

Fundamentals of RO-NF technology  
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Introduction

Membrane desalination is a mature technology, applied commercially worldwide to reduce salinity in potable water, wastewater reclamation and industrial applications. Power consumption of reverse osmosis (RO) desalination process is the lowest among the commercial desalination methods. The overall product water cost is compatible with other alternatives of potable water supply. Design, engineering and operation of reverse osmosis systems is well established process and desalination plants of capacity exceeding 300,000 m<sup>3</sup>/day are being currently built. Equipment used in reverse osmosis plants (pumps, piping, valves, instrumentation...) represents standard type equipment, used in number of process industries. Membrane elements from different manufacturers have the same geometry, outside dimensions and similar performance. They are easily interchangeable in the RO desalination systems. Manufacturers warranted longevity of membrane elements, in large commercial systems, currently exceeds five years of operation. The critical process issue in RO applications is prevention of membrane fouling, which is a process of deposition of feed water born substances on membrane surfaces. The problem of membrane fouling is practically non existing in RO plants operating on feed water from dedicated brackish wells. In RO plants, that utilize surface intake or treat wastewater effluent, membrane fouling prevention is an important issue that requires adequate design and operation of the feed water pretreatment system. In inland based RO and nanofiltration systems concentrate disposal is a major design issue affecting adversely economics of the desalination projects. The unique components of the reverse osmosis desalination system are membrane elements. The majority of current offering of RO elements are in spiral wound configuration. However, some seawater desalination systems utilize hollow fiber modules. The critical performance parameters of membrane modules are salt rejection and water permeability. These have been continuously improving. The average permeate flow per element in seawater system is about 12 m<sup>3</sup>/day and in brackish system is about 23 m<sup>3</sup>/day. The RO membranes are characterized by high rejection of total dissolved solids (TDS) in the range of 98% to 99.5%. The nanofiltration (NF) or softening membranes are characterized by higher water permeability than the RO membranes (therefore NF systems operate at lower feed pressure than it is required for the RO units) and significantly lower TDS rejection: from 95% down to non significant. However, the NF membranes have sufficiently high rejection of selected constituents, such as hardness, metals (Fe) and organic matters. This unique property enables improvement of impaired, low salinity, water sources to the potable quality standards, applying this low pressure membrane separation process. Membrane elements are operated in pressure vessels, 7 – 8 elements per vessel. RO trains consist of a parallel array of pressure vessels, up to few hundred pressure vessels per train. RO system permeate has very low hardness and alkalinity, and therefore, it has quite high corrosion potential. Before introduction of RO permeate to the potable distribution system network it has to be stabilized by increasing its calcium and alkalinity concentration levels. The major components of RO (or NF) systems are feed water supply unit, high pressure pumping unit, membrane trains, permeate water stabilization and

storage unit and the control system. The feed water supply unit consists of multiple wells (brackish RO and NF systems) or open intake (seawater RO). For seawater RO plants it is growing tendency to utilize as a feed water the hot outlet seawater from the steam condenser of seashore located power plant or thermal desalination systems. This approach reduces cost of the desalination system and simplifies the permitting process. The major objective of the feed water pretreatment system is to remove particulate matter from the raw water and add chemicals (acid or scale inhibitor) to prevent membrane scaling. For the well water sources, use of cartridge filtration, is a sufficient pretreatment process. Water originated from an open intake requires more extensive pretreatment: flocculation followed by media filtration and cartridge filtration. RO wastewater reclamation systems use almost exclusively membrane pretreatment (ultrafiltration or microfiltration). The high pressure pumping unit consists of pumps, to produce required feed pressure, and (in seawater RO systems) power recovery devices to recover energy of the concentrate stream. The efficiencies of pumps, electric motors and power recovery devices have been improved considerably during the last few years. Due to these improvements, power consumption in the range of 3 – 4 kwhr/m<sup>3</sup> is quite common in seawater desalination systems. In low pressure RO or NF systems specific power consumption is below 1 kwhr/m<sup>3</sup>. Operation of RO systems is highly automated using electronic sensors and programmable logic controllers. Manual labor is mainly limited to performance monitoring and equipment maintenance.

### System configuration

The selection of process components of RO-NF system is affected to the great extent by the type of water the membrane plant will process. In general a RO-NF plant will consist of the following system components and treatment steps:

- Raw water source
  - Wells
  - Intake
  - Concentrate disposal unit
- Pretreatment
  - Screening
  - Settling
  - Coagulation
  - Filtration (conventional or membranes)
  - Chemical conditioning (acid and/or scale inhibitor)
  - Cartridge filtration
- High pressure pumping unit
  - High pressure pumps
  - Power recovery equipment
- RO trains
- Permeate treatment, conditioning and storage.
- Instrumentation and control
- Electric system including motor control center
- Membrane cleaning unit.

Type of feed water and its quality will affect mainly configuration of the feed water pretreatment unit. In RO systems treating well water (brackish or seawater) the pretreatment can be limited just to addition of scale inhibitor and cartridge filtration (Fig 1). On the other side of the pretreatment configuration spectrum, when treating the surface water from an open intake, the pretreatment unit could include number of process steps: screening, coagulation, settling, multistage media filtration, acid or scale inhibitor addition and cartridge filtration (Fig 2). In locations with especially difficult raw water quality or severe footprint limitations, membrane pretreatment can be applied (Fig 3). In case of seawater system, using conventional pretreatment, the combined pretreatment system and RO building area requirements are about 35 – 40 m<sup>2</sup>/1000 m<sup>3</sup>/day permeate capacity. In case of membrane pretreatment the required area can be reduced by about 25%. The over all area of the plant site is usually 3 – 5 times the combined area of pretreatment and RO building.

#### Membrane elements and RO unit configuration.

The objective of the pretreatment system is to remove from the raw water the particulate matter that could otherwise plug feed channels of the reverse osmosis element. The spiral membrane element, shown in Fig 4, consists on number of membrane envelopes, connected to central perforated tube and wrapped around. The membrane envelopes are separated by feed spacer. The feed spacer, in addition to forming a feed channels also promotes turbulence and mixing of the feed – concentrate stream. The feed channel is about 0.7 mm thick. The commercial membrane elements are 20 cm in diameter, 100 cm long. Each element contains about 37 m<sup>2</sup> of active membrane area. In field applications seawater element produces 11 – 13 m<sup>3</sup>/day of permeate. Permeate capacity of brackish RO element is about double that of the seawater. Membrane elements are connected in series inside a pressure vessel (Fig 5). Pressure vessel can operate with 6 to 8 elements connected in series. For example a 100,000 m<sup>3</sup>/day permeate capacity seawater RO system would require about 8400 membrane elements and 1400 or 1050 pressure vessels. The number of pressure vessels will depend if six or eight elements per vessel configuration is being used. Number of pressure vessels affects cost of RO trains as it is function of the cost of pressure vessels and connecting piping. The recent design trend is to increase number of elements per vessel to eight. Pressure vessels are arranged in a train parallel array of a single or two stage configuration (Fig 6, 7 and 8). In some applications, if single pass can not produce required permeate quality, a partial or full second pass permeate processing is applied (Fig 9). In large commercial systems number of pressure vessels per train ranges between 100 to 200. This determines the permeate capacity per train, in seawater systems, as being 7,000 – 20,000 m<sup>3</sup>/day. In brackish water systems the corresponding train size will have twice the above capacity.

#### The pumping system – power consumption.

In RO system the process water flows through number of pumping stages. The raw water is pumped from the well or intake to the pretreatment system. Processing in the

pretreatment system may require additional pressure increase to reach feed water storage (clear well). At the clear well a transfer pump crates sufficient head for the feed water to flow through the cartridge filters to the suction of the high pressure pump. The transfer pump is usually equipped with variable frequency driver to adjust feed pressure according to fluctuation of temperature or feed salinity. Next, the feed water is pressurized by high pressure pump and enters the membrane array, where it is split into two streams: permeate and concentrate. Permeate leaves the membrane array at pressure slightly higher than the ambient pressure. Pressure of the concentrate is reduced, from the initial feed pressure, by the pressure drop across the array (1 – 3 bar per stage). The energy of the concentrate can be recovered by passing concentrate stream through energy recovery devices. For practical reasons the feed pressure has to be higher than the sum of osmotic pressure of the concentrate and pressure drop across the pressure vessel array. The required feed pressure is function of feed salinity, recovery rate, feed temperature and permeate flux rate. The power consumption of the RO process is sum of contributions of various components as listed in the following equations:

$$\text{Energy total} = E_{ws} + E_{tp} + E_{hpp} + E_{pr} + E_{aux} - E_{tur}$$

$$\text{Pump kWhr/m}^3 = 0.02724 * P_f / (R * E_{fp} * E_{fm})$$

$$\text{Turbine kWhr/m}^3 = 0.02724 * P_c * (1 - R) * E_{ft} / (R * E_{fm})$$

$P_f$  – pump pressure

$E_{fm}$  - motor efficiency

$P_c$  – concentrate pressure

$E_{ws}$  - energy for water supply

$R$  – recovery rate

$E_{tp}$  - energy for transfer pump

$E_{fp}$  – pump efficiency

$E_{hpp}$  – energy high pressure pump

$E_{ft}$  – turbine efficiency

$E_{pr}$  – energy of product pump

$E_{tur}$  – energy of turbine

$E_{aux}$  – energy of aux equipment

In seawater systems, usually the high pressure pumping unit provides the major contribution (over 85%) to the combined power consumption of the process (Fig 10). The fraction of power, recovered by the power recovery device, depends on type and efficiency of the power recovery equipment used. In the past, the frequent used power recovery device was a reverse running pump. It was replaced gradually by impact wheel (pelton wheel), which has higher transformation efficiency than reverse running pump, and the efficiency value does not change much with the fluctuation of flow or pressure of the concentrate. The system configuration, utilizing pelton wheel power recovery device is shown in Fig 11. The disadvantage of Pelton wheel equipment is that the concentrate exits from this device at atmospheric pressure and has to be able freely flow to the discharge, or has to be pumped. The efficiency of commercial pelton wheel device can reach 88%. New power recovery devices, being introduced recently commercially, are pressure exchangers. Pressure exchanger is a positive displacement type equipment. In some type of this equipment energy of the concentrate is transfer to the feed using moving metal diaphragm (piston). In other pressure exchangers there is a direct contact between concentrate and feed stream. A flow diagram of system with pressure exchanger is shown in Fig 12. In the pumping system configuration which utilizes pressure exchanger, the feed water stream is split into two streams F1 and F2. The F1 stream has the same flow rate as the permeate P. The flow rate of the F2 is the same as concentrate

stream C. The high pressure pump, P1, increases pressure of F1 to the required feed pressure. The F2 stream exchanges pressure with the concentrate stream C in the pressure exchanger device. The efficiency of pressure exchanger is high, in the range of 94 – 96%. After the pressure exchanger the pressure of F2 is about 15% lower than the feed pressure. This pressure boost is provided by the pump P2. Due to high efficiency of pressure exchangers the power consumption in systems using this device is lower than in systems with power recovery turbines. The disadvantages of the pressure exchanges are small throughput of these devices, currently not exceeding 100 m<sup>3</sup>/hr. Therefore large number of such units is required in large commercial systems. Another disadvantage is some degree of mixing between feed and concentrate. The mixing feed salinity between 1.5% to 3.0%, which results in some increase of required feed pressure and permeate salinity. Also, the control of operation of these devices is more complicated than the required for pelton wheel. Due to high efficiency of new power recovery devices the power consumption of RO seawater systems can be optimized in the wide range of recovery rate. Comparison of power consumption versus recovery rate for RO system operating on Mediterranean seawater, using design parameters listed in table 1, is shown in Fig. 13. According to presented results power consumption in the range of 2.5 – 3.5 kWhr/m<sup>3</sup> is attainable at optimized value of recovery rate. The results indicate also that using of high efficiency, advanced power recovery equipment allows operation at low recovery rate with little energy penalty for higher feed flow. However, for complete economic parametric analysis of process economics, a capital cost of larger pretreatment system and increased chemicals consumption at lower recovery rate, has to be included in the evaluation.

Table 1. Design parameters for power calculation

Case	A	B	C
Configuration	Low efficiency pump + Pelton wheel	High efficiency pump + Pelton wheel	High pressure pump + pressure exchanger
Pump efficiency, %	82	88	88
Pelton wheel/pressure exchanger efficiency, %	82	88	94
Electric motor efficiency, %	94	96	96
VFD efficiency, %	98	98	98
Raw water and pretreatment pressure losses, bar	4	4	4
Concentrate discharge pressure, bar	0.5	0.5	0.5
Permeate pumping, bar	10.0	10.0	10.0
Auxiliary equip., kWhr/m <sup>3</sup>	0.05	0.05	0.05

## Water cost

In the last decade there was a significant decrease of capital and operating cost . Desalted water cost, supplied to customer, decreased from \$2.0/m<sup>3</sup> in 1998 down to current (2004)

price of about \$0.5/m<sup>3</sup>. This decrease of water cost is even more remarkable if one considers, that on the average, the permeate water quality requirements are more stringent now than they were five years ago. The drivers behind these economical improvements are competition and improvement of process and membrane technology. A majority of large RO systems are built to provide water to municipalities, usually in the framework of build, own and operate (BOO) arrangements. The desalination projects are awarded as result of a very competitive bidding process. Competitive bidding process affected prices of every equipment component of RO systems (including membrane elements) and resulted in a broad price decline. Better performance of equipment and optimization of process design resulted in lower operating cost. The recent trend of water cost from large seawater RO installations is summarized in Fig. 14 and Table 2

Table 2. Water cost in recently built RO seawater plants.

Location	Permeate capacity, m <sup>3</sup> /day	Status	Water price, \$/m <sup>3</sup>
Eilat Israel	20,000	10,000 m <sup>3</sup> /day commenced operation in June 1997	0.72
Larnaca, Cyprus	56,000	Commenced operation in May 2001	0.83
Tampa, Fl	106,000	Commenced operation in May 2003	0.56
Ashkelon, Israel	272,000	Under construction, to be completed in 2004	0.54

The water cost is composed of capital cost, power consumption, maintenance and parts, membrane replacement, consumables and labor. Typical cost distribution in seawater RO plant is included in Fig 15. According to these values the major cost components in seawater RO systems are power and capital cost.

The system cost is calculated through cost contribution of major system components:

- Site preparation and building
- Intake and outfall
- Pretreatment
- RO trains
- RO membrane elements
- Piping
- High pressure pumps and power recovery turbines
- Electrical
- Permeate post-treatment and storage
- Membrane cleaning system
- Instrumentation and control system

To the above equipment and site cost figure one should add cost of:

- Contingency
- Engineering
- Owners cost
- Interest during construction

### Seawater RO systems

The construction cost of large capacity RO seawater desalination plants is reported to be in the range of \$900 – \$1,500/m<sup>3</sup>-day (1,2,3,4). At the discount rate of 6%, 25 years plant life and 95% on line factor this translates to capital cost component of product water of \$0.203 - \$0.338/m<sup>3</sup>. The plant construction cost is location specific, depending among other issues on the length of the project preparation process and process requirements in respect of raw water quality and product water quality specifications. The summary of individual cost components is listed in table 3.

Table 3. Summary of estimation of product water cost components for a large capacity (200,000 m<sup>3</sup>/d) RO seawater RO plant.

Product water cost component	\$/m <sup>3</sup>
Capital cost, including land fee (25 years @ 6.0% interest)	0.203 – 0.338
Electric power (\$0.060/kWhr)	0.180 – 0.240
RO membrane replacement (5 years membrane life)	0.025 – 0.035
MF membrane replacement (7 years membrane life)	0.000 – 0.030
Chemicals	0.020 – 0.025
Maintenance and spare parts	0.023 – 0.038
Labor	0.030
Total cost	0.481 – 0.706

### Brackish RO systems

The brackish RO systems treat low and medium salinity fed water and operate at feed pressure range of 10 – 15 bar. The recovery rate is in the range of 75% - 85%. The Recovery limiting factor is mainly concentration of sparingly soluble salts, mainly silica and CaSO<sub>4</sub>. The systems treating well water require very limited pretreatment, including only scale inhibitor addition and cartridge filtration. The cost of water produced in these systems is very low, in the range of \$0.2 – 0.3/m<sup>3</sup> (5). One of the significant problems of brackish systems is concentrate disposal. The usual methods of disposal are surface water discharge, disposal to wastewater system or deep well injection. Lack of convenient concentrate discharge will usually make building of RO plant economically unattractive. Another type of low salinity RO systems are wastewater reclamation plants. These plants treat secondary or tertiary effluents and include, almost exclusively, membrane pretreatment. Investment cost of these plants, due to expensive pretreatment

and low permeate flux, is high, in similar range as seawater RO plants (6). However, operating cost of wastewater reclamation plants is lower due to higher recovery rate (75% - 80%) and lower operating pressure: 10 - 15 bar compared to recovery rate of 50% and 55 - 65 bar feed pressure in seawater RO systems.

### Nanofiltration systems

The nanofiltration systems treat low salinity brackish or surface water. The nanofiltration systems configuration and economics is similar to the brackish RO systems. The objective of nanofiltration stems is to reduce concentration specific components from the feed water, usually hardness, iron, organics or color while allowing monovalent ions to pass through. Some of the nanofiltration systems operate mainly for removal of low concentration of pesticide sometimes present in the potable water at specific locations. Due to low salinity, low rejection and high permeability of nanofiltration membranes, the NF systems operate at low feed pressure, usually below 10 bar. Feed water to nanofiltration systems may contain high concentration of organics, therefore use of low fouling membranes for these applications is preferred.

### Potential for future cost reduction

The future reduction of desalted water cost can be achieved by reduction of capital cost and optimization of the process parameters. The most likely future development that can result in cost reduction will be introduction of large size membrane element. Current evaluation by consortium of membrane manufacturers (7) indicated possibility of up to 10% reduction of capital cost of seawater systems if element diameter will be increased to 16". It is difficult to envision other significant development, beside large diameter element, than would affect equipment cost, especially in seawater applications. There, high pressure process combined with corrosive environment, limits the choice of materials of construction and therefore equipment cost. It can not be expected that the regulations that affect permitting and construction cost of desalination plants will become less stringent. On the operating cost side the most promising directions is optimization of process parameters through more advanced automation. The cost contribution parameters that potentially could be optimized by more advanced automations are: electric power, RO membrane replacement, MF membrane replacement, chemicals usage and possibly maintenance (frequency of membrane cleaning).. It is expected that in the future "smart" automation system will control plant operation to optimize process parameters to produce water at the lowest cost according to water demand, conditions of the plant equipment, condition and availability of feed water and local economic parameters. So far very little has been done in this direction but some initial evaluations are being conducted. It is very likely that some cost reduction will be achieved in the future but most likely they will not be as significant as have been experienced over the last decade.

## References

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