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Field experience with a 20,000 m^3/d integrated membrane seawater desalination plant in Cyprus

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ABSTRACT

The desalination plant in Moni (Cyprus) is designed, built and operated by Nirosoft Industries Ltd. together with SubSea Infrastructure Ltd. The plant is a fully integrated membrane system using ultrafiltration (UF) membranes as pretreatment for sea water reverse osmosis (SWRO) membranes. The UF system consists of twelve racks with a total number of 792 DOW™ ultrafiltration modules; the SWRO system is a single pass design in three trains with 1,953 DOW FILMTEC™[1] elements. It was started up in December 2008, only nine months after signing the contract. Since then it supplies 20,000 m^3/d of potable water with less than 360 mg/l TDS and less than 1 mg/l boron to Limassol city and surroundings. This is a mobile plant, and the equipment can be removed to an alternate location or placed onto a barge at the end of the contractual period, which is the end of 2011. In order to optimize operational costs the operating conditions of the UF plant have been adjusted during the first months. The average transmembrane pressure (TMP) ranges at around 0.8 bar, and the consumption of acid, caustic and chlorine for chemical enhanced backwash (CEB) has been minimized. A cleaning-in-place (CIP) has not been required since the start-up in December 2008. The RO plant reliably achieves the required permeate flow at a recovery of 43–44% and feed pressure of 65–69 bar. Salt and boron rejection values have been better than predicted. The pressure drop has always been below 1 bar. The characteristics and the performance of the integrated membrane system, and the experiences during start-up and the first 1½ years of operation will be discussed in detail in this paper.

Keywords: Cyprus; Desalination; Case study; Integrated membrane system; Moni; Pretreatment; Seawater; Ultrafiltration

1. Introduction

One of the key characteristics of the Moni seawater reverse osmosis desalination plant is that it is a dual membrane system, i.e., ultrafiltration serves as pretreatment of reverse osmosis (RO). Traditionally, seawater desalination plants have been operated with a conventional pretreatment based on a single stage or on two stages of sand filtration preceded or not by a coagulation/flocculation process. This trend has been changing over the last years towards the use of ultrafiltration. The main reasons supporting this evolution are based on one hand on envi-

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ronmental criteria and secondly on economical benefits. Regarding the environmental aspects, several studies and field experience suggest that under certain conditions it is possible to run a seawater UF + RO installation only with a minimum pretreatment consisting of a mechanical filter and avoiding thus all the chemicals involved in a coagulation/flocculation process [1]. Moreover, the implementation of UF eliminates the environmental problems caused by the sand filter backwash streams. 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 attractive compared to conventional pretreatment. It has been stated that the current cost of a UF is half of its cost back in 1998 [3]. The significant progress in UF technology goes hand in hand with a significant increase of capacity of potable water produced by integrated ultrafiltration and seawater reverse osmosis systems, of which the capacity has increased by approximately factor 10 from 200,000 m^3/d to approximately 2,000,000 m^3/d [1,2].

According to published data in 2003 the cost of the water produced in a desalination plant equipped with a conventional pretreatment and with a capacity of 90,000 m^3/d was 51.23 UScts/m^3. The cost of the water produced by the same installation but operated with an UF pretreatment was estimated to be between 52 and 53.85 $USDcts/$m^3$ [5]. The same publication stated however that the cost of the water might decrease down to 47.23 UScts/m^3 in a relatively short period of time. More 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 [6]. 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 of real experiences. Chu et al [4] 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.

The Moni SWRO desalination plant is of special interest because it is one of the largest installations working at full capacity with UF pretreatment. In this publication, the main characteristics of the core pretreatment and RO units will be described together with the operational experiences and learnings after 18 months since the start up.

2. The Moni Seawater Reverse Osmosis desalination plant

2.1. Project background

In February 2008, Subsea Infrastructure Ltd, a marine engineering firm from the UK, and Nirosoft Industries Ltd., a desalination equipment manufacturer from Israel, signed a three year water supply contract with the Water Development Department, part of the Department of Agriculture and Natural Resources of Cyprus, for the construction of a mobile seawater reverse osmosis desalination plant at the Moni power station outside Limassol. The plant uses the electricity generated from the power station and it provides fresh drinking water to the inhabitants of Limassol. A local company, Silnir Cyprus, was formed by Subsea Infrastructure and Nirosoft Industries Ltd to manage the operations.

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 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 [7].

The Moni desalination plant is a fully membrane integrated 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 m^3/d of drinking water. Furthermore, the Moni plant is innovative for its low chemical consumption scheme.

2.2. Feed water characterization and product water requirements

The raw water is taken from an open intake. The boron content in the feed water is 5.2 mg/l. The RO feed water conductivity has been measured in average at 62,000 μS/cm and the RO feed water TDS at around 44,100 ppm (considering a conductivity/TDS factor of 1.4). The RO feed water TDS values are relatively high. This comes from a high raw water TDS combined with a partial salinity increase of the raw water due to the mixing done by the energy recovery devices.

The feed water temperature ranges from 15°C to 28°C. Sudden temperature changes of up to 5°C can happen due to local seawater currents.

The UF system is being fed with a water with an SDI_{15} of 5.3 in average (from 70 measurements). The UF feed turbidity measured ranges from 0.4–10 NTU with an average value of 1.8 NTU.

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

2.3. Plant description

The Moni desalination plant is an integrated membrane system using ultrafiltration as reverse osmosis pretreatment. The figure below show a simple flow diagram of the desalination process carried out at Moni desalination plant (Fig. 1).

The raw water source is an open seawater intake in 1,000 m distance from the beach and 22 m depth below the sea surface. The pumping station is located on the beach. An option for inline coagulation has been foreseen with the injection point just after the beach pumps. The use of coagulation is planned only in emergency cases when the fouling potential in the RO feed water is considered very high. The coagulant to be used is $Fe_2(SO_4)_3$. So far, this option of coagulant addition has never been used.

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× DOW™ ultrafiltration 2860 type modules of, a total of 792 DOW™ ultrafiltration 2860 modules for an operating flux of 60 l/m^{2}h. 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 × DOW FILMTEC™ SW30HRLE-400 elements are installed in the first positions of the vessel and 2 × DOW FILMTEC™ SW30ULE-440i elements are installed in the last positions. The total number of installed membrane elements is 1,953.

Some pictures of the Moni desalination plant are presented in Fig. 2.

3. Ultrafiltration system

3.1. DOW™ ultrafiltration

The DOW™ ultrafiltration hollow fiber membrane is formed from high grade polymeric chemicals. The uniformity of pore size and outside–in flow ensures the DOW™ ultrafiltration membrane creates the perfect barrier without sacrificing performance.

The DOW™ ultrafiltration modules are made from high strength, hollow fiber membranes that offer the following features [8]:

- 0.03 μm nominal pore diameter for removal of bacteria, viruses, and particulates including colloids.
- PVDF polymeric hollow fibers for high strength and chemical resistance
- Hydrophilic PVDF fibers for easy cleaning and wettability that help maintain long term performance
- Outside–in flow configuration for high tolerance to feed solids and the use of air scour cleaning
- U-PVC housings eliminate the need for pressure vessels and are resistant to UV light

The outside–in flow configuration is tolerant of wide ranging feed water qualities and allows air scour cleaning. The dead-end flow offers higher recovery and energy savings. The pressurized vertical shell-and-tube design eliminates the need for separate pressure vessels and allows easy removal of air from cleaning and integrity testing steps.

The hollow fiber membranes are 1.3 mm outside diameter and 0.7 mm inside diameter and are made from PVDF polymer.

The PVDF membranes are virtually defect-free and offer high chemical resistance and are tolerant to temperatures of 40ºC. The hydrophilicity and permeability of the PVDF fibers is increased by using a proprietary treatment during manufacturing. The 0.03 μm nominal pore size combines high filtration performance and high flux. The smaller pore size provides more stable long term filtration performance when compared to microfiltration [8].

DOW™ ultrafiltration 2860 is the module type used in the Moni desalination plant. It has an active area of 51 m^2. Its diameter is 8 inches (20.3 cm) and its length is 60 inches (152.4 cm) [9].

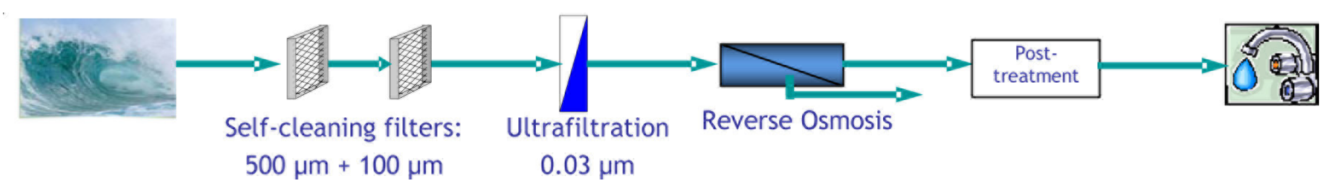

Fig. 1. Simple desalination process diagram used at Moni desalination plant.

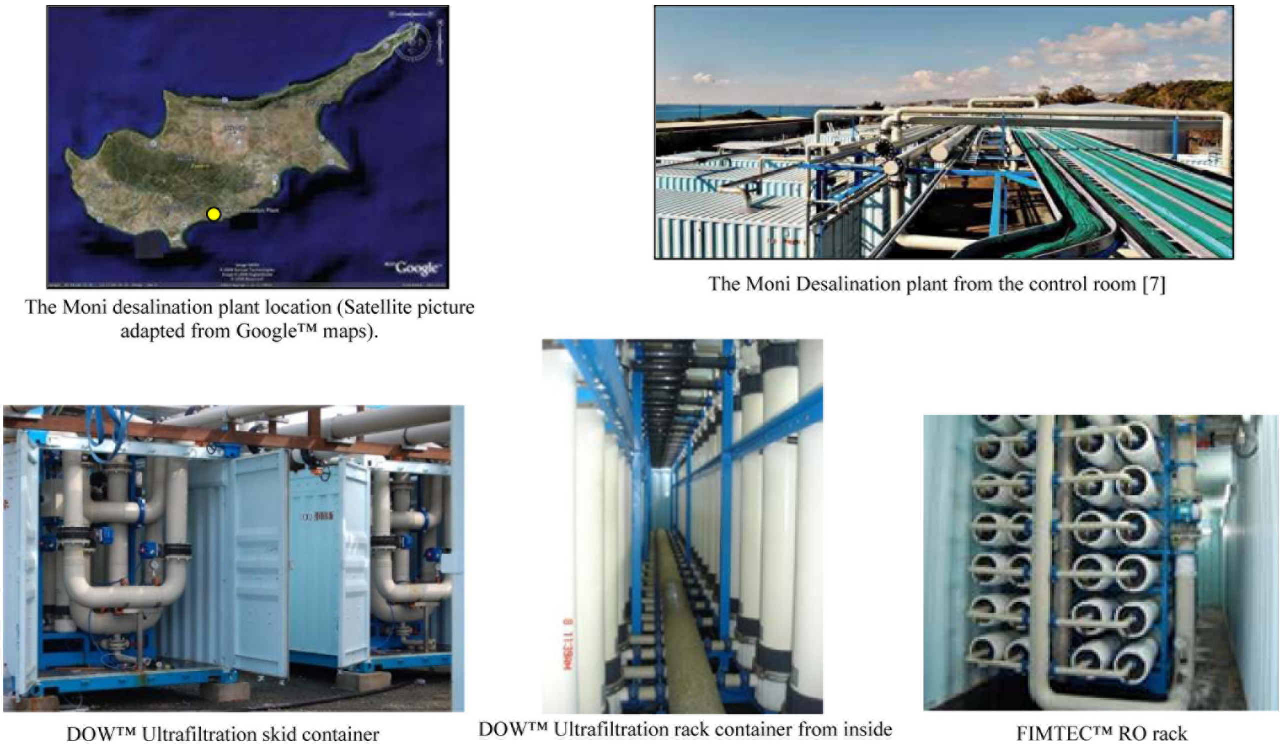

Fig. 2. Photographs of Moni desalination plant.

3.2. Ultrafiltration system operation conditions

The DOW™ ultrafiltration modules in the Moni desalination plant operate at an instantaneous flux of 60 l/h/m^2. The operating procedures of this ultrafiltration system have been optimized targeting a minimization of the chemical consumption. The system operates at very low chemical consumptions.

In terms of cleaning protocols, a differentiation can be made between the settings at the beginning of operations, and recent settings based on operational learnings and sequential optimization.

Backwash frequency is every 75 min, with a fairly long BW sequence of 5.5 min, involving 200 s of BW at 120 L/h/m^2, 80 s of air scouring and 50 s of forward flush at 60 equivalent L/h/m^2 (3.06 m^3/h/module). CEB was carried out initially every 80 h. Currently, the ultrafiltation system only requires chemical addition once every 7 days when a CEB is performed. No CIP is required.

Chemical consumption is extremely low however, the concentrations dosed cannot be disclosed in this report. Additionally, the details on the BW and CEB procedures can not be disclosed either in this report.

3.3. Ultrafiltration performance evaluation

In this chapter the UF system performance evaluation of the first 1½ years of operation is presented.

The TMP is the difference between feed pressure and filtrate pressure. The normalized trans-membrane pressure is temperature normalized at 25°C. The formula used to calculate the normalized TMP can be found in Eq. (1).

$$\begin{aligned}\text{Norm TMP} &= \text{Actual TMP} \cdot \frac{\mu\ (\text{at } T)}{\mu\ (\text{at } T_{\text{ref}})} \\ &= \text{Actual TMP} \cdot \frac{A \cdot 10^{B/(T-C)}}{A \cdot 10^{B/(Tref-C)}}\end{aligned} \quad (1)$$

The TMP (transmembrane pressure) is one of the key operational parameters to control during a UF membrane system. The TMP should always be lower than 2.1 bar to protect the UF fibers from mechanical damages. During the dead-end filtration the suspended matter is being accumulated on the outer side of the fibers and the fouling cake increases. Due to that the TMP increases with time and that is why regular backwashes are needed to remove the fouling layer and consequently reducing the TMP.

The membrane permeability is the flux (l/h/m^2) divided by the TMP (bar). The permeability represents the typical parameter showing status of the performance and the degree of fouling of the UF membranes. The permeability is also normalized by temperature (at 25°C) calculating it from the normalized permeate flow and the normalized TMP [Eq. (2)].

$$\text{Norm. permeability [l/(bar m}^2\text{h)]} = \frac{\text{Norm. permate flow [l/h]}}{\text{Total active area [m}^2\text{]} \cdot \text{Norm TMP [bar]}} \quad (2)$$

The normalized permeate flow indicates the UF filtrate flow normalized at 25°C. The formula used to normalize the permeate flow is shown in Eq. (3).

$$\text{Norm permeate flow} = \text{Actual permeate flow} \cdot \frac{\mu \text{ (at } T_{ref})}{\mu \text{ (at } T)} = \text{Actual permeate flow} \cdot \frac{A \cdot 10^{B/(Tref-C)}}{A \cdot 10^{B/(T-C)}} \quad (3)$$

where μ (T) is dynamic viscosity of water at a certain temperature [Pa s]; T_{ref} is the reference temperature which is 25°C [°C]; T is the actual temperature [°C]; $A = 2.414 \times 10^{-5}$ Pa s; B and C are empirical factors for the viscosity correlation: $B = 247.8$ K and $C = 140$ K.

The normalized TMP (Fig. 3) and normalized permeability (Fig. 4) 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).

Finding the optimum cleaning procedures and frequencies is one of the key actions that need to be done when putting a new UF system in operation. In this case a minimization of chemical consumption was target. During the first months of operation various UF cleaning protocols were tried and therefore more fluctuation of the UF performance parameters was observed (Figs. 3 and 4). Thanks to this continuous improvement focus the current low cleaning consumption scheme was achieved.

After optimization of the cleaning procedures the TMP has been well controlled (Fig. 3) and the normalized permeability has been increased (Fig. 4). The normalized TMP is 0.8 bar in average and the normalized permeability of the system is in average 83 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.

Based on the filtration and cleaning operation settings, recovery, availability, efficiency and net flux parameters have been calculated.

These parameters are defined in the below equations:

$$\text{Recovery (related to feed) [\%]} = \frac{\text{UF filtrate flow}}{\text{Average UF feed flow}} \cdot 100 \quad (4)$$

$$\text{Recovery (related to product) [\%]} = \frac{\text{UF filtrate flow}}{\text{Gross filtrate flow}} \cdot 100 \quad (5)$$

$$\text{Availability [\%]} = \frac{\text{Time in filtration mode}}{\text{Total time}} \cdot 100 \quad (6)$$

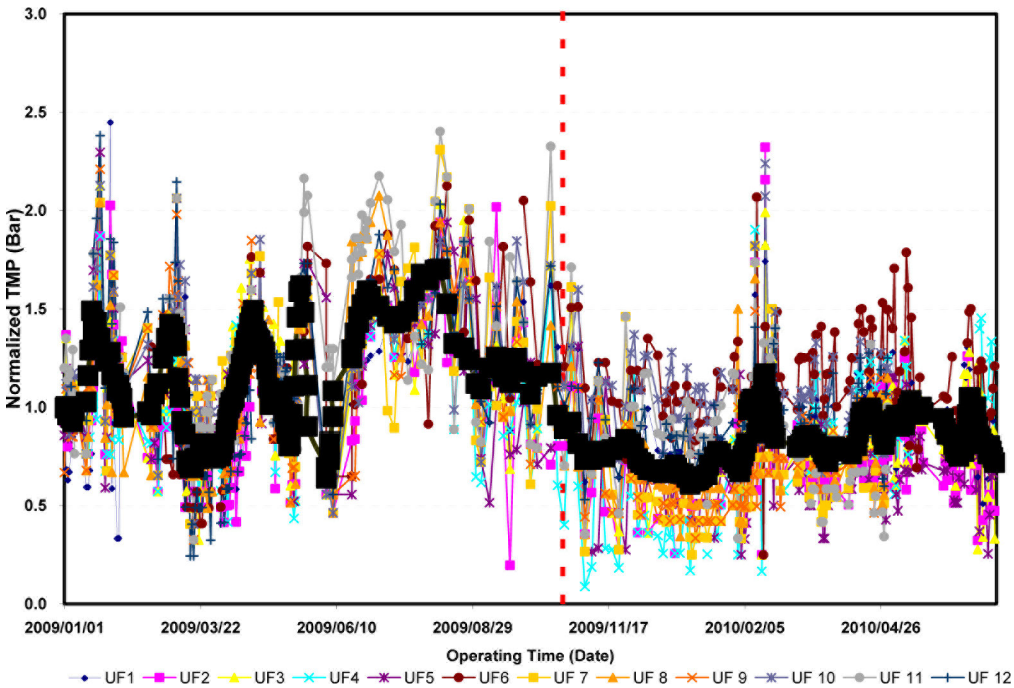

Fig. 3. Normalized TMP evolution for all individual UF racks and system average.

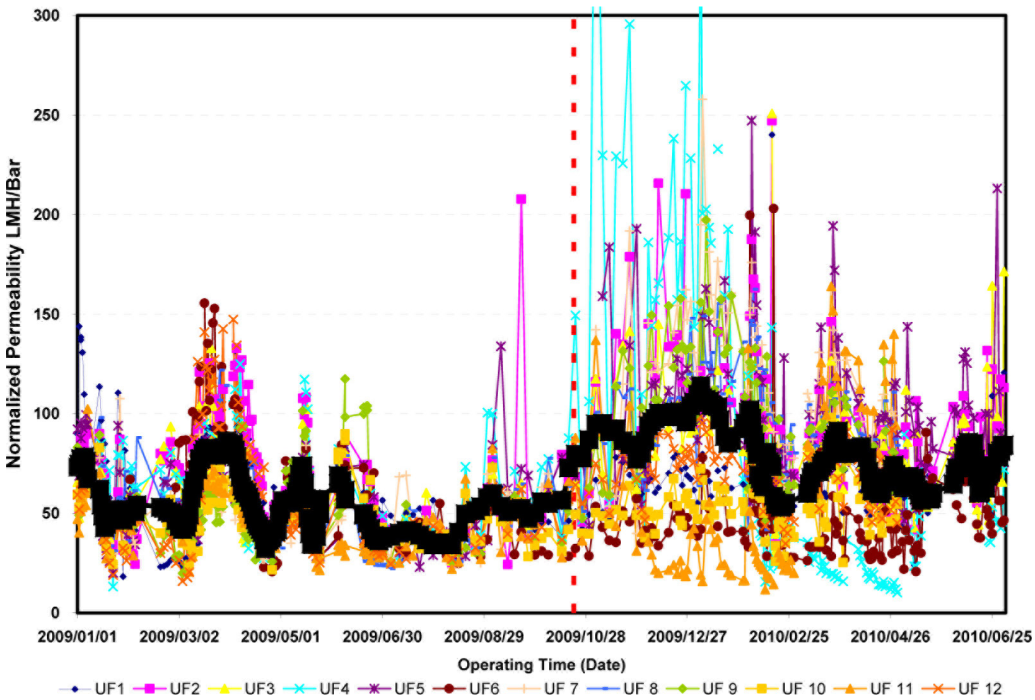

Fig. 4. Normalized permeability evolution for all individual UF racks and system average.

$$\text{Efficiency [\%]} = \frac{\text{Recovery (rel to product) [\%]} \cdot \text{Availability [\%]}}{100} = \frac{\text{Net UF filtrate flow}}{\text{Gross UF filtrate flow}} \quad (7)$$

$$\text{Net flux [l/h/m}^2\text{]} = \frac{\text{Net UF filtrate flow [l/h]}}{\text{UF active area [m}^2\text{]}} \quad (8)$$

The recovery (related to product flow) and availability of the Moni plant were calculated to be in the range of 91% and 92% respectively. This results in an overall efficiency of approximately 84% and a net flux of approximately 50.5 L/h/m².

These results are summarized in Table 1 and Fig. 5.

Only two CIP operations were carried out in the UF unit in nineteen months of operation (both in the commissioning phase, before appropriate CEB conditions had been determined), which results in negligible continuous equivalent concentrations of CIP cleaning chemicals

At punctual moments during the operation the TMP has exceeded the maximum recommended limits (2.1 bar). Nevertheless, Dow fibers have kept their integ-

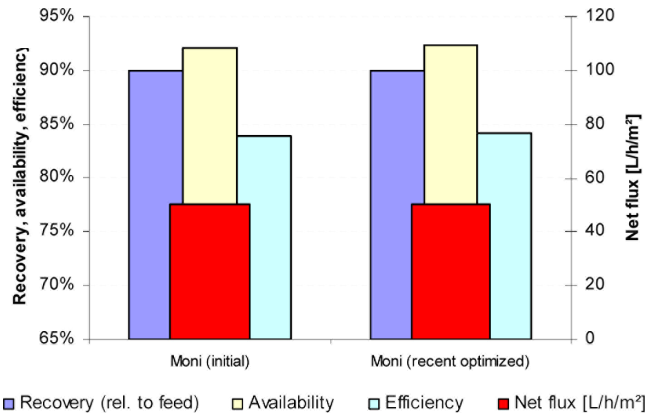

Fig. 5. Graph showing Moni UF system recovery, availability, efficiency and net flux.

Table 1
Moni UF system recovery, availability, efficiency and net flux

Location, test condition	Recovery (rel. to feed)	Recovery (rel. to product)	Availability	Efficiency	Net flux [L/h/m²]
Moni (initial)	89.9%	91.0%	92.1%	83.9%	50.3
Moni (recent)	90.0%	91.1%	92.4%	84.1%	50.5

rity as it has been proven by consistent good quality of the UF filtrate as it will be indicated in the next chapter.

3.3.1. 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 wide variety of analytical parameters, with significant difference in sophistication, resource requirements, accuracy and precision, and at different degrees of maturity is available to measure the amount of contaminants and are summarized in Table 2.

It is worthwhile to mention that no integrity loses have been found due to UF fibers breakage throughout this 1½ years of operating and thanks to this fact the good filtrate water quality could be maintained constant during all the time.

3.3.1.1. SDI

The SDI (silt density index) is the most common index to characterize the fouling tendency of an RO feedwater. The silt density index (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 measurements are regularly done by the plant operators with a manual SDI test kit on the UF feed and RO feed streams. The SDI measurements of RO feed are done on the actual water reaching the RO membranes (after the chemicals additions of sodium metabisulfite and antiscalant and after the pressure exchangers).

The UF feed water showed in average an SDI_{15} of 5.3%/min (from 70 measurements). The RO feed water showed in average an SDI_{15} of 1.2%/min (from 61 measurements).

Fig. 6 shows the distribution of the observations in different SDI_{15} value ranges. It can be observed that the great majority of observations fall in the range of 1.0–1.5%/min. Additionally, it can be said that in the 93% of the observations the SDI_{15} was below 2.

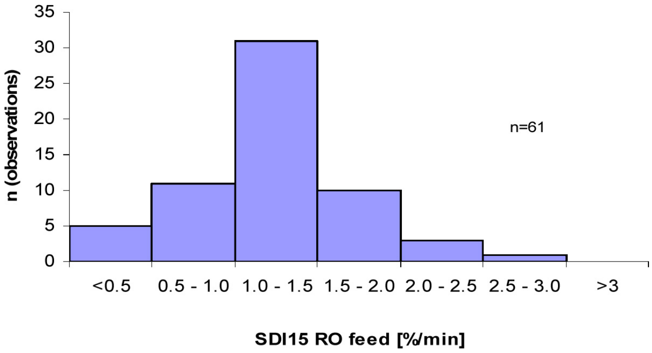

Fig. 6. Standard SDI measurements in the RO feed stream.

3.3.1.2. MFI

The modified fouling index (MFI) is, like the SDI, and index to characterize the fouling tendency on RO membranes due to particulate and colloidal contamination in a feed water. This method was developed to overcome the limitations of the SDI method by Schippers and Verdow [10]. MFI is proportional to the concentration of suspended matter and is a more accurate index than the SDI for predicting the tendency of a water to foul RO/NF membranes.

Various MFI measurements with a 0.45 µm filter ($MFI_{0.45}$) have been also done. The values obtained range between 0.5–1 s/L^2.

3.3.1.3. TEP

Additionally, the UF permeate was sampled for measuring transparent exopolymer particles (TEPs).

TEPs are a form of EPS (extracellular polymeric substance), abundant in fresh and marine waters and characterized as transparent, sticky and gel-like particles comprised mainly of acid polysaccvharides. TEPs are regarded by some experts as the major initiator of biofilm formation in membrane systems [11].

After the initial development of a technique to determine transparent exopolymer particles in seawater [12], Villacorte et al. [13] have applied this technique to various stages in SWRO desalination plants with conventional and UF/MF pre-treatments and compared performance.

In TEP analyses two types of TEPs are characterized: particulate TEP or p-TEP (> 0.4 µm size) and colloidal TEP

Table 2
Analytical parameters for UF and RO foulants in water

	Established methods	Methods in development
Suspended and/or colloidal contamination	Turbidity (NTU), particle count, total suspended solids (TSS), silt density index (SDI)	Modified fouling index (MFI), nanoparticle analysis by laser-induced breakdown (NPA-LIBD)
Organic and/or microbiological contamination	total organic carbon (TOC), chemical and oxygen demand (BOD, COD), specific UV absorption (SUVA) Total bacteria count (TBC), algae count (AC)	Liquid chromatography with organic carbon and nitrogen detection (LC-OCND) Fluorescence excitation emission matrix (F-EEM)

Table 3
TEP analysis results

Sample	TEP [abs/L]	TEP [abs/L]
50–100 nm	21.4	59%
100–200 nm	7.5	21%
20–400 nm	4.2	12%
>400 nm	3.2	9%
Total	36.3	100%

Sample	c-TEP (50–400 nm) [abs/L]	p-TEP (>400 nm) [abs/L]	t-TEP [abs/L]
UF feed	33.2	3.2	36.4
UF permeate	12.4	1.7	14.1
RO permeate	0	0	0
Removal UF (%)	63%	47%	61%

or c-TEP (0.05–0.4 μm size). Most of TEPs have comparable sizes to UF and MF membrane pore size. Therefore, tighter UF membranes might offer better TEP removal compared to MF or looser UF membranes.

TEP analyses of the raw water, the UF filtrate and RO permeate from Moni are shown in Table 3.

63% of colloidal TEP removal was measured in the analyses. The 47% removal rate observed for p-TEP seems to be low. This is probably due to being close to the limit of quantification of the analytical method. As can also be seen in the above results, 61% of total TEP (t-TEP) removal was quantified during the water analysis.

3.3.1.4. LC-OCD

LC-OCD (liquid chromatography–organic carbon detection) [15] is a technique that combines the universality of summarizing parameters with the specificity of compound identification. The chromatographic technique used is size exclusion chromatography (SEC). It enables segregating and quantifying polysaccharides, humic substances, building blocks, low molecular weight acids and low molecular weight neutrals, and thus establishing a specific fingerprint for each type of water. Salinas et al. [14] describe the application of this method to seawater desalination applications.

The Moni plant was sampled in April 2009 and results from UF feed and UF permeate streams from train 1 are shown in Table 4.

The DOC levels found are low which is relatively normal for SW samples. Very little removal of DOC is observed from the analyses results presented in Table 4. This is inline with the literature, where values up to 15% are reported. The low removal rates of the substances reported in Table 4 can be explained by the relatively low molecular weight of these substances (500–1000 g/mol) and by their sizes which are much smaller than the por size of the ultrafiltration membrane (30 nm).

The LC-OCD analysis also suggested the following (not shown in Table 4):

- Specific UV absorption (SUVA) level was in the range of 0.5 – 0.6 L/(mg.m), hence below 2, which suggests that this water is not dominated by humic substances, which is inline with the low humic content.
- Molecular weight of the humic fraction apparently is in the range of 400 g/mol
- Acids with <350 g/mol were not detected
- The dissolved organic nitrogen content in the biopolymer fraction is in the range of 4–6%

Fig. 7 represents humic substances concentration versus molecular weight. This figure also shows that the UF feed water and UF permeate water samples showed that the organic matter contained had very low humification: low molecular weight and low aromaticity.

3.3.1.5. F-EEM

Fluorescence excitation emission matrix (F-EEM) measurements were also performed on some water samples taken from UF feed and UF permeate streams. Salinas et al. [14] describe the application of this method to seawater desalination applications.

The fluorescence intensities are presented in Table 5.

The EEM spectra for the samples are presented in Fig. 8.

Table 4
LC-OCD analyses from Moni, April 2009

Sample	DOC [mg/L]	Bio-polymers [mg/L]	Humic substances [mg/L]	Building blocks [mg/L]	Neutrals [mg/L]
UF feed	0.81	0.07	0.36	0.157	0.218
UF1 permeate	0.73	0.07	0.36	0.157	0.145
Removal UF (%)	10%	0%	0%	0%	34%

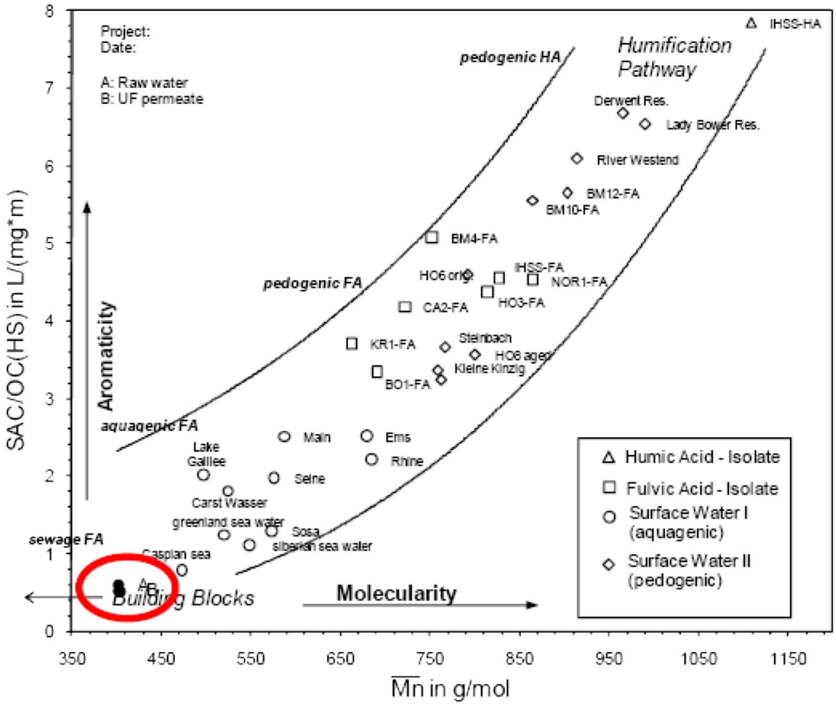

Fig. 7. Humic substances cocnentration vs. molecular weight (figure facilitated by UNESCO IHE).

Table 5
Fluorescence intensities in Raman units (R.U.) — Moni sampling April 2009

Sample	Humic like primary (Ex330–350, Em 420–480)	Humic like secondary (Ex250–260, Em 380–480)	Marine humic like	Protein like tyrosine (Ex270–280, Em 300–320)	Protein like tryptophan (Ex270–280, Em 320–350)
UF feed	0.239	0.449	0.297	0.476	0.423
UF1 permeate	0.145	0.314	0.123	0.164	0.262
Removal UF (%)	39%	30%	59%	66%	38%

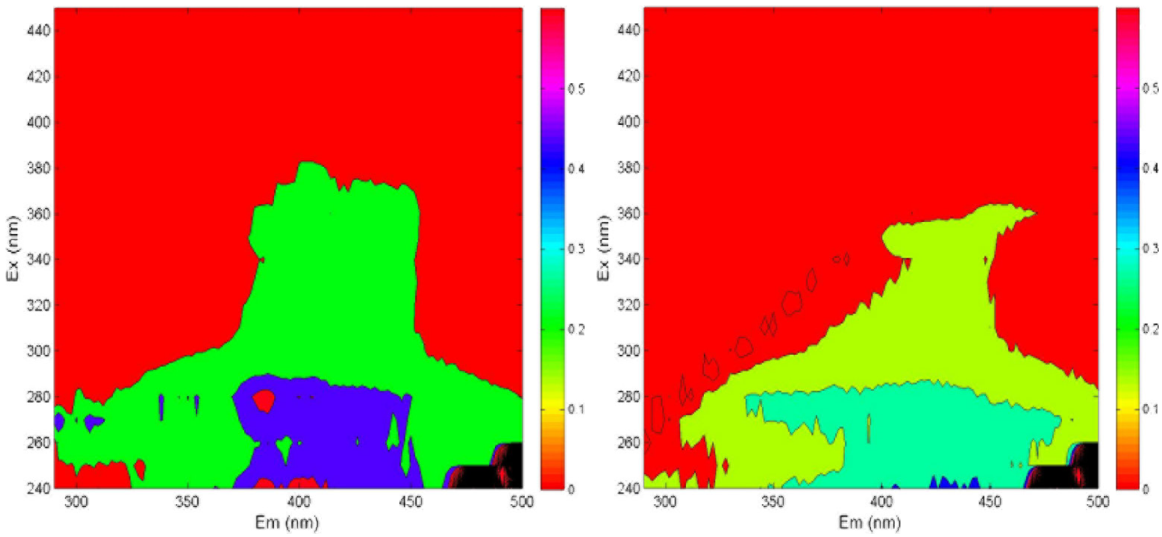

Fig. 8. FEEM, Moni, Apr-2009 (raw water left, UF permeate right).

As described in the pervious chapter, SUVA level of the humic fraction was in the range of 0.5–0.7 L/(mg.m), with a molecular weight of about 400 g/mol. A highly humidified water would amount to 4 3–7 L/(mg.m) and humic molecular weight of 800–1100 g/mol. This suggests that this water is not dominated by humic substances, which is inline with the low humic content. The fact that these waters are generally low in organic content and that the humic fraction is low and even the humic fraction is only very moderately humic suggests that the F-EEM results focusing on the humic fraction are possibly of limited relevance.

4. Reverse osmosis system

Advances in reverse osmosis membranes are ultimately linked to improved permeate quality and decreased feed pressure requirements. Both requirements are obviously conditioned to a stable and reliable long term performance. In the Moni SWRO desalination plant membrane types SW30HRLE and SW30ULE are combined in an ISD (internally staged design) configuration in order to attain the optimum hydraulic conditions inside the pressure vessels.

Early descriptions of the ISD design were presented in 2005 by Mickols et al. [16] and Busch et al. [17] and later by Garcia Molina et al. [19,20]. The ISD design is a combination of membranes with lower permeate flow performance in the front positions of the vessel and of membranes with higher permeate flow performance in the rear positions of the vessel. By following this criterion, fouling is minimized, feed pressure is reduced and longer membrane life can be expected [18–20].

DOW FILMTEC™ SW30HRLE membranes have been in the market since 2005, and their reliability together with good performance has been already demonstrated in many large installations. The key example is Ashkelon, where these membranes have been in successful operation for more than 5 years [21]. DOW FILMTEC™ SW30ULE membranes were introduced into the market in 2008 after a validation and piloting period longer than two years [20]. In 2009 and after more than 6 months of validated pilot trials in a Seawater Desalination plant in the Mediterranean coast, Dow launched the 440 ft^2 DOW FILMTEC™ seawater elements, which are already in operation in many installations such as Moni. The increased and guaranteed active membrane area of 440 ft^2 results in a permeate flow under standard test conditions of 8,200 gpd in DOW FILMTEC™ SW30HRLE-440i elements and of 12,000 gpd in DOW FILMTEC™ SW30ULE-440i elements.

4.1. Reverse osmosis performance evaluation

In this chapter the RO system performance evaluation of the first 1½ years of operation is presented.

The RO system is operated at a recovery of 43–44% at an average system flux of 11.5 lmh. A relatively low average system flux was selected in order minimize the energy consumption. During the evaluated 1½ years of operation the Moni desalination plant has reliably achieved the nominal plant capacity. The RO feed pressure ranged from 65 to 69 bar depending on the feed water temperature and feed water salinity increase due to energy recovery system. The RO performance has been evaluated using FTNORM tool. FTNORM is a Microsoft®

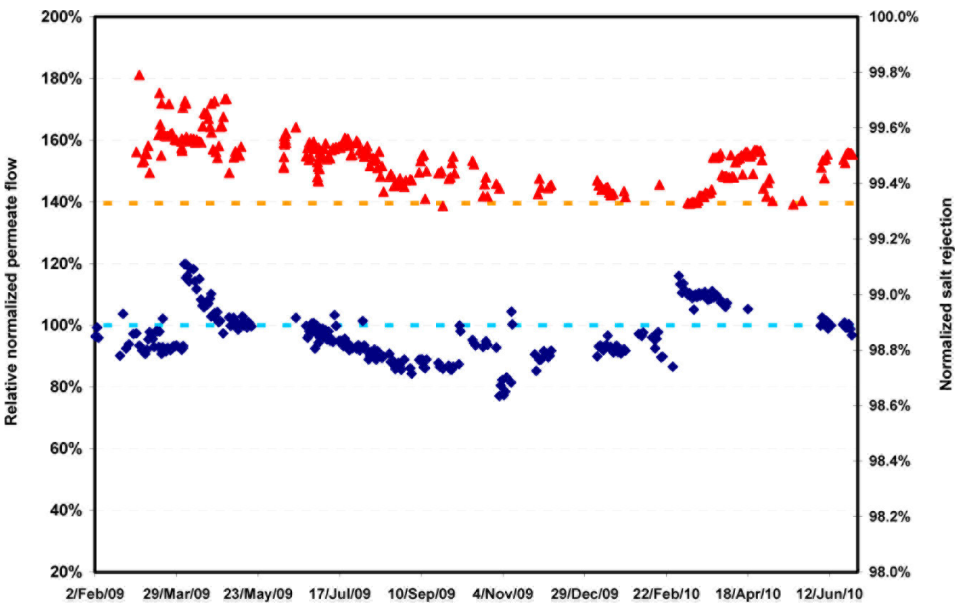

Fig. 9. Relative normalized permeate flow (blue diamonds) and normalized salt rejection (red triangles) of the RO system.

Excel® spreadsheet that allows keeping track of the RO plant performance at normalized conditions.

In Fig. 9 the relative normalized permeate flow compared to the design productivity of the plant (20,000 m^3/d) is shown together with the normalized salt rejection throughout the operating time. The flow performance of the system fluctuated around the design point, and the salt rejection was better than designed.

The pressure drop (ΔP) has been lower than the reference value throughout the first 1 ½ years of operation. A ΔP of 1.46 bar is the reference value obtained from a projection at start-up conditions using ROSA (reverse osmosis system analysis) design software. This value assumes 0.35 bar pressure drop in the piping from the high pressure pump outlet to the first RO membrane element.

The normalized pressure drop (ΔP) has been in average 0.91 bar, which represents a lower value than projected. The normalized pressure drop has been stable at the low level throughout this first 1½ years of operation. This is an indication of absence of particulate or biofouling on the RO membranes. This fact could be mainly attributed to the good filtration done during the pretreatment by means of the ultrafiltration membranes.

RO permeate quality has also been evaluated during the period studied. The RO permeate conductivity measurements show a median value of 350 µS/cm, a 25th percentile of 260 µS/cm and a 75th percentile of 462 µS/cm.

The discontinuous horizontal line in red color shown in Fig. 9 is the reference salt rejection level from the design (99.33%). From the graph below it can be observed that the salt rejection has been consistently higher than designed.

With regards to boron rejection, the boron concentration measurements in the permeate stream show a median value of 0.6 mg/l, a 25th percentile of 0.5 mg/l and a 75th percentile of 0.7 mg/l. Boron concentration has been always lower than 1 mg/l as required. The observed permeate TDS and boron concentrations have been calculated to around 15% and 10% lower than designed, respectively.

5. Summary and conclusions

The Moni seawater desalination plant is an integrated membrane system using DOW™ ultrafiltration as a pretreatment for DOW FILMTEC™ reverse osmosis membranes. Since December 2008 the plant continuously and reliably supplies 20,000 m^3/d of drinking water for the population of Limassol (Cyprus).

The plant is a mobile system where the various units are containerized. This mobility aspect of the system is regarded as one of the few options when an immediate solution against water scarcity is needed. The Moni desalination plant was successfully constructed by Subsea Infrastructure and Nirosoft Industries Ltd. constructed in less than eight months, which represents the world fastest construction of a desalination plant of this size.

The DOW™ UF modules in the Moni desalination plant operate at a flux of 55–65 l/h/m^2 with a BW frequency of 75 min. The ultrafiltration system shows a low environmental impact due to the very low chemical usage. The ultrafiltation system only requires chemical addition once every 7 days when a CEB is performed. Most remarkably no CIP was required since the start up in December 2008. After the CEB procedure has been improved the normalized TMP is controlled well around 0.8 bar. The normalized average permeability of the system is 83 lmh/bar.

Within the 1½ years between start up and the submission of this paper the UF filtrate has been constantly of good quality despite of variations in the UF feed water quality. No single loss of fiber integrity has been detected. The UF filtrate shows an average SDI_{15} of 1.2%/min and a TEP removal of 61%.

The RO system was constantly operated at a recovery of 43–44% and at a system flux of 11.5 l/m^2/h. The RO permeate TDS and boron concentrations have been calculated to be around 15% and 10% lower than designed, respectively.

Throughout this first 1½ years of operation the normalized ΔP has been at 0.91 bar, which is lower than projected. The normalized pressure drop has been stable at a low level throughout the reported time of operation. This is an indication of absence of particulate or bio-fouling on the RO membranes. This fact could be mainly attributed to the good filtration done during the pretreatment by means of the ultrafiltration membranes.

Abbreviations

BW	—	Backwash
CEB	—	Chemical enhanced backwash
CIP	—	Cleaning in place
DOC	—	Dissolved organic carbon
EPS	—	Extracellular polymeric substance
F-EEM	—	Fluorescence excitation emission matrix
ISD	—	Internally staged design
LC-OCD	—	Liquid chromatography with organic carbon detection
MFI	—	Modified fouling index
NTU	—	Nephelometric turbidity units
PVC	—	Polyvinyl chloride
PVDF	—	Polyvinylidene fluoride
RO	—	Reverse osmosis
SDI	—	Silt density index
SEC	—	Size exclusion chromatography
SUVA	—	Specific ultraviolet absorption
SWRO	—	Sea water reverse osmosis
TDS	—	Total dissolved solids
TEP	—	Transparent exopolymer
TMP	—	Transmembrane pressure
UF	—	Ultrafiltration
UV	—	Ultraviolate

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