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Pioneering demineralized and desalinated water cost reduction with innovative brackish water RO membrane technology

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ABSTRACT

Breakthrough reverse osmosis (RO) membrane chemistry and innovative materials of construction have been developed to achieve highest possible NaCl rejection while maintaining maximum element productivity. Novel brackish water reverse osmosis (BWRO) membrane element delivers to end users state-of-the-art salt rejection (99.7%) at 30% lower energy consumption compared to current high rejection BWRO membranes in addition to tailored salt passage reduction of critical solutes as nitrate, boron, silica, and ammonium. The novel module component, low differential pressure (LDP) feed spacers, provide end users with up to 15% savings in direct RO energy reductions via the lowest feed-side pressure drop available in the market. The LDP spacer outperforms other spacers by reducing pressure drop while maintaining high active area and a unique BWRO element with productivity up to 14,000 gallons per day has been achieved. A financial analysis was carried out with a refined cost model using different economic frame conditions. It shows RO plant energy costs can be reduced by up to 30% in industrial applications without compromising the product water quality. In SWRO application, the size of the BWRO pass can be reduced by 19%, resulting in an overall water cost reduction of 0.53 UScts/m^3 produced water.

Keywords: Low differential pressure feed spacer; Novel membrane chemistry; Energy reduction

1. Historical perspective of brackish water reverse osmosis elements

The standard 8-inch diameter by 40-inch long brackish water reverse osmosis (BWRO) element in 1990 contained only 330 ft^2 of membrane active area and produced 7,500 gallons per day (GPD) with typical NaCl rejection of 98% at standard test conditions of 225 psi, 2,000 ppm feed concentration, and 15% recovery.

Over the past two decades, research programs have made continuous improvements to the FT30 membrane chemistry, spacer materials, and associated element designs. This has resulted in commercial low energy membranes with the same productivity (i.e. flux rate) and significantly better NaCl rejection at one-third of the feed pressure of the early membranes. Element designs have taken advantage of new feed

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spacer technology and automated element manufacturing to achieve up to 400 and 440 ft^2 of active area with 34 and 28 mil feed spacers, respectively. Today's leading products can produce 12,650 GPD with a NaCl rejection of 99.5% or greater with a feed pressure of only 150 psi which delivers energy cost reduction of more than 40% for a typical two-pass brackish water (BW) system [1].

Research in reverse osmosis (RO) technology continues to target further cost reductions. Developmental low energy (LE) membranes have now demonstrated NaCl rejection of 99.7%, a 40% reduction in salt passage (SP). Novel feed spacers are providing significant reductions in feed side pressure drop for a typical 440 ft^2 element. This same feed spacer technology has also been leveraged to achieve active areas up to 500 ft^2 while maintaining pressure drop equivalent to today's standard elements (Fig. 1). These advances provide additional savings in energy and/or operational and capital costs of 10–16%. This paper describes the latest innovations in detail, and demonstrates the cost reduction impact in the price of demineralized and desalinated water.

2. Properties of the novel LE membrane

A recent innovation in membrane chemistry in Dow Water & Process Solutions R&D has allowed expanding the product line in brackish water portfolio towards breakthrough BWRO products. This section of the paper will concentrate on the novel membrane properties which set a new benchmark in BWRO LE segment.

Table 1 compares the membrane flux and SP measured at 150 psi, 2,000 ppm of NaCL feed for three sets of products (GEN I–III), LE, high rejection low energy (HRLE), and new Gen III LE. Also, they are compared with BW30HR membrane measured at 225 psi. As seen from the table, if we compare between the LE products (LE, HRLE, and Gen III LE), going from LE to Gen III LE results in nearly a 60% improvement in membrane SP. Comparing Gen III LE to BW30HR membrane shows a potential of 35% energy reduction as these two membranes have similar SP but differs in their pressure requirement to achieve the same performance. It is to be also noted that all these four membranes have same flow or productivity target.

The industry tendency is to specify RO element performance in terms of NaCl rejection, though in many cases the limiting quality factor for the product water, or permeate, is an individual ion, such as silica or total organic carbon in industrial water, boron in seawater desalination, nitrate in municipal, and ammonium in wastewater reuse application. The novel membrane chemistry has been tailored to reduce the SP of these solutes by an order of magnitude in addition to improvement in NaCl rejection.

As an example, the Gen III LE membrane sets new targets for nitrate rejection in the industry. Fig. 2 compares different Dow FILMTEC^{TM} BW membranes for nitrate rejection in laboratory conditions. The feed had 2,000 ppm of NaCl and 150 ppm of $NaNO_3$ at pH 8.

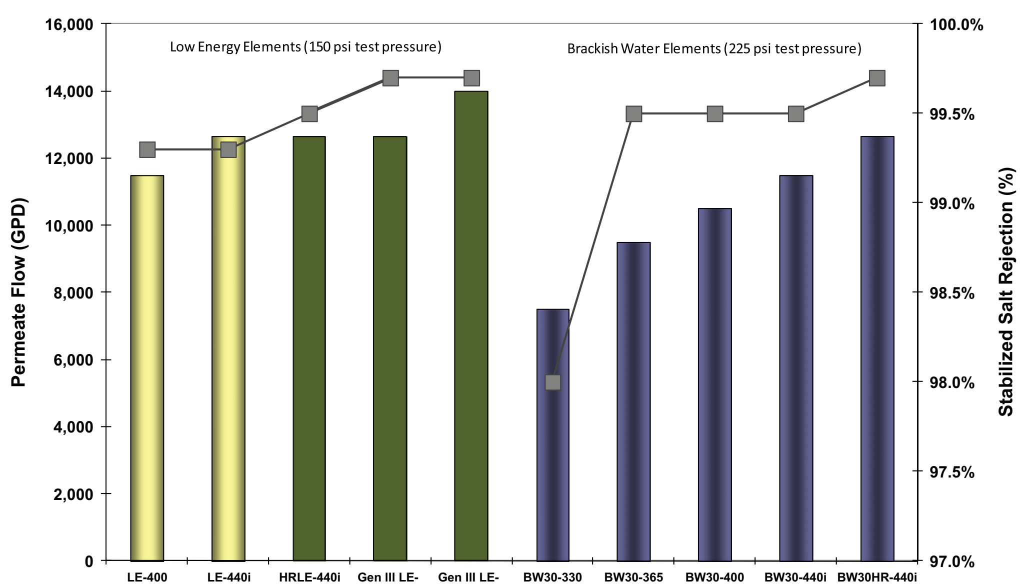

Fig. 1. Historical development of BWRO membranes from 1990 to 2012.

Table 1
Membrane flux and SP data for different BW membranes (150 psi, 2,000 ppm, pH 8)

Membrane	Testing pressure	Mean flux (GFD)	Mean SP (%)
LE	150	30	0.3
HRLE	150	30	0.5
Gen III LE	150	30	0.7
BW30HR	225	30	0.3

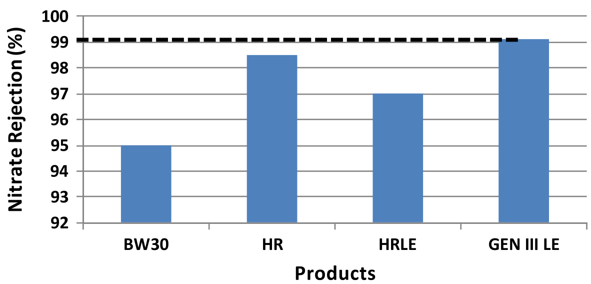

Fig. 2. Nitrate rejection (150 ppm) for different DOW membranes.

The membranes are categorized based on their testing pressure. BW30 and BW30HR (HR) were tested at 225 psi while Gen III LE and HRLE were tested at 150 psi. As seen, a significant increase in nitrate rejection was achieved with introduction of BW30HR over existing BW30 membrane. The LE HRLE product also has higher nitrate rejection than BW30 even though it is measured at a lower pressure. A breakthrough nitrate rejection (>99.0%) is achieved with introduction of Gen III LE. Not only it is measured at a 35% less pressure over BW30HR, it is also has the best in class nitrate rejection. Similar studies were conducted for other multisolutes such as boron, silica, and isopropynol alcohol.

3. Feed spacers

Feed spacers play a crucial role in the performance of the RO membrane module, impacting permeate quality, energy consumption, and response to fouling. By far, the most common feed spacer configuration used in RO is the biplanar extruded net (Fig. 3(a)). One of the early patents for making the net was obtained by Nalle [2], who described counter-rotating die (Fig. 3(b)) for producing a continuous, cylindrical mesh that was slit to create a flat web. Most RO feed spacers are made from polypropylene, which offers the preferred combination of extrudability, low cost, and chemical inertness. Thicknesses between 0.6 and 0.9 mm are typical.

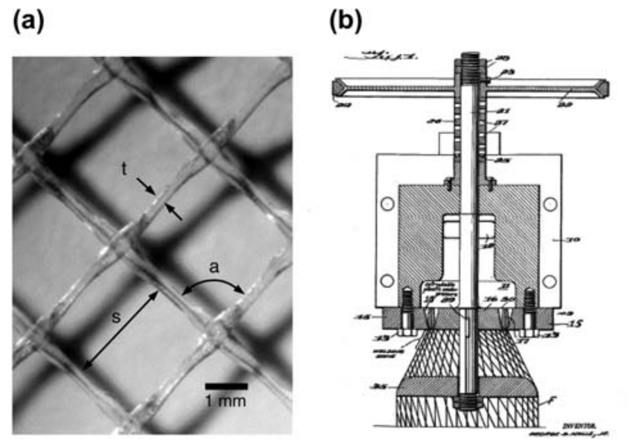

Fig. 3. (a) Biplanar extruded netting is comprised of two intersecting sets of parallel, extruded strands. (b) An early patent was obtained by Nalle [2].

3.1. Role of feed spacers

The feed spacer has two functions. It provides an open channel for the flowing feed water by maintaining separation between the membrane sheets. It also promotes mixing and the movement of rejected substances away from the membrane surface. The spacer mixing effectiveness, or more precisely the mass transfer effectiveness, is expressed in terms of the concentration polarization of a given specie, usually a dissolved salt, which is partially or entirely rejected by the membrane. The polarization factor, Γ, is defined as follows:

$$\Gamma = \frac{C_{\text{membrane}}}{C_{\text{bulk}}} \tag{1}$$

where C_{membrane} is the specie concentration at the membrane surface and C_{bulk} is the average concentration in the channel. Γ depends upon the local permeate flux, the mass diffusivity of the species of interest, the degree of rejection, and the extent of mass transfer.

For sodium chloride, conventional spacers and typical operating conditions provide average Γ in the range of 1.05–1.15. The osmotic barrier in many RO applications is therefore increased by 5–15% due to imperfect feed channel mixing. This increases direct energy consumption by about 2–4% in brackish water RO, and by about 4–8% in seawater desalination.

In addition to the energy penalty, imperfect mixing reduces salt rejection, promotes scaling at the membrane surface, and increases the rate of deposition of certain foulants. Fouling mitigation may represent the most significant opportunity for operational savings through improved feed spacer design. However, the magnitude of the potential improvement and the means by which spacers can reduce fouling through improved hydrodynamics are not yet well understood. Examples of recent spacer research include investigations of biofouling [3] and particulate fouling [4]. There appears to be less focus on the impact of spacers on other forms of fouling, such as colloidal and adsorptive organic fouling.

3.2. The pressure drop tradeoff

An unwanted byproduct of the mechanical support and mass transfer functions is feed channel pressure drop. Because RO modules are typically employed several in series within large systems, feed-side pressure drop impacts system performance by reducing the trans-membrane pressure, and consequently the permeate production, in the downstream modules. This under-utilization leads to over-utilization and increased rate of fouling in the upstream modules. These impacts are especially pronounced in low-energy brackish water applications.

Efforts to improve mass transfer through optimization of the biplanar extruded net and other configurations have not produced much change in commercial spacers, which remain similar to those used 20 years ago. Reasons for this include the relatively small magnitude of the potential benefit associated with improved mass transfer compared to that achieved historically through improvements in membrane chemistry. A second reason is the mass transfer tradeoff depicted in Fig. 4, which ties reduced polarization to increased pressure drop. A third reason is the low cost of existing spacers.

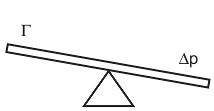

Fig. 4. The tradeoff between concentration polarization, Γ, and feed-side pressure drop, Δp, constrains feed spacer optimization.

For low-energy brackish water, performance is improved by manipulating the spacer design to reduce pressure drop while minimizing the accompanying increase in polarization. Computational fluid dynamics (CFD) has been an indispensible tool for carefully managing this tradeoff. Three-dimensional models of the extruded netting were used to predict the parametric impact of strand spacer (s), angle (a), and thickness (t) on pressure drop and mixing. An example of CFD applied to feed spacers is shown in Fig. 5.

3.3. Low pressure drop spacers

A family of low pressure drop feed spacers, developed by the approach just described, has been shown to reduce energy consumption, improve hydraulic balance in low energy RO systems, and lengthen the time between cleanings in applications where excessive feed-side pressure drop is the criterion by which cleaning intervals are determined.

3.3.1. Optimized 34-mil spacer for 400 ft^2 modules

In high-fouling feed waters, thicker spacers have shown improved response to fouling by slowing the rate of pressure drop increase [5]. In recent full-scale trials, a thick spacer optimized for lower pressure drop showed even greater value than its nonoptimized counterpart during side-by-side comparison. As shown in Fig. 6, three spacers were compared in a yearlong trial at an industrial RO plant that used conventional pretreatment. The spacers compared were a standard 28-mil thick (0.71 mm) configuration, a standard 34-mil (0.86 mm) spacer, and an optimized low pressure drop 34-mil spacer.

Membrane modules incorporating the three spacers were run in side-by-side vessels located in the first stage of the RO train. The vessels contained seven 8-inch modules in series, each module having 400 ft^2 (37 m^2) of active membrane area. The vessels were

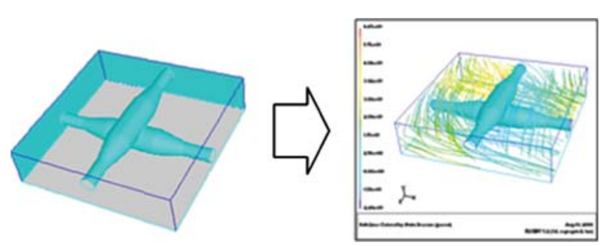

Fig. 5. Three-dimensional models of the feed spacer were used to optimize the tradeoff between pressure drop and mixing.

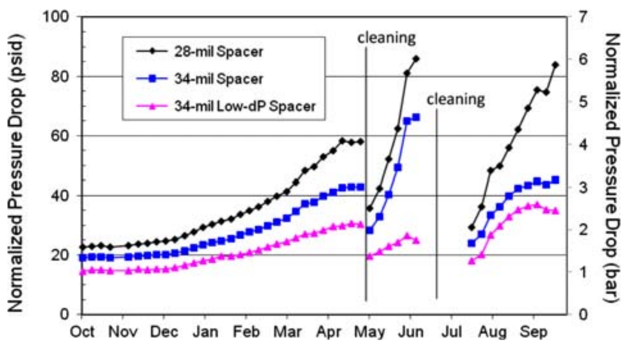

Fig. 6. Side-by-side comparison of three feed spacers in an industrial water application using a conventionally-pretreated, high-fouling feed.

automatically controlled to the same flux and recovery as described previously [6]. Identical chemical cleanings at high pH were applied simultaneously to all three vessels.

The optimized low pressure drop spacer showed lower initial pressure drop and a lower rate of pressure drop increase than either of the standard spacers. It also returned more closely to its initial pressure drop upon chemical cleaning than did the standard spacers.

3.3.2. *Low pressure drop 28-mil spacer for 440 ft^2 modules*

For the majority of feed waters, the fouling potential is less severe and a thinner spacer may be used, bringing with it the savings of increased module active area. The following side-by-side comparison was conducted using two spacers, a standard configuration of 28-mil (0.71 mm) thickness, and an optimized low pressure drop 28-mil spacer. The standard configuration is currently found in FILMTEC™ 8-inch modules with 440 ft^2 of membrane active area. The spacers were compared in a yearlong trial at a municipal RO plant that used conventional pretreatment. The spacers were compared in side-by-side vessels located in the first and second stages of the RO train. The vessels contained seven 8-inch modules in series, and were automatically controlled to the same flux and recovery [6].

As shown in Fig. 7, the optimized spacer reduced the feed-side pressure drop by approximately 60% in both the first and second stages. This improved the productivity of the downstream modules and lowered the required system feed pressure. In Fig. 8, the net applied pressure in the first stage was reduced by 7% with no change in first stage permeate quantity or quality. The reduction was sustained for the duration of the trial. The pressure drop reduction of the combined stages resulted in a projected 15% reduction in feed pressure and pumping power for the system.

3.3.3. *New 23-mil spacer for 500 ft^2 modules*

When feed water quality is exceptional, such as that found in second pass RO, an even thinner feed spacer may be used. A spacer with 23-mil (0.58 mm) thickness has been developed for use in an 8-inch diameter module with 500 ft^2 (46 m^2) of membrane active area for precisely this kind of application.

The pressure drop performance of this module is shown in Fig. 9, where feed-side pressure drop is plotted against feed flow rate. The pressure drop of the 500 ft^2 module is slightly lower than that of its 440 ft^2 counterpart. This is required in view of the higher feed flow rate anticipated in 500 ft^2 systems running at the same flux and overall recovery as similarly designed systems that use 400 ft^2 or 440 ft^2 modules.

3.4. *Economic evaluation*

The previously outlined membrane and feed spacer developments have a tangible impact on the economics of a RO installation, and largest benefits can be obtained when novel membrane is combined with a novel feed spacer. An end user value analysis was performed with two real life example cases representing two target applications, industrial water demineralization and seawater desalination.

3.5. *Industrial water demineralization*

In order to demonstrate the cost advantages of using these new elements in industrial application, the calculation basis is a ultrafiltration (UF)—one-pass RO—mixed bed (MB) system. The calculation basis is a small industrial size plant (80 m^3/h) treating surface water (487 ppm total dissolved solids [TDS]) to deliver makeup water for a power plant. The one-pass RO is operated at 75% recovery and at an average operational flux of 23.4 lmh. The plants consist of 84 elements with 10:4 staging with 6 elements per pressure vessel. The analysis compared two existing FILMTEC™ products and Gen III LE to two best available products from alternative membrane suppliers. A system performance simulation was done with reverse osmosis system analysis (ROSA) software for FILMTEC™ products and the same case was run with the equivalent design programs by other suppliers.

In the given scenario, the full RO permeate is further treated by a working MB ion exchanger polisher,

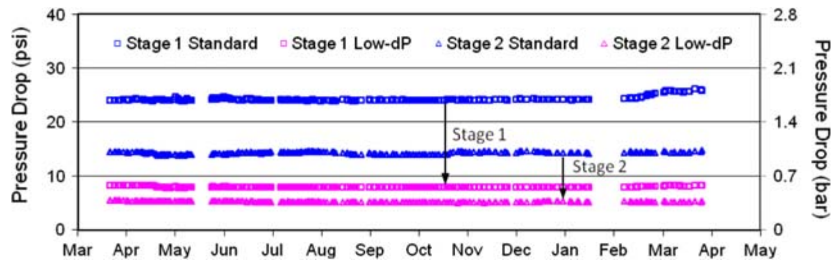

Fig. 7. Side-by-side trial of two feed spacers in a municipal water application—comparison of feed side pressure drop.

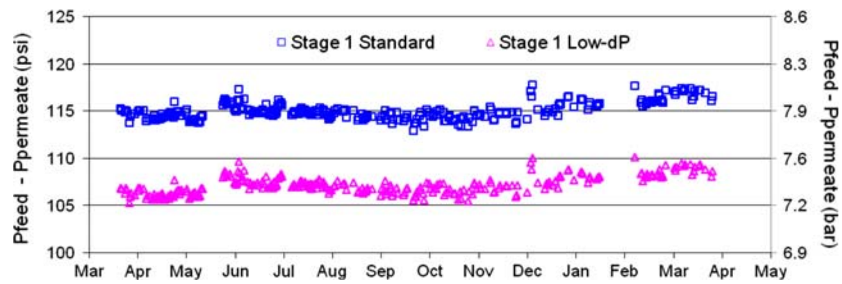

Fig. 8. Side-by-side trial of two feed spacers in a municipal water application—comparison of net applied pressure.

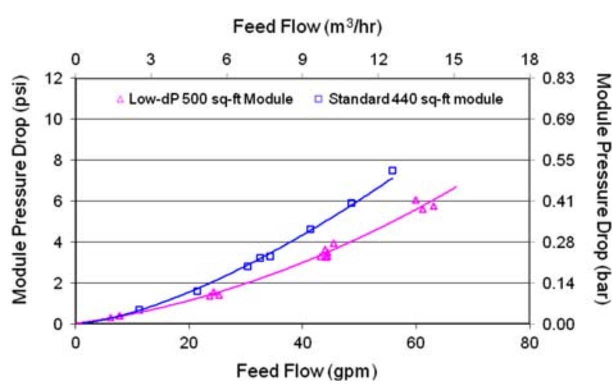

Fig. 9. Comparison of feed-side pressure drop for 8-inch diameter modules with 440 and 500 ft^2 of membrane active area.

simulated with CADIX software and using DOWEX™ Marathon™ C & DOWEX™ Marathon™ A resins. This made it possible to directly compare the importance of specific energy demand and permeate quality differences and to roughly compare the OPEX difference in both RO and IX operations. In all cases, the RO simulations were done at the highest temperature (30˚C) with new membranes (flow factor = 1, no SP increase). This refers to a situation where specific energy cost (pressure demand) is lowest, but SP through the membrane is the highest, and therefore the load to downstream IX is the highest. The OPEX cost savings were based on first year performance. Membrane deterioration (permeability decrease or SP increase) due aging or fouling was not included, and neither were possible membrane replacement costs. The energy cost was calculated per the specific energy consumption (kWh/m^3 produced permeate) given by ROSA and included an energy price of $0.11/kWh. Other simulation programs do not include specific energy calculation so the value given by ROSA was multiplied by the same percentage increase as seen in the feed pressure demand.

The working MB was sized for the lower permeate TDS values and the MB sizing was kept identical with all RO products and the difference was counted in the time (h) between regenerations. The OPEX costs were calculated only for the chemical consumption (NaOH and HCl) required annually. The price of NaOH (50%) was estimated at 350$/ton and the price of HCl (35%) at 500$/ton. No resin replacements or capacity decrease were taken into account.

The RO products compared were FILMTEC™ BW30HR-440i, HRLE-440i, Gen III LE, and best-in-class competitive products from supplier A and B (Table 2). The detailed RO feed composition as well as permeate quality in each case is presented in Table 3, and the energy comparison is presented in Table 4.

Compared to BW30HR-440i, we can see that HRLE-440i and Gen III LE offer an energy benefit of 23 and 31%, respectively. This corresponds to a yearly saving of $6,200 (HRLE) and $8,500 (Gen III LE), which equals to $73–101 yearly saving per RO element (Table 4). While according to the datasheet

Table 2
Datasheet specifications of the products used in economical comparison

Product label	Permeate flow rate GPD (m^3/d)	Stabilized salt rejection (%)	Test conditions
BW30HR-440i	12,650 (48)	99.7	1
HRLE-440i	12,650 (48)	99.5	2
GEN III LE	12,650 (48)	99.7	2
Supplier A	12,000 (45.4)	99.6	3
Supplier B	11,000 (41.6)	99.5	4

Notes: (1)—2,000 ppm NaCl, 225 psi (15.5 bar), 77 F (25˚C), 15% recovery, pH 8; (2)—2,000 ppm NaCl, 150 psi (10.3 bar), 77 F (25˚C), 15% recovery, pH 8; (3)—1,500 ppm NaCl, 150 psi (10.3 bar), 77 F (25˚C), 15% recovery, pH 6.5–7; and (4)—500 ppm NaCl, 110 psi (7.6 bar), 77 F (25˚C), 15% recovery, pH 7.

Table 3
Feed water composition and permeate quality according to software predictions

Pass streams (mg/l as Ion)						
Name	Adjusted feed	Permeate				
		Total BW30HR-440i	Total HRLE-440i	Total GEN III LE-440i	Total supplier A	Total supplier B
NH_4	0.29	0.02	0.03	0.02	0.008	0.01
K	0	0	0	0	0	0
Na	78.74	1.26	2.14	1.24	1.678	1.49
Mg	15.8	0.08	0.14	0.08	0.071	0.19
Ca	40.08	0.2	0.34	0.19	0.179	0.47
Sr	0	0	0	0	0	0
Ba	0	0	0	0	0	0
CO_3	0.72	0	0	0	0	0
HCO_3	207.42	3.53	5.91	3.48	4.039	4.39
NO_3	0.4	0.03	0.04	0.02	0.031	0.01
Cl	54	0.33	0.57	0.33	0.587	0.73
F	0	0	0	0	0	0
SO_4	85.8	0.27	0.47	0.27	0.234	0.61
SiO_2	3.9	0.02	0.04	0.03	0.05	0.1
Boron	0	0	0	0	0	0
CO_2	6.42	6.97	6.98	6.97	7.78	7.64
TDS	487.16	5.72	9.67	5.63	6.9	7.97
pH	7.6	5.9	6.12	5.89	5.91	5.95

Table 4
RO Energy requirements and economics of various BWRO membranes

	Case I BW30HR-440i	Case II HRLE-440i	Case III GEN III LE	Case IV Supplier A	Case V Supplier B
Electricity ($/yr)	$27,099	$20,902	$18,584	$23,486	$18,536
Feed pressure (bar)	7.50	5.76	5.26	6.50	5.13
Pass 1 electricity (kWh/m^3)	0.35	0.27	0.24	0.30	0.24
Energy saving ($/yr)	$0	$6,197	$8,514	$3,613	$8,563
Energy saving (%)	0	23	31	13	32

Table 5
Comparison of RO permeate quality and its impact on IX operation

Element	Permeate TDS (ppm)	Permeate SiO_2 (ppm)	IEX Runtime (h)	Net Throughput (m^3)	Feed pressure (bar)	Regeneration costs ($/yr)	Regeneration saving (%)
BW30HR-440i	5.72	0.02	41	3,294	5.13	36,044	0
HRLE-440i	9.67	0.04	33.5	2,692	5.76	44,114	−22
GEN III LE-440i	5.63	0.03	41	3,294	5.26	36,044	0
Supplier A	6.90	0.05	35.50	2,852	6.50	41,629	−15
Supplier B	7.97	0.1	33	2,652	5.13	44,782	−24

comparison (Table 2), the HRLE-440i and Gen III LE have the same productivity, the differentiation between products is achieved with utilization of the new low differential feed spacer, providing an additional 10% energy reduction. Comparison to alternative products shows that even though supplier A would offer 13% lower energy consumption than BW30HR-440i, it operates at 10–20% higher energy consumption than HRLE-440i or Gen III LE product, respectively. Supplier B is very equal in terms of energy consumption to Gen III LE product, but cannot provide a competitive TDS rejection, especially in terms of silica rejection (Tables 3 and 5), as the permeate silica concentration is actually over three times higher than achieved with Gen III LE.

Reaching similar solute rejection, BW30HR-440i and Gen III LE achieve the lowest permeate TDS and silica concentration, correlating to longest MB run times and respectively lowest regeneration costs. Compared to Gen III LE, supplier A and B require 15 and 24% higher regeneration costs, respectively. Based on the evaluation, the new Gen III LE product offers the best quality and energy balance in the given system, resulting operational savings between 16 and 19% in the combined RO-IX system.

3.6. Seawater desalination

In order to demonstrate the cost advantages of using the new elements in seawater desalination application, the calculation basis is large-scale seawater desalination plant. The plant produces 300,000 m^3/d permeate with 10 trains at a system recovery of 42.5%. The feed water is classified as open is intake with 41,100 ppm TDS and 5.43 ppm boron. The design is typical two-pass SWRO system with a concentrate recirculation from second pass to first pass feed and pH correction between passes. In each train, first pass has 300 pressure vessels housing eight SW30HRLE-440i elements (APF 14.16 lmh) and operates at 45% recovery. The second pass is a two-stage system with 82:40 staging each pressure vessel housing eight elements and operating at 90% recovery. The pH is corrected to 10.2 with NaOH. The used ROSA flow factors in this scenario are 0.9/0.95 for pass 1 and 2, respectively, and capacity design is done with the maximum temperature of 32˚C. In order to reach 0.3 ppm B with standard safety factor of 1.35, the system is designed for a limit of 0.22 ppm B.

Currently, the LE-440i membrane is the standard product used in existing second pass SWRO applications where the limiting factor for final permeate quality is usually boron concentration. The HRLE-440i, introduced in 2010, has then replaced LE-440i in new installations due its capability to operate at the same pressure as LE-440i, but in addition will offer significantly improved boron rejection (∼70 vs. 49%). A higher boron rejection can minimize the size of the second pass in SWRO application if blending is used or it will allow operation at lower pH increase resulting in savings on the chemical costs. The benefit of the Gen III LE is seen both in its improved boron rejection as well as increased element active area (440–500 ft^2) reducing the size of the second pass further.

The value analysis compares three scenarios, each presenting a generational development step:

Case 1: LE-440i membranes in second pass and full second pass (no blending), APF of 31.4 lmh
Case 2: HRLE-440i membranes in second pass with 5% (15,000 m^3/d) blending, APF of 31.4 lmh
Case 3: Gen III LE-500i membranes in second pass with 8% (24,000 m^3/d) blending, APF of 31.4 lmh

Between cases 1 and 2, the 5% blending rate reduces the size of the second pass by 60 pressure

Table 6
Obtained CAPEX saving in SWRO with increased blending and increased active area

Capital cost-BWRO	LE-440i	HRLE-440i	Gen III LE-500i
# Vessels	1,220	1,160	990
# Elements	9,760	9,280	7,920
Trains	10	10	10
Vessels per train	122	116	99
Transfer and flush pumps	10	10	10
Subtotal membranes and vessels	$5,612,000	$5,336,000	$4,554,000
Racks, piping, valve supports, and footings	$636,250	$636,250	$636,250
Inst. control valves, electrical equipment, wiring, etc.	$1,232,643	$1,232,643	$1,232,643
Cleaning system, cartridge filters	$300,093	$300,093	$300,093
High pressure pump, drives, and ERT	$4,871,671	$4,871,671	$4,871,671
Transfer pumps and flush pumps	$80,264	$80,264	$80,264
Subtotal RO process and equipment	$12,732,921	$12,456,921	$11,674,921
OEM engineering, profit, civil, direct labor, freight, Ins., construction overhead, and engineering	$6,883,986	$6,734,768	$6,311,984
Subtotal module construction cost	$19,616,908	$19,191,690	$17,986,906

Table 7
Obtained yearly saving in SWRO operation with increased blending

Yearly cost calculation	LE-440i	HRLE-440i	Gen III LE-500i
Total electricity	$29,705,804	$29,664,732	$29,540,736
Labor and overhead	$778,680	$778,680	$778,680
chemicals	$4,601,756	$4,551,523	$4,525,292
Replacement & repair	$1,286,236	$1,257,673	$1,178,414
Insurance	$266,318	$265,088	$262,198
Sub O&M	$36,638,794	$36,517,696	$36,285,320
Amortization	$11,686,672	$11,632,698	$11,505,912
Annual cost	$48,325,466	$48,150,394	$47,791,232
Water cost (UScts/m^3)	46.85	46.69	46.31

vessels e.g. 480 elements while keeping the same permeate quality. This translates to $M 425 savings in the BWRO CAPEX (Table 6). By utilizing the Gen III LE membranes, the size of the second pass is further reduced by 170 pressure vessels or 1,360 elements. This translates to $MM 1.2–1.6 savings compared to cases 2 and 1, respectively. The size of the second pass is 19% smaller with Gen III LE membranes compared to LE-440i. In both the cases 2 and 3, additional savings are obtained in reduced amount of chemicals and membrane replacement costs. The impact of this in yearly cost calculation of the SWRO plant is presented in Table 7. The price of water is reduced by 0.38–0.53 UScts/m^3 translating into annual savings of $M 175–$534, respectively.

4. Summary

Breakthrough RO membrane chemistry and innovative materials of construction have been developed to achieve highest possible NaCl rejection while maintaining maximum element productivity. Novel brackish water (BW) RO membrane element delivers to end users state-of-the-art salt rejection (99.7%) at 30% lower energy consumption compared to current high rejection BWRO membranes. Combined with new low differential pressure feed spacers, end users can enjoy additionally up to 15% savings in direct RO energy reductions via the lowest feed-side pressure drop available in the market. The feed spacer modification additionally enables a new 500 ft^2 active area 8-inch BWRO element, which is the highest active area

product in the market. A financial analysis was carried out with a refined cost model using different economic frame conditions. It shows RO plant energy costs can be reduced by up to 30% in industrial applications without compromising the product water quality. In SWRO application, the size of the BWRO pass can be reduced by 19%, resulting in an overall water cost reduction of 0.53 UScts/m^3 produced water.

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