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Long term membrane process and performance in Ashkelon Seawater Reverse Osmosis Desalination Plant

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ABSTRACT

In this paper the operation of Ashkelon SWRO desalination plant since it was started five years ago is reviewed. This particular installation is key for the history of seawater desalination by reverse osmosis not only because of its permeate production capacity of 100 Million m^3/a (later increased to 133 Million m^3/a) but also due to the low cost of water attained (50 US $/$m^3$) when it was started up. The performance assessment made to each one of the four stages in Ashkelon indicates that no major variation in terms of energy consumption, yearly production and permeate quality has occurred since the beginning of the operation. The evaluation has been made using normalization tools together with a direct comparison between the operating values collected at the start-up and the current performance. These findings are especially remarkable if we take into consideration that the big majority of the reverse osmosis elements installed in Ashkelon and still in operation are currently more than five years old.

Keywords: Ashkelon; Seawater desalination; FilmTec membranes; Reverse osmosis

1. Introduction

Ashkelon Seawater Desalination plant is a clear example of how human beings are able to face the difficulties imposed by the environment. This installation was actually, part of the desalination master plan launched by Israel in 2000 to minimize the water scarcity problem of the country. After Ashkelon was started in 2005, many desalination plants with large capacity have been put in operation, but so far, Ashkelon is the unique reverse osmosis desalination plant with such a high capacity which has been successfully producing water for more than five years in a sustainable way.

Ashkelon started producing water in 2005 and in 2006 it was awarded as the “Desalination Plant of the Year” through the Global Water Awards organized by Global Water Intelligence Publication. Two key aspects emphasized those days were on one hand the low cost of water $0.53/$m^3$ and secondly the large capacity, able to satisfy 13% of Israel’s potable water requirements and bring fresh water to one of the country’s driest corner.

Ashkelon not only represented a challenge for those companies involved in the BOT because of the large capacity but also due to the technological innovation involved in the project: the cascade design (patented by IDE Technologies Ltd), which resulted in an overall higher recovery than a conventional two pass design [1], the use of pressure centers as well as the installation of energy

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recovery devices [2]. All these points will be described later on in the text.

2. Key innovation aspects

The Ashkelon plant incorporated various major innovations, along with various incremental improvements at the same time, which allowed it to achieve a record low price of water, despite the very strict water quality standard.

The major innovations, both described in detail by Liberman [3], included:

- "Pressure center" concept: The grouping of several SWRO trains to only few operating large pumps, reduced capital cost (economy of scale) as well as operational cost (higher pump efficiency).
- "Cascade" concept: The multiple stage concept allows polishing of the first stage SWRO permeate to remove Boron and chlorides at a very high recovery of which is economic because the advanced treatment to reach a higher recovery is still lower cost than the investment in a larger first stage desalination unit would be. The stage concept is unique not only with regards to recovery, but also with regards to the water chemistry conditions and the water quality obtained.

Incremental improvements included:

- The use of FilmTec™ SW30HRLE-400 membranes: in the earlier phases of project planning and execution, SWRO membranes with a higher energy consumption had been foreseen, but after low energy technology became available in 2003, development work was undertaken at an already advanced stage within the project. After pilot tests with low energy technology confirmed the feasibility, the design was converted over to advanced SWRO membrane technology.
- Proactive quality management and piloting: A very proactive quality management system was implemented which started already by very systematic tracking of membrane quality. In addition an extensive pilot trial was carried, with multiple vessels in parallel and thorough data evaluation, which enabled a very reliable estimation of large scale plant performance.
- Pressure vessels with eight elements in series: Ashkelon desalination plant was the first large installation where pressure vessels with eight elements were installed. Despite the reluctance shown by some membrane experts at the time the projects was being defined, the consortium decided to utilize such configuration in order to optimize the recovery in every single stage of the installation.

3. Installation description

3.1. Pretreatment

Three options were initially considered for the feed water source of Ashkelon SWRO desalination plant: open submerged intake, seawater wells and cooling water discharge of a power station [4]. The alternative finally selected was the open intake due to previous experiences in desalination plants and due to the reliability and safety associated with this type of process. The intake consists thus of three parallel high density polyethylene pipes which ensures that at least 67% of the plant remains in operation. In addition, high-density plastic pipes gave a low tendency for bio-growth and are easy to clean by pigging.

The feedwater is directed towards the pretreatment process though vertical pumps. The pretreatment is divided in two lines, each one consisting of dual media gravity filters containing quartz and anthracite. Before the filtration stage, feedwater pH is adjusted (sulfuric acid) and coagulant (ferric sulfate) addition takes place. The installation is equipped as well with flocculant addition and chlorination/dichlorination stations, but these are not in use in normal operation. Cartridges filters are installed between the pretreatment and the reverse osmosis as an extra safety measure.

3.2. Reverse osmosis

The reverse osmosis installation consists of two stages each one with two passes. This peculiar design, named "Cascade Design" and patented by IDE Ltd. [5], was considered to be the optimum choice in order to attain the following three main targets:

- Accomplish the strict permeate quality requirements (chloride below 20 ppm and boron below 0.4 ppm)
- Achieve a high recovery rate in the whole process
- Diminish the risk of scaling despite the high recovery rates

In the cascade design, the seawater is treated in a first RO stage, where front and rear permeate are obtained. The rear permeate is treated in a second stage with high recovery and high pH for better boron removal. The front permeate is part of the total permeate and does not need further desalination. According to the previous description, the first two stages of the cascade design coincide with a two passes conventional design. The key feature of the cascade, is that the brine of the second stage is further treated in an extra two-passes installation (namely third and fourth stages). The third RO unit, consisting of two stages treats the brine of the second stage previously acidified to avoid scaling problems. In the fourth stage, also formed by two stages to accomplish a high recovery, the permeate of the third stage is treated. A scheme of the cascade design is shown in Fig. 1.

In every stage of Ashkelon desalination plant FilmTec™ reverse osmosis elements are in operation. Seawater elements (FilmTec™ SW30HRLE-400) were installed in the first stage and brackish water elements (FilmTec™

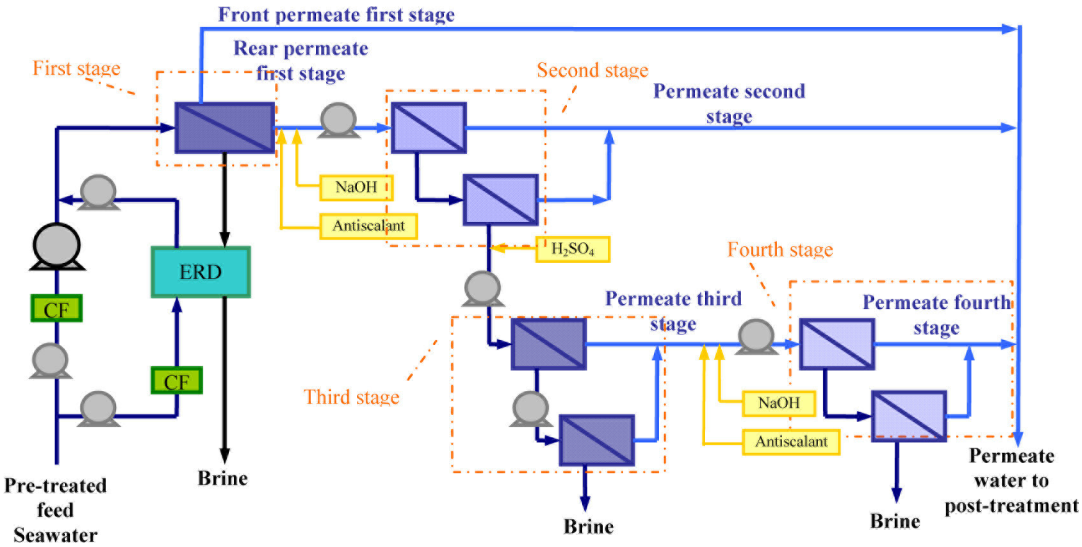

Fig. 1. Scheme of the cascade design.

BW30LE-440 and BW30-400) were installed in the subsequent stages. Detailed information about the number of trains and the type of membrane installed in every stage is indicated in Table 1.

3.3. Post-treatment

The product water produced in Ashkelon desalination plant consist of the front permeate of the first stage and of the permeate of second and fourth stages. In order to meet the drinking water quality standards and to prevent any corrosion effects in the distribution network, remineralization (lime) and adjustment of alkalinity, hardness and pH takes place.

4. Long-term operation

The contract of Ashkelon establishes a water production of 100 million m^3/y to be purchased by the government. The product water before post-treatment has to accomplish the following quality parameters: total dissolved solids (TDS) concentration below 80 ppm, chloride (Cl) content below 20 ppm, sodium (Na) concentration below 40 ppm and finally boron content below 0.4 ppm.

The project planning and execution involved accurate design and operation projections, an advanced RO element production quality control system, as well as advanced pilot testing before start-up of the facility. This enabled a very smooth start-up.

Accurate design and operation projections were based on the reliability of Dow Water and Process Solutions' ROSA (Reverse Osmosis System Analyzer) design software, which accurately predicts performance of FILMTEC™ SWRO and BWRO membranes, with highest possible precision and without any commercial bias. The program had to be optimized for the conditions in the stages two to four, which underlies novel water chemistry conditions (very high pH of 10–11, high boron content, very low content of total inorganic carbon, which causes a larger than expected pH increase from the feed to the concentrate). Comparatively higher accuracy of the ROSA design software as opposed to other software in

Table 1
Number of trains and type of elements installed in every stage

Stage	RO membrane installed	Specification
First	FILMTEC™ SW30HRLE-400	7,500 gpd, 99.75% salt rejection*
Second	FILMTEC™ BW30LE-440	11,000 gpd, 99.0% salt rejection**
Third	FILMTEC™ BW30-400	10,500 gpd, 99.5% salt rejection***
Fourth	FILMTEC™ BW30-400	10,500 gpd, 99.5% salt rejection***

* at 32,000 ppm NaCl, 800 psi, 8% recovery and pH 8
** at 2,000 ppm NaCl, 150 psi, 15% recovery and pH 8
*** at 2,000 ppm NaCl, 225 psi, 15% recovery and pH 8

the industry has been confirmed by Faigon and Hefer [1] for the case of pH change in a boron polishing stage as well by Salangos and Etxaniz [6] for the case of first pass SWRO design pressure and permeate salinity predictions.

The advanced quality control system included a philosophy which included proactive quality control of SWRO elements during production. This involved advanced verification of RO membrane performance ahead of element construction.

Based on a very deep understanding of membrane performance prior to start-up, the plant ramped up to full production very fast after its commissioning and already exceeded its yearly design capacity of 100 Million m³/a by 8% within the first year of operation, at an energy consumption which was 0.5 kWh/m³ lower than expected [7].

With a low level of modifications it has been possible in the mean time to increase the plant's production by 33% to 133 Million m³/a, over the original design capacity of 100 Million m³/a.

In this section, all four stages of Ashkelon are going to be described in detail and the operating experiences are going to be reviewed and compared to the first operating results published about this desalination plant [8].

4.1. First stage

The 1st stage of Ashkelon desalination plant is a conventional seawater RO desalination process, from the point of view of membrane operation: a certain number of large high pressure pumps form a Pumping Center supply seawater, via the common feed ring, to all the RO banks. An Energy Recovery Center comprising DWEER™ units collects the pressurized brine from all the RO banks, transfers the energy to the feed seawater, and pumps it to all the RO banks via the common feed ring [9].

As previously indicated, two permeate flows are produced in the first stage. The front permeate, of highest quality (lowest TDS content) is generated by the first membranes of the vessel and goes directly to the final product water. The permeate produced by the rear membranes of the vessels has a higher TDS (and boron) content and it is further treated in the second stage.

For the normalization in the Ashkelon SWRO plant, the FILMTEC™ normalization software FTNORM [10] was applied. FTNORM allows normalizing operating data and graphing the selected parameters, such as normalized permeate flow and normalized salt passage. Data of the first day of operation once the system was stabilized has been taken as reference point for normalization.

In Figs. 2 and 3 the normalized permeate flow and normalized salt passage of two different trains of the first stage are shown. From these graphs it can be concluded that both parameters (salt passage and permeate flow) have been relatively stable despite the long operational time. It is important to emphasize that the total number

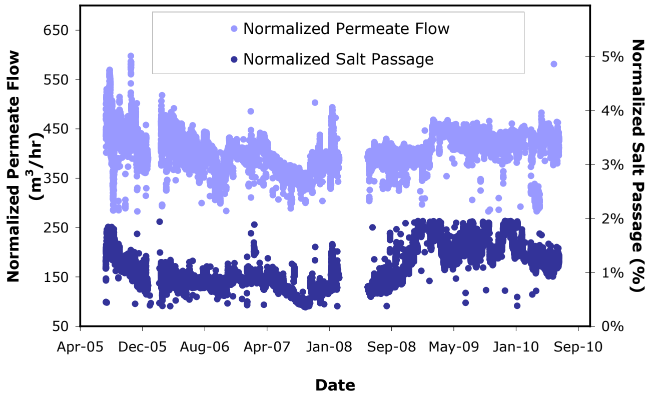

Fig. 2. Normalized permeate flow and normalized salt passage train 1 north (first stage).

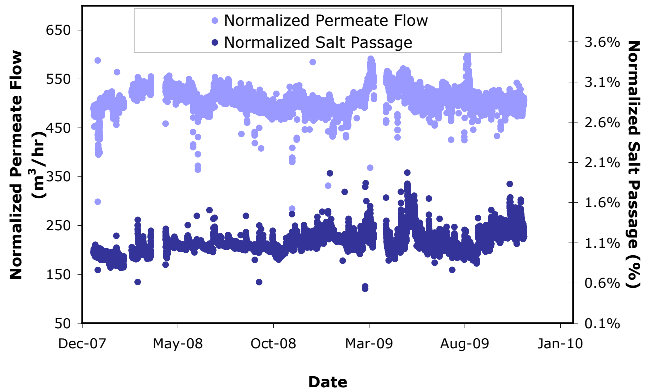

Fig. 3. Normalized permeate flow and normalized salt passage train 1 south (first stage).

of reverse osmosis elements replaced in Ashkelon up to now is far below initial design expectations. This means that even though most of the modules of the installation are 5 years old, the quality and quantity of the permeate produced still meets the requirements and the initial expectations.

4.2. Second stage

The second stage of the cascade treats the rear permeate of the first stage. It is operated at a relatively low recovery and high pH (>10). The permeate produced in this second stage has low concentration of boron and it actually represents the main stream of the total permeate. The concentration of Ca and Mg ions or $CaCO_3$ and $Mg(OH)_2$ in the brine stream might limit recovery, depending on the integrity of SWRO membranes (which influences Ca and Mg rejection) as well as the membrane selection (higher water and boron permeability membranes in the first and second stages of the cascade system may require higher pH values) and the split point in the first stage (higher split increases general salinity in the downstream stages — for this reason, the split point of the first stage should be carefully selected and evaluated).

In Table 2 the main operating conditions of stage 2 reported after the start up of the plant and the current conditions are summarized. Feed composition or salinity in this second stage mainly depends on the split ratio selected for the first stage. If the first stage global permeate salinity is relatively low, the feed flow rate going towards the second stage might be lower but its salinity might be higher. In other words, the higher the amount of water going into the second stage (lower split ratio), the lower its salinity. This is however not the optimum scenario since it gives an indication that more water needs to be treated in the cascade in order to attain the final required quality. According to the data shown in Table 2 the feed TDS of stage 2 is on average higher currently that in 2005. The data previously discussed about stage 1, stated that over these 5 years of operation, the normalized salt passage has been relatively stable, thus, the increase in the feed salinity in stage 2 is explained by considering that less water is needed to be circulated through the cascade to attain the final quality requirement. It is also important to emphasize that this second stage is currently operated at a slightly lower pH than at the beginning of the operation. The amount of caustic to be dosed obviously depends on the temperature: higher temperature, higher Boron passage and thus higher pH required in order to take benefit of the higher rejection of the boron dissociated species. At the lowest temperatures, the pH is around 10 and not varying a lot at high operation temperatures. It should be pointed out as well, that in summer 2010 a top temperature of 33°C has been recorded, whereas in 2005, the highest temperature was 32°C.

Regarding product TDS, the average salinity of the permeate produced by the second stage in 2010 is 7.6 ppm which is within the range of the values measured in 2005.

Table 2
Main operating conditions stage 2 period 2005–2010

Conditions	2005	2010
Element type	BW30LE-440	
TDS feed, mg/L	>300	Average 450 Min. 285 Max. 1350
Temperature, °C	19–32	Average 25 Min. 18.7 Max. 33
pH feed	> 10	± 10
Recovery, %	75–87	Average 67%
Performance data		
TDS product, mg/L	2–11	Average 7.6
Feed pressure, bar	Approx. 7	Stable

Taking all these operating parameters into consideration it can be concluded that the membranes, which are already 5 years old present similar performance compared to the values after the start up.

4.3. Third stage

The 2nd stage brine is further processed in the 3rd stage, which operates at a low pH of 6.5 and high recovery (> 85%). The intention at this stage is maximum removal of the Ca and Mg ions, under safe operating conditions. At these conditions most of the boron will remain in the 3rd stage permeate, which then needs further treatment in a subsequent stage (fourth stage). In Table 3 the main operating conditions and performance data monitored during the first days of operation in 2005 and in 2010 (after five years in operation is shown). Feed TDS or feed salinity was slightly lower in 2009 compared to the values monitored in 2005. Temperature reached 33 in 2009 while in 2005 the maximum was 19°C. Regarding feed pH, a proper control of the scaling risk conditions has allowed the possibility of operating this third stage at pH levels much higher than the initial range. In terms of the quality of the permeate produced, it should be noted that the salt content of the permeate was lower in 2009 than in 2005. On one hand the feed salinity was lower in 2009 but this stage has been operated at a relatively high recovery (which favors the salt passage). All together, the performance of the membranes in terms of salt passage is impressive.

4.4. Fourth stage

The 4th stage is designed for optimal boron removal at high pH (> 10) and high recovery (>85%) The 3rd stage permeate retains a high concentration of boron (as ionic borate) and cannot be used as product water. However it does not contain Ca and Mg cations. This combination of concentrated ionic boron and the absence of Mg cations

Table 3
Main operating conditions stage 3 period 2005–2010

Conditions	2005	2009
Element type	BW30-400	
TDS feed, mg/L	1,500–5,500	1,400 – 4,000
Temperature, °C	19–32	19-33
pH feed	± 6	± 8
Recovery, %	>85	Average 86% Min 79% Max 90%
Performance data		
TDS product, mg/L	25–120	10-87
Feed pressure, bar	Approx. 10	Stable

Table 4
Main operating conditions stage 4 period 2005–2010

Conditions	2005	2010
Element type	BW30-400	
TDS feed, mg/L	25-120	38–205
Temperature, °C	19–32	18–33.5
pH feed	>10	± 10
Recovery, %	85–90	87–92
Performance data		
TDS product, mg/L	3–7	3–20
Feed pressure, bar	Approx. 9	Stable

allows the use of high feed water pH values and obtains a high recovery.

In Table 4 the main operating conditions of stage four, together with some key performance items are included. As reported, the feed water salinity has been higher in 2010 compared to the values recorded in 2005, which explains a slightly higher permeate TDS in the current year. Feed pH was in 2005 higher than 10, whereas nowadays this particular stage is operated at a feed pH between 8.6–10.9. This is an indication of the good boron rejection attained by the reverse osmosis membranes. Recovery is also slightly higher than in 2005, which together with the higher feed salinity and the age of the membranes explains the two bar higher pressure monitored in 2010.

In a similar way as it was concluded for the other stages, the performance is excellent if we take into account that the membranes have been in operation for more than 5 years and that no major loss in production or rejection is observed.

5. Conclusions

Ashkelon Seawater Desalination plant has been a reference installation for the desalination world since the day the project was conceived. Some of its key features, such as the production (currently up to 133 Million m^3/y) and the low cost of water achieved, meant a revolution compared to the desalination plants previously built and operated. From a technological point of view, Ashkelon implemented for the first time the "Cascade Concept" (patented by IDE) to maximize the recovery of the plant and the pressure center to reduce capital expenses (economy of scale). From the point of view of the reverse osmosis membrane, Ashkelon meant a big step compared to previous experiences, mainly due to the very strict permeate water quality requirements.

Over 40,000 FilmTec™ reverse osmosis membranes (including seawater and brackish water membranes) were installed and put in operation five years ago. After half a decade of successful operation and having replaced a minor quantity of the total amount of membranes, Ashkelon continues supplying drinking water of the highest quality to Israel's population.

In this paper, the operating conditions and the main performance parameters such as permeate quality and feed pressure have been reviewed and compared to values of the first months of operation in 2005. According to the results of this evaluation, it can be concluded that the quality of the permeate, in terms of salinity or TDS has been stable over the five years of operation. In addition, no major permeate flow loss has been observed.

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