Desalination 261 (2010) 354–364

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Considerations for selection of seawater filtration pretreatment system

Nikolay Voutchkov *

Water Globe Consulting, LLC, 200 Broad Street, Suite 2450, Stamford, CT 06901, USA

ARTICLE INFO

Article history:
Received 25 March 2010
Received in revised form 30 June 2010
Accepted 2 July 2010
Available online 31 July 2010

Keywords:
Seawater
Pretreatment
Desalination
Membranes
Biofouling
Reverse osmosis
SWRO
Ultrafiltration
Microfiltration

ABSTRACT

Two types of pretreatment systems are typically used to protect seawater reverse osmosis membranes from fouling: conventional granular media filtration and membrane filtration. While granular medial filtration is still a dominating seawater pretreatment technology, microfiltration and ultrafiltration membrane systems for seawater pretreatment have evolved rapidly over the past decade and may offer cost and performance benefits for the site specific conditions and challenges of a given seawater desalination project. This article presents a critical review of widely used conventional granular and membrane pretreatment technologies and addresses key factors, and issues which would need to be taken under consideration when selecting a seawater pretreatment system.

1. Introduction

Seawater pretreatment is a key component of every membrane desalination plant. The main purpose of the pretreatment system is to remove particulate, colloidal, organic, mineral and microbiological contaminants contained in the source seawater and to prevent their accumulation on the downstream seawater reverse osmosis (SWRO) membranes (i.e., to protect the membranes from fouling). The content and nature of foulants contained in the source seawater depend on the type and location of the desalination plant intake.

Usually, subsurface intakes (wells and infiltration galleries) produce source water of an-order-of magnitude lower content of silt and particulates as compared to open-ocean intakes because the seawater is naturally prefiltered by the ocean bottom sediments. However, occasionally well source water may contain high levels of dissolved and colloidal foulants (iron, manganese, silica, etc.) and natural organic matter (NOM) that are difficult and costly to remove.

The fouling potential of source seawater collected through open ocean intakes also depends on the type and location of the plant intake. Deep off-shore intakes located away from underwater currents, wastewater discharges, industrial ports, ship traffic corridors, and river estuaries typically produce low-fouling seawater. The source water quality of on-shore intakes is often influenced by algal blooms, surface runoff and tidal movement, and could be quite variable and challenging.

Table 1 presents key source seawater quality parameters that have significant impact on the selection and configuration of the pretreatment system for a given desalination plant. This table also indicates threshold levels of significance of these parameters established based on full-scale experience.

Traditionally, seawater foulants are removed by a series of source water conditioning processes (coagulation, flocculation and pH adjustment) followed by conventional granular media (anthracite and sand) filtration. Over the past 10 years, advances in microfiltration (MF) and ultrafiltration (UF) membrane technologies, and their successful application for water and wastewater treatment have created an impetus for using membrane pretreatment in seawater desalination plants [1]. Both granular media and membrane filtration pretreatment technologies may offer advantages or face challenges depending on the source seawater quality and origin. Therefore, selecting the most suitable pretreatment technology for a given project should be based on a comprehensive performance and life cycle cost analysis, and whenever possible on side-by-side pilot testing. Pilot testing should target time frame encompassing events that could create pretreatment challenges such as: algal blooms, intake area dredging, heavy ship traffic, rainfall season, etc.

2. Granular media filtration overview

At present, granular media (conventional) filtration is the most widely used seawater pretreatment technology [2]. A typical

* Tel.: +1 203 253 1312; fax: +1 203 504 8342.
E-mail address: nvoutchkov@water-g.com.

0011-9164/$ – see front matter
doi:10.1016/j.desal.2010.07.002

Table 1
Seawater quality characterization for pretreatment.

Source seawater quality parameter	Pretreatment issues and considerations
Turbidity (NTU)	Levels above 0.1 mg/L are indicative of high potential for fouling. Spikes above 50 NTU for more than 1 h would require sedimentation or dissolved air flotation (DAF) treatment prior to filtration.
Total organic carbon (mg/L)	If below 0.5 mg/L – biofouling is unlikely. Above 2 mg/L – biofouling is very likely.
Silt density index (SDI_{15})	Source seawater levels consistently below 2 year-around typically indicate that no additional filtration pretreatment is needed. SDI > 4 - pretreatment is necessary.
Total suspended solids (mg/L)	This parameter is needed to assess the amount of residuals generated during pretreatment. Does not correlate well with turbidity beyond 5 NTU.
Iron (mg/L)	If iron is in reduced form, SWRO membranes can tolerate up to 2 mg/L. If iron is in oxidized form, concentration > 0.05 mg/L would cause accelerated fouling.
Manganese (mg/L)	If manganese is in reduced form, SWRO membranes can tolerate up to 0.1 mg/L. If manganese is in oxidized form, concentration > 0.02 mg/L would cause accelerated fouling.
Silica (mg/L)	Concentrations higher than 20 mg/L may cause accelerated fouling. Analyze for colloidal silica if concentration > 20 mg/L.
Chlorine (mg/L)	Concentrations higher than 0.01 mg/L would cause RO membrane damage.
Temperature (°C)	$T \leq 12$ °C would cause significant increase in unit energy use. $T \geq 35$ °C may cause accelerated mineral scaling and biofouling. $T > 45$ °C may cause irreversible RO membrane damage.
Oil and grease (mg/L)	Concentrations higher than 0.02 mg/L would cause accelerated organic fouling.
pH (units)	Typical pH of seawater is 7.6 to 8.3. Long term exposure to pH < 4 and pH > 11 may cause membrane damage.

schematic of desalination plant with granular media filters is shown on Fig. 1.

This process includes source seawater conditioning by coagulation and flocculation followed by filtration through one or more layers of granular media (e.g., anthracite coal, silica sand, garnet). Conventional filters used for seawater pretreatment are typically rapid single-stage dual-media (anthracite and sand) units. However, in some cases where the source seawater contains high levels of organics, algal content and suspended solids, two stage filtration systems are used. Under this configuration, the first filtration stage is mainly designed to remove coarse solids (i.e., particulates, algae) and organics in suspended form. The second-stage filters are configured to retain fine solids and silt, and to remove a portion (20 to 40%) of the soluble organics contained in the seawater by biofiltration.

Depending on the driving force for seawater filtration, granular media filters are classified as gravity and pressure filters. The main differences between the two types of filters are the head required to convey the water through the media bed, the filtration rate, and the type of vessel used to contain the filter media. Because of the high cost of constructing large pressure vessels with the proper wetted surfaces for corrosion resistance, pressure filters are typically used for small and medium size capacity SWRO plants. Gravity pretreatment filters are used for all sizes SWRO desalination plants but have found wider applications for large and medium size facilities.

Since the purpose of the pretreatment filters for SWRO plants is not only to remove over 99 percent of all suspended solids in the source water but also to reduce the content of the much finer silt particles by several orders of magnitude, the design of these pretreatment facilities is usually governed by the filter effluent silt density index (SDI) target levels rather than by target removal level of turbidity or pathogens.

Granular media filters are typically backwashed using filtered seawater or concentrate from the SWRO membrane system. Filter cell backwash frequency is usually once every 24 to 48 h and spent (waste) backwash volume is 2% to 5% of the intake seawater (i.e., recovery rate of 95% to 98%). Use of SWRO concentrate instead of filtered effluent to backwash filter cells allows reducing backwash volume and energy needed to pump source seawater to the desalination plant.

2.1. Seawater conditioning prior to granular filtration

Most seawater particles and microorganisms have a slightly negative charge which has to be neutralized by coagulation for efficient granular media filtration. In addition, these neutralized particles would need to be agglomerated in larger flocs that can be effectively retained within the filter media. Therefore, source seawater conditioning by coagulation and subsequent flocculation are necessary steps prior to granular media filtration.

Use of coagulant is critical for the effective and consistent performance of granular media filtration systems. Without coagulation

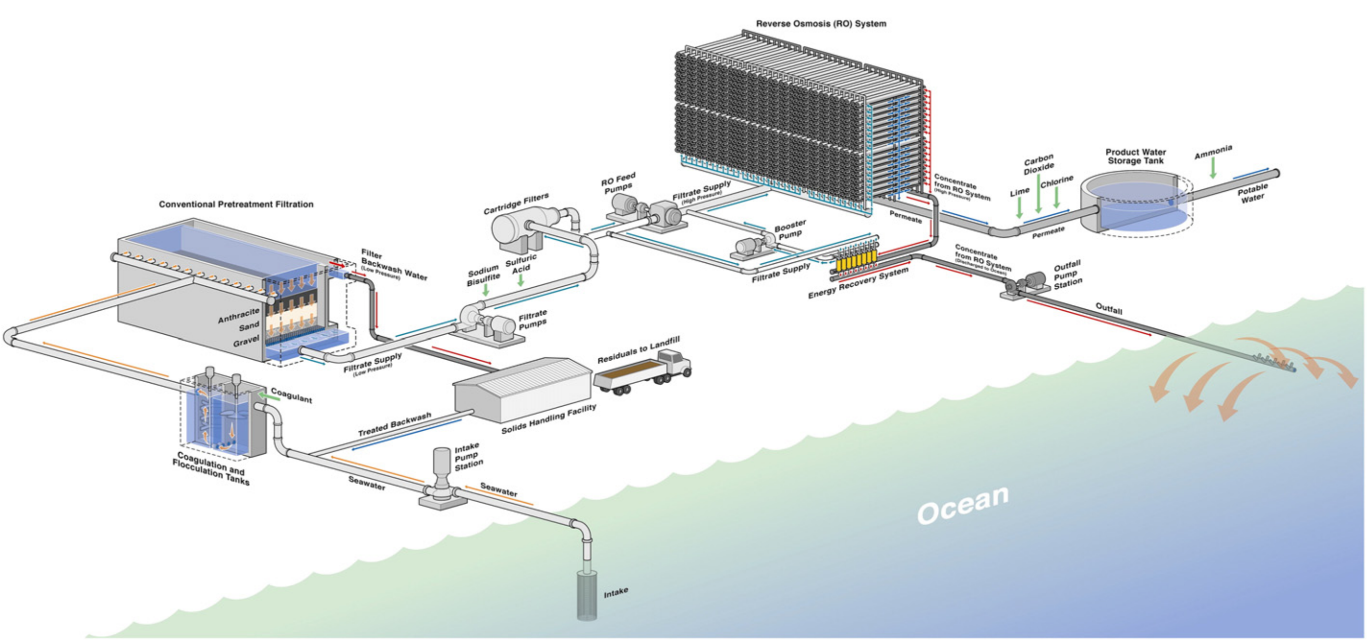

Fig. 1. Typical seawater desalination plant with granular media pretreatment.

of the particulates in seawater, conventional granular media filters are likely to remove completely only particles which are larger than 50 μm. Coagulation allows granular filtration process to remove finer particles and microplankton from the source seawater. Well operating filters can remove particles as small as 0.2 μm.

For comparison, membrane pretreatment systems can remove particles as fine as 0.1 μm (MF membranes) or 0.01 μm (UF membranes) by direct physical separation. Therefore, for these systems coagulation of the source water particles is not as important and usually is only applied when the seawater contains NOM that could be coagulated and removed via filtration.

The main purpose of the coagulation system is to achieve uniform mixing of the added coagulant with the source seawater and efficient coagulation of the particles contained in the seawater. The two types of mixing systems most widely used in seawater desalination plants are in-line static mixers and mechanical flash mixers installed in coagulation tanks.

In-line static mixers and subsequent in-pipe flocculation are significantly less expensive than the construction of separate coagulation and flocculation tanks and therefore, they are often preferred by engineering contractors. However, when the source seawater originates from deep open-ocean intakes (i.e., intakes located deeper than 10 meters below the ocean surface) very often the size and the charge of the particles contained in this water are very small. Therefore, the complete coagulation and flocculation of such particles require contact time much longer than that for particles contained in seawater collected within 5 m from the ocean surface. Adequate contact time and conditions for agglomerating fine particles originating from deep intakes can typically be achieved only by seawater conditioning in coagulation and flocculation chambers equipped with mechanical flash mixers. This is a common challenge in desalination plants with in-line coagulation and flocculation and source seawater originating from deep open intakes. Such challenge is usually unsuccessfully attempted to be solved by increasing of the coagulant dosage which only worsens the performance of the pretreatment and SWRO systems.

Coagulants most frequently used for source seawater conditioning prior to sedimentation or filtration are ferric salts (ferric sulfate and ferric chloride). Aluminum salts (such as alum or poly-aluminum chloride) are avoided because it is difficult to maintain aluminum concentrations at low levels in dissolved form since aluminum solubility is very pH dependent. Small amounts of aluminum may cause mineral fouling of the downstream SWRO membrane elements.

The optimum coagulant dosage is pH dependent and should be established based on an on-site jar or pilot testing for the site-specific conditions of a given application. In some cases, addition of sulfuric acid for source water pH reduction to 5.5 to 6 is practiced in order to optimize flock formation.

Overdosing of coagulants used for seawater pretreatment is one of the most frequent causes for SWRO membrane mineral fouling. When overdosed, coagulant accumulates on the downstream facilities and can cause fast-rate fouling of the cartridge filters and SWRO membranes. In such situation, a significant improvement of source water SDI can be attained by reducing coagulant feed dosage or in case of poor mixing, modifying the coagulant mixing and flow distribution system to eliminate the content of un-reacted chemical in the filtered seawater fed to the SWRO membrane system.

2.2. Seawater pretreatment prior to filtration

Most of the existing pretreatment systems in operation today are single-stage/dual granular media filters and are designed to operate without sedimentation or dissolved air flotation of the source seawater prior to filtration. However, source seawater may need to undergo additional pretreatment prior to filtration (sand removal, sedimentation, DAF, or initial filtration) depending on its quality.

2.2.1. Sedimentation

Sedimentation is typically used upstream of granular media and membrane filters when membrane plant source water has daily average turbidity higher than 30 NTU or experiences turbidity spikes of 50 NTU or more which continue for a period of over 1 h. If sedimentation basins are not provided, large turbidity spikes may cause the pretreatment filters to exceed their solids holding capacity (especially if pressure-driven granular media filters are used), which in turn may impact filter pretreatment capacity. If the high solids load continues, the pretreatment filters would enter a condition of continuous backwash, which in turn would render them out of service.

Sedimentation basins for seawater pretreatment are typically designed to produce settled source water of less than 2.0 NTU and SDI_{15} below 6. To achieve this level of turbidity removal, sedimentation basins are often equipped with both coagulant (most frequently iron salt) and flocculant (polymer) feed systems. The needed coagulant and flocculent dosages should be established based on jar and/or pilot testing.

If the source water turbidity exceeds 100 NTU, than conventional sedimentation basins are often inadequate to produce turbidity of the desired turbidity level of less than 2 NTU and low silt and algal content. Under these conditions, sedimentation basins should be designed for enhanced solids removal by installing lamella plate modules or using sedimentation technologies that combine lamella and fine granular media for enhanced solids removal.

Typically, enhanced sedimentation technologies are used for treating source water from open ocean intakes which are under a strong influence of river water or wastewater discharges of elevated turbidity. This condition could occur when the desalination plant intake is located in a river delta area or is influenced by a seasonal surface water runoff. For example, during the rainy season, the intake of the Point Lisas seawater desalination plant in Trinidad is under the influence of the Orinoco River currents which carry a large amount of alluvial solids. As a result, the desalination plant intake turbidity could exceed 200 NTU [3]. To handle this high solids load, the plant source water is settled in a lamella sedimentation tank prior to conventional single-stage dual media filtration.

2.2.2. Dissolved air flotation

Dissolved air flotation technology is suitable for removal of floating particulate foulants such as algal cells, oil, grease or other contaminants that cannot be effectively removed by sedimentation or filtration. DAF systems can typically produce effluent turbidity of $<$0.5 NTU and can be combined in one structure with dual-media gravity filters for sequential pretreatment of seawater.

DAF process uses very small air bubbles to float light particles (algae, fine silt, and debris) and organic substances (oil, grease) contained in the seawater. The floated solids are collected at the top of the DAF tank and skimmed off for disposal, while the low-turbidity seawater is collected near the bottom of the tank. The time (and therefore, the size of the flocculation tank) needed for the light fine particulates contained in the seawater to form large flocs is usually 2 to 3 times shorter than that in conventional flocculation tanks because the flocculation process is accelerated by the air bubbles released in the flocculation chamber of the DAF tanks. In addition, the surface loading rate for removal of light particulates and floatable substances by DAF is approximately 10 times lower than that needed for conventional sedimentation. Another benefit of DAF as compared to conventional sedimentation is the higher density of the formed residuals (sludge). While residuals collected at the bottom of sedimentation basins typically have concentration of only 0.3 to 0.5% solids, DAF residuals (which are skimmed off the surface of the DAF tank) contain solids concentration of 1 to 3%.

In some full-scale applications, the DAF process is combined with granular media filters to provide a compact and robust pretreatment of seawater with high algal and/or oil and grease content [4]. Although this combined DAF/filter configuration is very compact and cost-competitive, it has three key disadvantages: (1) it complicates the design and operation of the pretreatment filters; (2) DAF loading is controlled by the filter loading rate and therefore, DAF tanks are typically oversized; (3) flocculation tanks must be coupled with individual filter cells.

The feasibility of DAF use for seawater pretreatment is determined by seawater quality and governed by source water turbidity and overall life cycle pretreatment costs. The DAF process can handle source seawater with turbidity of up to 50 NTU. Therefore, if the source seawater is impacted by high turbidity spikes or heavy solids (usually related to seasonal river discharges or surface runoff), then DAF may not be a suitable pretreatment option.

In addition to source water turbidity concentration, another factor of key importance for the viability of DAF as pretreatment upstream of the filters is the type/size of plankton contained in the water. Often, plankton in seawater is be dominated by small algal cells with diameter of less than a few micrometers (μm) typically referred to as pico-plankton (0.2 to 2.0 μm [5]). As compared to fresh waters from lakes and rivers where pico-plankton usually does not dominate the algal community, in seawater pico-plankton is associated with more than 50% of the chlorophyll a (algal content) in most ocean waters [6] and in the cases of tropical or subtropical seawater, this content may reach 75% or more [7].

Bench testing experience at the Carlsbad seawater desalination demonstration project in California has indicated that pico-plankton may not be well removed by DAF even after elaborate coagulation and flocculation (observed removal efficiency of chlorophyll a and turbidity was typically less than 60%). In such cases, the use of conservatively designed deep single-stage dual media granular filters or two-stage dual media granular filters may render a better pretreatment than a combination of DAF and granular media or membrane filtration.

Taking into consideration the significant importance pico-plankton content may have on the selection of pretreatment system, it is essential to characterize both the algal concentration of the source water (measured as chlorophyll a) and the algal profile of the source water, which documents the total concentration of algal cells in cells/mL, as well as identifies the types of individual algae species contained in the sample, and determines the cell counts of these species in cells/mL. Algal profile should be completed under both normal and algal bloom conditions.

Although DAF systems have much smaller footprint than conventional flocculation and sedimentation facilities, they include a number of additional equipment associated with air saturation and diffusion, and with recirculation of portion of the treated flow, and therefore, their construction costs are typically comparable to these of conventional sedimentation basins. Usually, the operation and maintenance (O&M) costs of DAF systems are higher than these of gravity sedimentation tanks due to the higher power use for the flocculation chamber mixers, air saturators, recycling pumps, and sludge skimmers. The total power use of DAF systems is usually 2.5 to 3.0 kWh/10,000 m^3/day of treated source seawater, which is significantly higher than that for sedimentation systems (0.5 to 0.7 kWh/10,000 m^3/day of treated seawater).

DAF process with built-in filtration (DAFF) is used at the 136,000 m^3/day Tuas seawater desalination plant in Singapore [8]. This pretreatment technology has been selected for this project to address the source water quality challenges associated with the location of the desalination plant's open intake in a large industrial port (i.e., oil spills) and the frequent occurrence of algal blooms in the area of the intake. The source seawater has total suspended solids concentration that can reach up to 60 mg/L at times and oil and grease levels in the seawater could be up to 10 mg/L. The facility uses 20 build-in filter DAF units, two of which are operated as standby. Plastic covers shield the surface of the tanks to prevent impact of rain and wind on DAF operation as well as to control algal growth. Each DAF unit is equipped with two mechanical flocculation tanks located within the same DAF vessel. Up to 12% of the filtered water is saturated with air and recirculated to the feed of the DAF units.

A combination of DAF followed by two-stage dual-media pressure filtration has been successfully used at the 45,400 m^3/day El Coloso SWRO plant in Chile, which at present is the largest desalination plant in South America. The plant is located in the City of Antogofasta, where seawater is exposed to year-round red-tide events, which have the capacity to create frequent particulate fouling and biofouling of the SWRO membranes [9]. The DAF system at this plant is combined in one facility with a coagulation and flocculation chamber. The average and maximum flow rising velocities of the DAF system are 22 and 33 m^3/m^2.h, respectively. This DAF system can be bypassed during normal operation and is typically used during red-tide events. The downstream granular media filters are designed for surface loading rate of 25 m^3/m^2 h. Ferric chloride at a dosage of 10 mg/L is added ahead of the DAF system for source water coagulation. The DAF system reduces source seawater turbidity to between 0.5 and 1.5 NTU and removes approximately 30 to 40% of the source seawater organics.

Another example of large seawater desalination plant incorporating DAF system for pretreatment is the 200,000 m^3/day Barcelona facility in Spain [10]. The pretreatment system of this plant incorporates 10 high-rate AquaDAF units equipped with flocculation chambers; 20 first-stage gravity dual-media filters, and 24 s-stage pressurized dual-media filters. The purpose of the DAF system is mainly to remove algae during blooms and to reduce source water organic content. The intake of the desalination plant is located 2.2 km from the coast and 3 km away from the entrance of a large river (Llobregat River) to the ocean, which carries significant amount of alluvial (NOM-rich) organics. After coagulation with ferric chloride and flocculation in flash-mixing chambers, over 30% of these organics are removed by the DAF system.

2.3. Selecting granular filter media

Filter media type, uniformity, size and depth are of key importance for the performance of seawater pretreatment filters. Dual media filters have two layers of filtration media – typical design includes 0.4 to 0.8 m of anthracite over 1.0 to 2.0 m of sand. Deep dual media filters are often used if the desalination plant filtration system is designed to achieve enhanced removal of soluble organics from seawater by biofiltration and/or to handle seawater with high pico-plankton content. In this case, the depth of the anthracite level is enhanced to between 1.5 and 1.8 m.

If the source seawater is relatively cold (i.e., average annual temperature below 15 °C), and at the same time is of high organic content, a layer of granular activated carbon (GAC) of the same depth is used instead of deeper layer of anthracite because the biofiltration removal efficiency will be hindered by the low temperature. While during biofiltration a portion of the soluble organics in the seawater is metabolized by the microorganisms that grow on a thin biofilm formed on the granular filter media, the GAC media removes a portion of the seawater organics mainly by adsorption.

Tri-media filters have 0.45 to 0.60 m of anthracite as the top layer, 0.20 to 0.30 m of sand as a middle layer and 0.10 to 0.15 m of garnet or limonite as the bottom layer. These filters are used if the source seawater contains a large amount of fine silt or the seawater intake experiences algal blooms dominated by pico-plankton.

The depth of the filter bed is typically a function of the media size and follows the general rule-of-thumb that the ratio between the depth of the filter bed (l - in millimeters) and the effective size of the filter media (d_e - in millimeters), l/d_e, should be higher than 1500. For example, if the effective size of the anthracite media is selected to be 0.65 mm, the depth of the anthracite bed should be at least ($0.65\text{ mm} \times 1500 = 0.975$ mm, i.e., approximately 1.0 m).

The depth of the GAC media is estimated based on the average contact time in this media, which is recommended to be 10 to 15 min.

For example, if a filter is designed for a surface loading rate of 9 m^3/m^2 h, the depth of the GAC media should be at least 1.5 m (9 m^3/m^2 h × 10 min/60 min per h = 1.5 m).

When each of the filter media layers is first placed in the filter cells, and additional 3 to 5 cm of media should be added to the design depth of the layer to account for the removal/loss of fine particles from the newly installed bed after backwashing. It should also be pointed out that if the filters are designed to achieve total organic carbon (TOC) removal by biofiltration, it would take at least 4 to 6 weeks for the filters to create sustainable biofilm on the surface of the filter media that can yield steady and consistent filter performance and TOC removal. If the seawater temperature is relatively cold (i.e., below 20 °C), than biofilm formation process may take several weeks longer.

2.4. Considerations for selecting granular filter type

Depending on the driving force for seawater filtration, granular media filters are classified as gravity and pressure filters. The main differences between the two types of filters are the head required to convey the water through the media bed, the filtration rate, and the type of vessel used to contain the filter media. Because of the high cost of constructing large pressure vessels with the proper wetted surfaces for corrosion resistance, pressure filters are typically used for small and medium size capacity SWRO plants.

Typically, gravity filters are reinforced concrete structures that operate at water pressure drop through the media of between 1.5 and 2.5 m. Dual media gravity filters are a predominant type of filtration pretreatment technology presently used in desalination plants of capacity higher than 40,000 m^3/day. Down-flow filters are preferred because they allow to retain algal biomass contained in the source seawater at the upper layer of the filter media and to minimize algal cell rupture which could cause release of soluble biodegradable organics in the filtered seawater which accelerate SWRO membrane biofouling.

Gravity pretreatment filters have found application for both small and large desalination plants worldwide. Most large seawater desalination plants in operation today have deep open-ocean intakes and use single-stage/dual media gravity filters (i.e., 320,000 m^3/day Ashkelon SWRO plant in Israel; 250,000 m^3/day Sydney Water and 125,000 m^3/day Gold Coast desalination plants in Australia; and the 200,000 m^3/day Hamma SWRO plant in Algeria).

Pressure filters have filter bed configuration similar to that of gravity filers, except that the filter media is contained in steel pressure vessel. They have found application mainly for small and medium size seawater desalination plants – usually with production capacity of less than 20,000 m^3/day. An exception is Spain, where most of the pretreatment filters at seawater desalination plants are pressure filters.

In most cases for relatively good source seawater quality (TOC < 1 mg/L, SDI < 5 and turbidity < 4 NTU) pressure filters are designed as single stage, dual media (anthracite and sand) units. Some plants with relatively poor water quality use two-stage pressure filtration systems. For small desalination plants, pressure filters are very cost-competitive, more space efficient and easier, and faster to install, and operate as compared to granular media gravity filters.

Often when the source seawater is collected via open intake, two-stage dual media (sand and anthracite) pressure filters are applied. One of the key cost disadvantages of these filters is that they operate under pressure and therefore, use more energy than gravity filters. Single-stage pressure filters have found application for several large SWRO plants such as the 160,000 m^3/day Kwinana plant in Perth, Australia and the 120,000 m^3/day Carboneras SWRO plant in Spain.

2.4.1. Removal of algal material from seawater

Seawater always contains some amount of algae, which concentration usually increases several times during the summer period and with several orders of magnitude during periods of algal blooms. When predominant phytoplankton species causing the algal bloom contain red pigment (peridinin) they cause reddish discolorization of the seawater which is the main reason why such algal bloom is termed "red tide." A number of algal species can cause red tides. In California, for example algal blooms of red-pigmented dinoflagellates are the most common cause of red-tide tides in the summer.

Algal species in the seawater vary in type and size and as indicated in Section 2.2.2, often pico-plankton dominates the algal population. Some plankton species that occur during algal bloom events, including many red-tide causing dinoflagellates, have cells that are relatively easy to break under pressures as low as 0.4 to 0.6 bars. As the algal cells break under the pressure (or vacuum) applied by the filtration pretreatment system, they release their cellular cytoplasm in the seawater. This cytoplasm has a very high content of easily biodegradable polysaccharides which serve as a food source of marine bacteria. When the amount of polysaccharides released by the broken algal cells exceeds a certain threshold in the filtered seawater, they would typically trigger accelerated microbiological growth and subsequent biofouling on the SWRO membranes.

Because gravity filters operate at pressures below the algal-cell rupture threshold and pressure filters run at several times higher pressure than this threshold, use of gravity filtration in source seawaters frequently exposed to heavy algal blooms (i.e., SWRO plants with on-shore or shallow off-shore intakes) is more advantageous. It is important to point out that this potential disadvantage of pressure filtration and the associated accelerated biofouling of the SWRO membranes, will manifest itself only during periods of algal blooms of measurable magnitude (typically when the total algal content in the source water is over 2000 cells/mL and the TOC levels in source seawater exceed 2 mg/L).

Overview of the performance of seawater installations in Spain and Australia where pressure filters are successfully used for seawater pretreatment indicates that the source water quality of these plants is very good year round (TOC < 2 mg/L, SDI < 5 and turbidity < 5 NTU) and that the plants have deep open-ocean off-shore intakes or well intakes. At depth of 10 m and higher, the concentration of algae is significantly lower than that at the ocean surface – and therefore, as long as desalination plant intake is fairly deep, biofouling caused by rupture and decay of algal biomass may not be as significant a problem as it would be for shallow offshore intakes or intakes located at the ocean surface (i.e., near-shore open ocean intakes).

2.4.2. Useful live of the filter structure

Typically, gravity filters are concrete structures that have useful life of 50 to 100 years. Pressure filters are steel structures with a lifespan of 25 years or less. The internal surface of the pressure filters used for seawater desalination is typically lined up with rubber coating that needs to be replaced every 5 to 10 years and inspected occasionally.

2.4.3. Solids retention capacity and handling of turbidity spikes

Gravity media filters have approximately two to three times larger volume of filtration media and retention time than pressure filters for the same water production capacity. Therefore, this type of filters can retain proportionally more solids and as a result, pretreatment filter performance is less sensitive to occasional source water turbidity spikes.

Pressure filters usually do not handle solids/turbidity spikes as well because of their smaller solids retention capacity (i.e., smaller volume of inter-media voids that can store solids before the filter needs to be backwashed). If source seawater is likely to experience occasional spikes of high turbidity (20 NTU or higher) due to rain events; algal blooms; naval traffic; ocean bottom dredging operations in the vicinity of the intake; seasonal changes in underwater current direction; or spring upwelling of water from the bottom to the surface; then pressure filters will produce effluent with inferior effluent quality (SDI and turbidity) during such events. Therefore, the use of pressure filters would likely result in a more frequent SWRO membrane cleaning.

Alternatively, in order to handle solids/turbidity spikes pressure filters could be designed as two-stage pretreatment systems with two sets of pressure filters operating in series. In similar source water quality conditions, comparable filtered water quality and performance reliability could be produced by a conservatively designed single-stage gravity-filtration pretreatment system.

2.4.4. Identifying and addressing operational problems

Gravity filters are typically covered with light covers that protect the filter cells from direct sunlight. These covers, however, can be easily removed and the filter cells can be inspected visually for irregularities – malfunctioning filter backwash nozzles, weir corrosion, poorly backwashed areas of filter media, formation of "mudballs", etc. Pressure filters are completely enclosed and very difficult to inspect for the same problems. As a result, these filters have to be designed with higher contingency factor (reserve capacity). A 15 to 20% reserve capacity is recommended if pressure filters are used to accommodate for potential flow distribution problems and uneven backwash air and water distribution.

2.4.5. Costs

Pressure filters are prefabricated steel structures and their production costs per unit filtration capacity are 30 to 50% lower than these of concrete gravity filters. Since pressure filters are designed at approximately two to three times higher surface loading rates than gravity filters (25 to 45 m^3/m^2 h vs. 8 to 15 m^3/m^2 h), their volume and size are smaller and therefore, they usually are less costly to build and install. In addition, because the pressure filter vessels are prefabricated, the installation time of this pretreatment system is approximately 20% to 30% shorter than that of gravity filters with concrete structures, which also has a positive impact on overall project construction costs.

On the other hand, the operation and maintenance (O&M) costs associated with pressure filters are usually higher than that of gravity filters. The useful life of the metal structures of the pressure filters is limited to 20 to 25 years while the concrete structures of the gravity filters can be used for 50 to 100 years. Because pressure filters typically operate at several times higher feed pressures than gravity filters, the energy use for pressure filtration is proportionally higher.

In addition, contrary to pressure filters, the structure of the gravity filters could be designed to accommodate the installation of a vacuum-driven membrane pretreatment system and allow to take advantage of the advancement of membrane pretreatment technologies as they reach maturity in the next 5 to 10 years.

It should be pointed out that because the site-specific conditions and priority of a given project often have a significant weight on the selection of the most-suitable type of granular filtration system, worldwide experience shows that both gravity and pressure-driven filters have found numerous applications in all sizes of projects. Table 2 shows the type and key design criteria of recent seawater desalination projects using granular media pretreatment.

3. Membrane filtration overview

Application of UF and MF membrane filtration for seawater pretreatment is relatively new. At present, approximately a dozen operational full-scale seawater desalination plants worldwide are using membrane pretreatment [4]. However, another two dozen plants are currently under design and construction, and are expected to be in service by 2012.

Fig. 2 depicts a general schematic of seawater desalination plant with membrane pretreatment. As indicated on this figure, seawater pretreatment includes several key components: (1) coarse and fine screens similar to these used for plants with conventional pretreatment; (2) microscreens to remove fine particulates and sharp objects from the seawater which could damage the membranes; and (3) UF or MF membrane system. Often desalination plants with membrane pretreatment systems are constructed without the installation of cartridge filters between the pretreatment and SWRO membranes, taking under consideration the fact that the membrane filtration media size is an order-of-magnitude smaller than the size of the cartridge filters. However, some conservative designs incorporate cartridge filters to provide protection against the particulates that may be released into the filter effluent due to MF or UF fiber breakage.

MF and UF membrane systems have been shown to be very efficient in removing turbidity and non-soluble and colloidal organics contained in the source seawater. Turbidity can be lowered consistently below 0.1 NTU (usually down to 0.03 to 0.05 NTU) and filter effluent SDI_{15} levels are usually below 3 over 90% of the time. Both MF and UF systems can remove four or more logs of pathogens such as *Giardia* and *Cryptosporidium*. In contrast to MF membranes, UF membranes can also effectively remove viruses.

Table 2
Examples of desalination plants with granular media pretreatment.

Desalination plant location and capacity	Pretreatment system configuration	Average and maximum filter loading rates	Notes
Glen Rocky Plant, Gibraltar – 1400 m^3/day	Single-stage dual media vertical pressure filters	Filtration rate – 11 m^3/m^2 h (avg.) 16 m^3/m^2 h (max)	Intake – 2/3 of volume from wells and 1/3 from off-shore open intake
Ashkelon, Israel – 325,000 m^3/day	Single-stage dual media gravity filters	Filtration rate – 8 m^3/m^2 h (avg.) 12 m^3/m^2 h (max)	Open intake – 1000 m from shore
Tuas, Singapore – 136,000 m^3/day	Combined DAF and sand media filtration	DAF and filtration loading rates – 10 m^3/m^2 h (avg.) 14 m^3/m^2 h (max)	Near-shore open intake in industrial port
El Coloso, Chile – 45,400 m^3/day	DAF followed by two-stage dual media horizontal pressure filters	DAF rate – 22 to 33 m^3/m^2 h. Filtration rate – 25 m^3/m^2 h (avg.)	Open intake in industrial port frequently plagued by red tide events
Fujairah I, UAE – 170,500 m^3/day	Single-stage, dual media gravity filters	Filtration rate – 8.5 m^3/m^2 h (avg.) 9.5 m^3/m^2 h (max)	Open intake – high hydrocarbon content of seawater
Kwinana, Perth, Australia – 143,000 m^3/day	Single-stage dual media pressure filters	Filtration rate – 14.0 m^3/m^2 h (avg.) 18.0 m^3/m^2 h (max)	Offshore open intake
Carboneras, Spain – 120,000 m^3/day	Single-stage dual media pressure filters	Filtration rate – 12.0 m^3/m^2 h (avg.) 14.0 m^3/m^2 h (max)	Offshore open intake
Barcelona, Spain – 200,000 m^3/day	DAF, first-stage dual media gravity filters, second-stage dual media pressure filters	DAF rate – 25 to 40 m^3/m^2 h. Filtration rate (first stage) – 10–15 m^3/m^2 h. Filtration rate (second stage) – 20–25 m^3/m^2 h	Open intake – 1500 m from shore

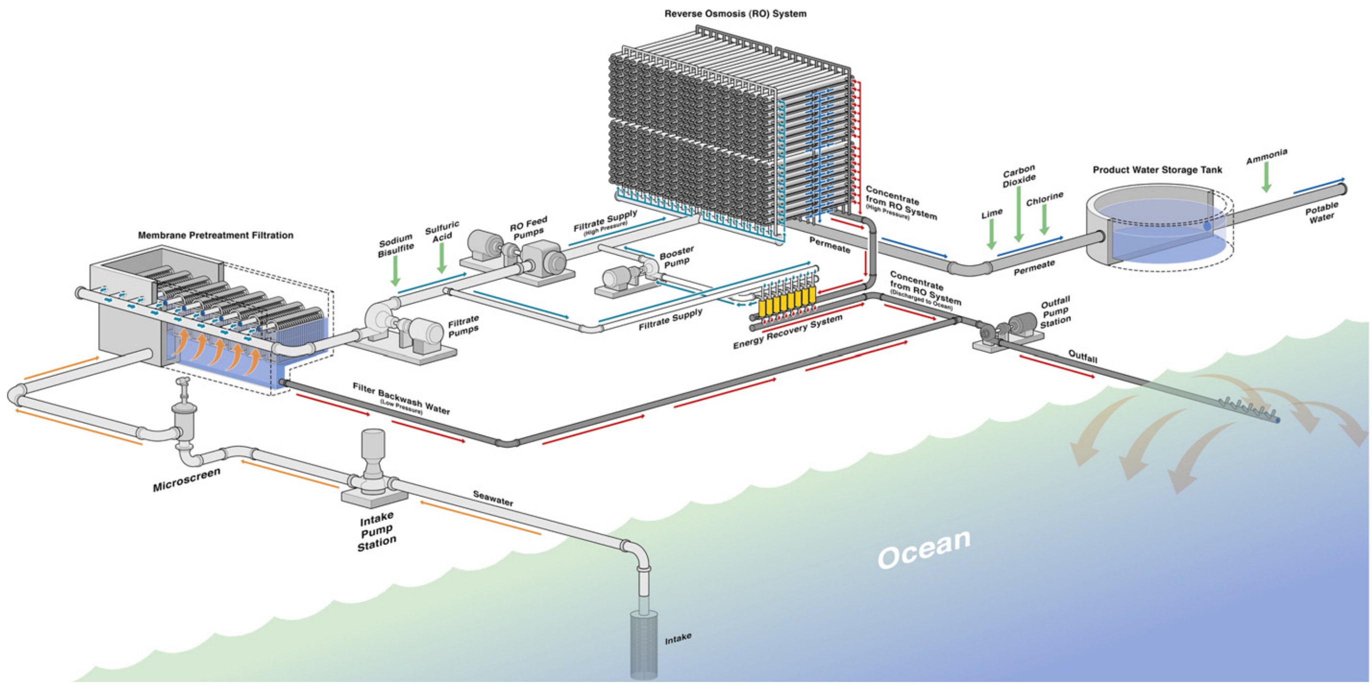

Fig. 2. Typical seawater desalination plant with membrane pretreatment.

It should be noted, however, that membrane pretreatment does not remove significant amounts of dissolved organics and marine microorganisms, which typically cause SWRO membrane biofouling. Because of the very short seawater retention time of the membrane pretreatment systems, they do not provide measurable biofiltration effect, unless designed as membrane bioreactors. For comparison, granular media filters, depending on their configuration, loading rate and depth, could remove 20% to 60% of soluble organics from source seawater.

Depending on the type of the driving filtration force, membrane pretreatment filters are divided into two categories – pressure and vacuum-driven. Pressure UF and MF systems consist of membrane elements installed in pressure vessels, which are grouped in racks (trains), similar to these of SWRO systems. Vacuum-driven pretreatment systems include a series of filtration modules submerged in open tanks of size and configuration similar to that of gravity granular media filters.

The two most important parameters associated with the design of any membrane pretreatment system are the design flux and feed water recovery. Membrane flux determines the amount of total membrane area and modules/elements needed to produce certain volume of seawater and is defined as the ratio between the total filtration area and the volume of source water filtered through the membranes. This parameter is typically expressed as either cubic meters per square meter per hour (m^3/m^2 h) or as liters per square meter per hour (L/m^2 h or lmh).

Feed water recovery indicates the fraction of the source seawater that is converted into filtrate suitable for seawater desalination. The recovery rate of membrane pretreatment systems is usually in a range of 88% to 94% and is typically lower than the recovery rate of granular media pretreatment filters for the same source water (95% to 98%). This is an important difference because it has an impact on the size of both plant intake and solids handling facilities.

Another important consideration is the operating pressure/vacuum of the pretreatment systems. Usually the vacuum-driven systems operate in a range of 0.1 to 0.8 bars. For comparison, pressure-driven systems typically run at pressures of 1.0 to 2.5 bars, which pressures are comparable to these of pressure-driven granular media filters.

As indicated in Section 2.4.1 operating pressure may have a measurable impact on the rate of biofouling on the downstream SWRO membranes, if the source seawater is exposed to frequent algal blooms. In the case of algal bloom occurrence, both pressure and vacuum-driven membrane systems would typically operate at pressures higher than the threshold at which many algal cells break and release easily biodegradable organics in the filtered seawater. Unless the algae are not gently removed by DAF or granular media filtration ahead of the membrane pretreatment system, the cell rupture caused by the membrane pretreatment system would accelerate SWRO membrane fouling. As a result, while membrane pretreatment systems may be able to produce better filtered water quality in terms of SDI and turbidity during heavy algal blooms they would often produce filter effluent of higher SWRO biofouling potential.

It is interesting to note that tests competed at the Carlsbad seawater desalination demonstration plant in 2005 when the plant was exposed to series of heavy algal blooms (red tides) for a prolonged period of time (between May and September) clearly support the observation of the negative impact that membrane pretreatment may have on the biofouling potential of the source seawater [11]. Site-by-site testing of granular media filtration and vacuum-driven UF pretreatment systems followed by separate SWRO systems operated at the same performance conditions (flux, recovery, feed pressures, and product water quality) under these algal bloom conditions indicated that granular media filtration produced low-fouling effluent that required only one SWRO membrane cleaning during the entire algal-bloom period (May through September), while the SWRO membranes downstream of the UF system required four cleanings during the same period to maintain comparable performance.

When the effect of UF system operating pressure on algal cell rupture was studied again during the same spring-summer algal bloom period of the following year (2006), it was found that if the maximum operating pressure of the UF system is limited down to the threshold for algal cell rupture of 0.4 bars (as compared to the usual maximum working vacuum of 0.8 bars), the fouling biofouling effect of the UF pretreatment system on the downstream SWRO membranes was reduced dramatically.

While operating membrane pretreatment systems at lower maximum driving vacuum (0.4 vs. 0.8 bars) during heavy algal blooms is a workable solution for lowering the SWRO membrane biofouling rate, it reduces the length of the membrane filter cycle in half, which in turn practically doubles the number of filter backwashes. This in turn increases the total volume of backwash reject from prealgal bloom levels of 6% to 8% up to approximately 12% of the total intake flow during algal bloom operations. Because of the significant impact of this algal-mitigation mode of operation of vacuum-driven membrane systems on intake and pretreatment system size capacities, its accommodation has to be reflected in the plant design. Alternatively, this algal bloom challenge could be addressed by installation of DAF or down-flow gravity granular media filters upstream of the membrane pretreatment to remove the algae cells without breaking them before they reach the membrane pretreatment filters.

Since pressure-driven membrane pretreatment systems always operate at feed pressures above the algal cell rupture threshold of 0.4 bars, the successful use of these systems for seawaters exposed to heavy algal blooms may require an upstream DAF or gravity granular filtration type of pretreatment, if the source seawater is collected using shallow offshore intakes or on-shore intakes.

3.1. Seawater conditioning prior to membrane filtration

Micro- and ultrafiltration have a wider spectrum of particle removal capabilities than conventional granular media filtration. Single or dual granular-media filters usually have lesser removal efficiency in terms of source water organics in suspended form, disinfection byproduct precursors, fine particles, silt and pathogens. Membrane filtration technologies are also less prone to upsets caused by seasonal changes in source seawater temperature, pH, turbidity, color, pathogen contamination, and size and type of water particles because their primary treatment mechanism is a mechanical particle removal through fine-pore membranes. Therefore, the upstream chemical coagulation and flocculation of the source seawater particles are of lesser importance for their consistent and efficient performance. In contrast, the pretreatment efficiency of the conventional media filtration technologies is very dependent on how robust the chemical coagulation and flocculation of the source seawater are ahead of the filtration process.

SWRO desalination plants equipped with vacuum-driven membrane pretreatment systems are typically designed to operate without coagulant addition or at coagulant dosages which are several times smaller than these needed for granular media pretreatment. Usually, pressure-driven pretreatment systems, however, always require source water coagulation prior to filtration. In this case the coagulation dosages are also smaller than these needed for source water conditioning for granular media pretreatment of the same water. Source seawater conditioning needs to address that mineral and colloidal fouling and biofouling are practically the same as these for granular media pretreatment (see Section 2.1).

3.2. Seawater pretreatment prior to membrane filtration

Seawater pretreatment for membrane filtration is similar to that needed for granular media filtration (see Section 2.2) with one exception. In order to protect the membranes from physical damage, the source seawater has to be treated by microscreening. Source seawater contains small sharp objects (such as shell particles), which can easily puncture the plastic pretreatment membranes and cause a rapid and irreversible loss of their integrity, unless the damaging particles are removed upstream of the membrane pretreatment system.

To remove sharp seawater particles that can damage the pretreatment membranes, the RO plant intake system has to incorporate a microscreening system of screen mesh size of 120 μm or less ahead of the membrane pretreatment system. Typically, previous experience with fresh surface source water (such as rivers or lakes) or wastewater indicates that 400 to 500-μm screens are adequate to protect the membranes from damage. However, numerous tests at the Carlsbad Seawater Desalination Demonstration Plant and West Basin Seawater Pilot Plant in California, USA indicate that screen size larger than 120 μm does not provide adequate protection of the membranes against sharp particles in seawater.

In addition, seawater contains barnacles, which in their embryonic phase of development are 130 to 150 μm in size and can pass the screen openings unless they are 120 μm or smaller. If barnacle plankton passes the screens, it could attach to the walls of downstream pretreatment facilities, grow colonies, and ultimately interfere with pretreatment system operations. Once barnacles establish colonies in the pretreatment facilities and equipment, they are very difficult to remove and can withstand chlorination, which is otherwise very effective biocide for most other marine organisms. Therefore, the use of fine microscreens (80 to 120 μm) is essential for reliable operation of the entire seawater desalination plant using membrane pretreatment. Micro-screens are not needed for pretreatment systems using granular media filtration because these systems effectively remove barnacles in all phases of their development.

The installation and operation of microscreening system are only needed if membrane filtration is used for pretreatment and therefore, its cost has to be taken under consideration when comparing conventional and membrane filtration pretreatment. The performance and reliability of the conventional granular media pretreatment systems are not sensitive to the content of sharp objects in the seawater and do not require elaborate and costly microscreening ahead of the filters. Usually, fine traveling screens of 3 to 10 mm openings provide adequate protection of conventional granular media pretreatment systems from coarse debris, large marine organisms, and particulates contained in the source water.

Typically, general selection choices of membrane pretreatment technology relate to the size of the membrane separation media (microfiltration or ultrafiltration) and the type of the driving filtration force (pressure or vacuum).

3.3. Considerations for selecting between UF and MF pretreatment

To date, UF membranes have found wider application for seawater pretreatment than MF membranes mainly because they usually provide better removal of suspended organics, silt and pathogens from the source seawater. Results from a comparative MF/UF study [12] indicate that "tight" UF membranes (i.e., membranes that can reject compounds of size of 20 kilo-Dalton or kDa or smaller) can produce filtrate of lower SWRO membrane fouling potential than 0.1 μm MF membranes. For comparison, these MF membranes produce filter effluent of turbidity and SDI similar to that of 100 kDa UF membranes.

Under conditions, where large amounts of silt particles of size comparable to the MF membrane pores are brought into suspension by naval ship traffic or ocean bottom dredging near the area of the intake, the silt particles may lodge into the MF membrane pores during the filtration process and ultimately may cause irreversible MF membrane fouling. Since UF membrane pores are an-order-of-magnitude smaller than these of the MF membranes, typically UF membrane pretreatment systems do not face this problem. The potential problem of this nature can usually be identified by side-by-side pilot testing of MF and UF membrane systems during periods of elevated silt content.

3.4. Considerations for selecting between pressure and vacuum-driven membrane filtration

Pressure and vacuum-driven membrane pretreatment systems mainly differ by their ability to handle source water quality variations and their cost and membrane housing equipment and configuration.

3.4.1. Source water quality variations

Vacuum-driven membrane pretreatment systems are usually more advantageous for treating seawater of variable quality in terms of turbidity, such as waters collected by near-shore or shallow-off shore intakes that experience frequent turbidity swings and turbidity spikes of 20 NTU or more. Pressure-driven membrane systems have limited capacity to retain solids due to the fact that the individual membrane elements are located in a tight membrane vessel of a very small retention volume. Therefore, if a pressure-driven system is exposed to a large amount of solids, the membrane elements and vessels would fill up with solids very quickly, which in turn would trigger frequent membrane backwash and could result in destabilization of the membrane system performance. To address this deficiency of the pressure-driven membrane systems, some membrane manufacturers offer membrane modules with adjustable fiber density, which allows customizing membrane system design to the more challenging water quality.

Typically, the tanks in which the vacuum-driven membrane elements are installed provide a minimum hydraulic retention time of 10 to 15 min and have an order of magnitude higher volume and capacity available to handle source seawater of elevated turbidity and to temporary store solids as compared to pressure-driven systems. This renders the vacuum-driven membrane pretreatment systems more suitable for high-turbidity water applications. The aeration scouring vacuum-driven systems typically applied for backwashing also improve their tolerance to high solid loads. In addition, since vacuum-driven systems usually operate at lower trans-membrane pressure, their rate of membrane fouling is lower and they have more stable operation during transient solids load conditions.

Pressure-driven membrane pretreatment systems, however, are often more suitable and cost-competitive for cold source seawaters (i.e., for seawaters of minimum monthly average temperature of 15 °C or less) or low turbidity and low organic, and algal content. Vacuum-driven system productivity is more sensitive to source water temperature/viscosity. The maximum trans-membrane pressure available for vacuum-driven membrane systems is limited to approximately one atmosphere. This makes pressure-driven systems often the membrane pretreatment of choice for desalination plants with deep off-shore open ocean intakes.

3.4.2. Equipment and construction costs and energy requirements

Depending on the size of the system and the intake seawater quality, the site specific conditions may favor the use of either pressure or vacuum-driven type membrane pretreatment system. Pressure-driven systems are typically very cost competitive for small installations because they can be manufactured and assembled in a factory off-site and shipped as packaged installations without the need of significant site preparation or construction of separate structures.

Equipment and construction costs of larger-size plants with more challenging source seawater quality are typically lower when using vacuum-driven membrane systems, especially for plant retrofits. An exception to this rule-of-thumb is the treatment of low-temperature seawater.

Because for the same water quality, vacuum-driven systems of the same type (MF or UF) usually operate at lower pressure, the total power use for these systems is lower. The vacuum-driven systems may use 10% to 30% less energy than pressure-driven systems for water sources of medium to high turbidity and temperature between 18 and 35 °C.

3.4.3. Technology commoditization potential

Currently, both vacuum and pressure-driven membrane systems differ by the type and size of the individual membrane elements; the configuration of the membrane modules; the type of membrane element backwash; and the type of membrane integrity testing method. However, the vacuum-driven systems are easier to standardize due to their simplified configuration.

The lack of membrane system unification, standardization and commoditization results in a significant dependence of the membrane plant owner on the membrane manufacturer supplying their system to continue to provide membrane elements for the system and to improve their existing technology in order to stay competitive and match the performance of other membrane manufacturers in the future. As a result, the owner of the membrane water treatment plant takes the risk of the membrane technology they use at the time of plant construction to become obsolete or out-of-date in the near future due to the accelerated dynamics in the development of new membrane technologies and products or due to the original system manufacturer exiting the membrane market.

The inherent risks associated with the incompatibility of the membrane technologies available today can be partially mitigated by selecting and designing a membrane pretreatment system that can be designed to accommodate the replacement of this system with at least one other existing system/membrane elements of similar type. From this point of view, conservatively designed vacuum-driven membrane systems offer a better opportunity to handle future changes.

Currently, the vacuum-driven systems available on the market have many more similarities than differences, as compared to pressure-driven systems. Typically, all existing vacuum-driven systems use similar size and depth tanks, which house their membrane modules/cassettes, and have comparable type of membrane clean-in-place (CIP) and backwash systems. The vacuum-driven systems could be designed around the use of a particular membrane technology, but because of their similarities their tanks and auxiliary facilities could be sized to accommodate the replacement of the initially selected membrane system with an alternative membrane system form other manufacturer, if needed in the future. For comparison, pressure-driven systems are more difficult to commoditize because of the major differences in terms of size, diameter, type of pressure vessels and type of backwashing system.

3.5. Lessons learned from existing MF/UF systems

At present, the seawater desalination industry has limited experience with the use of membrane pretreatment. Over the past 10 years a total of only two dozen large full-scale SWRO plants with membrane pretreatment have been constructed worldwide. The

Table 3
Large SWRO plants with membrane pretreatment.

Desalination plant location and capacity	Pretreatment system type and configuration	Hydraulic loading rate (flux)	Notes
Adelaide, Australia 300,000 m^3/day	Submersible UF membranes	Flux rate – 50 to 60 L/m^2 h	Offshore open intake
Fukuoka, Japan – 96,000 m^3/day	Pressure UF membranes	Flux rate – 60 to 80 L/m^2 h	Infiltration gallery
Kindasa, Saudi Arabia – 90,000 m^3/day	Dual media granular pressure filtration followed by pressure UF membranes	Dual granular media filtration rate – 15 to 20 m^3/m^2 h; Flux rate – 75 to 100 L/m^2 h	Near-shore open intake in industrial port
Palm Jumeirah, UAE – 64,000 m^3/day	Pressure UF system	Flux rate – 55 to 65 L/m^2 h	Offshore open intake
Yu-Huan, China – 34,500 m^3/day	Submersible UF membranes	Flux rate – 30 to 50 L/m^2 h	Offshore open intake
Colakoglu Steel Mill SWRO Plant, Turkey - 6700 m^3/day	Pressure UF system	Flux rate – 50 to 60 L/m^2 h	Offshore open intake

Table 4
UF/MF membrane system survey – lessons learned from ten US utilities [17].

Utility no.	Primary membrane system problems	Root cause of problem	Lessons learned
1	Unable to meet design capacity.	Lower achievable flux than projected. Pilot testing did not address extreme water quality conditions.	Pilot test during extreme water quality conditions. Use conservative safety factor when up-scaling pilot testing results.
2	High CIP frequencies. Excessive downtime and O&M costs.	Excessive membrane fouling. Pilot testing did not address extreme water quality conditions.	Pilot test during extreme water quality conditions. Additional pretreatment may be needed to address extreme water quality conditions
3	Unable to meet design capacity	Undersized membrane ancillary support systems.	Ancillary support systems could be a significant bottleneck if undersized.
4	Higher membrane replacement costs.	Lower than projected membrane life. Potential membrane fouling and lack of previous data by suppliers.	Additional pretreatment may be needed to obtain the useful membrane life indicated by membrane supplier.
5	Excessive downtime and maintenance. Lower than projected water quality.	Excessive fiber breakage. Fouling related to water quality deviations from specifications putting higher stress on the fibers than expected.	Lack of experience with use of membranes for the given water quality may require change in membrane chemistry and durability.
6	Unable to meet design capacity	Higher than anticipated downtime. Manufacturer missed to include valve opening/closing time for integrity tests. More membrane capacity needed to be installed	Complete thorough review of the downtime for all MF/UF system operational steps under worst-case operations scenario
7	Higher than expected O&M costs.	More frequent chemical cleaning needed than initially projected.	Pilot test during extreme water quality conditions. Use conservative safety factor when up-scaling pilot testing results.
8	Excessive system downtime	Failures in membrane potting. System not handling water pressure/potting materials not tested previously.	Never use membrane that has components or materials that have never been tested previously!
9	Difficult system operation	Insufficient system training for staff	Plan for additional staff training beyond the minimum offered by the MF/UF manufacturer
10	Excessive downtime. Failure to meet product water quality targets.	Frequently failing membrane integrity testing. Air leaking form gaskets and valves.	Make sure that replacement of failed gaskets, valves and seals is included in manufacturer membrane system warrantee

majority of these plants have been in a continuous operation for less than 5 years and some of the plants have faced performance challenges and have undergone a number of modifications [13–16]. At this time, most of the initial challenges have been overcome by the accelerated advancement of the membrane technology and development of new generation of membrane products tailored towards seawater pretreatment. Technological advancements have resulted in an exponential growth of membrane pretreatment applications for seawater desalination over the past 5 years, with more than a dozen of new large desalination plants planned to begin operation by 2012 [1,4]. Table 3 lists key features for some of the largest SWRO plants using membrane pretreatment.

It is interesting to note that all desalination plants listed in Table 3 use UF membrane pretreatment systems. Very few plants have additional source water treatment (DAF, coarse media filtration) upstream of the membrane pretreatment system.

While UF and MF membrane experience for seawater applications is fairly limited at present, over 15 years of such full-scale experience exists for fresh water applications. A recent survey completed at 10 fresh drinking water treatment plants in the US [17] has identified a number of challenges these plants experienced during their startup, acceptance testing and full-scale operations (Table 4). Most of the lessons learned from these applications are relevant to seawater pretreatment as well.

4. Summary and conclusions

Membrane seawater pretreatment is an attractive alternative to conventional granular media filtration. However, taking under consideration the numerous factors affecting the pretreatment costs of a full-scale seawater desalination plant, the selection of the most suitable pretreatment system for a given seawater desalination project has to be completed based on a thorough life-cycle cost analysis which accounts for all expenditures and actual costs associated with the installation and operation of the two systems.

As the desalination industry gains long-term experience with the operation of seawater membrane pretreatment systems in the next 5 to 10 years and the existing membrane pretreatment technologies evolve and converge into compatible, standardized and commoditized products, the use UF or MF membranes for seawater pretreatment is expected to become more competitive and attractive over time.

Acknowledgements

The author wishes to recognize Dr. Steven Le Page of M-REP Consulting for his marine biology work associated with the determination of the pressure threshold for algal cell rupture and assessment of algal bloom impacts on pretreatment technology performance.

References

[1] R.P. Huehmer, MF/UF pretreatment in seawater desalination: applications and trends, Proceedings of World Congress in Desalination and Reuse, International Desalination Association, IDAWC/DB09-253, Dubai, UAE, November 7-12 2009.
[2] N. Voutchkov, Pretreatment Technologies for Membrane Seawater Desalination, Australian Water Association, Sydney, Australia, 2008.
[3] K.J. Irwin, J.D. Thompson, Trinidad SWRO – Orinoco fluctuations fail to make filters falter, Desalination and Water Reuse, November/December 13/3 2006, pp. 12–16.
[4] M. Bush, R. Chu, S. Rosenberg, Novel trends in dual membrane systems for seawater desalination: minimum primary pretreatment and low environmental impact treatment schemes, IDA Journal 2 (1) (2010) 56–71.
[5] John McN. Sieburth, Smetacek, V.J. Lenz, Pelagic ecosystem structure: heterotrophic compartments of the plankton and their relationship to plankton size fractions, Lirnnol. Oceanogr. 23 (1978) 1256–1263.
[6] M. Takahashi, P.K. Bienfang, Size structure of phytoplankton biomass and photosynthesis in subtropical Hawaiian waters, Mar. Biol. 76 (1983) 203–211.
[7] M. Takahashi, T. Hori, Abundance of picoplankton in the subsurface chlorophyll maximum layer in subtropical and tropical waters, Mar. Biol. 79 (1987) 177–186.
[8] H.F. Kiang, W.W.L. Young, D.D. Ratnayaka, The Singapore solutions, Civil Engineering 77 (No. 1) (2007) .62–69.
[9] M. Petry, M.A. Sanz, C. Langlais, V. Bonnelye, J.P. Durand, D. Guevara, W.M. Nardes, C.H. Saemi, The El Coloso (Chile) reverse osmosis plant, Desalination 203 (2007) 141–152.
[10] J. Vila, J. Compte, T. Cazurra, N. Ontanon, M. Sola, F. Urrutia, Environmental impact reduction in Barcelona's desalination and brine disposal, Proceedings of World Congress in Desalination and Reuse, International Desalination Association, IDAWC/DB09-309, Dubai, UAE, November 7-12 2009.
[11] N. Voutchkov, J. Dietrich, Pilot testing alternative pretreatment systems for seawater desalination in Carlsbad, California, Proceedings of World Congress in Desalination and Reuse, International Desalination Association, SP05-095, Singapore, September 11-16 2005.
[12] S.A. Kumar, S. Adam, W. Pearce, Investigation of seawater reverse osmosis fouling and its relationship to pre-treatment type, Environmental Science and Technology 40 (2006) 2037–2044.
[13] G. Pearce, J. Allam, K. Chida, Ultrafiltraton pretreatment to RO: trials at Kindasa Water Services, Jeddah, Saudi Arabia, Proceedings of World Congress in

Desalination and Reuse, International Desalination Association, Paradise Island, Bahamas, September 28-October 3 2003.
[14] A. Hashim, T. Arai, K. Tada, H. Iwahori, N. Tada, S. Ishihara, M. Takata, Spiral-wound UF-membrane pre-treatment achievements for SWRO application in the Arabian Gulf Region, Proceedings of World Congress in Desalination and Reuse, International Desalination Association, IDAWC/DB09-121, Dubai, UAE, November 7-12 2009.
[15] P. Choules, M.B. Boudinar, B. Mack, Membrane pre-treatment design and operational experience from three SWRO plants, Proceedings of Annual Conference of the American Membrane Technology Association, Austin, Texas, 2009.
[16] F. Knops, R. Dekker, R. Kolkman, Ten years of ultrafiltration as pretreatment to SWRO in the Arabian Gulf, Proceedings of World Congress in Desalination and Reuse, International Desalination Association, IDAWC/DB09-071, Dubai, UAE, November 7-12 2009.
[17] A. Atassi, M. White, L.M. Rago, Membrane failure headlines: facts behind the hype regarding initial problems experienced at low pressure membrane installations, Proceedings of Annual American Water Works Membrane Technology Conference, 2007.