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Case study: directly comparing OPEX and CO_2 emissions associated with phosphonate and dendrimer antiscalants at Ashkelon SWRO plant

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ABSTRACT

The Ashkelon seawater reverse osmosis desalination plant being split over two identical (North and South) lines makes it an ideal location to directly compare one set of operating conditions with another. Since the plant opened in 2005, both lines have operated using phosphonate antiscalant to protect membranes from accumulating calcium carbonate mineral scale. In early 2022, the antiscalant on the South line was switched to a highly active dendritic polymer. Permeate production was maintained at desired levels and there was no significant increase in ΔP or frequency of Clean-In-Place on the South line. The authors have previously reported initial success of the South line operation but here offer a more detailed and complete view of the plant Supervisory Control and Data Acquisition (SCADA) output, allowing direct comparisons between operations on the North and South lines, which are identical save for the selection of antiscalant. The authors propose that dosing super-concentrated antiscalants can reduce operating expenses due to reduced volumes being shipped and stored. A thorough procedure for on-site dilution of super-concentrated antiscalant which reduces the need for international shipping of bulk chemicals by instead shipping a super-concentrate product for dilution at point of use is reported. Efficient dilution of the concentrated product in an intermediate bulk container and mitigation steps to address and prevent algal growth in the dilute product are outlined. It is reported that employing this technology could reduce cost and CO_2 emissions from transport of chemicals by up to 92%, as well as eliminating antiscalant contribution to algal blooms by nature of it's phosphorus-free formulation.

Keywords: Reverse osmosis; Seawater reverse osmosis; Polymer antiscalant; Green chemistry; Calcium carbonate scale; Scale inhibitor

1. Introduction

Ashkelon seawater reverse osmosis (Fig. 1) is widely viewed as a pioneering and innovative desalination plant, winning GWI's 'Desalination Plant of the Year' award a year after being commissioned in 2005. Since expansion in 2010, the Ashkelon seawater reverse osmosis (SWRO) desalination plant has been responsible for the production of approximately 360,000 m^3 of permeate water per day; enough to satisfy the needs of over 1 million people. The plant operates two identical SWRO units, conveniently referred to as the 'North' and 'South' lines. Both face the same operational challenges; high boron concentrations, constant demand for product water and strict local regulation to name a few.

Ashkelon has been a trend-setter for the desalination industry since its inception; being the first plant to use IDE's proprietary Pressure Centre Design, Triple Line Intake, ERS (energy recovery system) and a unique patented boron removal system for increased efficiency and significantly

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reduced water cost. Now, Ashkelon is again proving itself to be a visionary by utilising a new super-concentrated phosphorus-free antiscalant which claims to have reduced carbon footprint and operating expenses (OPEX) compared to traditional phosphonate antiscalant [1,2].

The unusual arrangement of having two identical lines side by side means that by comparing operational performance of the North and South lines for a statistically significant period of time, it is possible to directly compare two sets of operating conditions. For example, changing the type of membrane in the North line then comparing performance of the two lines over 3–6 months would show whether the new membrane performs better, worse, or approximately the same as the old membrane, which is still installed in the South line.

To persuade the industry that the new antiscalant used at Ashkelon is safe and effective, the authors must prove that plant performance is not affected by changing antiscalant. To do this, the authors herein present temperature normalised plant data from each RO pass. The scope of a previous study [3] has been extended to include more data from the first RO pass and initial data for dosing polymer antiscalant at every other dosing point on the South line.

2. Operational performance

If operated without antiscalant, the Ashkelon SWRO plant would precipitate calcium carbonate scale on RO membrane surfaces and in pipes carrying brine away from the plant. Once deposited, this scale would cause flux loss, an increase in pressure drop (ΔP), and increased salt passage; all of which combine to result in poorer quality permeate water with higher specific energy cost (cost per unit volume of permeate produced).

To mitigate the risk of scaling, Ashkelon doses antiscalant at three points on each line: ahead of the first, second and fourth RO pass. In this case study, the antiscalant used at all three dosing points on the South line and one dosing point on the North line were switched to a super-concentrated phosphorus-free dendrimer, while remaining points on the North line continued to use a time-tested phosphonate-based product.

Figs. 2–5 compare the temperature normalised permeate production (flux, dark green line) and temperature normalised pressure drop (ΔP, light green line) from the North line with data from the same date period on the South line.

Clean-In-Place (CIP) and routine maintenance have been omitted from Figs. 2–5, however a list of plant downtime is given in Table 1a and 1b for reference.

2.1. First pass

Conventionally, increasing the amount of permeate water produced means an increased scaling risk and faster increase of ΔP over time.

Consider Fig. 2b, a rise in permeate production on the South line first pass can be seen in the summer months of 2022. During and after this period of high flux, pressure drop steadily rose from a low of ~1.0 bar in early March to a high of ~1.3 bar in late August. In isolation, it is not possible to say to what extent the change of antiscalant contributed to the sustained rise in ΔP. However, comparing Fig. 2b with Fig. 2a elucidates more information. The rise in normalised permeate production on the North line first pass (Fig. 2a) was not as much as that on the South line first pass (Fig. 2b), but the rise in ΔP on the North line was greater in the same March to August period (0.9 → 1.4 bar). In other words, the North line had a greater increase in ΔP for a smaller

Fig. 1. Ashkelon seawater reverse osmosis.

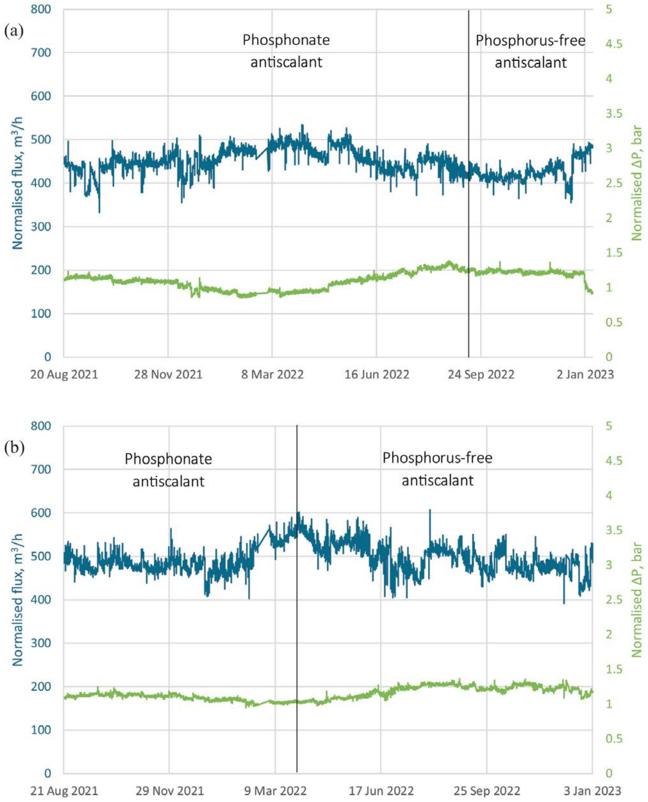

Fig. 2. Temperature normalised permeate flow and pressure drop for the (a) North line first pass and (b) South line first pass.

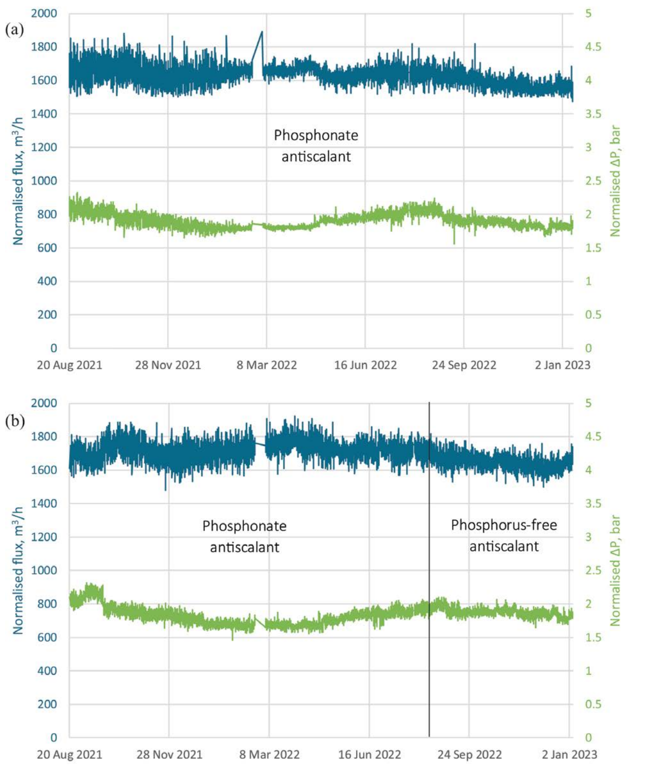

Fig. 3. Temperature normalised permeate flow and pressure drop for the (a) North line second pass and (b) South line second pass.

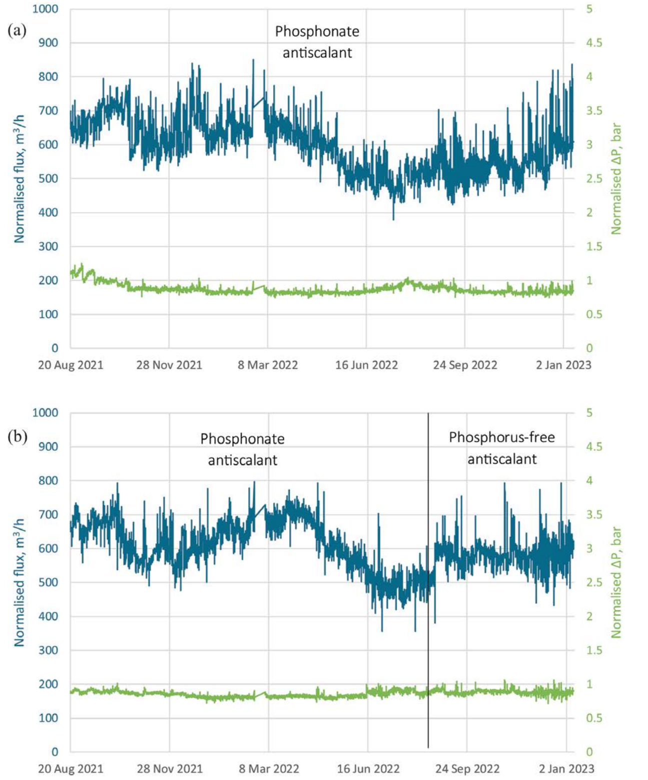

Fig. 4. Temperature normalised permeate flow and pressure drop for the (a) North line third pass and (b) South line third pass.

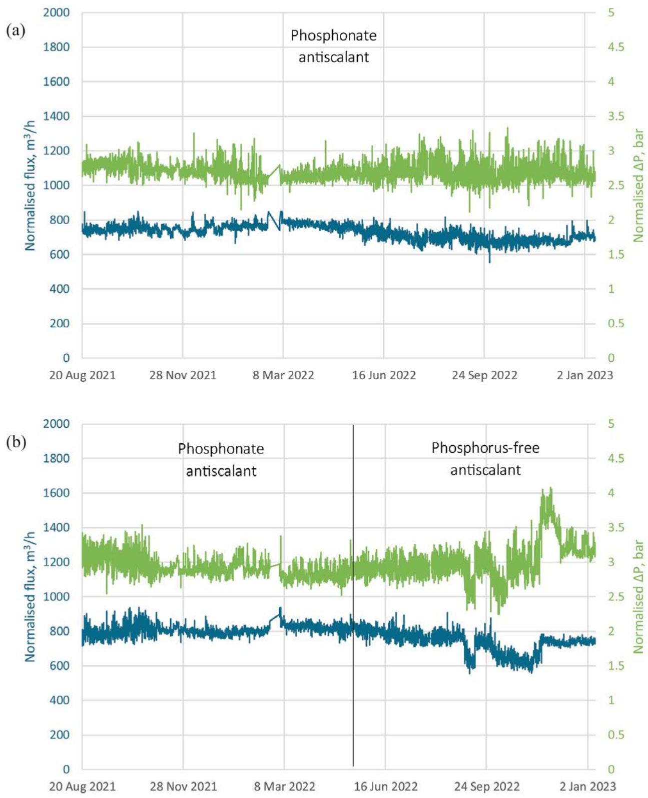

Fig. 5. Temperature normalised permeate flow and pressure drop for the (a) North line fourth pass and (b) South line fourth pass.

Table 1a
North line CIP schedule August 2022 – January 2023

First pass		Second pass	Third pass	Fourth pass
01 Sep 2021	13 Jun 2022	13 Sep 2021	13 Sep 2021	13 Sep 2021
13 Sep 2021	17 Jul 2022	04 Oct 2021	02 Aug 2022	04 Oct 2021
04 Oct 2021	02 Aug 2022	02 Mar 2022	13 Sep 2022	13 Sep 2022
01 Nov 2021	01 Sep 2022	13 Sep 2022	20 Dec 2022	20 Dec 2022
23 Nov 2021	13 Sep 2022	20 Dec 2022		
28 Dec 2021	(Antiscalant changed on 19 Sep 2022)			
18 Jan 2022	06 Nov 2022			
03 Mar 2022	29 Nov 2022			
05 Apr 2022	20 Dec 2022			
25 Apr 2022				
17 May 2022				

Table 1b
South line CIP schedule August 2022 – January 2023

First pass		Second pass	Third pass	Fourth pass
24 Aug 2021	29 Mar 2022	22 Sep 2021	22 Sep 2021	22 Sep 2021
22 Sep 2021	26 Apr 202	05 Oct 2021	05 Oct 2021	05 Oct 2021
05 Oct 2021	16 May 2022	03 Mar 2022	(Antiscalant changed on 15 Aug 2022)	(Antiscalant changed on 15 May 2022)
02 Nov 2021	04 Jul 2022	(Antiscalant changed on 15 Aug 2022)	12 Sep 2022	12 Sep 2022
30 Nov 2021	02 Aug 2022	12 Sep 2022	27 Dec 2022	27 Dec 2022
21 Dec 2021	30 Aug 2022			
01 Feb 2022	12 Sep 2022			
13 Feb 2022	02 Oct 2022			
(Antiscalant changed on 27 Mar 2022)	08 Nov 2022			
	06 Dec 2022			
	27 Dec 2022			

increase in flux. The South line first pass – using phosphorus-free antiscalant – operated with lower ΔP and higher flux than the North line first pass, which was operated under identical conditions expect for the antiscalant.

Furthermore, once the North line first pass was switched to phosphorus-free antiscalant there was a steady uptick in permeate production, while ΔP remained constant.

In conclusion, despite being operated to produce more permeate, the line using phosphorus-free antiscalant incurred less rise in ΔP than the line using phosphonate antiscalant.

To help keep track of which antiscalant is performing better overall, a point will be awarded the best antiscalant on each pass. After analysing the data from the first pass, the point was awarded to the phosphorus-free antiscalant.

Phosphorus-free: 1. Phosphonate: nil.

2.2. Second pass

The change from phosphonate to phosphorus-free antiscalant at the second and third pass occurred on a later date than the first and fourth. This means that there is slightly less data to compare phosphorus-free and phosphonate antiscalant for these two passes.

While comparing Fig. 3a and b, there is almost no difference in the shape of the graphs. Therefore, we conclude that the antiscalant choice had no noticeable impact on the permeate production or ΔP on this pass. This is a draw so a point goes to both antiscalants.

Phosphorus-free: 2. Phosphonate: 1.

2.3. Third pass

Like the second pass, there are only 4 months of side-by side data with which it is possible to directly compare phosphorus-free with phosphonate antiscalant.

Focussing in on the three months to the end of 2022 (September → December), the North line operated around 0.85 bar ΔP whereas the South line operated around 0.8 bar ΔP. Flux was slightly higher on the South line, at an average of 580 m^3/h compared to 550 m^3/h on the North line. As on the first pass, the South line produced more permeate with lower ΔP, so the point from the third pass goes to the phosphorus-free antiscalant.

Phosphorus-free: 3. Phosphonate: 1.

2.4. Fourth pass

In the fourth pass, the North line maintains constant ΔP for the entire 500 d trial period, with a mean permeate production around 700 m^3/h. On the South line, the same trend is observed up to August 2022. Around this time, the membranes became fouled and permeate production and ΔP suddenly dropped. The cause of irregular performance was foulant or scale accumulation on the membrane, which was removed by CIP. On 12 September 2022, the South line fourth pass was cleaned with HCl and performance briefly steadied out. The pass was cleaned again on 27 December 2022; activity noticeably improved after this second clean.

The point from this final pass goes to the phosphonate antiscalant for having the most consistent performance throughout the entire trial duration.

Phosphorus-free: 3. Phosphonate: 2.

2.5. Overall

The final score shows phosphorus-free antiscalant coming out just on top of the traditional phosphonate. But digging into the detail of the passes, a more complex picture emerges. Reflecting on the data from all four passes at Ashkelon, despite some instances where one antiscalant performed better than the other, there was overall no significant effect on normalised permeate production or ΔP due to changing antiscalant.

3. Antiscalant dosing

The phosphorus-free antiscalant used in this study was super-concentrated. 'Super-concentrated antiscalants' can be defined as those which have active concentration of >95%. Such antiscalants have their advantages and limitations, some of which are summarised in Table 2.

Many desalination plants use diaphragm pumps for antiscalant dosing, which depend on two variables:

- The volume pumped per stroke; and
- The number of strokes per minute.

Both are adjustable, however; a basic diaphragm pump is unlikely to deliver less than 0.01 L/h (10 mL/h). Besides this, antiscalant dosing pumps need to perform at least one stroke every 3 s (20 strokes/min) to ensure adequate product distribution. Intermittent or non-constant dosing would lead to non-constant membrane protection, giving brief periods where there was no antiscalant in the brine and scaling might occur.

Where the dosing pump cannot deliver constant product dosing it is necessary to dilute the antiscalant and adjust the dose accordingly to ensure continuous antiscalant addition. For example, if a plant is required to dose 0.3 ppm antiscalant in the RO feed, but the dosing pump can only deliver 0.5 ppm then by diluting the neat antiscalant by 2× (doubling the volume) would halve the active concentration therefore the dose rate should be doubled to 0.6 ppm, within the limits of the plants dosing equipment.

4. Reduced OPEX

Two OPEX savings which result from changing antiscalant have been realised during this study:

- Material cost of antiscalant.
- Benefits of super-concentrate.

A brief qualitative discussion is presented which outlines how each saving is achieved.

4.1. Material cost of antiscalant

Rising price and scarcity of the phosphonic acid derivatives (used in the production of phosphonate-based antiscalants) mean that the cost of phosphonate-based antiscalants has risen steeply in recent years. While polymer antiscalants have seen some recent price rises, largely due to the Covid-19 pandemic and war in eastern Europe, they have nevertheless still become a more financially appealing option to many plant operators.

4.2. Benefits of super-concentrate

By shipping super-concentrated antiscalant for dilution at point of use, the cost of packaging and shipping is reduced. This is because many fewer totes/intermediate bulk containers (IBCs) of antiscalant need to be transported from the manufacturer to the end user. Notwithstanding a recent slowdown in rising shipping rates, the general trend is that the cost of transporting goods has increased by well over 50% in the last 3 y. Table 3 outlines the increase in the cost of shipping since the start of the Covid-19 pandemic.

5. Reduced CO2 emissions

The data presented in this paper confirms that changing from phosphonate to dendrimer antiscalant does not lead to an increased pressure drop in the RO stage. This means that the phosphorus-free antiscalant used in this trial is just as effective at controlling scale deposition as the small-molecule phosphonate which had been used since the plant

Table 2
Advantages and limitations of super-concentrated antiscalant

Advantages	Limitations
- Low dose rates when dosed neat or as high concentration solution. - Reduced warehouse inventory. - Reduced packaging costs and plastic waste. - Reduced freight costs.	- May require dilution where dosing pumps cannot dose low enough for the plant. - Potentially more hazardous chemicals being stored on site. - Dilution generates large volumes of antiscalant which needs to be consumed before bio-growth occurs.

Table 3
Indicative prices for shipping 1× full container load (FCL) from the UK, expressed in GBP(£)[a]

Route	Price, January 2020	Price, April 2022 (% change since January 2020)	Price, January 2023 (% change since January 2020)	Price, April 2023 (% change since January 2020)
UK → Dubai, UAE 40′ FCL	£1,075	£2,000 (+86%)	£1,985 (+85%)	£1,950 (+81%)
UK → Oman 20′ FCL	£1,310	£2,175 (+66%)	£2,100 (+60%)	

[a]Prices are indicative only and are solely quoted to evidence changes in the cost of international shipping.

Table 4
Calculation of CO_2 emission savings realised by shipping an 11× super-concentrated antiscalant instead of dilute, functional concentration[a]

	Diluting at point of manufacture (USA) and shipping dilute product to Israel	Shipping super-concentrate product from USA and diluting at point of use (Israel)
Production of IBCs (11.95 kg CO_2 per IBC)	352 × IBCs = 4,206 kg CO_2	32 × IBCs = 382 kg CO_2
Road transport of product to Port of Los Angeles (~350 km) (0.792 kg CO_2 per km)	19.6 twenty-foot container units = 5,435 kg CO_2	1.8 twenty-foot container units = 500 kg CO_2
Sea transport from Port of Los Angeles to Port of Ashdod (~11,200 nm) (0.330 kg CO_2 per TEU 2 nm)	19.6 twenty-foot container units = 72,442 kg CO_2	1.8 twenty-foot container units = 6,652 kg CO_2
Road transport of product from Port of Ashdod to Ashkelon (~35 km) (0.792 kg CO_2 per km)	19.6 twenty-foot container units = 544 kg CO_2	1.8 twenty-foot container units = 50 kg CO_2
Total	82,626 kg CO_2	7,584 kg CO_2

[a]Calculation assumes that 18 IBCs can fit into one 20′ container and that part-filled containers will be filled with other goods therefore the carbon footprint can be scaled to the proportion of the container which is filled.
[b]Twenty-foot equivalent unit.

was commissioned nearly 20 y ago. There is therefore no change in the specific power consumption (kWh per tonne of permeate produced, directly correlated to CO_2 emissions) from permeate production using the phosphorus-free as using the phosphonate antiscalant.

By shipping a super-concentrated antiscalant for dilution at the point of use, the total volume shipped from the antiscalant supplier to the end user is reduced. At Ashkelon, the super-concentrated antiscalant was diluted by a factor of 11, meaning that 1 L of super-concentrate was blended with 10 L of RO permeate to prepare the usable antiscalant. Consequently 11× less container space was required on the shipping and road haulage route. The entire Ashkelon SWRO (North and South lines taken together) has an estimated annual antiscalant consumption of 352 IBCs. Using the 'Lifecycle Assessment – Carbon Footprint of Industrial Packaging' prepared by Schutz an estimated 75 tonnes of CO_2 can be saved per year by switching to a super-concentrated formulation (Table 4).

By reducing the overall volume shipped from the chemical supplier to the end user, there is a proportional reduction in the road and sea transport costs. When shipping an 11× concentrated antiscalant (such as that used at Ashkelon), the saving in transport costs is approximately 92%.

The authors have previously discussed other OPEX and carbon footprint benefits of super-concentrated phosphorus-free antiscalant [3].

5.1. Other environmental benefits

Antiscalants which contain phosphorus (usually phosphonates) have been shown to break down into a nutrient rich soup which causes eutrophication in the immediate region surrounding brine discharge [4]. The phosphorus-free antiscalant formulation eliminates such bioaccumulation as it does not contain any organic phosphonate at all.

6. Conclusions

As global demand for desalted water continues to grow, there remains much to be done to reduce the social, economic and environmental costs of desalination. The authors here reported the successful deployment of a super-concentrated antiscalant on a large SWRO plant. Supervisory Control and Data Acquisition (SCADA) output from 500 d of plant operation has showed that the phosphorus-free antiscalant was just as effective as traditional phosphonate. But nevertheless, the polymer alternative had lower cost and lower carbon footprint than the traditional technology.

Similar innovations in the desalination industry are essential to maintain the momentum for change, the authors look forward to exploring, piloting and sharing more successes with the industry in the near future.

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