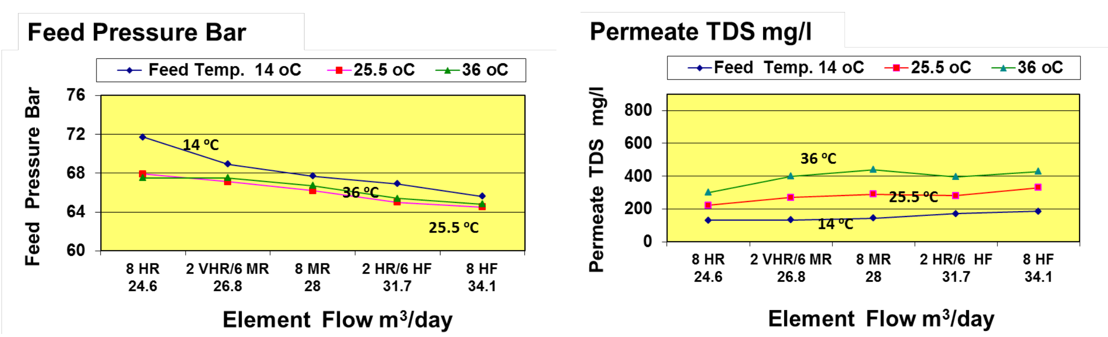


Fig. 5. The effect of SWRO membrane properties on permeate TDS and feed pressure in hybrid and non-hybrid designs.

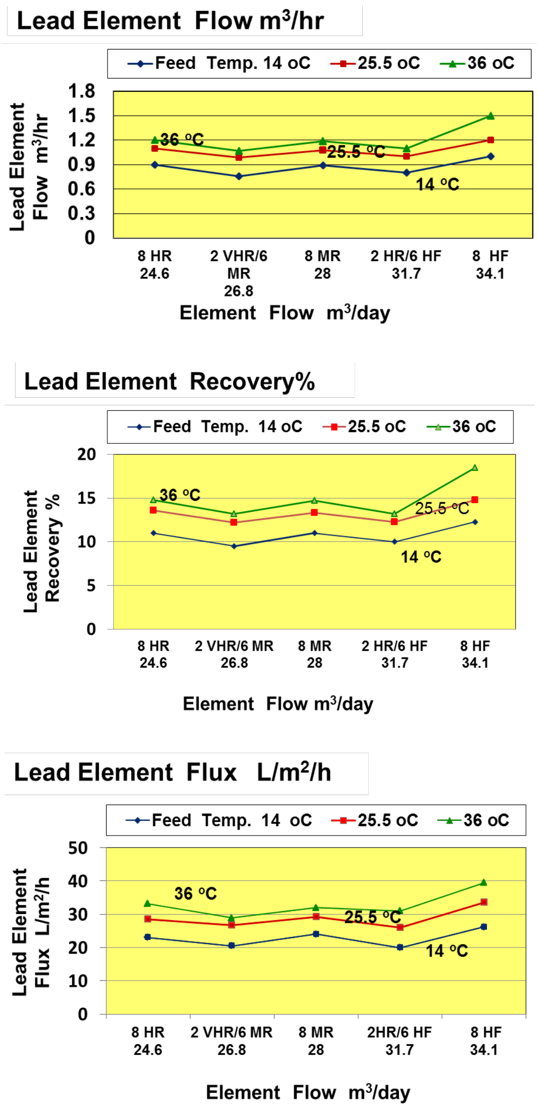


Fig. 6. Lead element flux rate, recovery and flow for various hybrid and non-hybrid designs.

shown in Table 3 and Fig. 5. The operating feed pressure was in the range of 66.7–67.7 bar, with permeate TDS in the range of 143–440 mg/l. Additionally, lead element flux and recovery at the maximum feed temperature of 36°C reduced to 32 l/m^2/h and 14.7% compared to the 8 HF element values of 39 l/m^2/h and 18.5%, respectively, as shown in Fig.6.

Introducing two very high rejection VHR elements in the lead position of the 8 MR element array as the Hybrid-1 design (2VHR/6 MR) with an average element flow of 26.8 m^2/d resulted in an additional reduction in lead element flux and recovery to approximately 28.9 l/m^2/h and 13.2%, respectively. Additionally, there is a slight improvement in the permeate TDS of Hybrid-1, which is approximately 132-400 mg/l, whereas the operating feed pressure increased by approximately one bar compared to the 8-MR element array.

The Hybrid-2 design (2HR/6 HF) employing 6 higher flow HF elements in the back resulted in increasing the average element flow up to 31.7 m^2/d compared to the Hybrid-1 design value of 26.8 m^2/d. The actual and projected results of the Hybrid-1 and Hybrid-2 designs indicated that there is a decrease in the Hybrid-2 operating feed pressure by approximately 2 bar compared to the Hybrid-1 design. The permeate TDS values of the Hybrid-1 and Hybrid-2 designs were in the range of 132–440 mg/l and 171–395 mg/l, respectively, at the minimum (14°C) and maximum (36°C) feed temperatures. Additionally, as shown in Fig. 6, the performances of the lead element in both configurations, in terms of the average flux rate and recovery, were approximately the same. Moreover, integration of both hybrid designs with a second pass BWRO system would lead to further improvements in SWRO process design parameters due to 2nd pass brine recirculation. However, the selection of the best combination or the use of a non-hybrid design will depend on the salinity requirements of the plant.Hybrid-1 and Hybrid-2 were designed to employ the advantages of higherflow elements in terms of higher productivity and lower feed pressures while optimizing the performance of lead elements. Hybrid design is recommended to capitalize on the benefits of higher flow elements.

As in the previous discussion on five different 8-element SWRO configurations, two arrangements have been selected for long-term operation and investigation. The first one was the Hybrid-1 design with an average element flow of 26.8 m^2/d at 46.5% recovery and a 12.5 l/m^2/h flux rate. The second was the Hybrid-2 design with an average element flow of 31.8 m^2/d at 48% recovery and a 12.9 l/m^2/h flux rate. Both hybrids were adopted in a split partial two-pass design with Gulf seawater for long-term operation.

3.4. Performance evaluation of hybrid split partial two pass design in long-term operation

3.4.1. Seawater feed

Seawater is fed from a non-chlorinated intake as previously described. The study was started in the winter of December 2016. The feed water temperatures during the trial varied between 15°C and a maximum of 37°C. Additionally, high-quality pretreated seawater, in terms of SDI values, ranged from 2.5–3.5, occasionally reaching above 4.1. The seawater feed conductivity was between 61,000 and 62,500 µS/cm, periodically reducing to 60,000–61,500 µS/cm due to mixing of second pass BWRO concentrate. Pretreated seawater TOC was in the range of 1–2 mg/l. The seawater feed boron concentrations were typically between 5 and 6 mg/l with both SWRO-1 and SWRO-2 receiving the same feed.

3.4.2. Hybrid-1 (split partial two pass design)

Fig. 7 exhibits the operation and performance parameters of the Hybrid-1 design, where the SWRO-1 array (2VHR/6MR) with an average element flow of 26.8 m^3/d is operated at 46.5% recovery at a flux and a flow rate of 12.45 l/m^2/h and 7.9 m^3/h, respectively. The feed pressure ranged from 62 to 71.7 bar, corresponding to a feed temperature range of 15–37°C. The average operating pressure was 66.5 bar. The differential pressure across SWRO-1 membranes was steady at 0.8–1 bar. As seen in Fig. 7, stable membrane performance was obtained with regard to prod-

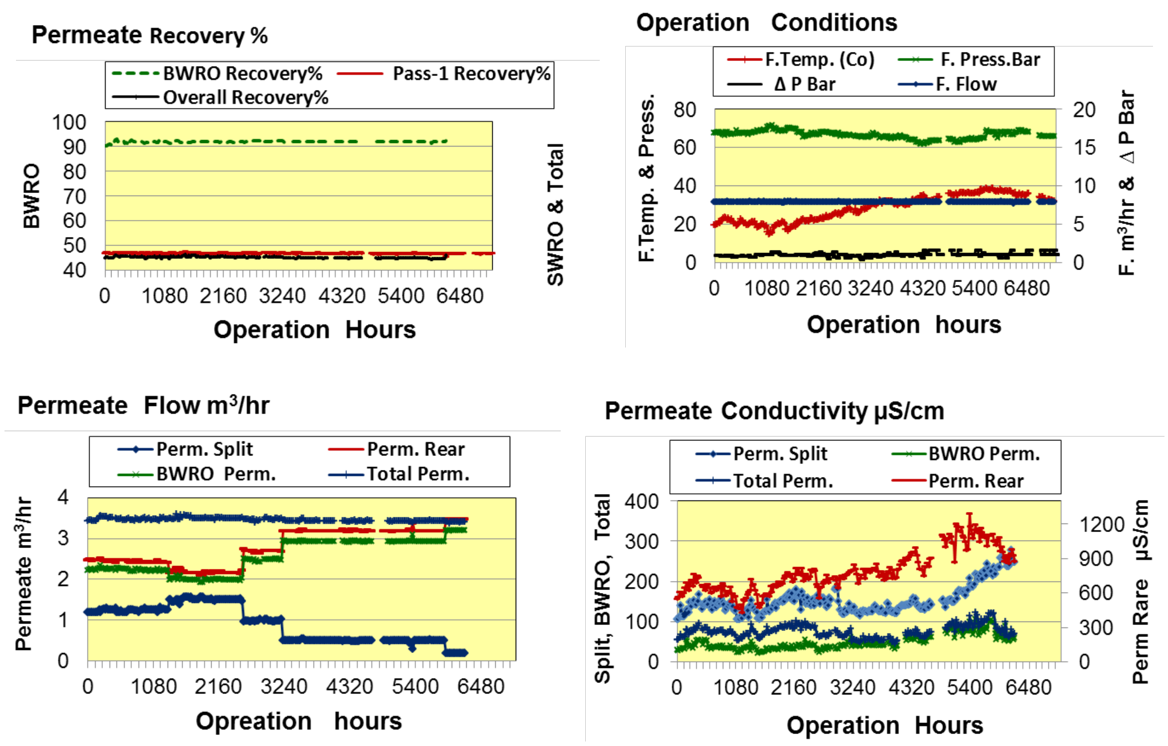


Fig. 7. Operation and performance parameters of Hybrid-1 (split partial two pass design) for 6100 hours of operation.

uct flow rates and recoveries. Based on feed temperature variations from 15 to 37°C, the permeate split stream ratio decreased from 40–30 to 15%. The decrease in the permeate split stream ratio was necessary to maintain a permeate conductivity of <100 µS/cm.

At the end of the trial, for approximately 250 operating hours, the permeate split ratio was decreased to 5% to improve the permeate quality. Accordingly, the overall permeate recoveries ranged from 44.2 to 46.1%, averaging 45.1%. The product flow rates for the 1st pass RO, 2nd pass (BWRO) and total product were 3.68, 2.59 and 3.46 m^3/h, corresponding to average recoveries of 46.6%, 91.9% and 45.1%, respectively.

The corresponding permeate conductivities for the 1st pass RO, 2nd pass (BWRO) and total product averaged 643, 48 and 76 µS/cm, respectively. The feed side permeate conductivity ranged from 105 to 278 µS/cm, compared to the rear end permeate conductivity of 426–1284 µS/cm. The final permeate conductivity ranged from 45 to 122 µS/cm, averaging 76 µS/cm. After 6100 h of operation, the BWRO unit was kept under shutdown to investigate the performance of SWRO-1 on seawater feed (without BWRO brine recirculation) and to perform chemical cleaning.

3.4.3. Hybrid-2 (split partial two pass design)

The Hybrid-2 design employs the SWRO-2 array (2HR/6HF). It has an average element flow of 31.7 m^3/d and is operated at 48% recovery with a flux and a flow rate of 12.85 l/m^2/h and 7.9 m^3/h, respectively (Fig. 8). The seawater feed pressure and temperature were in the range of 66.5–72 bar and 15–37°C, respectively. The operating feed pressure averaged 69.5 bar. The differential pressure across SWRO-2 membranes remained between 0.8 and 1 bar. To maintain total permeate conductivity < 100 µS/cm, the permeate split ratio started at 40% (at a feed temperature of 15°C), then decreased to 30% (at 28°C) and reduced to 15% (at 37°C). At the end of the trial (approximately 250 operating hours), the permeate split ratio was decreased to 5% to improve permeate quality. Based on the permeate split stream ratios, the overall recoveries varied between 45.5 and 47.2%, averaging 46.5%. The product flow rates for the 1st pass RO, 2nd pass (BWRO) and total product averaged 3.81, 2.66 and3.58 m^3/h, respectively. The average recovery ratios of the 1st pass RO, BWRO and overall product were 48%, 91.9% and 46.5%, respectively, with corresponding permeate conductivities averaging 671, 50 and 70 µS/cm, respectively.

The feed side permeate split stream conductivity was in the range of 59–225 µS/cm, compared to the rear side permeate conductivity, which ranged from 424–1305 µS/cm. The final permeate conductivity was between 44 and 108 µS/cm and averaged 70 µS/cm. After 6100 operating h, the BWRO unit was kept under shutdown to investigate the performance of SWRO-2 on seawater feed (without BWRO brine recirculation) and to perform chemical cleaning.

3.4.4. Second pass RO (BWRO)

BWRO was operated from the rear side permeates of SWRO-1 and SWRO-2. The rear-permeate ratios were increased from 60 to 95% due to feed temperature variations (15–37°C) to maintain total permeate conductivity below 100 µS/cm. Accordingly, the BWRO feed flow rates

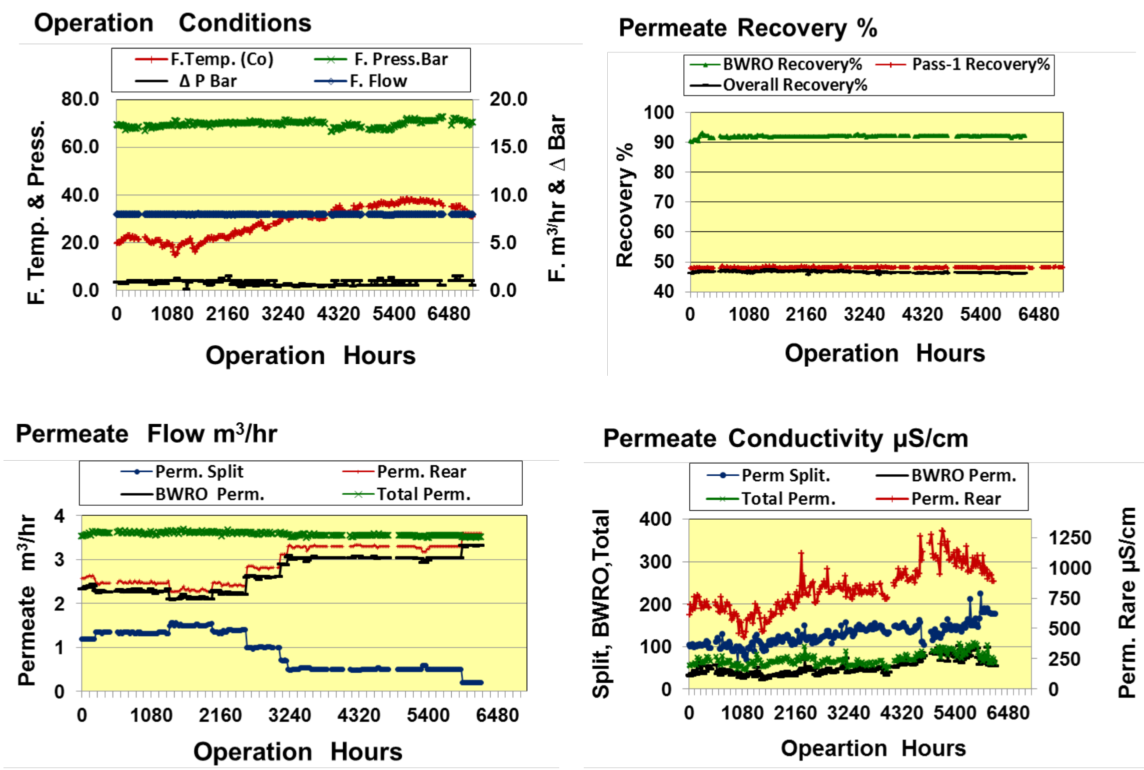


Fig. 8. Operation and performance parameters of Hybrid-2 (split partial two pass design) for 6100 h of operation.

ranged from 4.4 to 6.4 m³/h, with the flux rates varying between 24 and 35 l/m²/h. During maintenance shutdowns of an SWRO unit, the feed flow rates reduced to nearly 50%. BWRO brine ranging from 6500 to 13000 µS was mixed with SWRO-1 and SWRO-2 seawater feeds. BWRO was operated at approximately 90% recovery at the beginning of the study and then increased to 92%. BWRO showed stable performance in terms of product water recovery and permeate flow rates. Fig. 9 represents the recovery ratios, product flow rates and permeate conductivities for 6100 hours of operation.

The BWRO feed pressure ranged between 9.2 and 13.5 bar, averaging 11.7 bar. The differential pressure for the first and second stage BWRO remained steady, averaging 1.4 and 1 bar, respectively. The total ΔP reached 2.4 bar and then increased to 3.5 bar when the feed flow rates were elevated to 6.5 m³/h. The BWRO feed conductivity ranged from 350 to 1347 µS/cm, whereas the final product ranged from 15 to 100 µS/cm. The average BWRO product conductivity was 46 µS/cm. Tables 5 and 6 show the actual and projected performance of BWRO after approximately 2000 and 4500 h of operation at different conditions (feed TDS: 355 mg/l and 23°C, and feed TDS: 420 mg/l and 34°C, respectively). The total permeate TDS values under both conditions are similar to the projection.

3.4.5. Comparison of the performances of Hybrid-1 and Hybrid-2

Fig. 10 shows a comparison of the performances of Hybrid-1 and Hybrid-2 at a feed temperature range of 15–37°C. The feed pressure, differential pressure, permeate flow and conductivity from both designs were continuously monitored and used to normalize permeate flow and salt passage. As exhibited in Fig. 10, the operating feed pressures of SWRO-1 and SWRO-2 were in the ranges of 62–72 bar and 66.5–72.5 bar, averaging 66.5 and 69.5 bar, respectively.

During the first 2200 hours of operation, the feed temperature ranged from 15 to 23°C. The performances of SWRO-1 and SWRO-2 were stable, operating at 46.6 and 48% recovery with fluxes of 12.45 and 12.85 l/m²/h, respectively. Recovery was 45.3% for SWRO-1 and 46.6% for SWRO-2 with an average element flow rate of 26.8 and 31.7 m³/d, respectively. The difference in membranes (SWRO-1 and SWRO-2), receiving the same seawater feed, is that SWRO-2 has a looser membrane structure than SWRO-1.

With increasing feed temperature from 23 to 37°C, both SWRO-1 and SWRO-2 showed different trends. The SWRO-1 operating feed pressure decreased gradually from 68 to 62 due to increases in both feed temperature and BWRO brine recirculation flow. The operational impact on SWRO-1 as the temperature increased from 23 to 37°C resulted in a decrease in feed pressure from 68 to 62 bar when BWRO brine recirculation flow was applied. There was no significant difference between the actual and projected operating feed pressures, as seen in Tables 5 and 6. Additionally, the normalized permeate flow decreased from 3.67 to 3.1 m³/h. After 4600 operating hours, high and low pH cleaning in place (CIP) was performed on SWRO-1, but with no significant improvements in normalized flow. At the end of the trial, after approximately 6300 operat-

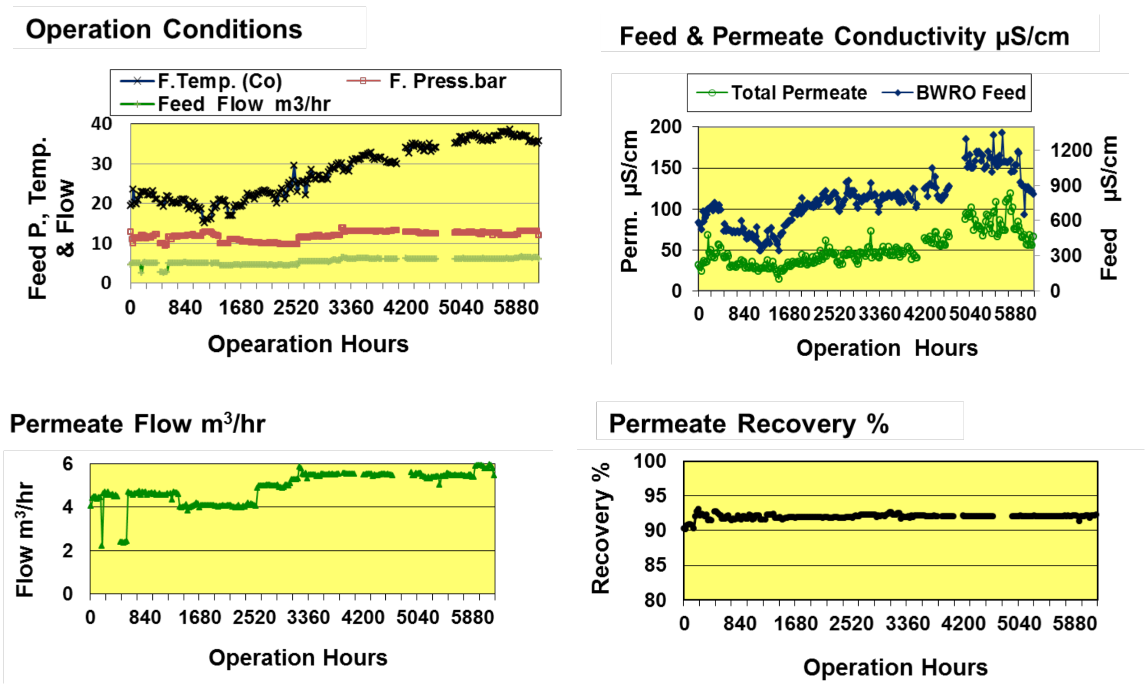


Fig. 9. Operation and performance parameters of second pass BWRO for 6100 h of operation.

Table 5
Actual and projected performances of the Hybrid-1 and Hybrid-2 split partial two pass designs after operating for 2000 h (40% permeate split ratio and 23°C)

Data	March 12, 2017					
	SWRO-1		SWRO-2		BWRO	
	Projected	Actual	Projected	Actual	Projected	Actual
Feed mg/l	45148		45539		320	355
Feed pH	7		7		5.5	
Feed temp °C	23		23	23	23	22.5
Perm flow m³/h	3.67	3.69	3.81	3.82	4.09	4.08
Recovery %	46.5	46.4	48	48.1	92	91.8
Feed pressure bar	66.2	66.5	66.3	69	9.3	10
Press. drop bar	1.4	1	0.9	0.7	1.9	2.6
1st pass perm mg/l	221	235	268	232	15	17
Perm. split µS	141	164	173	131		
Perm. rear µS	660	740	810	745		
Perm total TDS mg/l	43	41	44	36		
Perm total boron mg/l	0.88	0.84	1.25	1.1		

ing h, alkaline CIP was performed on SWRO-1 at pH 11.8 with increasing soaking time from 8 to 12 hours, resulting in an increase in normalized flow from 2.55 to 3.08 m³/h. The overall decrease in permeate flow was approximately 15%, which is higher than the typical 7% flow loss per year. The operating feed pressure decreased from 68 to 65.5 bar, which was similar to the projection.

The SWRO-2 operating feed pressure followed a different trend with increasing feed temperature from 23 to 37°C: first, it was maintained at approximately 69-70 bar for a long period and then decreased slightly to approximately 67.5 bar, as shown in Fig. 12. Additionally, the actual operating feed pressures were higher than the projected values by approximately 2.5 bars. After approximately 4700 operating h, high and low pH CIP was performed on SWRO-2, but with no significant improvements in normalized flow. Therefore, lead element was subjected to autopsy and analyses, where membrane surfaces and feed spacers were found to be in clean conditions, as shown in Figs. 13 and 14. Membrane autopsy confirmed that there was no mem-

Table 6
Actual and projected performances of the Hybrid-1 and Hybrid-2 split partial two pass designs after 4600 operating h (15% permeate split ratio and 35°C)

	June 30, 2017					
	SWRO-1		SWRO-2		BWRO	
	Projected	Actual	Projected	Actual	Projected	Actual
Feed mg/l	43824		44639		445	420
Feed pH	7		7		5.6	5.7
Feed temp °C	34.5		35		34	34
Perm flow m^3/h	3.67	3.69	3.81	3.81	5.52	5.58
Recovery %	46.5	46.7	48	48	92	92
Feed pressure bar	63.6	63.6	65	68.0	9	12
Press. drop bar	1.4	1	0.8	1	2.2	3.8
1st pass perm mg/l	394	371	395	410	29	27
Perm.cond. split µS	214	143	175	144		
Perm. cond. rear µS	929	876	920	873		
Perm total TDS mg/l	43	36	29	34		
Perm total boron mg/l	1.48	1.1	1.79	1.20		

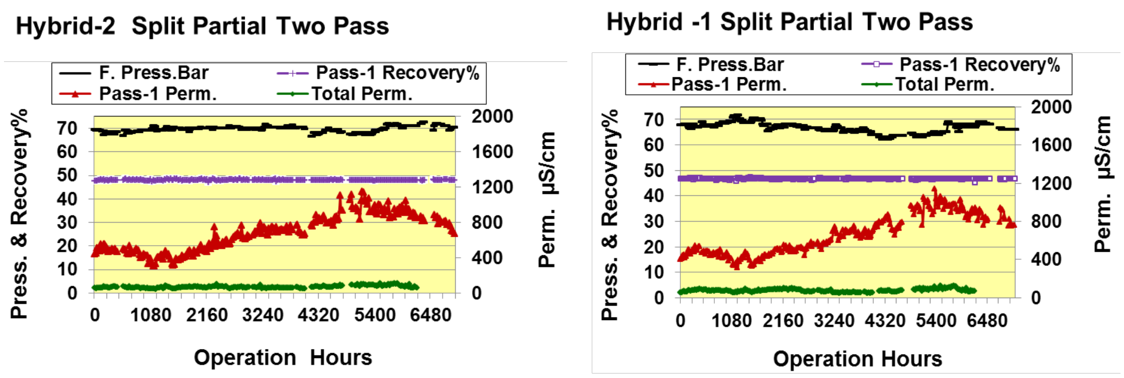


Fig. 10. Comparison of the performances of Hybrid-1 and Hybrid-2 split partial two pass designs for 6100 h of operation.

brane fouling. The membrane manufacturer confirmed that the loss in normalized permeate flow and the increase in feed pressure by approximately 2.5 bar compared to the projected may be due to improper storage (exposure to high temperature during storage) of SWRO-2 membranes. At the end of the trial, after approximately 6500 operating h, alkaline CIP was performed on SWRO-2 at pH 11.8 with increasing soaking time from 8 to 12 h, resulting in an increase in normalized flow from 2.6 to 3.07 m^3/h. The overall decrease in permeate flow was 18%, which is higher than the typical 7% flow loss per year. It was observed that the second chemical cleaning was more effective than the first cleaning due to the increase in pH from 11.5 to 11.8 and soaking time from 8 to 12 h. Based on the results obtained, it is concluded that CIP should be performed every 2500 h and that other different CIP procedures must be explored.

Regarding the 1st pass RO permeate quality, although SWRO-2 represents looser SWRO membranes, its permeate quality is approximately similar to that of SWRO-1, having tighter SWRO membranes, as shown in Fig. 10. This mainly occurs because SWRO-2 was operated at higher pressure than projected and at a pressure higher than the SWRO-1 feed pressure by approximately 2.5 bar.

The 1St pass RO permeate conductivities of SWRO-1 and SWRO-2 were in the range of 314–1138 and 303–1150 µS/cm and averaged 642 and 671 µS/cm, respectively. During the entire operation, a high-quality permeate was obtained from the 1st pass RO of both hybrid designs. Based on the permeate split stream ratio, a hybrid split partial two pass design for Gulf seawater can be adopted with high recovery operation under two different operation modes: 1- very stringent permeate quality, as recommended by SWCC regulations (permeate TDS < 50 mg/l), and 2- the normal potable specification of 400 ppm TDS. This study presents a hybrid design with higher average element flow (27 and 32 m^3/d) for the normal potable specification of 400 ppm TDS at 47–48% recovery. Actually, in the Middle East with high feed temperature and salinity, conventional single-stage SWRO is being used at approximately 40% recovery using typical SWRO membranes (24 m^3/d).

Fig. 11 shows that the normalized salt passages of SWRO-1 and SWRO-2 in the low feed temperature range

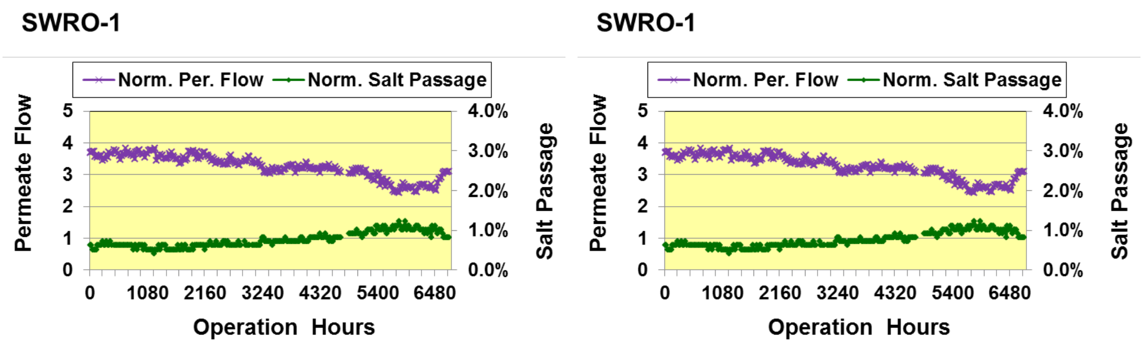


Fig. 11. Normalized salt passage and permeate flow of SWRO-1 and SWRO-2.

of 15–23°C were approximately the same. SWRO-1 and SWRO-2 started with 0.6 and 0.7% salt passage and remained at approximately 0.6 and 0.7%, respectively. With an increase in feed temperature to 37°C, the SWRO-1 and SWRO-2 salt passages increased to approximately 1% and 1.1%, respectively. At the end of the trial with decreasing feed temperature up to 32°C, the SWRO-1 and SWRO-2 salt passages were maintained at approximately 0.8%. However, based on optimizing the permeate split stream ratio, the final permeate conductivity of the Hybrid-1 and Hybrid-2 split partial two pass designs averaged 76 and 70 µS/cm, respectively, which was below 100 µS/cm, as recommended by SWCC regulations.

Moreover, the Hybrid-1 and Hybrid-2 split partial two pass designs produced high permeate quality in terms of boron concentration, which was below 1 mg/l at pH 7 (without injecting NaOH) compared to the seawater feed boron concentration of 5.2–5.8 mg/l, whereas the boron concentration in the 1st pass RO permeate was 1.35 mg/l on average. Fig. 12 shows the boron concentrations in seawater feed and different permeates. It is important to mention that 1st pass RO permeates at SWCC plants have high levels of boron that fall within the range of 2-3 mg/l [20].

Tables 5 and 6 present further confirmation of the actual and projected performances of the Hybrid-1 and Hybrid-2 split partial two pass designs after approximately 2000 and 4500 operating hours under two different conditions (40% permeate split ratio at 23°C and 15% permeate split ratio at 35°C), respectively. The analysis results are shown in Tables 4 and 5 based on data taken on March 12 and June 30, 2017. From the comparison, the actual and projected SWRO-1 feed pressures are approximately similar. There is no significant difference between the actual and projected feed pressures. Additionally, the actual permeate total TDS and boron content under the two different conditions are slightly better than the projected values. Regarding SWRO-2, the actual feed pressures are higher than those projected by approximately 2–3 bar. The actual total permeate TDS and boron are similar or slightly better than the projected values. As seen in Tables 5 and 6, both the Hybrid-1 and Hybrid-2 split partial two pass designs produced high-quality permeates in terms of TDS and boron content, as recommended by SWCC regulations (50 mg/l TDS, 25 mg/l chloride, boron < 2.4 mg/l).

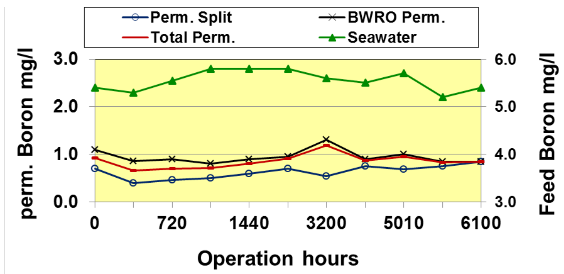


Fig. 12. Boron concentration in seawater feed and different permeates.

3.4.6. Biological results

Bacterial concentrations in the intake water remained within three orders of magnitude, slightly increasing in number but remaining within the same order of magnitude after the dual media filters (DMF). An elevation in bacteria concentration to six orders of magnitude was observed after cartridge filters until their replacement. After replacement, the concentrations remained within three orders of magnitude. The bacteria concentrations in the low and high salinity permeates of SWRO-1 and SWRO-2, as well as the final product, remained within 0 orders of magnitude. It is concluded that microbial rejection by membranes is nearly 100%.

3.4.7. Lead element autopsy

As mentioned earlier, the actual SWRO-2 operating feed pressure was higher than that projected by approximately 2–3 bar. Additionally, before membrane installation, a membrane storage solution with black deposits was observed. The solution was contaminated with biofilm and microbial species. The presence of biofilms and bacteria was confirmed by SEM/EDX analysis. Therefore, based on these findings, the SWRO-2 lead element was removed for testing its performance and for autopsy after approximately six months of operation. The autopsy included physical inspection of the element along with microscopic examination of the extract and biomass and ATP analysis. Membrane surfaces and feed spacers were found to be in clean conditions,

Fig. 13. Rolled and individual sheets with spacer.

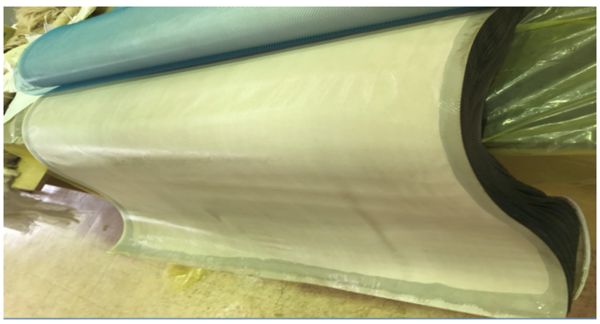


Fig. 14. Membrane discoloration from feed (right) to product (left) end.

as shown in Figs. 13 and 14, and discoloration was observed on membrane sheets. The membrane manufacturer indicated that discoloration of storage solution results from the presence of amines in the solution, which turns it to a blackish color if vacuum is lost during storage of elements.

3.4.7.1. Microbial biomass:

Biomass was determined by lyophilizing the sample. The biomass was determined to be 16.85 μg/cm^2. The biomass concentration was very low and relatively insignificant to be a primary source for membrane fouling.

3.4.7.2. Biochemical analysis

Adenosine triphosphate analysis (ATP) was conducted to measure the amount of biological activity on the membrane surface. The concentration of ATP was found to be

Table 7
Biomass and ATP concentration for autopsied sample

	Foulant mass μg/cm^2	ATP RLU/cm^2
Membrane	16.85	2.03×10^6

Table 8
Operation and performance parameters of lead element (SWRO-2)

	Start up	After 4600 operating h
Membrane weight (kg)	14	14.5
Feed temperature (°C)	24.5	35.1
Feed pressure (bar)	61.9	62
Brine pressure (bar)	61.5	61
Pressure drop	0.4	1
Feed flow (m^3/h)	7.95	8.04
Permeate flow (m^3/h)	0.64	0.64
Recovery (%)	8.05	7.96
Feed conductivity (μS)	61300	60500
Brine conductivity (μS)	65600	65200
Permeate conductivity (μS)	115	220
Normalized flow (m^3/h)	0.64	0.49

2.03×10^6 RLU/cm^2. The amount of ATP present in the sample per unit area was high, indicating that the membrane surface biological activity was high. It is important to note that although bacterial activity was high, it did not result in high levels of extracellular polymeric substance production (EPS-Biofilm).

Prior to membrane autopsy, the lead element was operated for approximately 30 min at 8% recovery and compared to its initial performance results, as shown in Table 8. The operation results indicated that there was no change in operating feed pressure with increasing feed temperature from 24 to 35°C, which were 61.9 and 62 bar. The normalized flow decreased from 0.64 to 0.49. Additionally, there was no increase in membrane weight, as confirmed by membrane autopsy. The membrane autopsy results and single element performance test indicated that there was no sign of membrane fouling.

4. Conclusions

1. The recommended configuration for high recovery operation on Gulf seawater is an 8-element array. It gives higher benefits and facilities in system operation, such as operating at higher recovery with optimized feed pressure.
2. The hybrid designs Hybrid-1 and Hybrid-2 employed an 8-element array and adopted asplit partial two pass system. The hybrid designs represent tighter and looser SWRO membranes with average element flow rates of 26.7 and 31.7 m^3/d, respectively.

3. Introducing higher flow SWRO elements into the Hybrid-2 design led to operating at 48% recovery and a 12.9 $l/m^2/h$ flux rate, compared to the Hybrid-1 design at 46.5% recovery and 12.5 $l/m^2/h$, with feed pressure ranges of 66.5–72.5 and 62–72 bar and averages of 69.5 and 66.5 bar, respectively.
4. Additional improvements in the hybrid design configuration can be achieved in terms of recovery and operating feed pressure by increasing the average element flow up to 35 m^3/d.
5. The Hybrid-1and Hybrid-2 split partial two pass designs produce high permeate quality averaging 76 and 70 µS/cm, respectively, which is below the target 100 µS/cm established by SWCC regulations.
6. The boron concentrations in the 1^{ST} pass RO permeate and total permeate were approximately 1.3 and 1 mg/l, respectively, compared to the values for existing SWCC SWRO plants of approximately 2–3 mg/l with hollow fiber membrane technology.
7. Based on the permeate split stream ratio, a hybrid split partial two pass design for Gulf seawater can be adopted with high recovery operation under two different operation modes: 1- very stringent permeate quality, as recommended by SWCC regulations (permeate TDS < 50 mg/l), and 2- the normal potable specification of 400 ppm TDS.
8. The use of spiral wound membrane technology with recent design approaches for Gulf seawater succeeded in maximizing the overall recovery up to 45–46.5% compared to the existing SWCC SWRO plants' overall recovery of 33–38%.
9. With this design concept, the achievement of 47% overall recovery for Red Sea source water is expected due to the lower salinity (TDS: 42500 mg/l).

Acknowledgment

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References

[1] IDA Desalination Inventory Report No. 19, International Desalination Association, Topsfield, MA, USA.
[2] IDA Desalination Yearbook 2015–2016, Water Desalination Report, Media Analytics Ltd., Oxford, UK, 2015.
[3] SWCC Annual Report, 2010.
[4] M. Katsube, K. Marui, S. Tanaka, M. Al-Thubaiti, Y. Al Jehani, H. Iwahashi, Around Twenty-year Operational history of Jeddah RO Plant using hollow-Fiber RO Modules, IDA World Congress-The Palm-Dubai, UAE November 7–12 (2009) DB09-183.
[5] 21st GWI/ IDA Worldwide Desalting Plant Inventory, 2008.
[6] H. Kotera, T. Yagi, T. Tanaka, N. Fujiwara, H. Tsuge, T. Hamano, 60% Recovery performance of advanced RO module at the Fukuoka Seawater Plant IDA World Congress-Maspalomas, Gran Canaria –Spain October 21-26, 2007, MP07-118.
[7] Z.A. Abou-Elfetouh, M.A. Farooque, F.A. Ghazzai, N.M. Kither, Significant improvements in NF seawater pretreatment up to 90% recovery, WSTA Gulf Water Conference, March, Sultanate of Oman, Oman (2010) 10-01.
[8] Z.A. Abou-Elfetouh, G. Al-Dowais, Cost effective alkalized NF/SWRO instead of conventional techniques for very severe boron regulation, IDA World Congress, San Diego, CA, USA, IDAWC15 (2015) 0491-000146.
[9] Z.A. Abou-Elfetouh, U.S. Patent No. 9,090,491 B2 (2015).
[10] KACST (KSA), King Abdulaziz City for Science and Technology (Code Number: 12-WAT2774-24).
[11] B. Liberman, M. Wilf, Evolution of Configuration of RO Seawater Desalination Systems, IDA SP05-059 (2005).
[12] M. Brusilovsky, M. Faigon, The impact of varying the number of elements per PV in SWRO plants - actual and future configurations, Desalination, 184 (2005) 233–240.
[13] Z.A. Abou-Elfetouh, M.A. Farooque, F.A. Ghazzai, N.M. Kither, S.I. Al-Khames, Optimum NF membrane arrangements in seawater pretreatment Part-1, IDAWC, Spain, MP07-165 (2007).
[14] D.T. Bray, U.S. Patent 4,046,685 (1977).
[15] E. Koutsakos, D. Moxey, Larnaca desalination plant, Cyprus-from an efficient to an effective plant operation, Desalination, 221 (2008) 84–91.
[16] L. Stevens, J. Kowal, K. Herd, M. Wilf, W. Bates, Tampa Bay seawater desalination facility: start to finish, IDA Conference, Bahamas, 2003.
[17] W.E. Mickols, M. Busch, Y. Maeda, J. Tonner, A Novel design Approach for Seawater Plants. IDAWorld Congress, 2005.
[18] M. Busch, M. Brusilovsky, W.E. Mickols, A novel approach for seawater desalination cost reduction, EDS Conference, 2006.
[19] M. Kim, M.K. Chung, Y.S. So, S.R. Snog, Optimum design of partial two-pass systems for SWRO plants by simulation programs, IDAWC/TIAN 13-303 (2013).
[20] R.A. Al-Rasheed, S.A. Al-Sulami, G. Hassain, Survey of boron levels in seawater desalination plants in Saudi Arabia, IDAWC, Spain, MP07-164 (2007).