DUAL MEMBRANE SYSTEMS IN SEAWATER DESALINATION: DRIVERS FOR SELECTION AND FIELD EXPERIENCES

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Abstract

Traditionally, Sea Water Reverse Osmosis (SWRO) plants have been operated with a conventional pretreatment based on a single or two staged media filtration very often preceded by a coagulation/flocculation process. In the last decade, microfiltration and ultrafiltration pretreatment have increasingly gained acceptance as viable pretreatment options for seawater desalination. This paper describes the commonly reported drivers for adopting membrane pretreatment techniques, such as: greater capability to cope with fluctuations and high solid loads in raw waters, smaller footprint, higher environmental sustainability, lower SWRO stage cost both from design as well as from the operation side. Among the drivers, this report will give special emphasis on the benefits that the membrane pretreatment technology offers to the desalination industry to respond efficiently to temporary and/or emergency fresh water needs, e.g. installing containerized and mobile units with compact and modular membrane pretreatment schemes.

Despite the fact that many SWRO installations include low pressure membrane pretreatment, there is few quantifiable performance data reported. Therefore, this publication will report field experiences of integrated membrane systems using ultrafiltration (UF) membranes as pretreatment for reverse osmosis (RO) membranes in the sea water desalination field. Two examples of industrial scale integrated membrane systems running with Ultrafiltration technology and DOW reverse osmosis membranes are the focus of the study.

One of the studied systems is the Moni Desalination plant, which is a mobile system using a complete membrane integrated scheme. The plant has been fully operational since the end of 2008 and supplies 20,000 m³/day of drinking water to the city of Limassol and surroundings (Cyprus). The plant reliably achieves reliably the required permeate flow together with the required permeate water quality (boron concentration lower than 1 mg/l). The plant presents optimized cleaning procedures which minimize the chemical consumptions during chemical enhanced backwash (CEB). The average transmembrane pressure (TMP) ranges at around 0.8 bar. The other system studied is a containerized integrated membrane system installed in a refinery in Taranto (Italy). This system has been operational since mid 2009. The plant produces 8,000 m³/day of SWRO permeate which is sent to a second pass of RO in order to produce boiler feed water. One of the key characteristics of this system is the successful operation of the system at a high recovery of 60% in the SWRO section requiring only one Cleaning In Place (CIP) per year. This, could be partially, attributed to the high water quality provided by the ultrafiltration membranes which positively affect the sustainable high recovery applied in the of a SWRO system.

The characteristics and the performance of these integrated membrane systems, and the operational experiences during the time of operation will be discussed in detail in this publication.

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I. INTRODUCTION

Traditionally, Sea Water Reverse Osmosis (SWRO) plants have been operated with a conventional pretreatment based on a single or two staged media filtration very often preceded by a coagulation/flocculation process. In the last decade, microfiltration (MF) and ultrafiltration (UF) pretreatment have increasingly gained acceptance as viable pretreatment options for seawater desalination. While in the period until 2002, mostly pilot studies were carried out, in recent years several large (> 100,000 m³/d) SWRO plants have implemented UF or MF pretreatment. There are already more than 40 large-scale desalination plants using low pressure membrane pretreatment, i.e., UF or MF [1]. Figure 1 shows the cumulative capacity of SWRO plants with UF pretreatment v.s. time, which gives a clear idea of the overall adoption speed of this membrane pretreatment technology.

![Figure 1: Cumulative capacity of SWRO plants with UF pretreatment [1]](image)

Systems combining Ultrafiltration (UF) or Microfiltration (MF) and reverse osmosis (RO) are usually called dual membrane systems or integrated membrane systems.

The selection of ultrafiltration as reverse osmosis pretreatment against conventional pretreatment schemes is driven by several considerations. The key drivers are described in this report.

Despite the fact that many SWRO installations include low pressure membrane pretreatment, there is few quantifiable performance data reported. Because of that, this publication will provide field experiences of two industrial scale systems using Ultrafiltration as pretreatment for the reverse osmosis membranes in the sea water desalination application. Both reported systems are operating with Ultrafiltration technology and DOW FILMTEC reverse osmosis membranes.

One of the field experiences with dual membrane systems reported in this paper is the Moni Desalination plant. The Moni plant is a mobile system using a complete membrane integrated scheme. The plant has been fully operational since the end of 2008 and supplies 20,000 m³/day of drinking water to the city of Limassol and surroundings (Cyprus). This study complements the previously published data from the first 1 ½ years of operation of the system [2] and provides extended performance data of 10 recent months.

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The other system studied in this publication is a containerized integrated membrane system installed in a refinery in Taranto (Italy). The plant produces 8,000 m$^3$/day of SWRO permeate which is sent to a second pass of RO in order to produce boiler feed water. A first part of the system of 4,800 m$^3$/day was started up mid 2009 and the second phase producing 3,200 m$^3$/day of SWRO permeate was started-up in October 2010.

In this publication, the main characteristics of the core pretreatment and RO units will be described together with the operational experiences since the start up.

II. ULTRAFILTRATION SELECTION DRIVERS

The key drivers that have been quoted frequently include the greater capability to cope with fluctuations and high solid loads in raw waters, smaller footprint, higher environmental sustainability, lower SWRO stage cost both from design as well as from the operation side. Additionally, some authors also highlight that membrane filtration technology could be break even or even be the lower unit operation cost compared to conventional pretreatment schemes, especially the more extensive ones. Easier design and operation has also been also mentioned as drivers. An extensive analysis of the market needs and Ultrafiltration adoption drivers has been done by Busch et al. [1].

This chapter describes some of the commonly reported drivers for adopting membrane pretreatment techniques and among them special emphasis is be given to the benefits that the membrane pretreatment technology offers to the desalination industry to respond efficiently to temporary and/or emergency fresh water needs, e.g. installing containerized and mobile units with compact and modular membrane pretreatment schemes.

2.1 Greater capability to cope with difficult waters – Primary pretreatment sage design

Ultrafiltration has a greater capability to cope with high solid loads in raw waters while maintaining a good filtrate quality constant despite of feed water quality fluctuations. Difficult waters often have required a very extensive pretreatment chain, consisting of coagulation, flocculation, clarification and media filtration in often multiple stages, in order to provide acceptable water quality to the RO stage. It has been mentioned and demonstrated repeatedly that ultrafiltration could achieve acceptable water quality without the use of extensive pretreatment [1].

2.2 Potential low environmental impact

Higher chemical doses and sludge quantities resulting from larger required coagulant doses in conventional pretreatment systems sometimes cannot be tolerated environmentally. This trend is apparent in some Australia and California projects.

Usually it is mentioned that ultrafiltration pretreatment can provide reductions in chemical consumption (mainly coagulant, acid and polymer). The key argument is that coagulation (which in conventional systems is using at a level of typically at least about 1 up to various mg/L of Fe) can be reduced or possibly eliminated altogether by the use of ultrafiltration. 40% of the pilot studies eliminate the use of coagulant. In most conventional systems with coagulation, significant acid dosing (range of 20-30 mg/L of HCl or H2SO4) is used to bring the pH to the optimum coagulation pH of approximately 7. In some systems, also polymers are used to enhance the flocs before media filtration – this chemical could also be eliminated in a UF scheme.
The possibility to avoid coagulation results in a direct, and significant, reduction of sludge mass created (in terms of TSS), by a factor in the range of 2 or larger (depending on raw water TSS as well as coagulant dose). In certain regions, sludge cannot be injected to the brine for discharge to the sea. Sludge needs to be concentrated, and then disposed of separately [3,4]. Both the sludge treatment as well as the disposal can represent significant cost items in plants that are forced to use this approach [4]. The reduction of sludge would be a significant cost saving enabled by membrane filtration.

2.3 Automation

Sometimes is reported that ultrafiltration systems can be provided with a higher degree of automation than a media filtration system [5]. Another argument is that in the case of UF, the operation and cleaning protocols and programming are provided from a very experienced UF technology supplier, while in the case of media filtration, both protocol and programming needs to be developed by the system integrator.

2.4 Spatial aspect – Containerized systems

UF systems usually require a smaller footprint than media filtration systems, especially where dual-stage media filters are combined with sedimentation or flotation. Site-specific conditions, building costs, and other limitations may affect footprint size.

Additionally, UF skids are smaller and more compact than conventional systems. Due to their more compact, modular characteristics and lower weight, ultrafiltration technology is the preferred choice for mobile units. There are multiple examples of mobile systems built and delivered in modular components (containers), or operated on barges which are moved to areas with highest water need. The benefits of building containerized systems is the minimization of civil works and related costs, mobility of the systems, faster system installation, etc..

The Moni sea water desalination plant is a containerized dual membrane system which was installed to provide potable water to the people of Limassol (Cyprus) for 3 years. The Moni desalination equipment can be removed to an alternate location or placed onto a barge at the end of the contract, thanks to the specially designed containers and movable plant. The Moni plant project was carried out during 2008 period when Cyprus was undergoing a severe drought. Therefore a fast action was critical to maintain the fresh water supply to the inhabitants from Limassol and surroundings. The plant was constructed and installed in less than eight months. There are no precedents in the global desalination industry for the successful completion of such a project in a few months. The unique mobility aspect of the solution as well as the speed of deployment is seen as one of the few options available to Governments facing immediate problems [6].

Taranto dual membrane system, which is described in section IV is also an example of a containerized system. An Ultrafiltration system in Madagascar to provide direct potable water using Dow™ Ultrafiltration technology also uses the containerized approach.

Examples of plants using ultrafiltration as SWRO pretreatment operated on barges can be found in United Arabic Emirates [7] and Saudi Arabia [8]. Shoaiba Barge SWRO plant is located off the shore of Saudi Arabia represents the world’s largest sea-based desalination plant producing 52,000 m$^3$/day of permeate water [8].

2.5 Lower SWRO stage cost
The vast majority of benefits have been described in the SWRO stage. The SWRO stage is the heart of the process and represents the highest complexity part and the highest capital cost part of the system. All of these potential benefits obviously build on the better UF water quality, which is expected to smoothen operation of the SWRO stage. Many authors [e.g. Henthorne 2005, Knops 2006, Knops et al 2007] have actually assumed a higher cost for the UF pretreatment (as opposed to media filters), but compensate for the higher pretreatment cost by the potential benefits, and hence cost savings in the SWRO stage. The benefits that Ultrafiltration can provide to the SWRO part could be divided into two:

- **Lower SWRO Stage Capital Cost.**
The potential for downstream capital costs reduction is a key consideration and it considers that thanks to the better quality of the RO feed provided by the UF the SWRO operation can be reliably maintained at higher flux and/or higher recovery. SWRO costs typically amount to a multiple of the pretreatment costs ranging from 3 to 10 [1]. In one of the field experiences reported in this paper (Taranto system, see section IV) the SWRO system is operating reliably at a very high recovery of around 60%.

- **Lower Cost SWRO Stage Operation.**
UF may reduce energy costs, membrane replacement costs, and SWRO cleaning costs by delivering water with a lower fouling tendency.

Recent cost estimations stated similar capital expenses related to a UF pretreatment and to a two stage conventional pretreatment and 15% lower operating expenses in the installation with UF pretreatment [4]. In all these calculations however, the positive effects of ultrafiltration pretreatment on the operation of the reverse osmosis plant, i.e., lower fouling rates, lower cleaning frequencies and longer life times are difficult to estimate and require a solid fundament based on real experiences.

2.6 Pretreatment stage economical aspects

In terms of the costs, 15 years ago the use of UF as a pretreatment for SWRO resulted not economically viable but since approximately year 2005, the cost of the UF has become more and more competitive compared to conventional pretreatment. It has been stated that the current cost of a UF is half of its cost back in 1998 [9]. Chu et al [10] have clearly dissected pretreatment and SWRO cost and shown how technology changes in UF have made UF systems cost comparable to media filtration pretreatments, even in absence of cost improvements in the SWRO section. The significant reduction of cost of UF pretreatment systems to an equivalent or possible even advantaged cost position of conventional pretreatment systems is a significant turning point for the industry which is expected to even more accelerate adoption of ultrafiltration technology.
III. FIELD EXPERIENCES: MONI DESALINATION PLANT

This chapter provides a description of the main characteristics of the Moni Desalination plant as well as a detailed evaluation of the UF and RO system performances of the 2 ¼ years of operation. This study complements the previously published data by Gasia-Bruch et al [2] from the first 1 ½ years of operation of the system and provides extended performance data of 10 recent months.

3.1. The Moni desalination plant - description

The Moni Desalination plant is located at the Moni power station outside Limassol (Cyprus). The plant uses the electricity generated from the power station and it provides fresh drinking water to the inhabitants of Limassol. The plant is owned by Subsea Infrastructure Ltd. and was constructed with Nirosoft Industries Ltd. in 8 months, which represents the fastest execution of a large scale desalination plant to date. A local company, Silnir Cyprus, was formed by Subsea Infrastructure and Nirosoft Industries Ltd to manage the operations. The contract with the Cyprus Government is for a build, operate and remove plant for three years duration. The plant is mobile and in December 2011 it can be dismantled, transported and then reassembled in a new location within a three month period. The main parts of the desalination system are containerized (UF skids, RO racks, high pressure pumps and energy recovery devices).

The Moni desalination plant uses ultrafiltration technology to pretreat sea water before feeding the reverse osmosis unit. The plant is a fully integrated membrane system that uses DOW™ Ultrafiltration as a pretreatment for DOW FILMTEC™ reverse osmosis membranes. The plant was started up in December 2008. Since then it supplies more than 20,000 m³/day of drinking water. Furthermore, the Moni plant is innovative for its low chemical consumption scheme.

The Moni desalination plant is an integrated membrane system using ultrafiltration as reverse osmosis pretreatment. Figure 4 shows a simple flow diagram of the desalination process.

Figure 2. Satellite picture of Moni desalination plant location and photograph of the plant

Figure 3. Photographs of UF and RO racks of the Moni desalination plant
The raw water source is an open seawater intake in 1,000 meters distance from the beach and 22 m depth below the sea surface. The details of the average feed water quality are presented in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Feed water quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>16 – 28</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>8.2</td>
</tr>
<tr>
<td>RO feed conductivity</td>
<td>µS/cm</td>
<td>62,000</td>
</tr>
<tr>
<td>RO feed TDS conc.</td>
<td>mg/l</td>
<td>44,100*</td>
</tr>
<tr>
<td>RO feed boron conc.</td>
<td>mg/l</td>
<td>5.2</td>
</tr>
<tr>
<td>UF feed water SDI15</td>
<td>%/min</td>
<td>2.7 - 6.2 (5.3 in average)</td>
</tr>
<tr>
<td>Turbidity</td>
<td>NTU</td>
<td>0.4 - 10 (1.8 in average)</td>
</tr>
</tbody>
</table>

The warranted RO permeate water quality is defined by a boron content below 1 mg/L and a TDS below 360 mg/l.

No coagulation is used in the feed water. The feed water passes through a set of self-cleaning filters of 500 µm screen size followed by another set of 100 µm filters. The UF unit consists of 12 racks each containing 66 x DOW™ Ultrafiltration modules, a total of 792 DOW™ Ultrafiltration modules at an operating flux of 60 L/m²h. The DOW™ Ultrafiltration module used is the 2860 module type [11], featuring 51 m² of active area. Each rack is housed in a 40-feet container. The UF filtrate water is collected in a tank which feeds the RO system. The RO system is configured as a single pass with a single stage. The system is divided into three trains; each train has one pump container and three membrane containers. The pump container houses the feed supply pump, eight isobaric energy recovery devices, the booster pump and the high pressure feed valve. The high pressure feed pump is located outside of the pump container. Each membrane container has 31 pressure vessels with 7 membranes elements each. Two types of DOW FILMTEC™ membrane elements are installed within the pressure vessels in an Internally Staged Design (ISD) configuration. Within each pressure vessel, 5 x DOW FILMTEC™ SW30HRLE-400 elements are installed in the first positions of the vessel and 2 x DOW FILMTEC™ SW30ULE-440i elements are installed in the last positions. The total number of installed membrane elements is 1,953.

Figure 4. Simple desalination process diagram used at Moni desalination plant
3.2. Dual membrane system performance

3.2.1. Ultrafiltration performance evaluation

The normalized TMP (see Figure 5) and normalized permeability (Figure 6) are plotted below. These figures show the evolution of the mentioned parameters by each individual UF rack and the UF system average values (thicker black colored line).

*Figure 5 Normalized TMP evolution for all individual UF racks and system average*
After optimization of the cleaning procedures the TMP has been well controlled (see Figure 5) and the normalized permeability has been increased (see Figure 6). The normalized TMP is 0.86 bar in average and the normalized permeability of the system is in average 74 lmh/bar.

The current normalized TMP is very close to the designed initial TMP 0.6-0.7 bar. This indicates that the current BW and CEB procedures are effective in removing the fouling and restoring the UF modules performances.

3.2.1. UF filtrate quality

The main objective of a pretreatment is to reduce suspended and colloidal solid, organic microbiological contamination, in order to reduce or eliminate fouling in the SWRO system. A detailed study of the UF filtrate quality from the Moni system has been published earlier [2]. In that study the following water analyses were performed: SDI (Silt Density Index), MFI (Modified Fouling Index), TEP (Transparent Exopolymer Particles), LC-OCD (Liquid Chromatography-Organic Carbon Detection) and F-EEM (Fluorescence Excitation Emission Matrix).

In this chapter a large pool of SDI$_{15}$ values obtained throughout the 2 ¼ years of operation have been studies. The SDI test is a means of quantifying the amount of particulate contamination in a water source for predicting the rate of colloidal and particulate fouling of Reverse Osmosis (RO) membranes. SDI$_{15}$ analyses on UF feed and RO feed (after the chemicals additions of sodium metabisulfite and antiscalant and after the pressure exchangers) streams are regularly done by the operators of the Moni plant. The UF feed water has in average an SDI$_{15}$ of 5.2 %/min (from 155 measurements), while the RO feed water presents an averaged SDI$_{15}$ of 1.1 %/min (from 183 measurements). More detailed look was done at the UF filtrate (RO feed) SDI$_{15}$ results. Figure 7 depicts the percentage of SDI$_{15}$ results distributed in various intervals. As can be seen the vast majority (84%) of the results fell in the range of 0.5 – 1.5 %/min. Additionally, it is important to mention that in the 97% of the measurements SDI$_{15}$ was below 2.
IV. FIELD EXPERIENCES: TARANTO DESALINATION PLANT

This section presents the field experience of the dual membrane system in Taranto site.

3.1. The Taranto desalination plant - description

The dual membrane system studied in this section is located in the refinery site of Eni SpA. close to Taranto city (Italy). The seawater desalination plant was constructed and it is being operated by the Italian OEM, Bernardinello Engineering SpA. The desalination plant produces demineralized water using a full integrated membrane system consisting of ultrafiltration followed by a double pass system of reverse osmosis. The product water is used to feed the boilers of the refinery. The desalination plant was constructed in a modular set-up. The Ultrafiltration and reverse osmosis trains were installed inside 40 feet containers. The use of Ultrafiltration as pretreatment helped to minimize the footprint of the plant and the use of containers to house the skids helped to minimize the costs related to civil works needed to construct the plant.

Figure 8 shows a picture of the containers housing the desalination plant pretreatment and reverse osmosis trains.

Figure 8. Photograph of the plant. Courtesy of Bernardinello Engineering SpA.

Figure 9. Photographs of UF (left) and RO (right) racks of the Taranto desalination plant. Courtesy of Bernardinello Engineering SpA.

Figure 7. SDI15 measurements in the RO feed stream

![Figure 7. SDI15 measurements in the RO feed stream](image-url)
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