Finding the biofouling control balance for SWRO plants

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ABSTRACT

This paper focusses on biofouling issues sea water reverse osmosis plants (SWRO) are experiencing. Finding the balance of an optimum intake seawater system and the prevention of biofouling growth on the reverse osmosis (RO) membranes, presents significant operational challenges for plant owners and operators. With seawater, a variety of marine biofouling organisms enter the intake system. Intake structures are in general, an ideal environment and provide optimal conditions for settlement and growth of marine biofouling organisms. Marine biofouling results in an increased wall roughness and reduction of the inner pipe diameter which leads to a significant head loss in the intake structure. This has a high impact on the operational reliability of the intake system and often results in an unplanned shutdown. To prevent settlement and growth of marine biofouling species, biocides are generally dosed at the seawater intake. Chlorine (as sodium hypochlorite) is used at many SWRO plants to prevent marine growth in the seawater intake however, this has a direct impact on the rate of organics and biofouling growth on the RO membranes. There is clear evidence that the use of chlorine oxidises large organic molecules in the seawater, breaking them down into smaller organic species. The large organic molecules generally exhibit a relatively low biodegradability and a proportion of them can be removed to varying degrees by pre-treatment processes (coagulation, sand filtration, membrane filtration). In contrast, the smaller organic molecules exhibit a much higher biodegradability and cannot be sufficiently removed by coagulation or membrane filtration processes. As a consequence, whilst the use of chlorine in intake pipes can control the rate of growth in the seawater intake it does have an adverse affect on the downstream processes and in particular, the RO membranes. Establishing the correct methodology in terms of chlorination is essential to maintain a balance between the condition of the sea water intake system and the long term operability of the SWRO plant.

Keywords: Desalination, biofouling, Chlorine, membrane fouling, operational reliability

I. INTRODUCTION

Reverse osmosis (RO)membrane-based desalination plants represent about 65% of the global installed desalination capacity. Desalination has moved increasingly towards the use of reverse osmosis, replacing thermal and mechanical processes. According GWI, RO technology achieved remarkable gains in the production of desalinated water from seawater (in 2015; 6.9 km^3 year−1 of the 12.9 km^3 year−1 total global desalinated water production from seawater [9]. This is directly attributable to the significant technological progress that has occurred with membrane-based desalination [3, 4, 6, 15]. Design and operation of seawater reverse osmosis plants strongly depends on the raw seawater quality to be treated. The performance of desalination based RO systems relies upon the production of high-quality pretreated water, and the selection of the best pretreatment technology depends on the raw seawater quality and its variations. Many operating SWRO plants throughout the world are evidence of the criticality of understanding the seawater quality and its nuances, as well as selecting optimum pretreatment.

Biofouling can have a significant impact on the performance of a desalination plant. The cause of the microbiological and organic fouling on the RO membranes is often due to the marine fouling that takes place in seawater intake pipes. Desalination plants around the world are challenged to find an effective balance to control biofouling within the intake system as well as that which occurs on the surface of the RO membranes. The fact that the type and rate of biofouling is largely influenced by local specific conditions such as biological and organic species, temperature and overall seawater composition and variability, makes it difficult to find the correct balance in seawater pretreatment.

1.1 Marine biofouling

Surfaces of man-made solid structures, such as seawater intakes and pipe work, are colonized in standard patterns by organisms present in seawater. Firstly, organic molecules are deposited, followed immediately by the attachment of bacteria which can form a biofilm. This forms the basis whereon larvae of biofouling species such as mussels, oysters or barnacles, can settle. The type of biofouling species depends on the geographical location. Seasonal effects and the availability of nutrients determine mainly which type and number of biofouling species are available. Marine species are considered as biofouling when they can settle and grow on the substrate within a water system. Upon entering the intake system, fouling organisms can readily colonise the available substrates, e.g. concrete, metal, wood, and glass-reinforced plastic (GRP) and HDPE surfaces in the intake system, cooling water conduits, condensers, heat exchangers, and cooling tower.

1.1.1 Typical operational problems due to marine biofouling

Biofouling can have a significant impact on hydraulics and can result in major operational problems, including unplanned plant shutdowns due to head loss. The amount of biofouling settled can build up a potential biomass of up to hundreds of tons within two years. The effect of settled marine biofouling organisms that cement themselves (barnacles and some oyster species) is irreversible, even when the species are killed. Fouling organisms will settle on the surface of intake pipes and may, in competition for substrate, grow on top of each other forming thick layers. A study carried out in 2011 [11] showed the impact of biofouling settlement in intake pipes on the hydraulics and efficiency of pumping capacity.

Upon entering the intake system, fouling organisms can readily colonise the available substrates, e.g. concrete, metal, wood, and glass-reinforced plastic (GRP) surfaces in the intake system, cooling water conducts, condensers, heat exchangers, and cooling tower. A coastal power station (1,000 MW) can build up a potential biomass of up to hundreds of tons within two years. Both the diameter of the pipeline and the wall roughness are affected by biofouling. The growth rate of biofouling depends mainly on the type of species, water temperature and the availability of nutrients. Biofouling species typically grow on top of each other forming layers which can form mattresses of organisms (Figure 1).

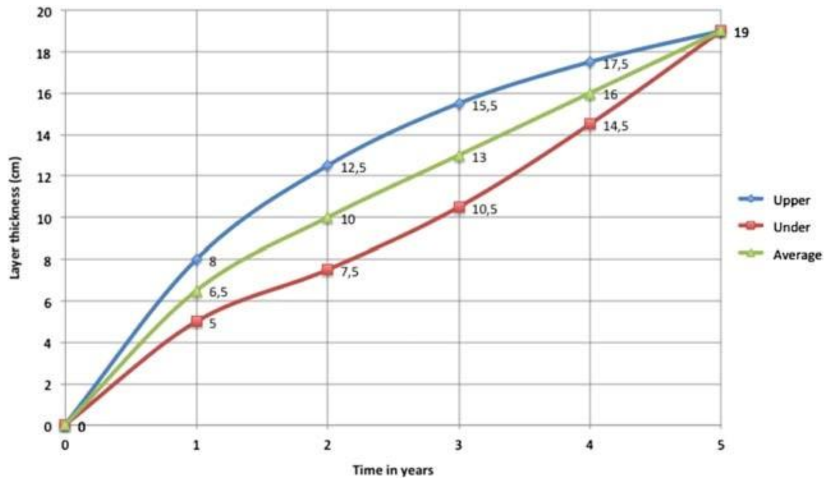

Figure 1 Biofouling layer growth rate (Polman 2011)

Consequently, the seawater flow is interfered due to the decreased diameter size of the pipe and the increased wall roughness. This results in an increased head loss and decreased efficiency for the pumping station [7, 14], frequently resulting in an unplanned outage of the plant. Operators associated with seawater intake systems suffer significant losses due to head loss cost caused by biofouling. This is often not quantifiable, due to lack of information. Therefore, it is very important to have a preventative approach to ensure the settlement of marine biofouling larvae in the seawater system in minimized to the greatest extent possible

1.2 Membrane biofouling

1.2.1 Typical operational problems due to RO membrane biofouling

Biofouling is caused by bacteria which grow on the membrane surface [5, 13]. A single bacterium is required to seed the membrane surface, and this initial seed then reproduces exponentially, using organic and inorganic nutrients (organic carbon, nitrogen and phosphorous) in the seawater. The bacteria produce an extracellular polymeric (gel like) substance, which adheres to the membrane surface and to provide a protective barrier between the bacteria and the seawater. This extracellular polymeric substance appears like a brown-orange jelly which covers the surface of the membrane and collects in the membrane feed spacers. As this gel like substance collects in the membrane feed spacers, it restricts the area available for flow across the membrane surface, thereby increasing the feed to brine differential pressure (DP). Increasing DP increases energy consumption and the biofouling has to be removed by chemical cleaning which increases chemical consumption and reduces plant availability. Excessive chemical cleaning can also reduce the membrane lifetime. If the biofouling is allowed to increase without effective chemical cleaning, then the biofouling can actually block flows to whole parts of the membrane surface, thereby reducing the effective membrane area and increasing flux.

This causes increased feed pressure (and therefore high electricity consumption) and can cause membrane design guidelines to be exceeded in the active area of the membrane element. These blocked areas are also extremely hard to access by chemical cleaning, since the chemical is carried by feed to brine flow, and this can therefore result in what are effectively dead zones of the membrane. Finally, the DP creates a very great force on the structure of the membrane, and it is common for the feed spacer to be moved along the membrane element and become extruded out the far end. This can also cause loss of effective membrane area, and in extreme cases, there is no option but to replace the membrane.

II. COMMON PRACTISE FOR SEAWATER PRE-TREATMENT AT SWRO PLANTS

2.1 Intake seawater treatment

Globally, the typical industrial anti-fouling practice involves continuous low-concentration chlorination of seawater and/or periodic shock-dosing at higher concentrations. This regime is applied throughout the year, especially in coastal areas at the Arabian Gulf. The practice is generally based on retrospective observation of biofouling control efficiency or performed as an attempt to meet the discharge or system utility limits of residual biocide concentrations. Chlorination for plants where RO is the desalination process unit can be challenging as the thin film composite membrane have very limited tolerance to free chlorine. It is therefore imperative, that chlorination is carefully controlled, and any free chlorine is removed prior to the sea water coming into contact with the RO membranes. It is for this reason that shock dosing, e.g. one hour per day, is applied with a relative high concentration of free chlorine with the objective to prevent biofouling settlement in the seawater intake. These chlorination practices are not based upon ecotoxicological evaluation of the fouling species. Shock dosing is commonly applied in the erroneous belief that it prevents biofouling species from settlement and growth however, this approach to chlorine dosing regimens does not always prove to be sufficiently effective and biofouling growth occurs.

2.2 Pretreatment RO membranes

Pretreatment for RO has traditionally focused on removal of particulate material, typically measured by the Silt Density Index (SDI). The pretreatment process depends on the quality of the seawater used and can range from simple cartridge filters for very high-quality groundwater sources to extensive treatment trains involving various combinations of screens, strainers, micro/ultrafiltration, coagulation, flocculation, dissolved air flotation, clarification, multi media filtration and cartridge filters, for more difficult to treat waters.

While SDI is a very good indicator of particulate fouling potential, it is a poor indicator of biofouling potential. The rate of biofouling depends on the availability of nutrients, temperature and lack of conditions which impede bio growth (toxins, pH extremes, rapid changes in salinity etc). Typically, the nutrient which dictates the rate of biofouling is organic carbon. Organic carbon is measured in water using the parameter Total Organic Carbon (TOC). TOC is a poor indicator of the propensity for biofouling potential because it does not provide a meaningful indication of the types of organics and how bacteria might use these as a food source. A compound like a humic acid might contribute a very significant amount of TOC, but is virtually non-biodegradable, and would only contribute to a very slow rate of biofouling. On the other hand, a small organic acid like acetic acid is extremely biodegradable and would therefore result in rapid biofouling even for a very small amount measured as TOC.

Small organic molecules are generally much more biodegradable than large organic molecules. Chlorine has been recognized as a proven oxidant to break down large organic molecules into smaller organic molecules. This is of particular importance when chlorination is used for drinking water plants. Feed waters that have high levels of organics and are chlorinated are particularly susceptible to the formation of disinfection by-products. It is acknowledged that these organic molecules can result in adverse health impacts. In addition, these small organic molecules are also far more biodegradable than the pre-cursors, so chlorinating water increases the concentration of readily biodegradable organics in the water. Normally, the chlorine itself restricts the growth of biofilm, because of its toxicity. However, with RO membranes, the chlorine has to be neutralised so it doesn't oxidise the RO membrane, which means that the rate of biofouling is far greater if the feed water is chlorinated and dechlorinated than if it is not chlorinated.

Theoretically, Assimilable Organic Carbon (AOC) should be a very good measure of biofouling potential in SWRO systems, because it is a measure of the amount of organic carbon consumed by bacteria under standard conditions. However, the analysis is not straightforward, and there is massive variability in the values of AOC which can be measured by different laboratories. Consequently, it is difficult to use AOC as a standard measure of biofouling potential. The lack of a rapid, simple and consistent method of measuring biofouling potential in SWRO feed water makes research in this area much more complex and makes it very difficult to objectively compare results from different sites. It is therefore the current industry practice that biofouling potential to be measured based on the rate at which SWRO membranes foul (rate of DP increase and CIP frequency).

Most SWRO pre-treatment systems are designed based on turbidity/suspended solids and the potential for algal blooms in the raw seawater. Virtually all open seawater intakes would have some form of filtration, either deep media filtration (eg dual media filters with anthracite and sand) or membrane filtration (microfiltration or ultrafiltration). In the majority of cases, a provision would be made for the dosing of a coagulant (typically ferric chloride), certainly with deep media filtration. If the raw seawater experiences periods of high solids loadings (sediment flushed from rivers during a rainy season) or at risk of experiencing an algal bloom (eg. red tide), then it is likely that a clarification process (either Dissolved Air Flotation (DAF) or sedimentation) would be provided upstream of the filtration process, and a coagulant is almost always used with a clarification process.

Whilst algal blooms and solids loadings are nearly always taken into account in designing a pre-treatment system for SWRO, it is much less likely that the impact of the type of biofouling control mechanism for the intake will be taken into account in designing the pre-treatment system. This is despite the fact that the type of biofouling control mechanism used at the intake can have a profound impact on the rate at which the SWRO system biofouls, especially if continuous chlorination – dechlorination is practiced. In fact, the type of biofouling control used for the intake should determine whether or not some form of biological filtration is required as part of the pre-treatment process in order that the rate of biofouling of the RO membranes is acceptable.

III. BIOFOULING CONTROL AT AL FATAH SWRO PLANT

3.1 Biofouling challenges and operational history

Al-Fatah Water & Power Jubail SWRO Plant was built in 2008 as a temporary solution to produce potable water and process water to MARAFIQ who supply the industrial city of Al Jubail, KSA. An upgrade of the pre-treatment system and an expansion phase was completed in 2014 with an installed potential plant capacity of 103,500 m3/day of which, 75,000 m3/day is current output capacity.

Since the plant start-up, the intake water supply to the RO plant has been taken from MARAFIQ's Sea Water Cooling Channel by gravity. At the location of feed water extraction, the Free Residual Chlorine (FRC) average recorded from 2008 to 2015 was 7.5ppm. The Arabian Gulf is one of the most challenging sources of water for desalination plants, characterized by high salinity, dissolved organics, and prone to algae blooms

This quality of water is challenging and in order to attain an efficient RO plant, Al-Fatah focused on selecting efficient pretreatment configuration by conducting many pilot filtration trials in Jubail city over a period of 8 months. The selected pretreatment configuration was pressureised DMF followed by self cleaning strainer and UF membrane filtration as polishing process unit. The new pre-treatment system was installed and in operation in 2014 (Fig-2).

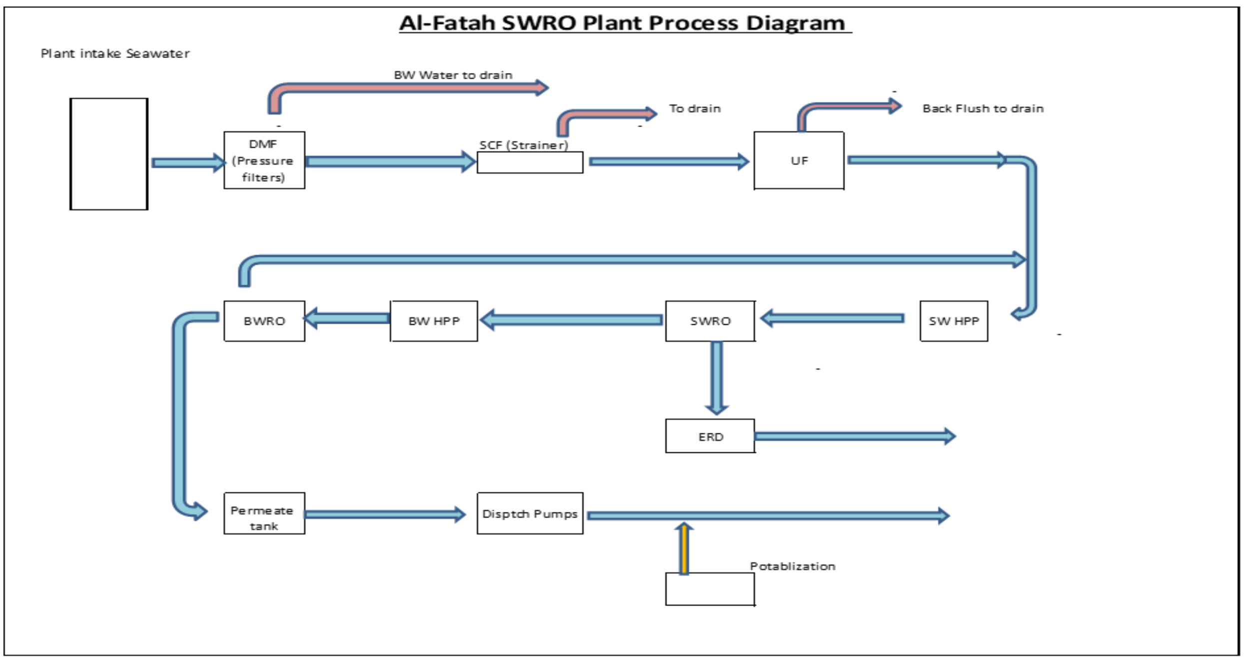

Figure 2 Al-Fatah SWRO Plant Process Digram

The operational challenges encountered between 2014-2017 can be sumerized in the following points:

1- As the water is highly chlorinated, signifant quantities of chemicals (Sodium metabisulphate, SMBS) were consumed.
2- Chlorinated water passes to the UF downstream, then neutrilized with SMBS. This resulted in a high rate of biofouling for the RO membranes, as indicated by sharp increases in RO membrane's differiential pressure (dp), in a rate of 0.08 bar/d.
3- Frequent CIP for RO membranes, which has increased the operational costs and shortened RO membranes life.

The Al-Fatah process design was to partially dechlorinate the intake water in the reciving chamber, and allow the rest of the chlorine to disinfect the piping and the DMF.As a result of the high concentration of chlorine, organics are broken down resutling in small organic molecules which result in both organic and biological fouling on the RO membranes. This is shown by the differential pressure across the RO membrane system (see Figure 3). It is also evident that the CIP is effective in reducing the DP however, there is again a subsequent increase resulting in the need for more frequent CIPs. This results in reduced plant availability, higher chemical costs and reduced membrane life.

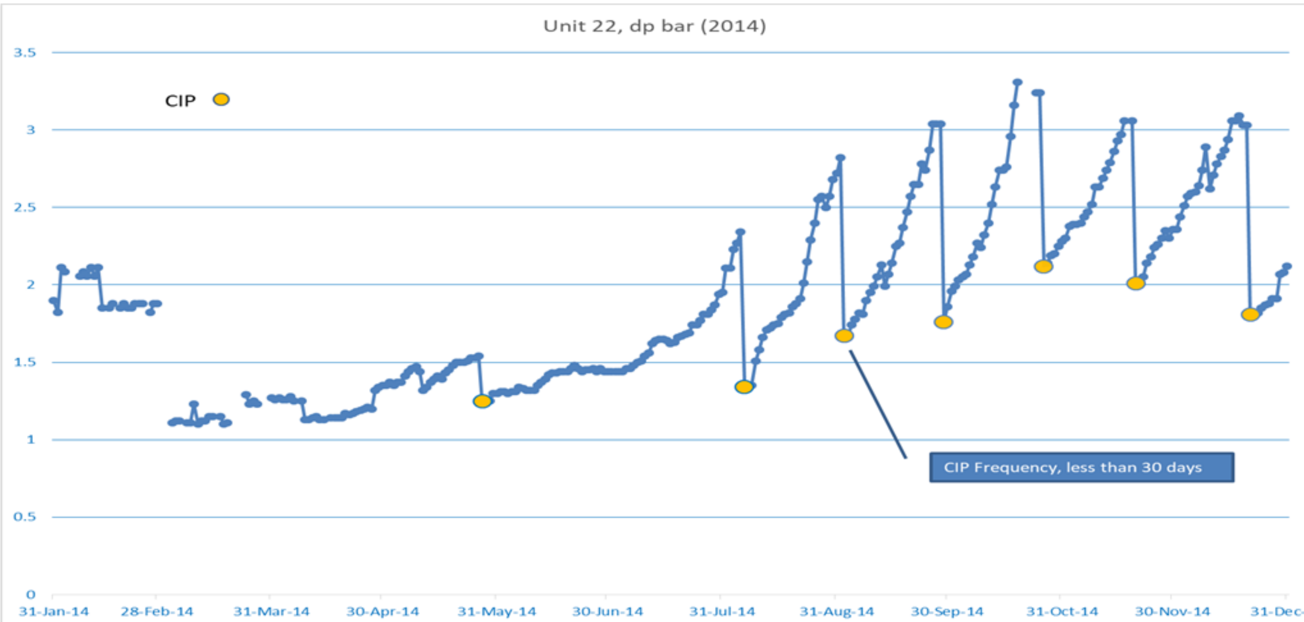

Figure 3 RO membrane's differiential pressure (dp) and CIP frequency

Al-Fatah resolved the effect of uncontrolled high concentration of chlorine by installing a new independent seawater intake which was commisioned in Septermber 2017. Before receiving water from the new independent intake, the plant suffered from marine biofouling settlement in the receiving chamber during the period of several months of no chlorine dosed in the received intake water from Marafiq.

The seawater in this part of the Arabian Gulf is known to contain a high variety of biofouling species. During site surveys in the Jubail area it could be concluded the main biofouling species are oysters (*Pinctada* species), mussels (*Brachidontes variabilis*), tubular chalk worms (*Serpulorbis variabilis*) and barnacles (*Amphibalanus amphitrite*). These biofouling species have different spawning periods throughout the year [1, 2, 8]. From previous surveys in the Arabian Gulf it is known that an effective marine biofouling control in the seawater intake and pipes should be applied throughout the whole year.

3.2 Optimisation biofouling treatment.

Al-Fatah made two important actions before and after installing the new independent intake system. These actions consisted of:

- Changing the dosing point of the SMBS five meter upstream of DMF, October 2015 .
- Applying Ecodosing to cotrol biofouling in the seawater intake using a minimum amount of chlorine September 2017.

Al Fatah uses sodium hypochlorite to prevent biofouling settlement in the seawater intake and pipes towards the DMF. Since a continuous application of chlorine was not preferred based on the previous experience resulting in a high CIP frequency at the RO membranes a study was carried out to reduce the use of sodium hypochlorite. The objective was to prevent marine biofouling settlement in the seawater intake pipes using a minimum amount of hypochlorite. Fortunately, scientific methods now offer opportunities for provide a site-specific biocide dosing regime. The Ecodosing method is developed to tailor marine biofouling control using an absolute lowest amount of biocide, e.g. sodium hypochlorite.

3.2.1 Ecodosing procedure

Ecodosing takes advantage of the natural life cycles of local biofouling organisms (including mussels, oysters and barnacles) and their response to biocides under local conditions to calculate the most effective dosing method to control settlement and growth. When exposed to a biocide, organisms normally close their shell to protect themselves. During the closure the organism switches from aerobic to anaerobic metabolism and uses a minimum amount of energy to survive the period of biocide dosage. Since the organism uses only a minimum amount of energy it can withstand this period of dosing for longer times, up to several weeks. When the dosing is stopped, the organism opens again to restart filtering activity to gain oxygen and nutrients from the water and recover from the dosing period. The organism is however only capable to do so when its fully open. Ecodosing makes use of this specific type of behavior by forcing the animals to become highly active due to intermittent periods of biocide dosage which forces the organisms to open and close their shells at a high frequency. In Figure 4 this behavior is graphically presented. Cleary the difference in activity of the specie is observed between a continuous dosing wherein the animal uses a minimum of energy to survive, and the Ecodosing regime wherein the animal is stimulated to become highly active.

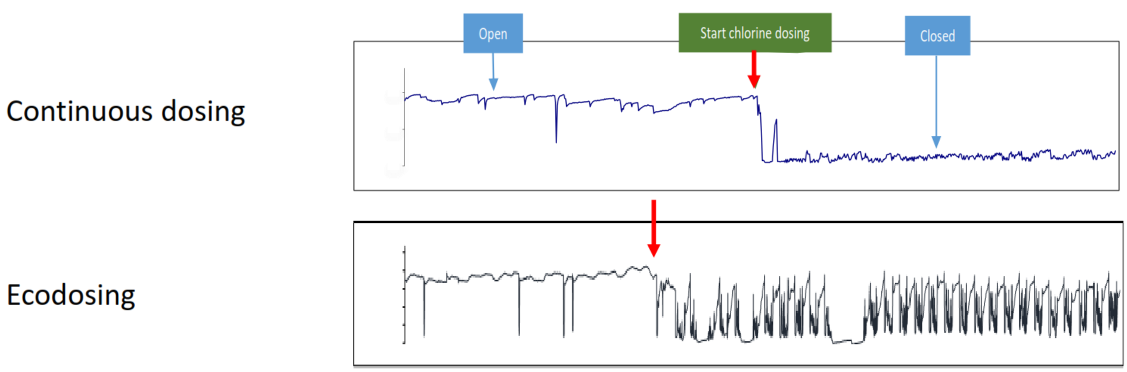

Figure 4 Behaviour of biofouling species during continuous and Ecodosing

The method, previously known as Pulse-Chlorination®, has a proven track record to prevent marine biofouling in seawater intakes and cooling water systems around the world [10, 12]. Due to the ability to protect themselves for a short chlorine dosing by closing their shells, it has been observed at many locations that solely a shock dosing regime is not effective to prevent settlement and growth of marine biofouling.

3.2.2 Results after 19 months of operation

In 2017 a site study was carried out to determine the optimal Ecodosing regime for Al Fatah Jubail SWRO plant. This regimen was determined based on local conditions (seawater) and biofouling animals which were collected from the nearby seashores. During a test period of several weeks the animals were exposed to different chlorine dosing regimes and the reactional behavior was measured and analyzed using under water cameras. Based on the data collected a chlorine dosing regime could be defined which will be prevent settlement of marine biofouling species using the lowest amount of chlorine possible to remain effective. The defined Ecodosing regime was implemented in September 2017. During this period the seawater intake pipe proved free of biofouling settlement and the CIP frequency at the RO membranes remained low and comparable during the period non-chlorinated seawater was used (Figure 5).

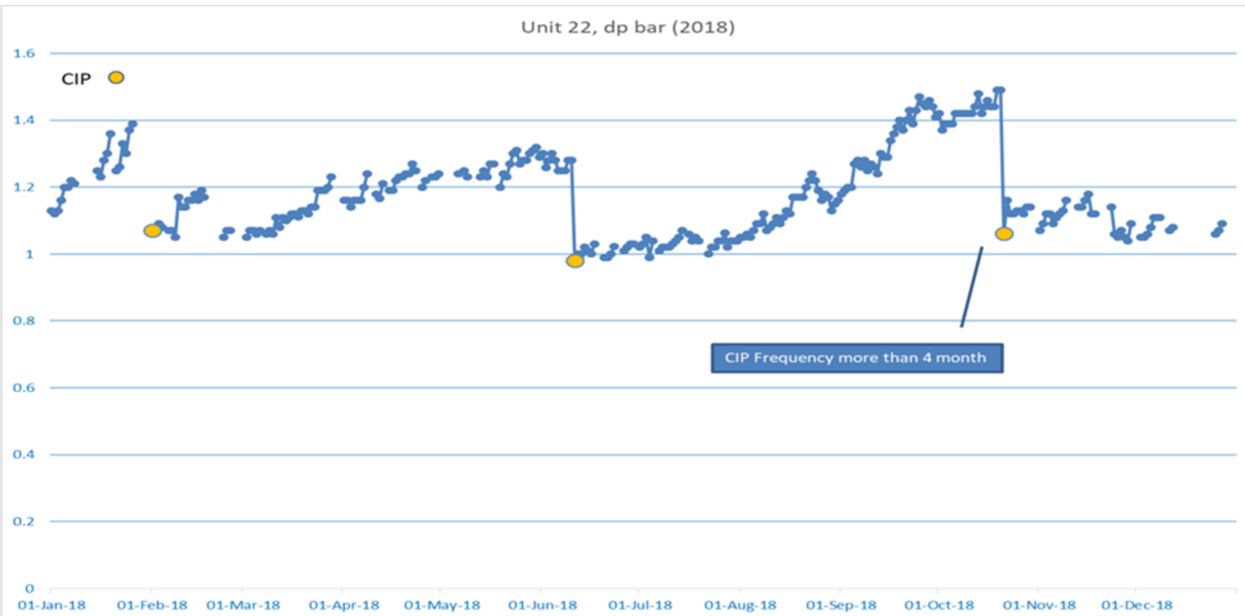

Figure 5 RO membrane's differiential pressure (dp) and CIP frequency after changes to system where made (changing dosing point SMBS and applying Ecodosing.

The results achieved at Al-Fatah showed that the control of biofouling at the seawater intake and the biofouling rate at the RO membranes could be balanced in an acceptable way for the plant owner. The reduction of CIP frequency is significantly lower with a controlled chlorination process such as Ecodosing. The control of marine biofouling settlement at the seawater intake proved effective while the CIP rate maintained at a level observed when non-chlorinated seawater was used.

IV. FUTURE BIOFOULING CHALLENGES FOR SWRO PLANTS

Since the amount and impact of marine biofouling can vary significantly from location to location, the efficiency of a treatment procedure can also vary. It is a known challenge to find a right operational balance without being exposed to either marine biofouling in the intake pipes or membrane biofouling. The results as observed at Al-Fatah SWRO plant provide field experience that a balance between marine biofouling control and biofouling on the RO membranes can be achieved when taking local specific conditions into account. However, it is noted that each site and set of site-specific conditions needs to be considered independently to test and implement and effective chlorination process that finds the optimum balance between prevent marine biofouling on the intake system whilst minimizing organic and biological fouling on the SWRO. At locations where algal blooms are prevalent, the operational approach for chlorination may also need to be altered accordingly to manage these events, when they occur.

V. CONCLUSIONS OR RESULTS

The uniqueness of each sea water, intake system and desalination system make it a challenge to determine how to maximize the efficacy of chlorination on the intake while minimizing biofouling on the SWRO membranes. Chlorination followed by de-chlorination of seawater can significantly increase the rate of biofouling in downstream RO membranes, compared to if the seawater is not chlorinated. In addition, chlorination regimen at the seawater intake have proven at some locations to be effective and not causing an increase in the biofouling rater on RO membranes. Further work is required in this regard to understand how best to monitor and control biological and organic fouling resulting from the chlorination process.

To find the balance between marine biofouling control and RO membrane biofouling control proves still to be a challenge. Local parameters have a large influence on the efficiency and possible side effects and therefore there is no silver bullet available at this moment. Chlorination followed by de-chlorination of seawater can significantly increase the rate of biofouling in downstream RO membranes, compared to if the seawater is not chlorinated. In addition, chlorination regimes at the seawater intake have proven at some locations to be effective and not causing an increase in the biofouling rate on RO membranes. Further work is required in this regard to understand how best to monitor and control biological and organic fouling resulting from the chlorination process.

VI. REFERENCES

1. Al-Sayed H.A, Al-Rumaihi E.M, Al-Rumaidhm M.J Some Morphometric Measurements and Population Structure of the Pearl Oyster Pinctada radiata at two Different Coasts in Bahrain. Report to Bahrain Centre for Studies and Scientific Research, pp 17. 1993.
2. Asma, K.M., Saber, K., Hossein, R., Zohreh, H.Z.. Seasonal Histological Comparison of Gonad and Gametogenesis in Female Pearl Oyster (Pinctada radiata) of the Persian Gulf. Journal of the Persian Gulf (Marine Science)/Vol. 5/No. 15/March 2014/8/17-24. 2014
3. Cooley, H., Ajami, N. Key Issues for Seawater Desalination in California: Cost and Financing. Pacific Institute, Oakland, California, p48. 2012.
4. Flemming, H.C., Microbial Biofouling: Unsolved Problems, Insufficient Approaches, and Possible Solutions. Biofilm Highlights pp 81-109, 2011.
5. Ghaffour, N., Missimer, T.M., Amy, G.L. Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability. Desalination 309, 197- 207. 2013.
6. Elimelech, M., Phillip, W.A., The Future of Seawater Desalination: Energy, Technology, and the Environment. Science 333, 712-717, 2011.
7. Hall L.W. Power Plant Chlorination, first ed., Electric Power Research Institute, Palo Alto, CA, 1981.

8. Khamdan, S.A. Aspect of reproduction in pearl oyster, Pinctada radiata (Leach). In: A., Otsuki, M.Y., Abdulraheem, R.M., Reynolds, (Eds.), Offshore Environment of the ROPME Sea Area after the War-Related Oil Spill, TERRAPUB, Tokyo, pp. 203–214. 1998.
9. Lu Gao, Sayaka Yoshikawa, Yoshihiko Iseri, Shinichiro Fujimori and Shinjiro Kanae, 2017. An Economic Assessment of the Global Potential for Seawater Desalination to 2050. Water 2017, 9, 763; doi:10.3390/w9100763.
10. Polman H.J.G, Bruijs M.C.M., Venhuis L.P., van Dijk S.A. More than 10 year experience with Pulse-Chlorination® dosing regime against macrofouling. Published in 2nd edition Handbook "Heat Exchanger Fouling - Mitigation and Cleaning Technologies" PP-Publico Heat exchanger fouling, mitigation and cleaning technologies pag 240 - 251 (ISBN 3-934736-20-3), 2011.
11. Polman H.J.G., Verhaart F., Bruijs M.C.M. Impact of biofouling in intake pipes on the hydraulics and efficiency of pumping capacity. Desalination and Water Treatment, DOI:10.1080/19443994.2012.707371, 2012.
12. Polman H.J.G., Bruijs M.C.M. Cost effective fouling control in (cooling) water intake systems with environmental and operational benefits. International Conference on Desalination, Environment and Marine Outfall Systems held in Muscat, Oman, 13-16 April 2014.
13. Saeed, M.O., Jamaluddin A.T., Tisan I.A. Biofouling in a seawater reverse osmosis plant on the red seacoast, Saudi Arabia. Desalination, 128 pp 177-190. 2000.
14. Woods Hole Oceanographic Institution, Marine Fouling and its Prevention, first ed., US Naval Institute, Annapolis, MD. 1952.
15. Zhou, Y., Tol, R.S.J. Evaluating the costs of desalination and water transport. Water Resources Research 41, W03003. 2005.