Conventional or Membrane Filtration for Seawater RO?

Two types of pretreatment systems are typically used to protect SWRO membranes from fouling: conventional granular media filtration and membrane filtration. Which one is better?

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Seawater pretreatment is an integral part of every seawater reverse osmosis (SWRO) desalination plant. The key purpose of the pretreatment system is to remove particulates, debris, microorganisms, suspended solids and silt from the source seawater prior to reverse osmosis separation. Ideally, after pretreatment the only solids left in the source seawater would be the dissolved minerals and as long as the seawater system is operated in a manner that prevents minerals from precipitating on the membrane surface, the SWRO membranes could operate without any cleaning for a very long time. Practical experience shows that in close to ideal source seawater quality, SWRO membranes may not need to be cleaned for one to two years and their useful life could extend beyond ten years.

In actuality, however, pretreatment systems remove most but not all of the suspended solids contained in the source seawater. The suspended solids, particulates and silt that remain in the seawater after pretreatment accumulate on the surface of the SWRO membranes and cause loss of membrane productivity over time. In addition, because seawater naturally contains bacteria as well as dissolved organics that could serve as food for these bacteria, a biofilm of bacteria could form and grow on the SWRO membrane surface causing loss of membrane productivity as well. Excessive membrane fouling is undesirable and besides a negative effect on SWRO membrane productivity it also results in increased use of energy for salt separation.

Typically, fouling could be reversed by periodic cleaning however, membrane fouling could be irreversible and cleaning may not recover membrane productivity, which in runs may require the replacement or some or all of the SWRO membranes.

All SWRO membranes foul over time. However, the rate and reversibility of fouling are the two key factors that have most profound effect on the performance and efficiency of the seawater reverse osmosis separation process. These factors in turns are closely related to the source seawater quality and the performance of the desalination plant's pretreatment system.

Two types of pretreatment systems are typically used to protect the SWRO membranes from fouling: conventional granular media filtration and membrane filtration. Currently, conventional granular media filtration is the predominant pretreatment technology for large and medium size desalination plants. Conventional seawater pretreatment filters have configuration and media similar to these used in fresh water filtration applications and could be either gravity or pressure-driven filters. Gravity pretreatment filters have been used for some of the largest SWRO desalination plants in the world in operation today such as the 325,000 m³/day Ashkelon plant in Israel.

Pressure granular media filters for example, are used for the 160,000 m³/day plant in Perth, Australia and practically all seawater desalination plants in Spain, including the 120,000 m³/day Carboneras SWRO plant, which is the largest in Europe. Pressure filters are also widely used in small seawater desalination plants worldwide because they 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.

Application of membrane filtration is for seawater pretreatment is relatively new. At present, less than a half-a-dozen full-scale seawater desalination plants worldwide are using membrane pretreatment. These pretreatment systems apply ultrafiltration (UF) or microfiltration (MF) membranes installed in modules through which source seawater is filtered using either pressure or vacuum. The 200 m³/day Carlsbad seawater desalination demonstration plant in California uses a vacuum-driven UF pretreatment system. The City of Long Beach Prototype Seawater Desalination Testing Facility in California uses pressure-driven MF pretreatment system.

The largest full-scale seawater membrane pretreatment system in the world is located at the 140,000 m³/day SWRO plant in Addur, Bahrain. This plant, as well as the largest membrane pretreatment system in Asia, located at the 96,000 m³/day Fukuoka desalination plant in Japan, use pressure-driven UF membranes for seawater pretreatment.

To date, UF membranes have found wider application for seawater pretreatment than MF membranes mainly because they typically provide better removal of suspended organics, silt and pathogens from the source seawater. Often silt particulates contained in seawater have size similar to that of the pore openings of MF membranes. When large amounts of silt are brought into suspension by naval ship traffic or ocean bottom dredging near the area of the intake, the silt particles contained in the source seawater may lodge into the MF membrane pores and ultimately may cause irreversible MF membrane fouling. Since UF membrane pores are significantly smaller than these of the MF membranes, typically the UF membrane pretreatment systems do not face this problem.

Many recent studies have indicated that membrane filtration technologies have a number of advantages for seawater pretreatment as compared to conventional granular media filtration systems. Granular media filtration however, is a well understood and widely used seawater pretreatment technology with a proven track record, which has a number of features that may render it very cost-competitive and viable. Therefore, the selection of filtration technology for seawater pretreatment should be based on a thorough life-cycle cost-benefit analysis. Side-by-side pilot testing of the two types of systems is also highly recommended to develop background system performance information for objective pretreatment technology selection. The following issues should be taken into consideration when selecting between granular media and membrane pretreatment filtration for seawater desalination:

Effect of Source Seawater Quality

Micro- and ultrafiltration have a wider spectrum of particle removal capabilities than conventional media filtration. Single or

dual-medial filters usually have lesser removal efficiency in terms of raw 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 is of a lesser importance for their consistent and efficient performance. In contrast, the pretreatment efficiency of the conventional media filtration technologies is very dependent on how efficient chemical coagulation and flocculation of the source seawater is ahead of the filtration process. Typically, coagulation and flocculation water chemistry is more sensitive to changes in seasonal water quality than the mechanically driven membrane particle separation processes.

Therefore, for applications where intake water quality experiences significant seasonal variations and presents a challenge in terms of high pathogen, fine particles and elevated particulate organics contamination, membrane filtration technologies are likely to offer performance benefits. However, if the source water for the desalination plant is collected from an open intake located far from the surf zone and at adequate depth to be exposed to only limited seasonal variations (typically 20m or deeper), granular media filtration may offer a very cost-effective pretreatment alternative to membrane filtration.

Source seawater temperature is a very important factor when selecting pretreatment system. Application of vacuum driven membrane pretreatment systems is usually less cost-effective than pressure membrane filtration and conventional granular media filtration for seawater of temperature lower than 12 ºC, because the productivity (flux) of vacuum-driven membrane filtration is dramatically reduced by the significant increase in unit weight of seawater at low temperature.

Another condition under which the use of sand media filtration may have certain additional benefits is for a seawater source that is very likely to be exposed to sudden and unpredictable changes of water quality such as: very high or low pH chemical spills; large oil and grease spills; frequent exposures to high water temperature, or other contaminants that may damage the MF or UF pretreatment membranes irreversibly. If the membrane elements are permanently damaged, the cost of their replacement could be significant, especially for large membrane SWRO treatment plants. Typically, granular filter media can handle a wider range of the extreme intake water quality conditions and the cost of media replacement is significantly lower than that for replacing all membrane elements for the same size plant.

This issue is of a very significant importance for pretreatment systems for seawater desalination plants with surface intakes. Often the source seawater contains small sharp objects (such as shell particles), which can easily puncture the pretreatment membranes and result in a very quick 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 membranes from the seawater, the RO plant intake system has to incorporate a microscreening system of screen mesh size of 120-micron or less ahead of the membrane pretreatment system. Typically, 500-micron 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 microns does not provide adequate protection of the membranes against sharp particles in seawater. These particles are finer and sharper than the particles usually occurring in fresh surface water or wastewater effluent.

In addition, seawater contains barnacles, which in their embryonic phase of development are 130 to 150 microns in size and can pass the screen openings unless they are 120 microns or smaller. If barnacle plankton passes the screens, it attaches to the walls of downstream pretreatment facilities grows on the walls and ultimately interferes 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-micron size) is essential for reliable operation of the entire seawater desalination plant using membrane pretreatment. Microscreens 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 is 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. Typically, fine traveling screens of 1/8 to 3/8-inch (3 to 10 mm) openings provide adequate protection of conventional granular media pretreatment systems.

However, membrane pretreatment eliminates the need for a cartridge filter system ahead of the SWRO pumps. Cartridge filters are needed when granular filtration system is used for pretreatment in order to protect the downstream SWRO membranes from damage caused by fine sand particles which may be occasionally conveyed with the pretreated seawater.

Occurrence of frequent and prolonged red tides or other algal blooms in the area of the seawater intake is another important factor to consider. Many of the marine microalgae which grow excessively during algal blooms cannot withstand external pressure of more than 0.5 bars and their cells would break when exposed to pressure or vacuum-driven

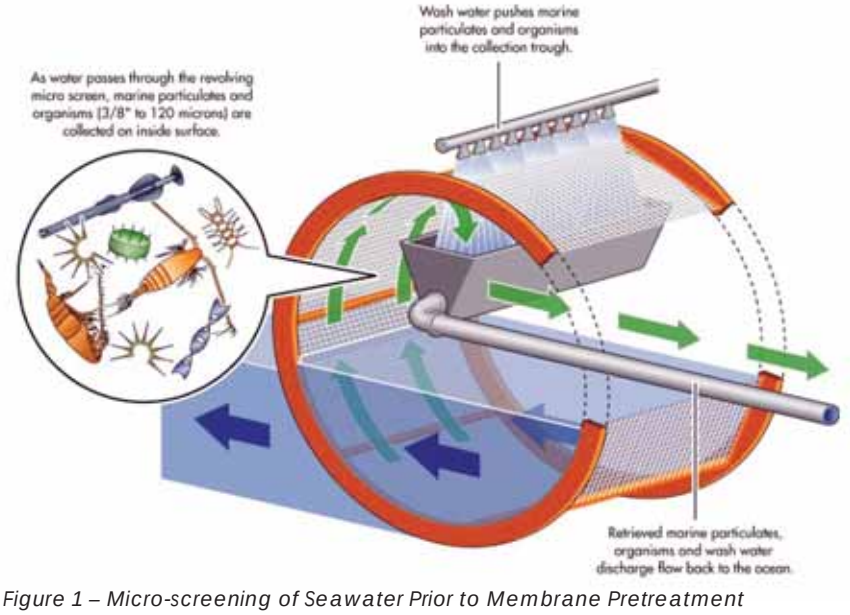

Figure 1 – Micro-screening of Seawater Prior to Membrane Pretreatment

Figure 2 – Cartridge Filter Vessel

Figure 3 – Seawater intake during red tide event

filtration. When algal cells break, they release easily biodegradable organic compounds, which could trigger accelerated growth and formation of biofilm of marine bacteria on the SWRO membranes. In turns, the accelerated biofilm formation, can foul the SWRO membranes and result in significant reduction of desalination plant production capacity within several weeks from the beginning of the algal bloom. In such source water conditions, gravity down-flow granular media filtration may be more desirable than membrane pretreatment because it allows to gently remove micro-algae from the source water without braking their cells and creating accelerated fouling of the SWRO membranes.

If membrane pretreatment is selected for desalination plants with open ocean intakes prone to frequent and extensive red tides or algal blooms, the use of dissolved air flotation (DAF) or granular media filtration system ahead of the membrane pretreatment facility is highly recommended.

Footprint

Membrane technologies are more space-efficient as compared to granular media filtration. The smaller footprint benefits of membrane filtration are usually of greater importance when upgrading existing water treatment plants of limited site area availability or where the cost of new land acquisition is significant and would weight heavily towards the use of more space-efficient technology.

Depending on the type and size of the membrane modules and the intake water quality characteristics, the membrane filtration system may have 20-60% smaller footprint than a conventional filtration system. The space benefits of membrane filtration are more significant for high-turbidity seawater where two-stage granular media filtration may be required to achieve comparable performance to a single stage membrane pretreatment system. For a more difficult to treat intake seawater, which requires the granular media filtration system to be designed for surface loading rates of less than 10 $m^3/m^2.hr$, or where two-stage granular media filtration is needed to produce comparable filter effluent, the membrane filtration systems may have up to 60% smaller footprint.

As a rule of thumb, under typical surface-water quality conditions, the footprint of granular media filters, designed at a surface loading rate of 8.5 to 12.2 $m^3/m^2.hr$ is approximately 30-50% larger than that of an ultra or micro-filtration systems producing similar filtered water quality. For better-than-average influent water quality where granular media filters can perform adequately at surface loading rates of 15 to 20 $m^3/m^2.hr$ of hydraulic surface loading rate, the total footprint difference is usually 20-40% in the benefit of membrane pretreatment.

Waste Stream Quantity and Quality

Conventional and membrane pretreatment systems differ significantly by the type, quality and amount of the generated waste streams. Typically, conventional media filtration systems generate only one waste stream – waste filter backwash. The volume of this stream in a well designed plant varies between 4 to 6 % of the total plant intake source water volume. In addition to the solids that were originally in the source water, this waste stream also contains coagulant (typically iron salt) and polymer.

The membrane pretreatment systems typically generate two large waste streams: waste membrane wash water and membrane cleaning solution. The volume of the membrane wash water stream is typically 8 to 12 % of the plant intake source volume – i.e. approximately 2 times larger than the waste filter backwash generated by conventional pretreatment systems. The waste stream difference is even larger, taking into account that the microscreens required to be installed to protect the pretreatment membrane filters will generate additional waste discharge for their cleaning. While conventional traveling fine bar screens use less than 0.5 % of the intake source water for cleaning, the microscreens would require wash volume which equals 1 to 3 % of the intake flow. The relatively larger waste stream volume of the membrane pretreatment system would require proportionally larger intake source volume, which in turn would result in increased size and construction costs for the desalination plant intake facilities and higher operation, and maintenance costs for source water pumping to the pretreatment facilities.

In addition to daily membrane washing and monthly membrane cleaning, cost competitive design and operation of membrane pretreatment systems often requires short daily chemically enhanced membrane backwash (CEB) using high dosage of chlorine and base and acid over a short period of time. This performance enhancing CEB also adds to the volume of the waste streams generated at the RO membrane plant and to the overall cost of source water pretreatment.

One advantage of the main membrane waste backwash stream is that it typically contains relatively less source water conditioning chemicals (coagulant and polymer) and therefore, it is more environmentally friendly as compared to the waste filter backwash stream from conventional pretreatment facilities. However, the other two waste streams generated during the CEB and monthly pretreatment membrane cleaning have to be pretreated on-site in a neutralization tank, prior to discharge. The additional treatment and disposal costs of the waste membrane cleaning chemicals have to be taken under consideration when selecting the use of membrane pretreatment systems over conventional granular media filtration.

Chemical Use

Typically, conventional granular media pretreatment systems use source water conditioning chemicals for effective solids separation. This adds to the plant chemical costs. However, they do not use any chemicals for media cleaning (outside of occasional addition of chlorine). The membrane pretreatment systems use significant amounts of membrane cleaning chemicals, which may be comparable in total annual cost to the source water conditioning chemicals used by the conventional granular media filters. The cost of these cleaning chemicals has to be considered in the cost-benefit analysis of the plant pretreatment system.

Another factor that has to be accounted for in the overall plant chemical use and cost analysis is that the RO system cleaning frequency, and therefore the SWRO membrane cleaning costs, may be reduced by using membrane pretreatment due to the typically better solids and silt removal capabilities of this type of pretreatment.

Power Use

Conventional pretreatment systems use limited amount of power to separate particulates in the source water. As mentioned

previously, large SWRO desalination plants typically include gravity granular filtration pretreatment process which has minimum power requirements. On the other hand, depending on the type of the membrane system (pressure or vaccum-driven) the membrane systems use approximately two times more power to remove particulates from the source water as compared to gravity granular media filters. More power is not only used to create a flow-driving pressure through the membranes, but also for membrane backwash and source seawater pumping. The total power use has to be taken into consideration when completing a life-cycle cost comparison of conventional versus membrane pretreatment system for a given application.

Economy of Scale

Membrane and granular media pretreatment systems may yield different economies of scale depending on the water treatment plant capacity. Usually, both technologies have a comparable economy of scale for plant capacity of up to 10 MGD (40,000 m³/day). For desalination plants with capacity of 10 to 50 MGD, the granular media filtration systems typically yield better economy of scale benefits. The anticipated economy of scale reduction of construction costs for membrane plant capacity increase from 10 MGD to 50 MGD) is in a range of 3 to 5 percent – i.e. the unit construction cost expressed in $/MGD of 10 MGD plant will be 3-5% higher than that for 50 MGD plant. In turn, granular media filtration plants may yield 10% or higher economy of scale related construction cost benefits.

The main reason for the smaller economy of scale benefit of the membrane pretreatment technologies for large-capacity plants is the maximum size of membrane modules currently available on the market. Typically, depending on the manufacturer and the membrane technology, the largest membrane modules available today are between 0.5 MGD to 1 MGD (2,000 to 4,000 m³/day) water production capacity, although recently some immersed membrane system manufacturers offer membrane modules of up to 5 MGD (20,000 m³/day) of production capacity. In comparison, the maximum size of the individual granular media filter cells can reach 8 MGD or more, thereby allowing higher overall construction cost reduction due to the fewer filter cells, and economy of scale associated with reduced service equipment and piping.

One of the current water treatment trends worldwide is the use of membrane technologies for large plant applications. As the number and type of large plant membrane application opportunities increases in the future, it is likely that the membrane manufacturers will develop larger-scale individual membrane modules, which would improve membrane system economy of scale and competitiveness for large plants.

Frequency of Filtration Media Replacement

Well-operating granular media filters lose 5-10% of filter media per year, which has to be replaced to maintain consistent performance. The costs of granular media replacement are usually well predictable and relatively low. At present, the useful life of membrane elements typically varies from three to five years. Assuming five years of useful life, on average approximately 20% of the membrane elements would need to be replaced per year to maintain system production capacity and performance.

An additional factor that may contribute to the need for more frequent replacement of membrane elements is the failure of membrane element integrity. In fact, a recent study of existing membrane systems in the US and worldwide indicates that in most or the surveyed installations, the main reason triggering the need for early membrane element replacement was the loss of integrity rather than the loss of production capacity. The limited track record of long-term use of membrane systems and the uncertainty related to the factors triggering the need for their replacement have to be taken under consideration when selecting between granular media and membrane pretreatment technology for RO plants. The risk of loss of membrane integrity has to be handled accordingly in the membrane element useful life warranty provided by the membrane manufacturer/supplier.

Taking under consideration that the annual costs for replacement of pretreatment membranes are usually comparable to the annual expenditures for replacement of the SWRO membranes they are installed to protect, the large expenditures for replacement of pretreatment membranes often render this type of pretreatment technology less attractive than conventional granular media pretreatment. Although theoretically, the use of membrane pretreatment instead of granular filtration should reduce the frequency of SWRO membrane cleaning and replacement, because of the lack of full-scale track record to prove this assumption, at present most SWRO membrane suppliers are reluctant to provide guarantees for longer useful life or cleaning cycles for their seawater membrane products. As a result, the potential benefit of membrane pretreatment cannot be easily accounted for in an actual cost-benefit analysis for full-scale seawater desalination projects.

Diversity of Membrane Elements and Configurations

Currently, all UF and MF membrane manufacturers offer their own design, size and configuration of membrane elements and systems. The membrane systems differ by the type of filtration driving force (pressure vs. vacuum); the size of the individual membrane elements; the size of the membrane vessels; the configuration of the membrane modules; the type of membrane element backwash; and the type of membrane integrity testing method.

The lack of product uniformity and commoditisation in the membrane market today is a sign of a fast-growing field of the water equipment industry and caries some benefits and disadvantages. The availability of multiple membrane suppliers and systems allows to better accommodate the site-specific needs of a given membrane application, thereby increasing the use of membrane systems for water treatment. In addition, the lack of commoditization of the MF and UF membrane market along with the increase in membrane applications in recent years, spurs the interest of many manufacturers which traditionally do not produce membranes to enter the membrane market with new products. This in turn, results in increased competition and in accelerated development of new membrane technologies and equipment. Several years ago, there were less than six membrane manufacturers which offered MF and UF membrane systems to the municipal market. This number has increased dramatically and today practically all large and many medium-size equipment manufacturers offer their own unique MF or UF membrane system.

The absence of standardisation of membrane size, vessels and configuration however, has a number of disadvantages that may hinder membrane system use, especially for large seawater desalination plants. As the membrane market gets oversaturated with manufacturers offering similar membrane products, the market growth is likely to exceed the demand, which would trigger the exit of some players. As a result, the manufacturers exiting the membrane market will no longer produce membrane elements and provide maintenance and support for their existing systems. Since their system configuration and membrane element and vessel type will be unique, the owners of such membrane systems will have to invest significant funds to modify their membrane installations in order to accommodate alternative membrane equipment.

The current diversity of membrane element sizes and configurations, and lack of standardization and commoditisation may have a number of disadvantages for the membrane plant owner in a long run. If an existing membrane manufacturer discontinues the production of membrane elements or a given type of membrane system (for example abandon production of pressure membrane systems in favor of submersible systems), the membrane plant owner would

incur additional costs to procure and install a new pretreatment system because the other available membrane systems would be incompatible with the owner's existing system. While replacing/retrofitting the existing system to accommodate new membranes, the membrane plant owner would likely face reduced plant production capacity due to the downtime needed for membrane system replacement and the fact that the productivity of old membrane elements, which cannot be replaced with alternative membrane product when needed, will decrease over time.

The membrane plant owner is likely to also incur additional costs to train their staff in operating and maintaining the new membrane pretreatment system. In addition, the membrane plant owner may experience a potential increase in unit membrane element and vessel costs over time, because the membrane elements have to be purchased from a sole-source manufacturer rather than to be competitively procured at market price. Considering that the membrane element costs have been reduced dramatically over the last ten years, this disadvantage may have significant consequences. The use of non-standardised membrane elements and vessels limits the opportunity of the membrane plant owner to take advantage of the use of new and improved membrane technologies, which might be available in the near future.

Recently, one of the key manufacturers of membrane elements, Dupont's subsidiary - Permasep decided to exit the market. At one time, Permasep had a dominant portion of the membrane seawater desalination market supplying hollow-fiber membrane elements to several thousand membrane installations worldwide. The hollow-fiber membrane elements and vessels used by Permasep were different from these used by other hollow-fiber membrane manufacturers, and incompatible with these of other manufacturers offering seawater desalination membranes. Permasep's exit from the membrane seawater desalination market triggered the need for significant modifications and expenditures by their customers to accommodate the necessary changes.

The standardization of membrane systems, elements and vessels has another significant advantage to the owner of the membrane facility, which has been proven by the desalination membrane market – the drastic reduction of membrane costs. Currently, the seawater desalination membranes and vessels are standardised in size and can be used interchangeably. The commoditisation of the seawater desalination market contributed to the two to three fold reduction of desalination membrane element costs over the past ten years, which on the other hand spurred the development of new large seawater desalination plants worldwide.

Another, often forgotten, benefit of membrane technology unification is the potential reduction in the cost of membrane plant funding, and therefore, of the overall cost of water production. The capital cost of a given project consists of two key elements – cost of construction and cost of capital needed to complete this construction. Since the cost of capital is typically 20 to 30% of the total capital cost of the entire project, using commoditized membrane systems could yield cost benefits sometimes higher than the savings resulting from using new and unique top-of-the-line technologies or equipment.

A membrane system which can accommodate a number of different membrane elements, vessels and equipment is considered a lower investment risk and therefore, a lower cost-of-capital system. Therefore, considering all other conditions being equal, the cost of capital (for example bond interest rate) for funding a project using standardised membranes or well-proven conventional granular media pretreatment system would typically be lower as compared to that for a system that uses a unique membrane system configuration and membrane elements, which cannot be supplied competitively from alternative manufacturers.

Although a new top-of-the-line membrane treatment system that has unique features may yield appreciable near-term construction and operation cost savings, these savings may be compromised over the useful life of the project, which is typically 30 years or more, if the system design is not flexible enough to accommodate the benefits of future membrane technologies, especially taking under consideration that the UF and MF membrane technologies are in an exponential stage of development today and new or improved products and systems are available almost every year.

Based on the current status and diversity of the micro and ultrafiltration technologies, a sound approach towards reducing risks associated with the funding and implementation of a membrane system is to design the system configuration in such a manner that would accommodate the replacement of this system/membrane elements with at least one other existing system/membrane elements of similar type. For example, if the preliminary engineering analysis and subsequent pilot testing indicate that a submersible vacuum driven type of membrane system is more suitable for a particular application, this membrane plant has to be designed to accommodate at least two submersible membrane systems currently available on the market. The additional construction and installation cost expenditures to provide flexible membrane system configuration that allows future membrane system modifications and use of alternative suppliers of the same type of membrane elements at minimal expenditure or replacement, are very likely to be compensated by lowering the funding costs (costs of capital) for the project and by minimizing the overall life-cycle costs of the membrane plant.

Lifecycle Costs

At present, the cost of production of desalinated water using membrane pretreatment is typically 5-10% higher than that for freshwater produced by desalination plants with conventional seawater pretreatment. In some cases, such as conditions when the cost and availability of land are at premium and/or unit chemical costs and energy are relatively low, membrane pretreatment may be more cost advantageous.

Key factors that are often underestimated or omitted when comparing conventional and membrane pretreatment systems are: (1) the additional capital and O&M costs of the micro-screening system needed to protect the pretreatment membranes; (2) the actual chemical costs and frequency of pretreatment membrane cleaning and chemically enhanced backwash; (3) the useful life and replacement costs of the pretreatment membranes – most analyses assume 5 years while actual operational data shows that membranes need to be replaced in approximately 3 years due to loss of integrity; (4) erroneous assumption that the SWRO membrane manufacturers will guarantee lower RO membrane replacement and cleaning frequencies if membrane pretreatment is used; (5) the higher cost of project financing associated with the use of membrane pretreatment because of the long-term risk associated with the use of technology of limited full-scale track record, especially for large-scale installations.

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. **AW**

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