

Advances in Seawater Desalination Technology

Why look to the ocean for fresh water?

World oceans contain over 97.2 percent of the planet's water resources. Because of the high salinity of ocean water and the significant costs associated with seawater desalination, most of the global water supply has traditionally come from fresh water sources—groundwater aquifers, rivers and lakes. Today, however, changing climate patterns combined with population growth pressures and limited availability of new and inexpensive fresh water supplies are shifting the water industry's attention. In an emerging trend, the world is reaching to the ocean for fresh water.

The ocean has two unique and distinctive features as a water supply source—it is drought-proof and is practically limitless. Over 50 percent of the Earth's population lives in urban centers bordering the ocean. In many arid parts of the world such as the Middle East, Australia, northern Africa and southern California, the population concentration along the coast exceeds 75 percent. Usually coastal zones are the highest population growth hot-spots as well. Therefore, seawater desalination provides the logical solution for sustainable, long-term management of the growing water demand pressures in coastal areas.

Until recently, seawater desalination was limited to desert-climate dominated regions. Technological advances and an associated decrease in water production costs over the past decade have expanded its use in coastal areas traditionally supplied with fresh water resources. Recent examples are the 86 mgd (325,000 m³/day) Ashkelon Seawater Desalination Plant in Israel and the 36 mgd (136,000 m³/day) Tuas Plant in Singapore. Both plants began operation in the second half of 2005 and currently produce high-quality water for potable, agricultural and

By Nikolay Voutchkov

nology of choice (mainly due to access to lower-cost fuel and traditional use of facilities co-generating power and water).

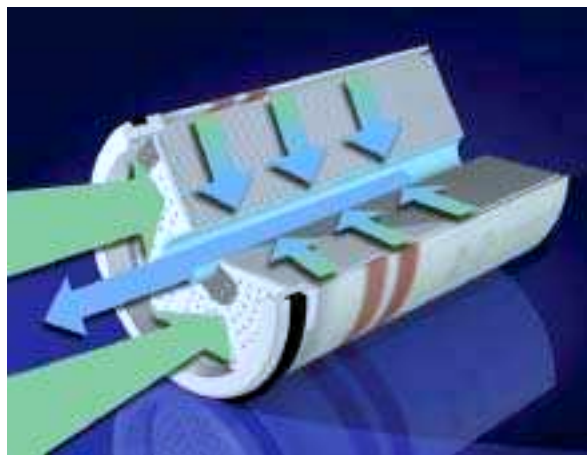


Figure 1. RO membranes—the 'work horse' of today's desalination plants

industrial uses at a price of US \$2/1,000 gallons and US \$1.81/1,000 gallons (US \$0.53/m³ and US \$0.48/m³), respectively.

Today, desalination plants provide approximately one percent of the world's drinking water supply and this percentage is increasing by the year. Over US \$10 billion of investment in the next five years would add 5.7 million cubic meters per day of new production capacity. This capacity is expected to double by the year 2015.

Two basic types of technologies have been widely used to date to separate salts from ocean water: thermal evaporation and membrane separation. In the last 10 years, seawater desalination using semi-permeable seawater reverse osmosis (SWRO) membranes (see Figure 1) has gained momentum and currently dominates desalination markets outside of the Middle Eastern region, where thermal evaporation is still the desalination tech-

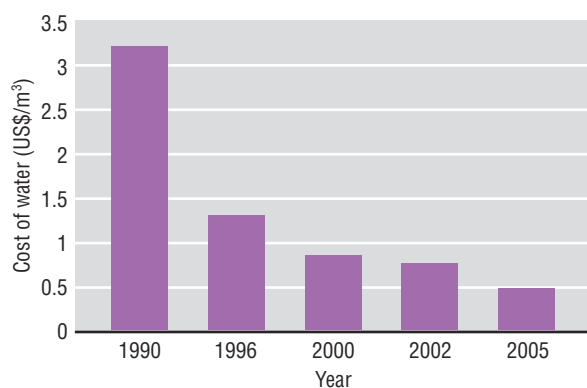
SWRO membrane technology and cost trends

Developments in seawater RO desalination technology during the past two decades, combined with transition to construction of large-capacity plants, co-location with power plant generation facilities and enhanced competition by using the Build-Own-Operate-Transfer (BOOT) method of project delivery have resulted in dramatic cost decreases. Figure 2 illustrates the trend of decreasing cost of water produced by membrane seawater desalination.

One of the key factors that contributed to reduction in the cost of seawater desalination is the advancement of the SWRO membrane technology. Today's high-productivity membrane elements are designed with two features that yield more fresh water per membrane element: higher surface area and denser membrane packing. Increasing active membrane leaf surface area allows it to gain significant productivity using the same size (diameter) membrane element. Active surface area of the membrane leaf is typically increased by improving and automating the membrane production process.

The total active surface area in a membrane element can also be increased by increasing membrane size/diameter. Although eight-inch (20.3-cm) SWRO membrane elements are still a standard size most widely used in large, full-scale applications, larger-size membrane elements have been used in the past and are

Figure 2. Historic trend of desalinated water cost reduction



expected in the not-so-distant future.

The newest membrane elements provide flexibility and choice and allow users to trade productivity and pressure/power costs. The same water product quality goals can be achieved either by (1) reducing the system footprint/construction costs by designing the system at higher productivity or by (2) reducing the system's overall

power demand by using more membrane elements, designing the system at lower flux and recovery and taking advantage of the newest energy recovery technologies, which further minimize energy use if the system is operated at lower recoveries (35 to 45 percent).

Technological advances lower energy use

Energy is one of the largest expenditures associated with seawater desalination. Figure 3 shows a typical breakdown of seawater desalination costs.

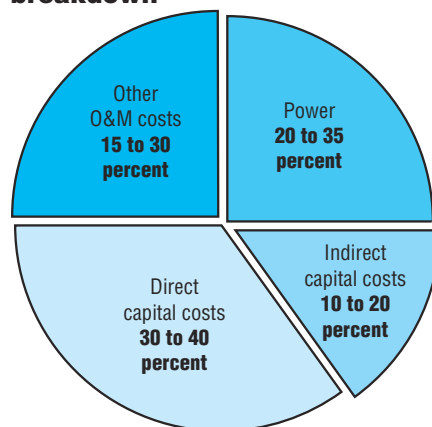
Advances in the technology and equipment allowing the recovery and reuse of the energy applied for seawater desalination have resulted in a reduction of 80 percent of the energy used for water production over the last 20 years.

At present, the majority of the existing seawater desalination plants use Pelton Wheel-based technology to recover energy from the SWRO concentrate. The largest Pelton Wheel system in the world is installed at the 36 mgd (136,000 m³/day) Point Lisas Seawater Desalination Plant in Trinidad (Figure 4). This power plant uses approximately 14.4 kWh/1,000 gallons (3.8 kWh/m³) of produced water. The Pelton Wheel sys-

currently commercially available.

In the second half of the 1990s, the typical eight-inch (20.3-cm) SWRO membrane element had a standard productivity of 5,000 to 6,000 gpd at salt rejection of 99.6 percent. In 2003, several membrane manufacturers introduced high-productivity seawater membrane elements that are capable of producing 7,500 gpd at salt rejection of 99.75 percent. Just one year later, even higher productivity (9,000 gpd at 99.7 percent rejection) seawater membrane elements were released on the market. Membrane elements combining productivity of 12,000 gpd and high-salinity rejection are

Figure 3. Desalination cost breakdown



tems allow recovery of 25 to 35 percent of the power initially applied by the SWRO system's feed pumps.

Over the past few years, the Pelton Wheel energy recovery systems have led the way to a newer, pressure exchanger-based technology. The key feature of this technology is that the energy of the SWRO system concentrate is directly applied to pistons that pump intake seawater into the system. Pressure-exchanger technology typically yields five-to-15-percent higher energy recovery savings than the Pelton Wheel-based systems. Therefore, pressure exchangers have been installed on most of the newer large desalination plants, including the recently completed 37 mgd (140,000 m³/day) Kwinana Seawater Desalination Plant for the city of Perth, Australia (see Figure 5).

Figure 6 depicts the configuration of a pressure exchanger-based energy recovery system planned to be used for the 50 mgd (200,000 m³/day) Carlsbad Seawater Desalination Plant in California, USA. This desalination plant will include 13 racks of RO membranes, each equipped with a separate pressure exchanger system. After membrane separation, most of the energy applied for desalination is contained in the concentrated stream (brine) that also contains the salts removed from the seawater. This energy-bearing stream (shown with red arrows on Figure 6) is applied to the back side of pistons of cylindrical isobaric chambers, also known as pressure exchangers (shown as yellow cylinders on Figure 6). These pistons pump approximately 45 to 50 percent of the total volume of seawater fed into the RO membranes for salt separation. Since a small amount of energy (four to six percent) is lost during the energy transfer from the concentrate to the feed water, this energy is added back to feed flow by small booster pumps to cover for the energy loss. The remainder (45 to 50 percent) of the feed flow is handled by high-pressure centrifugal pumps. Harnessing, transferring and reusing the energy applied for salt separation at very high efficiency by the pressure exchangers allows a dramatic reduction of the overall amount of electric power used for seawater desalination.

As a result of the use of this state-of-the-art technology, the total energy needed for the Carlsbad desalination plant to produce fresh drinking water

from seawater for one household per year (~2,000 kW/yr) will be less than the energy used to run the household's refrigerator.

In 2005, a group of US federal and state agencies, public utilities and private desalination industry leaders formed the



Figure 4. Largest Pelton Wheel energy recovery system in the world (Trinidad)

Affordable Desalination Collaboration (ADC), a team that has taken up the challenge to design a SWRO plant aimed at achieving the lowest currently possible power demand using state-of-the-art pumping and energy recovery equipment and latest membrane technology. The ADC team has installed a pilot SWRO plant at the US Navy's test facility in Pt. Hueneme, California (Figure 7) and operated this plant for a period of over nine months. The results show that potable water with salinity of less than

500 mg/L can be produced from Pacific Ocean water (salinity concentration of 33,500 mg/L) using less than 9.5 kWh/1,000 gallons (2.5 kWh/m³) of energy.

The main constraints today associated with achieving such low-energy use in large-scale desalination plants are the quality of the product water in terms of boron, chlorides and bromides and the efficiency of the available off-the-shelf pumps and motors used for source water collection, transfer and feed to the SWRO system. Often, the above-mentioned product water quality targets are driven by other more stringent uses, such as irrigation of boron- or chloride-sensitive crops and ornamental plants, rather than by water quality requirements for human consumption. Achieving these goals requires the addition of one or more water quality polishing facilities after the main SWRO desalination process, which in turn increases the overall energy consumption for water production.

While the quest to lower energy use continues, there are physical limitations to how low the energy demand could go using RO desalination. The main limiting factors are the osmotic pressure that would need to be overcome to separate the salts from the seawater and the amount of water that could be recovered from a cubic meter of seawater before the membrane separation process is hindered by salt scaling on the membrane surface and the service systems. This



Figure 5. Aerial view of Kwinana Seawater Desalination Plant (Perth, Australia)

Courtesy: Water Corporation of Western Australia

theoretical limit for the entire seawater desalination plant is approximately 4.5 kWh/1,000 gallons (1.2 kWh/m³).

Shifting the desalination plant design paradigm

As the costs of seawater desalination continue to fall in the future, SWRO plants are likely to become a prime (rather than a supplemental) source of water supply for many coastal communities with limited traditional local sources of fresh water supply. The SWRO plants servicing such areas have to be designed with the operational flexibility to match desalination plant production with the potable water demand patterns and to have a capacity availability factor of 96 percent or higher.

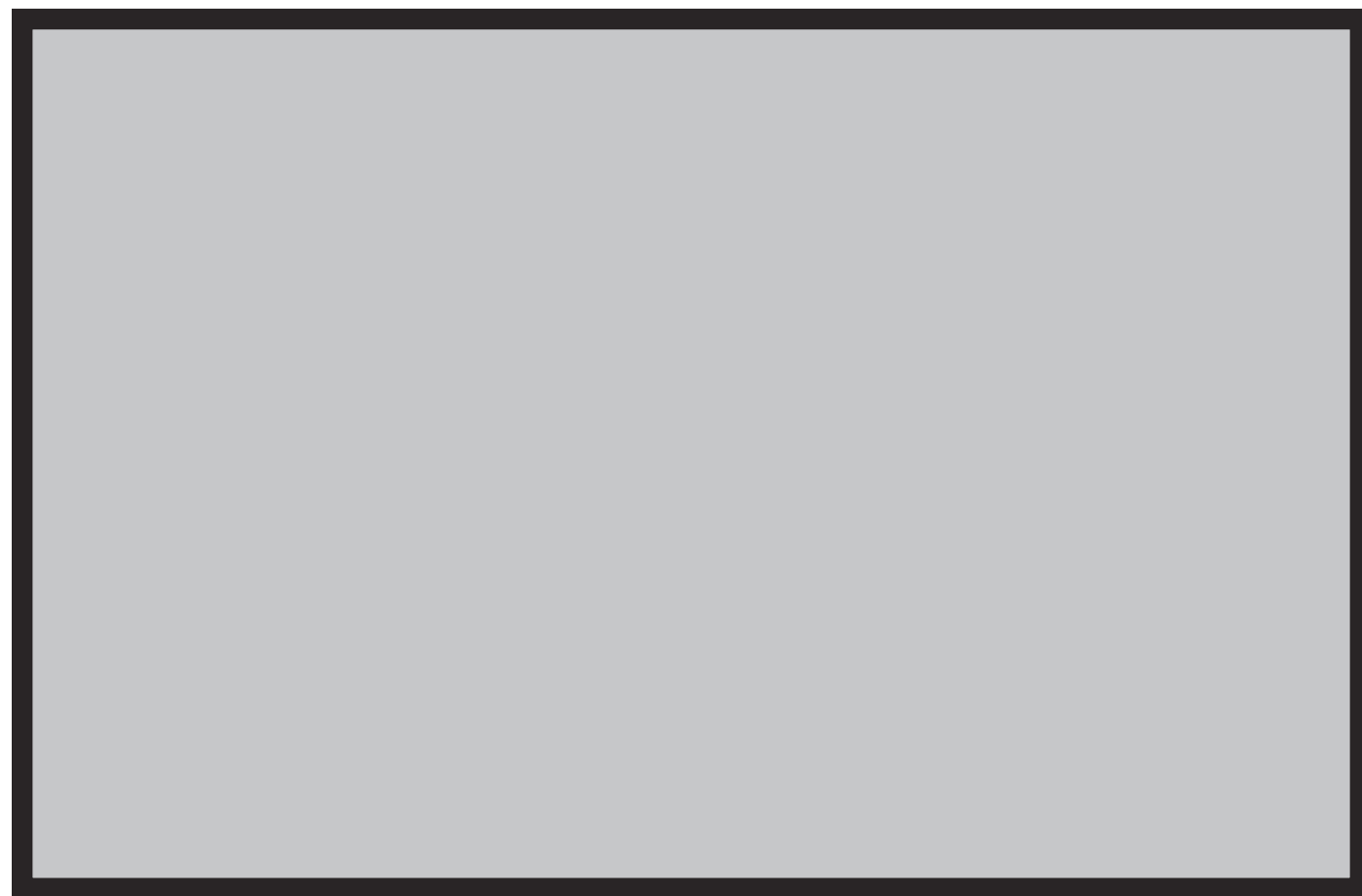
Shift of the SWRO plant operational paradigm from constant to variable production flow requires a change of the typical SWRO configuration from one that is most suitable for constant production output to one that is most cost-effective for delivery of varying permeate flows. A response to this paradigm shift is the three-center RO system configuration, which was implemented for the first time at the Ashkelon plant in Israel (see Figure 8). Under this configuration, the RO membrane vessels, high-pressure

pumps and the energy recovery equipment are no longer separated in individual RO trains, but are, rather, combined in three functional centers: a high-pressure RO feed pumping center, a membrane center and an energy recovery center. The three functional centers are interconnected via service piping.

The SWRO feed pumping center includes only a few large-capacity, high-pressure pumps that deliver seawater to the RO membrane center. The main benefit of using a limited number (one or two) of large-capacity, high-pressure pumps rather than a large number of small-capacity units is the gain in overall pumping efficiency. Typically, the smaller the ratio between the pressure and the flow delivered by a given pump, the better the pump efficiency and the 'flatter' the pump curve (i.e., the pump efficiency is less dependent of the variation of the delivered flow). Therefore, pump efficiency can be improved by either reducing pump pressure or by increasing pump flow. Since the pump operating pressure decrease is limited by the RO system target salt separation performance and the associated osmotic pressure, the main approach used in the three-center design to improve pump efficiency is to increase unit pump flow.

While a conventional-size, high-pressure RO feed pump of small capacity would typically have maximum total energy use efficiency of 80 to 83 percent, the use of 10-times larger-sized pumps may allow an increase of pump efficiency of 85 to 88 percent, especially for large SWRO plants. This beneficial feature of the three-center design is very valuable in the case of systems delivering varying product water flow.

While in a conventional RO train design, the membrane vessels are typically grouped in 100 to 200 units-per-train and in two to 20 RO trains, the membrane center configuration contains two to four times more RO vessel groups (banks) and a smaller number of membrane vessels per bank. Under this configuration the individual vessel banks are directly connected to the high-pressure pump feed lines and can be taken out of service one at a time for membrane replacement and cleaning. Although the feed water distribution piping for such membrane center configuration is more elaborate and costly than that of individual RO trains that contain two to three times more vessels per train, what is lost in capital expenditure is gained in overall system performance (reliability and availability). A recent reliability analysis



completed for a 95,000 m³/day SWRO plant recently completed by IDE Technologies indicates that the optimum number of vessels per bank for this scenario is 54 and number of RO banks-per-plant is 20. A typical RO train-based configuration would include two to four times more (108 to 216) vessels per RO train and two to four times less (five to 10) RO trains. According to this analysis, the use of the three-center configuration instead of the conventional RO train-based approach allows increased RO system availability from 92 to 98 percent, which is a significant benefit in terms of the additional amount of water delivered to customers and improvement in water supply reliability.

The centralized energy recovery system included in the three-center configuration uses high-efficiency, pressure exchanger-based energy recovery technology. This configuration allows improvement of the overall energy efficiency of the RO system and reduces system power, equipment and construction costs. Because of the high efficiency of the pressure exchangers, the energy penalty for operation at lower recovery is small. This allows operating the SWRO plant cost-effectively at a wide range of plant recovery while delivering variable product water flow. For example, if the SWRO plant output has to be reduced by 30 percent to accommodate low diurnal demand, an SWRO system with RO train-based configuration has to shut down 30 percent of its trains and if this low demand persists, it has to flush these trains in order to prepare them for the next start up. Frequent RO train starts and stops result in increased membrane cleaning costs, shorter membrane useful life and higher labor expenditures. An RO system with the three-center configuration would only need to lower its overall recovery in order to achieve the same reduction in diurnal water production. Although temporary operation at lower recovery would result in elevated costs

for pumping and pretreatment of larger volumes of source water, these extra operational expenses are typically compensated by the lower osmotic pressure needed to operate the SWRO system at lower recovery and by the high-energy recovery efficiency of the pressure-exchanger energy recovery system.

As indicated above, designing the SWRO plant around a higher capacity availability factor (90 percent versus 98 percent) results in an increase in the plant construction costs. Typically, the incremental cost of water increase to improve capacity availability from 90 percent to 95 percent is in a range of three to five percent. Increasing plant capacity availability factor from 95 to 98 percent usually is more costly and would result in five to 10 percent of additional water production costs. However, in many cases, the incremental costs associated with improved reliability can be compensated by the increased plant production capacity and reliability.

Future desalination technology advances

The future improvements of the SWRO membrane technology are forecasted to encompass:

- development of membranes of higher salt and pathogen rejection and productivity and reduced trans-membrane pressure and fouling potential;
- improvement of membrane resis-

Figure 7. ADC Seawater Desalination Facility (Pt. Hueneme, California)



tance to oxidants, elevated temperature and compaction;

- extension of membrane useful life beyond 10 years;
- integration of membrane pretreatment, advanced energy recovery and SWRO systems;
- integration of brackish and seawater desalination systems;
- development of a new generation of high-efficiency pumps and energy recovery systems for SWRO applications;
- replacement of key stainless steel desalination plant components with

plastic components to increase plant longevity and decrease overall cost of water production;

- reduction of membrane element costs by complete automation of the entire production and testing process;
- development of methods for low-cost continuous membrane cleaning which

Figure 6. Pressure exchanger energy recovery system

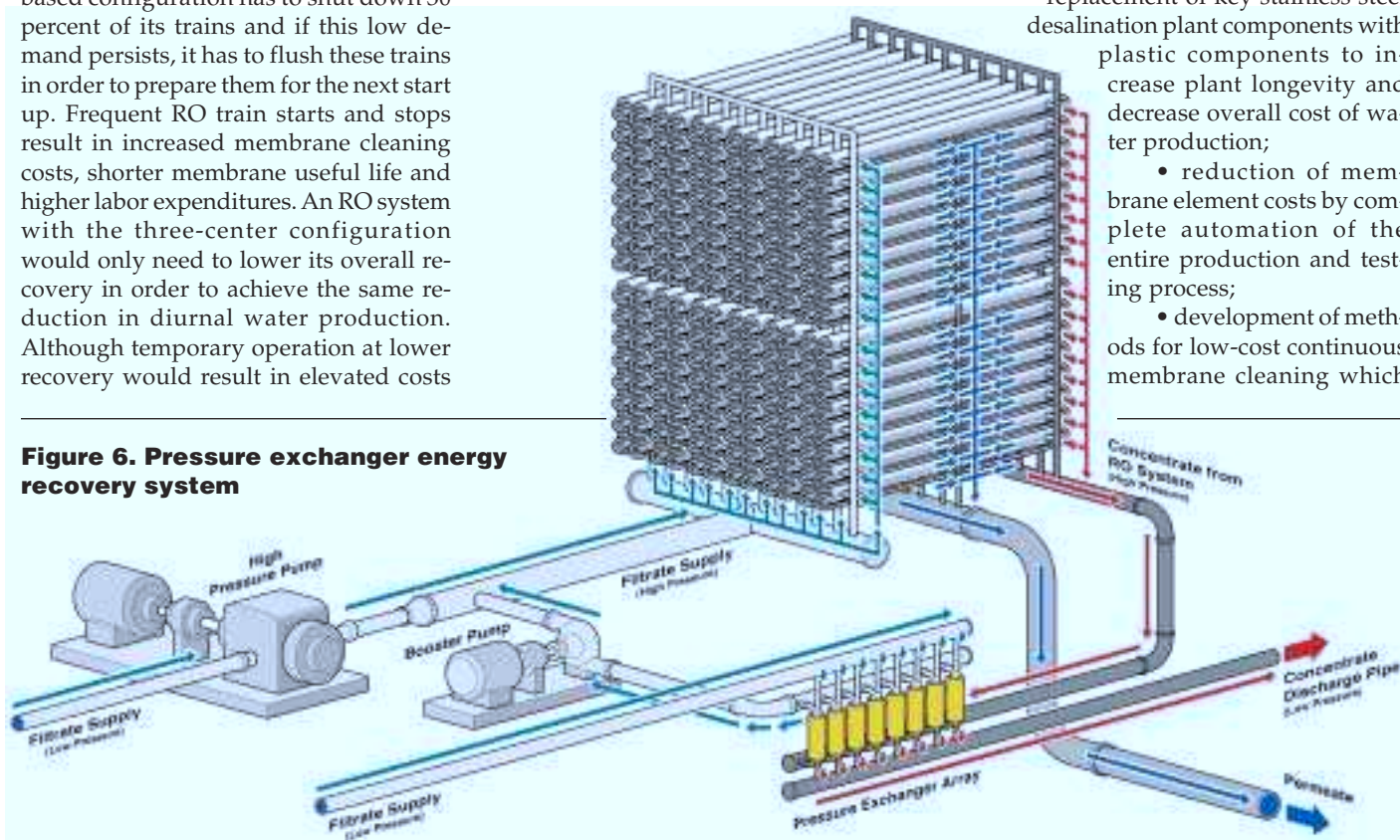
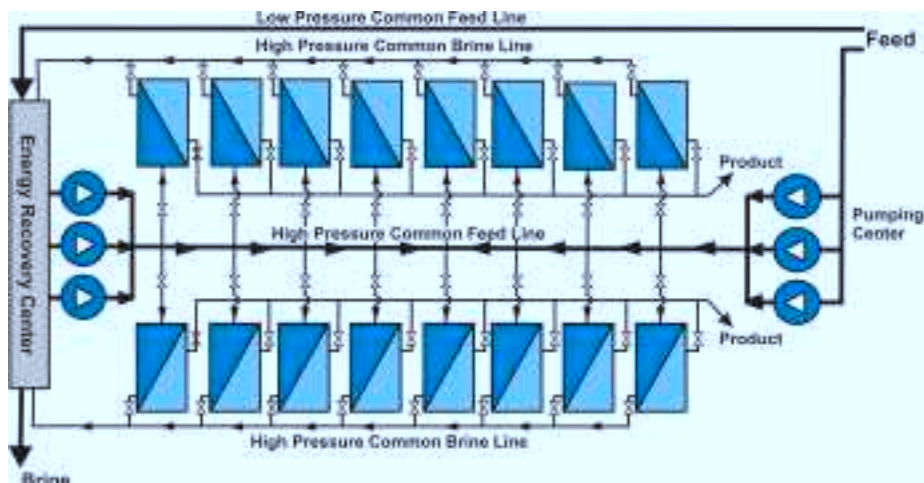


Figure 8. Three-center SWRO system

Courtesy: IDE Technologies



allow reduced downtime and chemical cleaning costs;

- development of methods for low-cost membrane concentrate treatment, in-plant and off-site reuse and disposal.

Key areas of development of RO membrane technology are associated with the increase in the productivity of the membrane elements, their resistance to fouling by the contaminants contained in the source water and their durability and longevity. The quest for an increase

of the productivity of the RO membrane elements has taken two directions: development of larger diameter membrane elements and the improvements in the membrane structure and chemistry that can allow more flow to be produced by a square inch of RO membrane area.

Over the last three years, several 16- to 20-inch diameter brackish and seawater RO elements were introduced as commercially available products on the market. These large-diameter RO ele-

ments are more competitive than the current standard eight-inch diameter RO membranes used mainly for large brackish water and seawater desalination applications, where they can yield 10 to 27 percent construction cost savings. Savings are less significant for water reclamation applications (seven to 17 percent). It is expected that the variety of commercially available large-size RO products will consolidate around a standard size 16- or 18-inch membrane element that is projected to find industry-wide use for large RO plants over the next five to 10 years.

Researchers at the University of California-Los Angeles have recently developed a new RO membrane that uses a cross-linked matrix of polymers and engineered nano-particles, which are specifically designed to provide accelerated draw of water ions but reject nearly all contaminants. While the structure of the existing RO membranes is such that the water molecules have to pass through a lengthy curvilinear path to reach the other side of the membrane, the matrix of the new membranes is structured at the nano-scale to create molecular tunnels which shorten and expedite water transfer and thereby produce more fresh water per square of membrane. This new

thin-film, nano-composite RO membrane technology would almost double the productivity of the membrane elements and further reduce capital, operation and maintenance costs for water production. In addition, the new technology is expected to have lower fouling properties and repel organics, thereby reducing costs for membrane cleaning and energy use by 25 to 50 percent as well as increasing the useful life of the membrane elements. The new RO membrane technology is in the early stages of commercial development and is expected to be available within the next five to eight years.

The advance of RO technology is closest in dynamics to that of computer technology. While conventional technologies, such as sedimentation and filtration have seen modest advancement since their initial use for potable water treatment several centuries ago, new, more efficient seawater desalination membranes and membrane technologies and equipment improvements are released every several years.

Similar to computers, the RO membranes of today are many times smaller, more productive and cheaper than the first working prototypes. Over the last 10 years, the cost of producing desalinated seawater dropped more than two-fold.

Although, no major technology breakthroughs are expected to bring the cost of seawater desalination down further dramatically in the next two to three years, the continued advances in RO membrane science and technology are likely to yield new breakthroughs in the reduction of water production costs, which coupled with increasing costs of conventional water treatment driven by water scarcity, global warming and more stringent regulatory requirements, are expected to accelerate the current trend of increased reliance on the RO technology in all areas of water supply: water reclamation and reuse, brackish water desalination and seawater desalination. This trend is forecasted to continue in the future and to further establish the role of RO technology in fresh water production worldwide.

About the author

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About the company

◆ *Poseidon Resources is a company that develops, invests in and manages water supply projects with a focus on seawater desalination, water treatment and reuse. Providing an essential service for local governments, Poseidon participates in public-private sector partnerships in which private enterprise assumes the risk of project development while enabling local governments and water authorities to fund other essential needs. Poseidon is ranked as a top 10 developer and has developed, financed and constructed over \$2.8 billion of infrastructure projects. They are headquartered in Stamford, Conn. with offices in Long Beach and San Diego Calif. Currently, the company is developing the largest seawater desalination projects in the US: 50 mgd plants in Carlsbad and Huntington Beach, Calif.*

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