Design Guidelines for *TORAY* Membrane Elements

The purpose of following reverse osmosis (RO) and nanofiltration (NF) guidelines is to acquaint the process engineer with proper concepts for pretreatment and design of RO and NF desalting systems. WINCAROL, a computer projection program developed by ROPUR, is the mechanism through which these design concepts are applied and optimized. WINCAROL also contains many options such as internal brine circulation, interstage pressure boost, permeate staging, blending etc. This flexible program alerts the user by warnings and alarms to design limitations. These limitations have been determined from field experiences. The results derived from WINCAROL have been calculated in a conservative manner to make sure that plant operations meet customer specifications.

The following guidelines explain the design philosophy of ROPUR and have been established to enable skilled engineers to properly construct a desalting plant. The guidelines are not intended to supplant existing knowledge. Such technical "know-how" remains still the basis for a qualified and proper plant design. For large size plants, the customer is requested to contact ROPUR to obtain long term warranties.

1 Source of Raw Water

There are several sources of raw water, normally employed as feed for RO/NF plants

1.1 Surface Water

This water may contain various concentrations of suspended particles and colloids. It represents, generally, a high fouling potential (SDI 3-5), which can vary seasonally. In seawater especially, the biofouling potential is high and thus, conservative flux safety factors for the net driving pressure (NDP) and permeate salinity must be used. If the water is being used for cooling in heat exchangers or towers before the membrane plant, biofouling potential may be further increased, as can the concentrations of corrosion products. The plant must include a well-designed membrane cleaning system.

1.2 Well Water

Water from wells usually contains low concentrations of suspended particles and colloids. The biofouling potential is generally quite low with SDIs <2. Exceptions may occur with new or over worked wells or if the wells are located too close to the open sea. This water typically requires only a simple pretreatment system. With brackish water care must be taken to avoid scaling due to sparingly soluble salts (especially $BaSO_4$), and membrane plugging by iron and manganese. If the well water is being used for cooling prior to the RO/NF plant, the same problems as noted above may occur.

1.3 Potable Water

Potable water, as feed source for RO/NF plants, can be at least difficult to pretreat. SDIs are usually <2, but can be substantially higher if the water is removed from old and decaying piping systems (corrosion products), or from newly constructed piping which has been

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improperly flushed. At very low temperatures, silica scaling potential has to be considered and prevented. During the summer months, and in case flooding or snow melting has occurred in the head waters of the supply system, the plant have to employ chlorine shock treatment of the feed water to control microbial activity. In such instances, the RO/NF feed must be dechlorinated, generally with $NaHSO_3$, before it enters the 1st stage pressure vessels to prevent damaging the polyamide polymeric membrane. If ClO_2 is employed as the disinfecting agent, the 'bisulfite' chemical treatment is not effective and an activated carbon filter should be used as a deoxidizing/dechlorination agent.

1.4 Waste Water

To further a world-wide need for water reclamation, more and more tertiary treated and industrial waste waters (SDI 4-5) are being processed by RO/NF. In case of an industrial waste water, multiple combinations of contaminants such as high salinity, high or low pH, suspended matters, heavy metals, grease, solvents etc. can be expected. Tertiary treated waste water has the potential for $Ca_3(PO4)_2$ scaling and significant microbial activity. Large buffer storage tanks should be avoided because of the potential for corrosion or biological activity (often in conjunction with odor), all of which make the water unusable as a RO/NF feed. The composition of waste water is site specific, so pilot testing is very strongly recommended before plant design is finalized.

2 Fouling

Among the many variables, which influence product flow and quality, module life and plant reliability, fouling and scaling probably have the most adverse effects if not controlled. There are two basic types of fouling:

- Colloidal fouling (clay, soil, colloidal silica, corrosion products, dead biomass)
- Biofouling (living bacteria, fungus, virus, algae and other advanced microorganisms which have the capability to form a biofilm)

Fouling occurs in two different ways: 1). It may form a layer onto the membrane surface, or 2). It may plug the feed/brine spacer. The first is normally caused by colloidal matter, sometimes by biofouling, whereas the latter is mostly caused by suspended particles and also sometimes by biofouling (especially in case of seawater).

QUANTIFYING OF FOULING POTENTIAL

2.1 The most common and worldwide-accepted procedure to estimate the fouling potential of feed water is the SDI (15 min) test (ASTM D4189). The biggest advantage of this method is its relative simplicity. The largest disadvantage is its inability to cover a large particle size range, as the 'cut off' is at 0.45 µm and also to differentiate among various types of fouling materials.

2.2 Turbidity measurement (NTU) is an acceptable procedure to complement the SDI test in estimating the potential fouling risk caused by colloids. In addition, turbidity instruments can be installed on-line to continuously monitor and, if necessary, alarm when values exceed desired levels. The highest allowed value for turbidity is usually NTU<1. A properly functioning pretreatment system typically provides a NF/RO feed with a turbidity of < 0.5.

2.3 For biofouling, bacteria counts across equipment pieces have been used extensively to assess the extent of the problem. When microbes are present in large numbers, they will form a biofilm on the surfaces of pipes and RO/NF membranes. This biofilm not only greatly affects plant performance, but it also protects microorganisms against shear forces caused by the flowing water and cleaning agents. A monitoring can be established by installing test membranes that are often examined for biological activity and by frequent inspection of piping surfaces and feed end of the RO/NF elements. Indications of the presence of a biofilm are 'slimy' surfaces and odor.

3. Scaling

Scaling by sparingly soluble salts, corrosion products and silica also have a major impact on the performance of NF/RO elements. Scaling problems are avoided by proper pretreatment, careful control of system recovery, selection of adequate antiscalant and/or suitable adjustment of feed water pH. Suspended particles and colloids can also influence the scaling potential of a feed water by providing nucleation sites for sparingly soluble salt precipitation and by forming a layer on the membrane surface, thereby increasing concentration polarization. If scaling does occur, immediate action is necessary to remove the precipitants. Aging scale, especially sulfate compounds, metal oxides and silica, can be very difficult to clean from membrane surfaces.

3.1 Prevention of Scaling without Antiscalants

Compound	SDI ≤ 3	SDI > 3
$CaCO_3$ (LSI ≤ 5000, S&DSI > 5000 mg/l)	: ≤ -0.1	≤ -0.2
Sulfate/Fluoride compounds	: ≤ 0.9 × K_{SP}	≤ 0.8 × K_{SP}
Silica	: ≤ 90%	≤ 80%

3.2 Prevention of Scaling with Antiscalants *)

Compound			ROPUR Antiscalants (RPI-Series)
$CaCO_3$ (LSI ≤ 5000, S&DSI > 5000 mg/l)	: ≤ 2.5	<2.0	2000, 2500A
$CaSO_4$	: ≤ 2.5 × K_{SP}	<2 × K_{SP}	3/4000A, 4500A
$SrSO_4$	: ≤ 50 × K_{SP}	40 × K_{SP}	4000A, 4500A
$BaSO_4$	: ≤ 50 × K_{SP}	40 × K_{SP}	4000A, 4500A
CaF_2	: ≤ 100 × K_{SP}	80 × K_{SP}	4900A
SiO_2	: ≤ 240%	< 200%	5000A

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*) During plant shut downs, antiscalants have only limited, if any, effectiveness. Therefore, it is recommended that the brine be flushed rapidly from the RO/NF modules at low pressure (< 2 bar) using, preferably, permeate or softened water. If raw water is employed, adequate high quality water should be assured.

3.3 Ion Exchange Softening

3.3.1 Ion Exchange Softening stabilizes colloids, thereby reducing colloidal fouling by removing multivalent metal ions from the feed water. It also prevents aluminum silicate scaling. Therefore, a saturation of SiO_2 up to 100% without adding an antiscalant is acceptable.

3.3.2 When the pH is >8 on, humid acids are mostly dissociated, so that the fouling potential and permeate TOC level are reduced.

3.3.3 The affinity of Ba^{2+} to strong acid cation exchangers is very high. Thus, a reduction of its concentration in the feed water in excess of 90% can be assumed. This affinity also means that the regeneration of the ion exchanger resin with NaCl can be difficult and large quantities of this salt solution are necessary to replace the barium ion in the resin with sodium ion.

3.4 Weak Acid Cation Exchange Resin Dealkalization

3.4.1 The affinity of Ba^{2+} to weak acid cation ion exchangers is far from being as strong as it is to strong cation ion exchangers. Thus, a reduction of not more than 65% can be assumed, except, practical experiences in particular cases show other results.

3.4.2 $Ca(HCO_3)_2$ will be mostly removed leaving only a small residual in the RO/NF feed.

3.4.3 Due to the reduction of Calcium ion, this treatment step is also suitable to prevent other Calcium salts from scaling. Antiscalant dosing can thus be optimized or even eliminated.

3.4.4 Please keep in mind that the optimum pH range for salt rejection is around 6 – 8 (Advanced Ultra Low Pressure Elements) respectively 5 - 8 (Standard Low Pressure Elements) and that the salt rejection decreases on either side of this optimum. Therefore, the carbon dioxide has to be removed prior the RO/NF plant. Otherwise increase of salt passage has to be accepted due to the low pH-value in the range of 4.3 - 5.

4 Flux Decline

Optimization of flux is one of the most important items to be managed. The criteria for such a determination are in addition to product quantity, quality and energy consumption, the quality of the feed (to minimize fouling), operating and differential pressures and fre-

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quency of cleaning. It has to be kept in mind, that the complete characterization of feed water quality by SDI, especially with waste water, is limited.

Maximum Flux Front-End Elements [*3)] / Average Flux of Plant [l/m²/h] as a Function of Feed Water Quality

SDI_{15}	Brackish Water	Sea Water	Waste Water
< 1 RO-Permeate	55/39	51/36 [1*)]	2*)
< 2 UF/MF-Permeate	51/36	35/25	
< 2 Well water	46/32	30/21	
< 3	40/28	27/19	
< 4	34/24	24/17	20/14
< 5	20/14	20/14	15/10

[1*)] 2nd pass feed is permeate of 1st pass

[2*)] Strongly dependent from ‘Cut Off‘ and composition of waste water. For example, the flux with UF/MF-permeate from emulsion separation plants used for RO-feed is usually only in the range of 5-10 $l/m^2/h$.

[3*)] It is recommended to keep the average flux not higher than 70% of the maximum flux at the front end elements.

Active Membrane Surface [m^2/ ft^2] of Membrane Elements

SUL-G10 SUL-G10P SUL-G10TS SU-710L SU-810 SU-610	SU-710P	SU-710R	SU-820	SU-720 SU-720L SU-820 SU-820L SU-620	SU-720P SU-820FA	SU-720R	SU-720F SU-720LF SU-720TS SUL-G20 SUL-G20TS SUL-G20P SU-620F	SUL-G20F
7 / 75	8 / 86	9 / 97	28 / 302	29 / 312	32 / 344	34 / 366	35 / 377	39 / 420

5 Adjustment of Adequate Flow Pattern

Formation of secondary layers on the membrane surface, scaling tendencies by exceeding solubility limits as well as permeate quality are greatly affected by the feed flow rate and the brine to permeate ratio (B/P). The reason for this is the increased concentration of dissolved, colloidal and particulate compounds on the membrane surface caused by the accumulation of these rejected substances. Minimum feed flow and proper B/P tend to control concentration polarization and are, therefore, essential for proper operation.

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Flow Pattern in Last Element in Pressure Vessel

SDI [%/min]	1	2	3	4	5
B/P - ratio	3	4	5	6	10
RCV [%]	25.0	20.0	16.7	14.3	9.1

The brine flow has to be determined with the flux > 80 l/min for 8" Elements
And > 20 l/min for 4" Elements

6 Consideration of Irreversible Flux Decline by Fouling

Irreversible flux decline, caused by fouling of the membranes, occurs in most operating plants, but the degree varies considerably. It is necessary, therefore, to compensate for this irreversibility. This is accomplished by fouling factors added to the net driving pressure (NDP), using a 10% of NDP safety factor for the high pressure pump and providing 10% extra rack space for future membrane additions. If the newly developed ultra low pressure elements are installed, with their significantly low NDP, further compensation has to be given to the effect of fouling. This case has not yet been suitably quantified.

Fouling-Factors [% of NDP/annum]

Element Type	SU-8xx SU-8xxL SU-820FA	SU-7xxR	SU-7xx SU-7xxL SU-7xxTS TMLxx	SUL-Gxx SUL-GxxF SUL-GxxTS	SU-6xx SU-6xxF TMHxx
Brackish water	4	4	5	7	10
Seawater	7 *1)		2 *2)	3 *2)	

*1) Beach well. If an open sea intake multiply by 1.5
*2) 2nd pass. Feed is permeate from 1st pass

7 Further Aspects for Design of NF/RO Plants

7.1 Total Recovery Rate

The recovery rate of membrane separation plants has a large effect on the rentability of these systems. It is generally, limited by the required permeate quality, solubility limits of sparingly soluble salts and osmotic pressure. Other factor influencing the recovery rate are the concentrations of unknown substances which may be harmful to the membranes, heavy metals from old and rotting piping systems, increase in operating temperature by internal circulation etc. The following are the typical recommended recovery rates for brackish water plants:

- Conventional brackish water systems 65 – 85%
- Double pass systems 60 – 80% (total)

With smaller plants using brine recirculation, ROPUR recommends that the above lower values be used.

Sea water plants usually operate at recovery rates of 30% to 45%, though they can be up to 70% in Brine Conversion Systems.

7.2 Recovery Rates of Single Stages

As salt rejection and permeability of modern ultra low pressure membranes have continuously improved, there is a tendency to move to ever higher recovery rates, even when the feed salinity is several thousand mg/l. In doing so, several problems may occur:

- Too high flux at the front end elements of the 1st stage modules
- Too high recovery rate of the 1st stage, resulting in insufficient feed flow to the last elements
- Very small flux of the elements in the last stage, resulting in unsatisfying product quality

There are several options to manage these problems:

- The most simple way is to put a permeate backpressure on the 1st stage. The flux of the 1st stage elements will be reduced, their B/P ratio improved and the flux in the elements in the following stages increased.
- A slight increase in operating pressure will give improved flow conditions and better permeate quality. This option is often employed in small capacity plants.
- For higher capacity systems, an interstage pressure boost can achieve the same results as described above.
- Another option is to install membrane elements with a lower flux in the first stage than what is present in the other stages.

The criteria to be used for adopting these procedures are

❑ $Q_{Pn} < 50\% \ Q_{P1}$	Q_P:	Permeate flow/vessel
❑ NDP < 0.1 MPa, last membrane element	NDP:	Net driving pressure
	n:	Bank 1,2 …n

7.3 Pressure Drop

Water flowing through the feed/brine channel of the modules will create a pressure drop. To be safe and prevent the modules from incurring mechanical damage, it is desirable to calculate the value of this pressure drop and to estimate its increase by fouling - partial plugging of the feed/brine spacer. Depending on the expected fouling tendency of the feed water, the following maximum design differential pressures per pressure vessel have to be met:

SDI < 3	< 200 kPa
SDI < 4	< 180 kPa
SDI < 5	< 150 kPa

The maximum allowable feed flow for a standard 4" and 8" element is 3 m^3/h and 12 m^3/h.

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8 System Warranties

Warranties for product quantity and quality for large projects have to be negotiated with and approved by ROPUR before granting them to customers. In case of smaller plants e.g. standardized systems and during the early stages of project activity, the following correction factors have to be applied to the results (after 3 years of operation) obtained from WINCAROL:

Brackish water

Permeate TDS mg/l (required)	≤ 5	≤ 10	≤ 15	> 15
Correction factor, SDI ≤ 3	2.0	1.7	1.5	1.3
Correction factor, SDI > 3	2.5	2.2	2.0	1.8

For double pass plants, producing WFI, according USP 23, a correction factor of 1.3 is generally foreseen

Seawater

	SDI < 2	SDI < 3	SDI 3-4
Permeate TDS mg/l (required)	400-600	400-600	400-600
Correction factor	1.8	2.0	2.2

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