Environmental Engineering Research

Environ. Eng. Res. 2011 December,16(4) : 205-212

Review Paper

http://dx.doi.org/10.4491/eer.2011.16.4.205
pISSN 1226-1025 eISSN 2005-968X

Pretreatment in Reverse Osmosis Seawater Desalination: A Short Review

Ramesh Valavala[1], **Jinsik Sohn**[2†], **Jihee Han**[2], **Namguk Her**[3], **Yeomin Yoon**[1]

[1]*Department of Civil and Environmental Engineering, University of South Carolina, Columbia, SC 29208, USA*
[2]*Department of Civil and Environmental Engineering, Kookmin University, Seoul 136-702, Korea*
[3]*Department of Chemistry and Environmental Sciences, Korea Army Academy at Young-Cheon, Young-cheon 770-849, Korea*

Abstract

Reverse osmosis (RO) technology has developed over the past 40 years to control a 44% market share in the world desalting production capacity and an 80% share in the total number of desalination plants installed worldwide. The application of conventional and low-pressure membrane pretreatment processes to seawater RO (SWRO) desalination has undergone accelerated development over the past decade. Reliable pretreatment techniques are required for the successful operation of SWRO processes, since a major issue is membrane fouling associated with particulate matter/colloids, organic/inorganic compounds, and biological growth. While conventional pretreatment processes such as coagulation and granular media filtration have been widely used for SWRO, there has been an increased tendency toward the use of ultrafiltration/microfiltration (UF/MF) instead of conventional treatment techniques. The literature shows that both the conventional and the UF/MF membrane pretreatment processes have different advantages and disadvantages. This review suggests that, depending on the feed water quality conditions, the suitable integration of multiple pretreatment processes may be considered valid since this would utilize the benefits of each separate pretreatment.

Keywords: Coagulation, Desalination, Low-pressure membrane, Pretreatment, Reverse osmosis

1. Introduction

While water scarcity occurs frequently in arid regions, pollution and the use of groundwater aquifers and surface water have also led to a reduction in the quantity and/or quality of available natural water resources in many countries. Over 1 billion people are without clean drinking water, and approximately 2.3 billion people (40% of the world population) live in regions with water shortages [1]. However, the ongoing growth of population, industry, and agriculture is further increasing the demand for water. In addition, higher living standards, especially in industrial countries, have resulted in higher per capita water consumption and in intensified water scarcity. Exploitation of natural fresh water resources combined with higher water demand has led to an increased demand for alternative fresh water resources. Both desalination and water reuse have been successfully incorporated to provide additional fresh water production for communities using conventional water treatment and fresh water resources [2, 3]. Throughout the world, a trend towards the intensified use of desalination as a means to reduce current or future water scarcity can be observed. Seawater desalination provides such an alternative source, offering water otherwise not accessible for irrigational, industrial, and municipal use [4]. Desalination has become an important source of drinking water production, with thermal desalination and membrane processes being developed over the past 60 and 40 years, respectively [5]. In thermal desalination, salt is separated from water by evaporation and condensation, whereas in membrane desalination, water diffuses through a membrane, while salts are almost completely retained [6]. The decision for using a specific desalination technique is influenced by the feed water salinity, required product quality, and site-specific factors such as labor cost, available area, energy cost, and local demand for electricity.

A great share of the world's desalination capacity is installed in the Middle East, and although reverse osmosis (RO) is rapidly gaining the market share, thermal processes still dominate this market due to the low cost of fossil-fuel-based energy in this region and their suitability for combining with the generation of electric energy (cogeneration of steam and electricity). RO technology has been developed over the past 40 years to control a 44% market share in the world desalting production capacity and an 80% share in the total number of desalination plants installed worldwide [7]. The use of RO has increased in seawater desalination over the last decade, since materials have improved and costs have decreased. Because RO membranes effectively reject monovalent ions such as NaCl, seawater RO membranes

---

This is an Open Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (http://creativecommons.org/licenses/by-nc/3.0/) which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

Received December 30, 2010 **Accepted** November 23, 2011

†Corresponding Author
E-mail: jinsiksohn@kookmin.ac.kr
Tel: +82-2-910-4528 Fax: +82-2-910-8597

©Copyright The Korean Society of Environmental Engineers

have very high salt rejections (>99%) [8, 9]. Some membranes have shown extremely high salt removal rates of as high as 99.7–99.8% when operated under standard test conditions (32,000 mg/L NaCl, pH 8, 5.5 MPa, and 8% recovery) [10].

Several limitations remain in the use of an RO membrane in seawater RO (SWRO) treatment. One of the major problems for SWRO is membrane fouling associated with particulate matter/colloids, organic/inorganic compounds, and biological growth. Suspended and colloidal particles foul a membrane by coagulating together and forming a cake-like layer on the membrane surface, while dissolved organics interact directly with the membrane surface and with each other to cause fouling [11]. Colloidal particles are often composed of clay, organics, and metal inorganics, such as aluminum and iron silicates. Although calcium carbonate precipitation in SWRO is another concern, the lower SWRO recoveries (limited by osmotic pressure) prevent any precipitation problems. As a result, precipitation is unlikely to occur in SWRO applications [12]. Biological fouling associated with bacteria, fungus, or algae occurs when microbial cells accumulate and attach to the surfaces of a membrane and promote growth as a biofilm [13, 14]. As membrane fouling occurs, basic membrane functions deteriorate, including salt passage through the membrane, permeate flow, and pressure drop across the membrane. Inorganic scaling caused by exceeding the solubility of soluble salts is considered relatively less problematic since this can be controlled by pH and adding antiscalant [15]. In addition, chemical cleaning using acid and/or base is often used for RO membrane fouling [16].

It is necessary to pretreat feed water in SWRO to lower undesirable fouling materials, since poor feed water quality leads to a short RO membrane lifetime, short operation period, and high maintenance. Pretreatment can alter the physicochemical and/or biological properties of feed water and improve the performance of SWRO. Various conventional and advanced pretreatment methods have been used in SWRO desalination. In general, conventional pretreatment includes coagulation/flocculation, pH adjustment, scale inhibition, and media filtration. However, a new pretreatment trend has focused on the use of large pore size membranes, including microfiltration (MF) and ultrafiltration (UF), to pretreat SWRO feed water. At present, a very significant trend includes the use of membrane-based pretreatment to improve the performance in SWRO [4, 17-25]. The objective of this paper is to review the major pretreatment processes that have been used in SWRO and to review case studies on low-pressure membrane pretreatment (UF/MF).

2. Pretreatment for SWRO Desalination

Seawater resources typically have a higher tendency for membrane fouling and require more extensive pretreatment processes than surface water and groundwater resources [7]. Therefore, a main factor for the successful operation of SWRO is maintaining a constant high feed water quality.

2.1. Conventional Pretreatment

Thus far, coagulation is the most popular treatment process used for the removal of potential foulants such as aqueous particulate and colloidal matter. The role of coagulation is to combine small particles into larger aggregates/flocs (i.e., large groups of loosely bound suspended particles) by neutralizing the charges of the particles [26]. Inorganic coagulants, including iron salts, are commonly used in the SWRO desalination plant in Madinat Yanbu Al-Sinaiyah, Yanbu Industrial City, Saudi Arabia; the plant has a capacity of 13.3 million gallons per day (MGD) [27]. In the case of this plant, in order to reduce the amount of suspended solids and colloids in the feed water, inline coagulation and flocculation using ferric chloride and organic polyelectrolyte are employed for pretreatment. For pretreatment in water, Al and Fe salts are probably the most commonly used coagulants; they first react with water to form a series of cationic hydrolytic species and weakly charged or uncharged precipitates [28]. However, for SWRO, aluminum is not as frequently used as a pretreatment coagulant prior to membrane filtration due to potential damage to the membrane system. Typically, a wide range of inorganic coagulants (5–30 mg/L) is used, while a significantly smaller dose is required for a polymer coagulant (0.2–1 mg/L) [29].

When the feed seawater quality becomes relatively less poor and does not require the full process of flocculation and sedimentation, inline coagulation can be used prior to media filtration. In this process, the coagulated water is directly introduced to the membrane filtration system. Inline coagulation that changes the surface chemistry of the suspended particles enhances their attachment to the media filter. Inline coagulation in the absence of flocculation/sedimentation can reduce the footprint of the entire membrane filtration facility [30]. In a full-scale SWRO plant, flocculants (ferric chloride sulfate) are added to the untreated water at the inlet to the destabilization tank [21]. In the study, an acid dosing system was used to prevent carbonate scaling, a polyelectrolyte dosing system and three in-line coagulation filters with ferric chloride sulfate were used to further reduce the silt density index (SDI) of the feed to less than 3.0, sodium hydrogen sulfite dosing was used to remove residual chlorine, and three cartridge filters were used to remove particles larger than 5 μm. Although the pretreatment with coagulation significantly enhances the removal of colloidal and particulate matters, a previous study showed that coagulant residuals from the pretreatment process may negatively affect RO membrane performance when either aluminum/iron salts or chloramines are used [31]. In that study, both the specific flux (up to 60%) and salt rejection were significantly reduced when alum was used with multiple RO element testing for over 100 hr of operation.

SWRO membranes can be subject to salt precipitation and membrane scaling. Precipitation has been widely investigated in the RO process between two bench-scale brackish water RO units that increased the water recovery from the typical 90-98% overall [32, 33]. The precipitation process consisted of using either calcium carbonate (calcite) or calcium sulfate seeding, along with pH control, to remove slightly soluble salts. While gypsum seeding achieved a calcium removal of only 30%, calcite seeding achieved 92–93% calcium removal within 30 min [33]. In SWRO treatment, one of the most challenging issues is to remove boron. Boron has adverse reproductive and development effects and causes plant and crop damage [34]; it is difficult to remove by RO membranes, since it naturally exists as a non-ionic species due to a relatively high pKa (pKa = 9.2 for fresh water and 8.5 for seawater) in seawater within the concentration range of 4.5–6.0 mg/L [12, 35]. Boron rejection can be increased by increasing the feed water pH. However, increasing the pH can cause salt precipitation and subsequent membrane scaling (i.e., deposition of salt precipitates on the RO membrane). Therefore, multiple RO stages are often required to enhance boron removal at different pH conditions, where the first stage (at lower pH) achieves salt removal and the second stage (at higher pH) achieves boron removal [36-39]. pH adjustment can effectively control calcium carbonate scaling, while scale inhibitors using antiscalants have been used to control various carbonate, magnesium hydroxide, sulfate, and calcium scaling [20].

Conventional packed-bed filters using granular media such as sand, anthracite, pumice, gravel, and garnet with different effective sizes are beneficial in terms of regeneration, since hydraulic backwashing has proven to be effective in conventional water treatment in restoring capacity [18, 40, 41]. For constant physicochemical conditions, the granular media filtration process is effective at removing particles significantly larger than a few micrometers or smaller than 0.1 μm [42]. As water passes through the filter bed, the suspended particles contact and adsorb onto the surface of the individual media grains or onto previously deposited material [20]. To achieve a high treated water quality, the surface charge, size, and geometry of both suspended particles and filter media are major parameters. The U.S. Army Water Desalination Technical Manual suggests effective grain sizes of 0.35–0.5 and 0.7–0.8 mm for fine sand and anthracite filters, respectively [43]. The turbidity of media filtrate is often around 0.1 NTU [2, 18]. The media filtration SDI can be sensitive to feed water changes containing algal blooms and oil contamination. In particular, oil contamination is a difficult problem and is most often removed using dissolved air flotation (DAF) during membrane pretreatment [44]. In addition to oils, DAF is a commonly utilized process for removing a number of pollutants, including colloids, fine and ultra-fine particles, precipitates, ions, microorganisms, and proteins [45]. In this study, compared to the typical sedimentation process, DAF allows light particles that settle slowly to be removed more effectively and in a shorter time; it also usually produces a low generation of sludge from the system. The RO feed water was maintained to be less than 0.25 NTU and had an SDI of less than 1.5 on average with the coagulation (ferric chloride) and DAF pretreatment processes raw seawater quality is characterized by a high conductivity level (37,900–52,000 μS/cm), total dissolved solids (TDS) in the range of approximately 25,000–50,000 mg/L, pH 8–8.5, and turbidity in the range of 5–20 NTU [18].

2.2. Membrane Pretreatment

As previously described, the conventional pretreatment process has been widely used for SWRO. However, since it needs to be carefully designed and diligently operated, there has been an increased tendency toward using UF/MF instead of the conventional treatment to provide SDI values well below 2, which thus enables an SWRO plant to perform at its original design capacity with reduced downtime [46]. Frequently, colloids and suspended particles that pass through conventional pretreatment contribute to difficult-to-remove (and possibly irreversible) RO membrane fouling [8]. Therefore, the use of larger pore size membranes such as UF and MF has gradually gained acceptance in recent years as the preferred pretreatment for SWRO [47]. Pilot and/or full-scale plants have been operated in many parts of the world to examine the capacity and reliability of UF/MF pretreatment systems in preparing compatible feed water for the SWRO membrane [8, 19, 20, 22]. In addition, successful implementation of nanofiltration (NF) pretreatment has been conducted for the RO process [48-50]. Among the NF, UF, and MF membranes, UF membranes seem to be the most common preference in research studies and pilot testing [8, 19, 25, 29, 47, 51-53] and represent perhaps the best balance between contaminant removal and permeate production of the three membrane types; UF membranes have smaller pore sizes than MF membranes and higher flux than NF membranes. However, each membrane can be selected depending on the specific contaminant removal issues, since they have different advantages. For instance, MF membranes are the appropriate choice for removal of larger particulate matter at higher permeate fluxes, whereas NF membranes are used to remove dissolved contaminants as well as particulate and colloidal material [7].

Several pilot and/or full studies using a membrane pretreatment system have been conducted with various seawater quality conditions, different low pressure membranes, and different operating conditions. Gulf seawater with high salinity and bioactivity was treated at the SWRO plant in Bahrain; the plant consisted of a prechlorination unit, sand filtration, and UF membranes (20 nm pore diameter, molecular weight cutoffs of 100,000–150,000, average flux of 70 million liters per hour, filtration time of 17–20 min, and chemical-enhanced backwash) [19]. Stable operation at a constant flux was achieved during the summer months. The Multibore membranes (Inge AG, Greifenberg, Germany) allow for a substantial reduction in chemical and energy consumption compared with existing spiral-wound UF modules. In a separate study, a field testing program was conducted at Ashdod on the Mediterranean to compare performances of RO seawater systems operating on the surface seawater using conventional pretreatment and the UF membrane technology [22]. The Mediterranean Sea has turbidity in the range of 1–10 NTU, a TDS value of 40,500 mg/L, an SDI consistently above 6.5, and suspended solids in the range of 2–14 mg/L. The SDI was reduced to 2.6–3.8 for the conventional system and 2.1–3.0 for the UF membrane system. In addition, in spite of the fluctuating seawater quality, the filtrate produced by the UF system could still be accepted by the RO membrane system. Another study was conducted over four months on a pilot plant platform installed at the desalination plant of ONDEO Services in Gibraltar [8]. The seawater at Gibraltar is known to be difficult because it is subject to algae blooms twice a year and is characterized by a conductivity of 48.7 mS/cm at 20℃ and an SDI of between 13 and 15. The study first showed that the removal of fouling constituents of seawater was more efficient with UF pretreatment than with conventional pretreatment: UF reduced SDI from 13–25 to less than 0.8, whereas with the dual media filter, the filtrate SDI remained between 2.7 and 3.4. The UF permeate had a constant quality for the entire duration of the experiment, whereas the quality of the dual media filter (DMF) filtrate fluctuated significantly with respect to turbidity.

While UF and MF membranes are more highly preferred than NF membranes, they may still need pretreatment processes including coagulation, adsorption, oxidation, and media filtration to reduce membrane fouling and/or increase the removal of certain aquatic contaminants. Major mechanisms and the effects of these pretreatments are summarized in Table 1 together with the advantages and disadvantages of these pretreatments. The effects of coagulant dose on membrane fouling are related to the properties of coagulants [54-56] and the type of UF and MF membranes [55, 57]. Although the cost-effective coagulant doses reported in the literature for membrane fouling reduction can differ from the optimal doses for conventional water treatment, bench-scale or pilot-scale tests are often necessary in order to determine the effects of coagulant dose on a particular source water and membrane of interest [40]. As briefly summarized previously, coagulation pretreatment can significantly improve low-pressure membrane performance (less fouling and greater rejection), while it 1) requires a proper dose that can be difficult to meet if feed water quality varies rapidly/significantly, 2) may exacerbate fouling, 3) produces solid wastes, and 4) may be ineffective in mitigating the fouling by hydrophilic neutral organics (Table 1).

Absorbents are favorable to UF and MF membranes as they are poor at removing the small substances [58]. The most intensively studied adsorbent for UF/MF filtration is powdered activated carbon (PAC). The efficacy of PAC in removing organic contaminants is strongly dependent on the PAC type [59, 60], dose and properties of the organics [61, 62], and the competition of other aquatic constituents [63]; PAC may also remove inorganic contaminants, such as arsenic [64]. Granular activated carbon (GAC) filters have been integrated with low-pressure membrane filtration in pilot-scale testing [65, 66]. These studies found that GAC prefiltration/adsorption effectively reduced the irreversible fouling of some UF membranes in treating natural surface water. Recently, carbon nanotubes (CNTs) have drawn special research attention due to their unique properties and potential environmental applications: sorbents, high-flux membranes, depth filters, antimicrobial agents, environmental sensors, renewable energy technologies, and pollution prevention strategies [67, 68]. In addition, CNT technology has the potential to support point-of-use in water treatment since, unlike many microporous adsorbents, CNTs possess a fibrous shape with a high aspect ratio, a large accessible external surface area, and well-developed mesopores, all of which contribute to the superior removal capacities of these macromolecular biomolecules and microorganisms [69]. Due to these unique characteristics of CNTs, the potential applications of CNT-UF/MF can have considerable benefits in water/wastewater treatment/reclama-

Table 1. List of the mechanisms, effects, and applications of major pretreatments for membrane filtration [40]

Pretreatment	Coagulation	Adsorption	Preoxidation	Prefiltration
Chemicals applied	Coagulants (or flocculants) at proper dose	Porous or nonporous adsorbents in suspension or fixed contactor	Gaseous or liquid oxidants	Granular media with/without coagulants, membranes
Dose effects	Under-, optimal, or overdose (optimal for enhanced coagulation)	Minimal effective dose if used as suspended particles	Minimal effective dose	None
Physical mechanisms	Increases the size of aquatic contaminants to filterable level	Binds small contaminants to adsorbents much larger than membrane pores	May cause dissociation of organic colloids into smaller sizes or the release of EPS by aquatic organisms	Removes coarse materials that may cause cake/gel layer formation on downstream membranes
Chemical mechanisms	Destabilizes contaminants to cause aggregation or adsorption on coagulant precipitates or membrane surfaces	Provides new interfaces to adsorb/accumulate substances detrimental to membrane performance	Oxidizes and/or partially decomposes NOM, possible mineralization if VUV used	Selectively removes contaminants or other particles that are sticky to filter media and downstream membranes
Biological mechanisms	Partially removes autochthonous NOM and hinder bacterial growth in feedwater or on membrane	May adsorb organic contaminants relevant to biofouling	Suppresses microbial growth	Partially removes microorganisms that can cause biofouling
Targeted contaminants	Viruses, humic/fulvic acids, proteins, polysaccharides with acidic groups, colloids smaller than membrane pores	Humic/fulvic acids, small natural organic acids, some DBPs, pesticides and other synthetic organic compounds	Viruses and organic contaminants with ozonation	Particulate and colloidal organic/ inorganic substances, microbiota
Effects on membrane fouling	Reduces colloidal fouling and NOM fouling	May increase or decrease membrane fouling	May reduce biofouling and NOM fouling	May reduce fouling to different extents
Advantages	Significantly improves LPM performance (less fouling and greater rejection)	Increases the removal of DBPs and DBP precursors	Reduces the occurrence of biofouling; increases organic removal (ozonation)	May reduce biofouling, colloidal fouling, and/or solids loading
Disadvantages	1) Requires proper dose that can be difficult to meet if feedwater quality varies rapidly/significantly, 2) may	1) Possible exacerbation of LPM fouling, 2) difficulty in removing PAC powders from treatment facilities	1) Formation of DBPs; 2) may damage membranes incompatible with	1) Performance of prefilters may deteriorate and be difficult to recover,

NOM: natural organic matter, DBPs: disinfection byproducts, PAC: powdered activated carbon.

tion and seawater desalination, although they have not been studied. Adsorption is advantageous to combat the increase in disinfection byproducts (DBPs) and DBP precursors as well as membrane foulants. However, adsorbents can possibly exacerbate membrane fouling and be difficult to remove from treatment facilities (Table 1).

Seawater containing microorganisms such as bacteria, algae, fungi, and viruses can cause serious biological fouling. This biofouling can be controlled by chemical oxidants (chlorine, bromine, iodine, or ozone), ultraviolet irradiation, biofiltration to remove nutrients, and the addition of biocide [4]. At oxidant doses practical for pretreatment, previous studies of conventional water treatment have demonstrated that chlorine and permanganate can be added to the feed water to suppress the growth of microorganisms and maintain oxidative conditions in the water; ozone can partially oxidize natural organic matter (NOM) and increase the assimilable organic carbon that may be removed by downstream biological filters [70]. A previous study found that the concentration of manganese in the permeate of a pilot-scale UF system decreased from 0.16–0.19 mg/L to below the targeted 0.05 mg/L with the addition of $KMnO_4$ as a result of oxidation and precipitation of soluble Mn species [71]. The presence of low levels of ozone may also improve the removal of organic or organic-coated particles by coagulation and filtration, which indicates a change to the stability or reactivity of aquatic particles with respect to coagulation or deposition [72, 73]. While preoxidation is valid for reducing the occurrence of biofouling and NOM removal, it has several disadvantages such as the formation of DBPs, membrane damage, and ineffectiveness in suppressing the growth of some microbiota resistant to oxidation [40]. Table 2 summarizes a more detailed case study analysis of conventional and UF/MF pretreatment for SWRO with various feed waters and operating conditions.

3. Summary and Recommendation

Different pretreatment technologies often preferentially remove certain types of aquatic contaminants or have different effects on SWRO membrane fouling. Therefore, depending on the feed water quality conditions, it may be necessary to consider the proper integration of multiple pretreatments and combine the benefits of each separate pretreatment. Raw water with aggressive and fluctuating chemistry quality presents a challenging task for designers in selecting the appropriate pretreatment technology for fending off design deficiencies at a later stage [46]. The conventional treatment scheme may not work in every scenario and may not always be the right choice. In terms of an economic point of view, although the integration of multiple pretreatments may increase the capital costs of the system, the

Table 2. Detailed case study analysis of conventional and UF/MF pretreatments for SWRO

Pretreatment	Feed analysis	Performance	Remark
DMF + $FeCl_3$	TDS, 43,300 mg/L; SDI 5.5-6.0; pH 6.5	56,800 m^3/day; SDI, <4.0; 35% recovery; permeate Cl^-, <82 mg/L	Membrane degradation due to chlorination; seawater seasonal variation [74]
DAF + $FeCl_3$ (2-5 mg/L)	TDS, 25,153-50,491 mg/L; SDI, 6.2 (3.6-20); pH 8-8.5, 5-20 NTU	37.5 MGD; filtered water SDI, <2.6-3.3	Valid for turbidity, algae and hydrocarbon removal [18]
DMF + $FeClSO_4$ (Fe^{3+}), 3.04 mg/L; beach well intake; MF	TDS, 47,000 mg/L; SDI, > 6.5; pH 8.2	Filtrate SDI: conventional, <3.6; beach well, 1.2; MF, 2.02	Total cost (capital + operating), fils/m^3: conventional, 28,153; beach well, 11,082; MF, 12,264 [21]
DMF; UF (MWCO, 100 kDa)	Conductivity, 48.7 mS/cm; SDI, 13-24; 0.7 NTU; pH 8.1	UF filtrate SDI, <0.8; DMF filtrate SDI, 2.7-3.4	Good control for UF membrane fouling with a pre-coagulation at low dose [8]
UF (MWCO, 100 kDa)	Conductivity, 50-57.3 mS/cm; SDI, 6.1–6.4; pH 8.0; 4 NTU; TOC, 2.7-6.1 mg/L	UF permeate: SDI, 1-2; <0.1 NTU; >90% recovery	No RO fouling rate during 30 days trial [75]
UF (0.01 m) and MF (0.1 m): hollow fiber	TOC, <1.0 mg/L; SDI, 6.1-6.5	UF filtrate SDI, 0.9-1.2; MF filtrate SDI, 2.5-3.0	Chemical costs, US$/$m^3$: UF, 0.00027; MF, 0.00218 [20]
UF ; $FeCl^3$ (0.3-0.7 mg/L)	TDS, 40,500 mg/L; SDI, 6.5, SS, 2-14 mg/L; 1-10 NTU	45-55% recovery; 0.1-0.2 for conventional and 0.09-0.16 for UF; SDI, 2.6-3.8 for conventional and 2.1-3.0 for UF	$FeCl^3$, 0.33 US$/kg; total UF filtration cost, 0.048-0.057 US$/$m^3$ [22]
UF multibore (MWCO, 100-150 kDa)	TDS, 45,000 mg/L; SDI, 16-19; pH 8.2	10 MIGD; TDS, <500 mg/L; 35% recovery; SDI, 2.8-4.2	Substantial reduction of chemical consumption and energy saving compared with existing spiral wound UF modules [19]

UF: ultrafiltration, MF: microfiltration, SWRO: seawater reverse osmosis, DMF: dual media filter, TDS: total dissolved solid, SDI: silt density index, DAF: dissolved air flotation, MGD: million gallons per day.

Table 3. Cost analysis comparison of conventional and UF/MF pretreatments [46]

Parameter	Conventional pretreatment	UF/MF pretreatment	Benefits
Capital costs	Cost competitive with MF/UF	Slightly higher than conventional pretreatment. Costs continue to decline as developments are made	Capital costs of MF/UF could be 0–25% higher, whereas life cycle costs using either of the treatment schemes are comparable
Energy requirements	Calls for larger footprint	Significantly smaller footprint higher than conventional	Footprint of MF/UF could be 30-50% of conventional filters
Footprint	Less than MF/UF as it requirements	Higher than conventional	MF/UF requires pumping of water through the membranes. This can vary depending on the type of membrane and water quality
Chemical costs	High due to coagulant and process chemicals needed for optimization	Chemical use is low, dependent on raw water quality	Less chemicals
RO capital cost	Higher than MF/UF since RO operates at lower flux	Higher flux is logically possible resulting in lower capital cost	Due to lower SDI values, RO can be operated at 20% higher flux if feasible, reducing RO capital costs
RO operating costs	Higher costs as fouling potential of RO feed water is high resulting in higher operating pressure. One experiences frequent cleaning of RO membrane	Lower RO operating costs are expected due to less fouling potential and longer membrane life	The NDP (net driving pressure) is likely to be lower if the feed water is pretreated by MF/UF. Membrane cleaning frequency is reduced by 10–100%, reducing system downtime and prolonged element life.

UF: ultrafiltration, MF: microfiltration, RO: reverse osmosis, SDI: silt density index.

operational costs may decrease if membrane fouling can be effectively reduced by the integration. Table 3 shows a cost analysis between the application of conventional pretreatment and the UF/MF pretreatment [46]. This overview indicates that it is feasible to combine UF/MF with RO, which is a well-established technique for water desalination and reuse in the Middle-Eastern states. In addition, lower chemical cleaning frequency and RO membrane replacement are expected due to the superior UF/MF permeate water quality as well as the benefits of a reduced footprint and easier operation of UF/MF [4].

Acknowledgments

This research was supported by a grant (07SeaHeroB01-01) from the Plant Technology Advancement Program funded by the Ministry of Land, Transport, and Maritime Affairs of the Korean government. This study was also supported by the University of South Carolina in USA.

References

1. Service RF. Desalination freshens up. *Science* 2006;313:1088-1090.
2. Sanza MA, Bonnélyea V, Cremerb G. Fujairah reverse osmosis plant: 2 years of operation. *Desalination* 2007;203:91-99.
3. Sauvet-Goichon B. Ashkelon desalination plant - a successful challenge. *Desalination* 2007;203:75-81.
4. Prihasto N, Liu QF, Kim SH. Pre-treatment strategies for seawater desalination by reverse osmosis system. *Desalination* 2009;249:308-316.
5. Gleick PH. The world's water, 2006-2007: the biennial report on freshwater resources. Washington, DC: Island Press; 2006.
6. Fritzmann C, Löwenberg J, Wintgens T, Melin T. State-of-the-art of reverse osmosis desalination. *Desalination* 2007;216:1-76.
7. Greenlee LF, Lawler DF, Freeman BD, Marrot B, Moulin P. Reverse osmosis desalination: water sources, technology, and today's challenges. *Water Res.* 2009;43:2317-2348.
8. Brehant A, Bonnelye V, Perez M. Comparison of MF/UF pretreatment with conventional filtration prior to RO membranes for surface seawater desalination. *Desalination* 2002;144:353-360.
9. Reverter JA, Talo S, Alday J. Las Palmas III - the success story of brine staging. *Desalination* 2001;138:207-217.
10. Reverberi F, Gorenflo A. Three year operational experience of a spiral-wound SWRO system with a high fouling potential feed water. *Desalination* 2007;203:100-106.
11. Tran T, Bolto B, Gray S, Hoang M, Ostarcevic E. An autopsy study of a fouled reverse osmosis membrane element used in a brackish water treatment plant. *Water Res.* 2007;41:3915-3923.
12. Magara Y, Kawasaki M, Sekino M, Yamamura H. Development of reverse osmosis membrane seawater desalination in Japan. *Water Sci. Technol.* 2000;41:1-8.
13. Her N, Amy G, Chung J, Yoon J, Yoon Y. Characterizing dissolved organic matter and evaluating associated nanofiltration membrane fouling. *Chemosphere* 2008;70:495-502.
14. Her N, Amy G, Jarusutthirak C. Seasonal variations of nano-

filtration (NF) foulants: identification and control. *Desalination* 2000;132:143-160.

15. Yoon J, Yoon Y, Amy G, Her N. Determination of perchlorate rejection and associated inorganic fouling (scaling) for reverse osmosis and nanofiltration membranes under various operating conditions. *J. Environ. Eng.* 2005;131:726-733.
16. Lee H, Amy G, Cho J, Yoon Y, Moon SH, Kim IS. Cleaning strategies for flux recovery of an ultrafiltration membrane fouled by natural organic matter. *Water Res.* 2001;35:3301-3308.
17. Abdessemed D, Nezzal G. Coupling softening - ultrafiltration like pretreatment of sea water case study of the Corso plant desalination (Algiers). *Desalination* 2008;221:107-113.
18. Bonnelye V, Sanz MA, Durand JP, Plasse L, Gueguen F, Mazounie P. Reverse osmosis on open intake seawater: pretreatment strategy. *Desalination* 2004;167:191-200.
19. Burashid K, Hussain AR. Seawater RO plant operation and maintenance experience: Addur desalination plant operation assessment. *Desalination* 2004;165:11-22.
20. Chua KT, Hawlader MN, Malek A. Pretreatment of seawater: results of pilot trials in Singapore. *Desalination* 2003;159:225-243.
21. Ebrahim S, Abdel-Jawad M, Bou-Hamad S, Safar M. Fifteen years of R&D program in seawater desalination at KISR Part I. Pretreatment technologies for RO systems. *Desalination* 2001;135:141-153.
22. Glueckstern P, Priel M, Wilf M. Field evaluation of capillary UF technology as a pretreatment for large seawater RO systems. *Desalination* 2002;147:55-62.
23. Pervov AG, Andrianov AP, Efremov RV, Desyatov AV, Baranov AE. A new solution for the Caspian Sea desalination: low-pressure membranes. *Desalination* 2003;157:377-384.
24. Van Hoof SC, Hashim A, Kordes AJ. The effect of ultrafiltration as pretreatment to reverse osmosis in wastewater reuse and seawater desalination applications. *Desalination* 1999;124:231-242.
25. Xu J, Ruan G, Chu X, Yao Y, Su B, Gao C. A pilot study of UF pretreatment without any chemicals for SWRO desalination in China. *Desalination* 2007;207:216-226.
26. Sinha S, Yoon Y, Amy G, Yoon J. Determining the effectiveness of conventional and alternative coagulants through effective characterization schemes. *Chemosphere* 2004;57:1115-1122.
27. Khawaji AD, Kutubkhanah IK, Wie JM. A 13.3 MGD seawater RO desalination plant for Yanbu Industrial City. *Desalination* 2007;203:176-188.
28. Bache DH, Gregory R. Flocs and separation processes in drinking water treatment: a review. *J. Water Supply Res. Technol. AQUA* 2010;59:16-30.
29. Wilf M, Bartels C. Integrated membrane desalination systems--current status and projected development [Internet]. 2006. Available from: http://www.membranes.com/docs/papers/New%20Folder/Abstract%20for%20Tianjin%20-%20Hydranautics.pdf.
30. Choi KY, Dempsey BA. In-line coagulation with low-pressure membrane filtration. *Water Res.* 2004;38:4271-4281.
31. Gabelich CJ, Yun TI, Coffey BM, Suffet IH. Effects of aluminum sulfate and ferric chloride coagulant residuals on polyamide membrane performance. *Desalination* 2002;150:15-30.
32. Gabelich CJ, Williams MD, Rahardianto A, Franklin JC, Cohen Y. High-recovery reverse osmosis desalination using intermediate chemical demineralization. *J. Membr. Sci.* 2007;301:131-141.
33. Rahardianto A, Gao J, Gabelich CJ, Williams MD, Cohen Y. High recovery membrane desalting of low-salinity brackish water: Integration of accelerated precipitation softening with membrane RO. *J. Membr. Sci.* 2007;289:123-137.
34. Nadav N, Priel M, Glueckstern P. Boron removal from the permeate of a large SWRO plant in Eilat. *Desalination* 2005;185:121-129.
35. Gaid K, Treal Y. Le dessalement des eaux par osmose inverse: l'expérience de Véolia Water. *Desalination* 2007;203:1-14.
36. Glueckstern P, Priel M. Optimization of boron removal in old and new SWRO systems. *Desalination* 2003;156:219-228.
37. Koseoglu H, Kabay N, Yüksel M, Sarp S, Arar Ö, Kitis M. Boron removal from seawater using high rejection SWRO membranes - impact of pH, feed concentration, pressure, and cross-flow velocity. *Desalination* 2008;227:253-263.
38. Mane PP, Park PK, Hyung H, Brown JC, Kim JH. Modeling boron rejection in pilot- and full-scale reverse osmosis desalination processes. *J. Membr. Sci.* 2009;338:119-127.
39. Taniguchi M, Fusaoka Y, Nishikawa T, Kurihara M. Boron removal in RO seawater desalination. *Desalination* 2004;167:419-426.
40. Huang H, Schwab K, Jacangelo JG. Pretreatment for low pressure membranes in water treatment: a review. *Environ. Sci. Technol.* 2009;43:3011-3019.
41. Múñoz Elguera A, Pérez Báez SO. Development of the most adequate pre-treatment for high capacity seawater desalination plants with open intake. *Desalination* 2005;184:173-183.
42. O'Melia CR. Aquasols: the behavior of small particles in aquatic systems. *Environ. Sci. Technol.* 1980;14:1052-1060.
43. Water desalination. Technical manual TM 5-813-8. Washington, DC: U.S. Department of the Army; 1986.
44. Peleka EN, Matis KA. Application of flotation as a pretreatment process during desalination. *Desalination* 2008;222:1-8.
45. Rubio J, Souza ML, Smith RW. Overview of flotation as a wastewater treatment technique. *Miner. Eng.* 2002;15:139-155.
46. Vedavyasan CV. Pretreatment trends - an overview. *Desalination* 2007;203:296-299.
47. Pearce GK. The case for UF/MF pretreatment to RO in seawater applications. *Desalination* 2007;203:286-295.
48. Choi YH, Kweon JH, Kim DI, Lee S. Evaluation of various pretreatment for particle and inorganic fouling control on performance of SWRO. *Desalination* 2009;247:137-147.
49. Hamed OA. Overview of hybrid desalination systems - current status and future prospects. *Desalination* 2005;186:207-214.
50. Van der Bruggen B, Vandecasteele C. Distillation vs. membrane filtration: overview of process evolutions in seawater desalination. *Desalination* 2002;143:207-218.
51. Kamp PC, Kruithof JC, Folmer HC. UF/RO treatment plant Heemskerk: from challenge to full scale application. *Desalination* 2000;131:27-35.
52. Pearce GK. UF/MF pre-treatment to RO in seawater and wastewater reuse applications: a comparison of energy costs. *Desalination* 2008;222:66-73.
53. Teuler A, Glucina K, Laine JM. Assessment of UF pretreatment prior RO membranes for seawater desalination. *Desalination* 1999;125:89-96.
54. Kimura K, Maeda T, Yamamura H, Watanabe Y. Irreversible membrane fouling in microfiltration membranes filtering coagulated surface water. *J. Membr. Sci.* 2008;320:356-362.

55. Tran T, Gray S, Naughton R, Bolto B. Polysilicato-iron for improved NOM removal and membrane performance. *J. Membr. Sci.* 2006;280:560-571.
56. Wang J, Guan J, Santiwong SR, Waite TD. Characterization of floc size and structure under different monomer and polymer coagulants on microfiltration membrane fouling. *J. Membr. Sci.* 2008;321:132-138.
57. Howe KJ, Marwah A, Chiu KP, Adham SS. Effect of coagulation on the size of MF and UF membrane foulants. *Environ. Sci. Technol.* 2006;40:7908-7913.
58. Schäfer AI, Fane AG, Waite TD. Cost factors and chemical pretreatment effects in the membrane filtration of waters containing natural organic matter. *Water Res.* 2001;35:1509-1517.
59. Lee J, Walker HW. Effect of process variables and natural organic matter on removal of microcystin-LR by PAC - UF. *Environ. Sci. Technol.* 2006;40:7336-7342.
60. Yoon Y, Westerhoff P, Snyder SA, Esparza M. HPLC-fluorescence detection and adsorption of bisphenol A, 17β-estradiol, and 17α-ethynyl estradiol on powdered activated carbon. *Water Res.* 2003;37:3530-3537.
61. Najm IN, Snoeyink VL, Lykins BW, Adams JQ. Using powdered activated carbon - a critical review. *J. Am. Water Works Assoc.* 1991;83:65-76.
62. Westerhoff P, Yoon Y, Snyder S, Wert E. Fate of endocrine-disruptor, pharmaceutical, and personal care product chemicals during simulated drinking water treatment processes. *Environ. Sci. Technol.* 2005;39:6649-6663.
63. Yoon Y, Westerhoff P, Snyder SA. Adsorption of 3H-labeled 17-β estradiol on powdered activated carbon. *Water Air Soil Pollut.* 2005;166:343-351.
64. Tien VN, Chaudhary DS, Ngo HH, Vigneswaran S. Arsenic in water: concerns and treatment technologies. *J. Ind. Eng. Chem.* 2004;10:337-348.
65. Tsujimoto W, Kimura H, Izu T, Irie T. Membrane filtration and pre-treatment by GAC. *Desalination* 1998;119:323-326.
66. Yuasa A. Drinking water production by coagulation-microfiltration and adsorption-ultrafiltration. *Water Sci. Technol.* 1998;37:135-146.
67. Mauter MS, Elimelech M. Environmental applications of carbon-based nanomaterials. *Environ. Sci. Technol.* 2008;42:5843-5859.
68. Pan B, Xing B. Adsorption mechanisms of organic chemicals on carbon nanotubes. *Environ. Sci. Technol.* 2008;42:9005-9013.
69. Upadhyayula VK, Deng S, Mitchell MC, Smith GB. Application of carbon nanotube technology for removal of contaminants in drinking water: a review. *Sci. Total Environ.* 2009;408:1-13.
70. Crittenden J, Montgomery Watson Harza. Water treatment principles and design. 2nd ed. Hoboken: John Wiley; 2005. p. 75-90.
71. Vos G, Brekvoort Y, Oosterom HA, Nederlof MM. Treatment of canal water with ultrafiltration to produce industrial and household water. *Desalination* 1998;118:297-303.
72. Plummer JD, Edzwald JK. Effects of chlorine and ozone on algal cell properties and removal of algae by coagulation. *J. Water Supply Res. Technol. AQUA* 2002;51:307-318.
73. Wilczak A, Howe EW, Aieta EM, Lee RG. How preoxidation affects particle removal during clarification and filtration. *J. Am. Water Works Assoc.* 1992;84:85-94.
74. Hasan Al-Sheikh AH. Seawater reverse osmosis pretreatment with an emphasis on the Jeddah Plant operation experience. *Desalination* 1997;110:183-192.
75. Lorain O, Hersant B, Persin F, Grasmick A, Brunard N, Espenan JM. Ultrafiltration membrane pre-treatment benefits for reverse osmosis process in seawater desalting. Quantification in terms of capital investment cost and operating cost reduction. *Desalination* 2007;203:277-285.