The Evolution of **RO Desalination**

By Val S. Frenkel

How RO technology got its start, and where it stands today

Figure 1. Average Nominal Rejection Rates

Contaminant	% nominal rejection
Aluminum	96-98
Bacteria	99+
Boron	60-80
Cadmium	93-97
Chloride	92-95
Copper	96-98
Fluoride	92-95
Iron	96-98
Manganese	96-98
Mercury	94-97
Nitrate	90-95
Phosphate	95-98
Potassium	93-97
Silica	80-90
Silver	93-96
Sulfate	96-98
Zinc	96-98
Ammonium	80-90
Borate	30-50
Bromide	90-95
Calcium	93-98
Chromate	85-95
Cyanide	85-95
Hardness Ca & Mg	93-97
Lead	95-98
Magnesium	93-98
Nickel	96-98
Orthophosphate	96-98
Polyphosphate	96-98
Radioactivity	93-97
Silicate	92-95
Sodium	92-98
Thoisulfate	96-98

How did reverse osmosis (RO) technology get started? In order to understand its history, let's begin with a close look into osmosis. One of the most interesting and fascinating natural phenomena, osmosis is the basis for RO, today's fastest-growing desalination technology. Natural osmosis governs how waters transfer between solutions with different concentrations. It is also the basis for the way in which human skin and organs function, and how flora and fauna maintain a water balance.

Due to the nature of the RO process, it cannot be characterized as a filtration process or as treatment. As in natural osmosis, water tends to flow from a solution with a lower concentration to a solution with a higher concentration. Where there is a semi-permeable barrier such as a membrane, when pressure is applied to a concentrated solution that exceeds osmotic pressure, clean water will be displaced out of the concentrated solution while salts will remain in the concentrated solution.

Theoretically, salts should not pass through the membrane, but in practice salt leakages occur as a result of the diffusion despite the fact that membrane "openings" are much larger than the molecules of water and many other ions in the water that may pass through the membrane.

The RO process attracted the attention of many scientists and engineers in the middle of the 20th century, but efforts to develop a commercial RO membrane were unsuccessful until the late 1950s. In 1959, a group of scientists at the University of California Los Angeles (UCLA) led by Sidney Loeb and Srinivasa Sourirajan demonstrated an RO membrane that worked. The asymmetric, or anisotropic cellulose acetate, membrane demonstrated by the researchers provided adequate salt rejection at that time. This was the beginning of desalination by RO and membrane desalination. Besides membrane desalination, this was also the beginning of the commercial development of membrane technologies for solid-liquid separation.

The RO process has three major streams:

1. Feed;
2. Permeate (product water); and
3. Concentrate (reject or brine).

The mass balance for the entire system can be represented as follows:

$$Qf \times Cf = Qc \times Cc + Qp \times Cp$$

In this equation:

- Qf = feed flow (gpm or cu meters/hour);
- Cf = salt concentration in feedwater (mg/L or ppm);
- Qc = concentrate flow (gpm or cu meters/hour);
- Cc = salt concentration in concentrate (mg/L or ppm);
- Qp = product flow (gpm or cu meters/hour); and
- Cp = salt concentration in product water (mg/L or ppm).

The smallest module of the RO system is the RO membrane element. As RO technology developed, the industry came to a consensus on manufacturing standard-size RO membrane elements. The major diameters of the spiral-wound elements are 2.5, 4 and 8 in., with the standard length of single elements at 40 and 60 in.

More recently, the RO industry has developed larger RO elements with diameters of 16, 17, 18 and 18.5 in. While there is no consensus currently on a standard for large-diameter RO—each supplier produces a different size—this situation may change as time passes. Each model of the RO element has certain "fixed" properties that are described and can be found in the element's specification sheet. Little variation is allowed from the membrane element specification when each element is subjected to factory wet tests.

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In a full-scale system, the RO elements are encapsulated in pressure vessels that can hold from one single element up to eight elements per vessel. A number of vessels are mounted on the RO rack or train and can be operated in parallel or in series. Despite the fact that an RO system comprises a number of RO membrane elements with very similar properties, there are a number of design and operational techniques that can make RO system design and operation extremely flexible.

Because they cannot tolerate particulate matter of any kind, RO membranes require pretreatment consisting of different types of filtration and/or separation processes as well as feedwater conditioning by chemicals. In addition, treated water or RO product water needs conditioning and stabilization due to the fact that it is unstable and corrosive as a result. The RO reject carries significant energy, which can be returned back to the process, minimizing and optimizing the overall energy demand for the RO process. The entire RO system should be optimized for capital, operation and maintenance (O&M) and life-span costs of the produced water.

Following the development of RO membranes came development of the low-pressure membranes: microfiltration (MF) and ultrafiltration (UF), which were commercialized for drinking water treatment about a decade ago. Because they provide significant technical benefits and have become cost-competitive, membrane technologies rapidly are displacing and replacing traditional processes verified by the centuries.

As a result, four major membrane types, categorized by membrane pore size, are in commercial use at the present time:

1. MF, with screens particles from 0.1 to 0.5 microns;
2. UF, with screens particles from 0.005 to 0.05 microns;
3. Nanofiltration (NF), with screens particles from 0.0005 to 0.001 microns; and
4. RO, with ranging molecular sizes down to 10 MWCO.

The differences in membrane shape and the type of driving forces can be categorized as follows:

- ***Membrane shape type***: Spiral wound, hollow fiber or flat sheet; and
- ***Membrane type depending on driven pressure***: Pressure driven (low-pressure MF, UF and high-pressure NF and RO) and immersed, vacuum driven (low-pressure MF, UF only).

Desal by RO

Given the Earth's available water resources, there are few alternatives. Engineers and scientists were challenged by President John F. Kennedy in April 1961 when he said: "If we could ever competitively, at a cheap rate, get freshwater from salt water, that would be in the long-range interest of humanity and would dwarf any other scientific accomplishments." In the long run, seawater is the only long-term, completely reliable source of drinking water for future generations.

Long before desalination by RO was developed, thermal desalination processes already were well commercialized. The oldest non-membrane desalination methods are based on evaporating water and collecting the condensate. The best-known thermal technologies are: multistage flash (MSF), multi-effect distillation (MED) and vapor compression (VC). While MSF, MED and VC use thermal power to separate water from the brine, electrodialysis reversal uses high-voltage current to remove cations and anions from the stream.

The newest commercial technology for desalination is based on membrane treatment. RO and brackish water RO, or seawater RO (SWRO), are the fastest-growing desalination techniques, with the greatest number of installations around the globe. Desalination by RO is beginning to dominate the current and future desalination markets. Many business forecasts predict that desalination by RO will grow at a compound annual growth rate of about 10% annually and will eventually triple the market capacity over the next 10 years, reaching about 55 billion cu meters of water per year. Desalination by membranes, SWRO is beginning to dominate the current and future desalination markets due to the energy recovery utilization, improved membrane properties and lower costs for membrane elements. The current number of membrane desalination installations is close to 80% of all desalination facilities.

While membrane plants using desalination by RO have the largest number of installations, they still provide only a comparable capacity to the thermal processes. The lack of correlation between the number of installations and overall capacities can be explained by the development of desalination. Thermal processes have been on the market for more than five decades, and most of them provide relatively high capacities. This ratio is expected to change significantly, though, because most of the desalination systems currently designed, constructed and considered for construction are based on membrane technology.

For example, currently the largest operational membrane desalination plant in the U.S. is the Tampa Bay SWRO, with a capacity of 25 million gal per day (mgd), with provision for up to 35 mgd. The plant went into operation in 2003. The newly considered 50-mgd Carlsbad desalination plant plans to use SWRO membrane technology. A much larger membrane desalination facility was commissioned in May 2005 in Israel: the Ashkelon SWRO, with a capacity of 44 mgd, which was expanded to 88 mgd at the end of 2005. In addition, very large SWRO projects are currently being developed in Australia and Spain.

When different technologies, including thermal processes, were evaluated for these large desalination facilities, membrane desalination SWRO provided the most cost-effective solution for all considerations, including capital expenditures, O&M and cost per 1,000 gal of treated water based on 20 to 30 years of operation. As positive results emerge from large SWRO facilities in operation, there will be greater security and confidence in building SWRO plants with larger capacities. A major factor that has prevented the widespread use of membrane desalination has been the high energy demand for the process, which is affected mainly by the water salinity (total dissolved solids), water temperature and system recovery.

Advances in the development of major SWRO components have led to a preference for membranes over thermal processes and have boosted growth in the number of RO plants worldwide. These include:

- The development of the energy recovery exchangers of different configurations with a typical energy recovery of more than 90% of the concentrate stream;
- Development of new advanced membrane materials such as thin-film composite (TFC) membranes with advanced membrane properties;
- Advances and collection of design and operational experience in the use of SWRO;
- Improvements in pretreatment, such as the introduction of MF and UF; and
- Significant reduction in capital and O&M costs.

Advances in SWRO have fueled a preference for membranes over thermal processes and increased growth of RO plants worldwide.

Salt rejection and individual ion rejection by RO technology is very high, reaching 99.8% salt rejection by one single RO membrane element at the standard conditions that are available on the market. When compiled with the RO system, the overall salt rejection by the RO system can reach 95% or more. The average nominal rejection of individual ions by RO is shown in Figure 1.

Osmosis & RO Outlook

Three major improvements in the technology can be identified:

1. ***Improvements of the RO technologies and RO process.*** Membrane materials, energy optimization, large-scale plant design optimization, construction and procurement optimization.
2. ***Nanomaterials and nanoparticles.*** Modification of the RO materials utilizing nanomaterials and nanoparticles to achieve lower energy demand for the process and higher permeability of the membranes while keeping membrane fouling low or comparable to the existing commercial RO membrane materials.
3. ***Forward osmosis.*** Utilizing draw solution with high osmotic pressure when utilizing ammonia, carbon dioxide or other ingredients for the draw solution.
4. ***Pressure-retarded osmosis.*** Utilizing differences in osmotic pressure of different solutions to generate osmotic power where rivers meet oceans or wastewater is discharged to the sea.

RO has become one of the key technologies for desalinating water. RO is one of the fastest-growing technologies spreading around the globe due to its advanced features and the reduction in cost as the technology develops. It has become cost effective for many water and wastewater treatment and desalination applications, replacing conventional processes while providing benefits for new construction, upgrades and retrofits of existing facilities.

RO also offers the advantages of high effluent water quality, a compact footprint and simpler operation compared to conventional treatment processes. MT

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