The Right Fit CSM®

TECHNICAL MANUAL

REVERSE OSMOSIS MEMBRANE

TORAY

Toray Advanced Materials Korea Inc.

1 Introduction to TAK

1-1 History of Toray Advanced materials Korea Inc.

1999	Launch of Toray Saehan Industries, joint venture with Toray
2000	Establishment of Technology Research Institute
2001	Winner of Energy Innovation Management Awards
2002	Development of IT Material Business
2003	OHSAS 18001, First certification
2004	Establishment of Advanced Material Research Center
2005	Gumi 4-Factory Construction Co., Ltd.
2008	Opening of Photovoltaic Power Generation at Gumi Plant 3
2009	Establishment of New Technology Research Institute
2010	Change of Company name Toray Advanced materials Korea Inc.
2011	ISO 50001, certification
2012	Establishment of TCK textile
2013	Super engineering plastic PPS, Business
2014	Establishment of Gunsan Plant
2015	Establishment of TCK micro-filter
2016	Gumi 5-Factory Construction Co., Ltd.
2017	Opening of TAK, a Chinese subsidiary
2018	Construction of the Korea Toray R&D Center

1-2 History of Reverse Osmosis Membrane Business

1990	Research on the reverse osmosis membrane commences at the R&D center
1994	Development of high salt rejection and flux reverse osmosis membranes Completion of membrane testing pilot plant at R&D center Membranes receives Japanese High Polymer certificate Membranes become FDA approved
1995	Commercialization of reverse osmosis membranes for industrial and residential use Export to China, Taiwan and India
1997	Completion of main manufacturing facility at Gyungsan Plant Reverse osmosis membranes receive Industrial Research 52 Award from the Korean Ministry of Science and Technology and the KT mark (new technology award)
1998	Development of reverse osmosis membranes for seawater applications
2000	Development of fouling resistant reverse osmosis membranes
2003	Expansion of reverse osmosis membrane manufacturing capacity at Gumi Plant I Development of reverse osmosis membranes for ultrapure water applications

2 Introduction to Reverse Osmosis Membrane

2-1. Overview of Reverse Osmosis Membrane Applications

Rapid technological advancement brought about many benefits to our life and also concurrently caused pollution to our environments such as contaminating water sources from industry effluents.

Moreover, natural fresh water source could not meet the ever increasing water demand from our growing population and industries. Additionally, uneven seasonal rain fall makes the water shortage problem worse. Therefore, insuring enough quantity and quality of water is one of the most serious issues in the world, especially in Europe, the United States, China and Middle East and North Africa.

Distillation has been traditionally used to obtain pure water from contaminated water sources. Other processes such as ion exchange and electrodialysis have been employed for water purification since 1950. Recently, RO membrane was applied to the desalination of sea water and brackish water.

RO has been proven to be the most economical technology not only for the desalination of water containing salts, but also for purifying water contaminated with heavy metals, pesticides and other contaminants. Especially, seawater desalination particularly with the utilization of a reverse osmosis (RO) membrane, has been a rapid growth in the global market. In many Middle Eastern countries such as Saudi Arabia, the United Arab Emirates, and Kuwait, significiantly, desalinated seawater occupies a major portion of their available water resources. Although thermally driven processes are still used in a majority of their desalination plants, most plants built after 1990 adopt the RO membrane separation process due to its lower operational/maintenance costs and smaller environmental footprint.

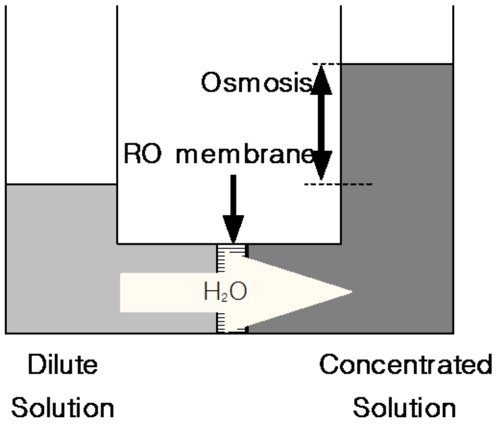
And also RO can be used for recycling waste water and reclaiming useful materials from waste stream such as the recovery of dyes from dye industry effluents. The applications for RO also include food and beverage processing. In addition, advances in the fields of biotechnology and pharmaceuticals, coupled with advances in new membrane development, are making membranes an important separation step, which offers energy savings without leading to thermal degradation of the products.

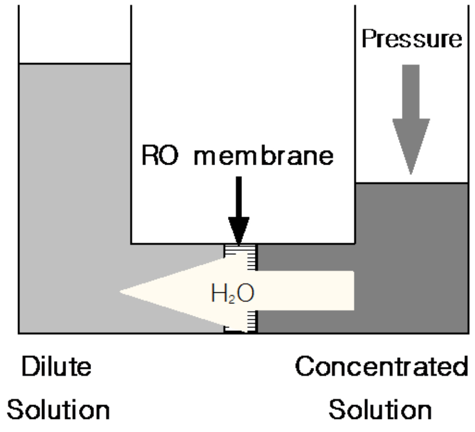
2-2. Theory of Reverse Osmosis Membrane

The phenomenon of osmosis is illustrated in the Figure below.

A semi-permeable membrane (RO membrane) is placed between two compartments. An RO membrane is consisted of a supporting layer with 50㎛ in thickness and a barrier layer with about 0.2㎛ in thickness. The phenomenon of osmosis occurs when pure water flows from a dilute saline solution in one compartment through the RO membrane into a higher concentrated saline solution in the other causing a rise in the height of the salt solution in the compartment of the higher concentrated solution.

The water flow will stop when the pressure of the column of the salt solution equals to the difference in chemical potential between the two aqueous solutions. The equilibrium point of the water column height in terms of water pressure against the membrane is called osmotic pressure. If a force is applied to this column of water, the direction of water flow through the membrane can be reversed. This phenomenon is called reverse osmosis. This reversed flow produces pure water from the salt solution, since the membrane is not permeable to salt. By this manner, relatively pure water passes through membrane, and the dissolved solids are retained in the other section Consequently, the water in this section is purified or demineralized and the solids in the other section are concentrated or dewatered





2-3. Types of Reverse Osmosis Membrane

◎ Asymmetric Membrane --- Cellulose Acetate(CA) Membrane

Historically, the asymmetric membrane is formed by casting a thin film acetone-based solution of cellulose acetate(CA) polymer, which was developed by Loeb and Sourirajan in 1962 and the first commercially viable RO membrane.

The resulting CA membrane has an asymmetric structure with a dense surface layer of about 0.1 - 0.2㎛ which is responsible for the salt rejection property. The rest of the membrane, which is 100-200㎛ thick and supports the thin surface layer mechanically, is spongy and porous, and has high water permeability. Salt rejection and water flux of a CA membrane can be controlled by variations in temperature and duration of the annealing step.

◎ Thin Film Composite Membrane --- Polyamide(PA) Membrane

Thin film composite (TFC) polyamide membranes are consisted of a porous support layer and a thin film dense layer which is a cross linked membrane skin and is formed in situ on the porous support layer, usually made of polysulfone. The thin film dense layer is a cross-linked aromatic polyamide made from interfacial polymerization reaction of a polyfunctional amine such as m-phenylenediamine with a polyfunctional acid chloride such as tri-mesoyl chloride. This TFC manufacturing procedure enables independent optimization of the distinct properties of the support and salt rejecting skin. The TFC membrane is characterized by higher specific water flux and higher salt rejection than cellulose acetate membranes.

◎ Comparison of Polyamide TFC Membranes with Cellulose Acetate(CA) Membranes

TFC membranes have advantages over single-material asymmetric membranes in that, the top-separating layer is formed in situ and hence the chemistry and performance of the top barrier layer and the bottom porous substrate can be independently studied and modified to maximize the overall membrane performance. As mentioned above, the TFC membranes exhibit higher water flux and higher salt rejection than CA membranes which had been used widely until the commercial introduction of TFC membranes in 1981. TFC membranes are stable over a wider pH range and operable at lower pressure than CA membranes. Detailed comparisons between the two types of membranes are shown in the table below.

Parameters		PA Membrane	CA Membrane
Operating pH range		2~12	4~8
Operating Temperature (°C)		0~45	0~35
Salt Rejection (%)	TDS	99+	98
	Silica(SiO_2)	99+	< 95
Productivity (Flux)		High	Low
Salt Rejection Change after 3years		99%→98.7%	98%→96%
Chlorine Tolerance		<0.1 ppm	1 ppm
Membrane Fouling		Moderate	Low
Compaction Resistance		High	Low
Susceptibility to Biodegradation		Negligible	High

2-4. General Property of CSM RO Membranes

◎ General Separation Property of RO Membrane

1) Inorganic solutes are rejected by RO membrane better than organic solutes.
Organic solutes with molecular weight (MW) larger than 100 are also well rejected by the membrane
2) Ionizable solutes are rejected better than non-ionizable solutes.
3) Ionizable solutes with higher charges are rejected better than lower charges.
For examples, aluminum ion (Al^3+) is rejected better than magnesium ion (Mg^{2+}) which is in turn rejected better than sodium ion (Na^+).
4) The rejection of inorganic solutes depends also on the size of the ions and the size of hydrated ions. The bigger the ions and the hydrated ions, the better they are rejected
5) The bigger the non-ionizable solutes (the higher the molecular weight), the better the rejection.
6) Gases with MW lower than 100 can easily permeate through the membrane.
For example, the rejection of ammonia, chlorine, carbon dioxide, oxygen and hydrogen sulfide is very low.
7) The rejection of weak acids is low, which also depends on the MW of the acids. The rejection of the following acids is decreasing in the order of citric acid, tartaric acid and acetic acid as the MW of the acids decreases.
8) The greater the dissociation, the higher rejection, for example boric acids are rejected better at higher pH
9) The more branching, the greater rejection, for example, isopropanol is rejected better than normal propanol

◎ Characteristic Property of CSM RO Membranes.

1) High permeate flux and high salt rejection
2) Chemically stable in a wide range of pH (pH2 - 12)
3) Long membrane life time
4) Resistant to a biological attack
5) Operable in a wide range of pressure (20 - 1000psi)
6) Operable at a wide range of temperature(4 - 45℃)
7) Economical

2-5. Solute Rejection Property of CSM RO Membranes

◎ Solute Rejection of BE and BN Grade of CSM

NO	Solute	Rejection (%)	Molecular Weight
1	NaF	99	42
2	NaCN	98	49
3	NaCl	99	58
4	SiO_2	99	60
5	$NaHCO_3$	99	84
6	$NaNO_3$	97	85
7	$MgCl_2$	99	95
8	$CaCl_2$	99	111
9	$MgSO_4$	99	120
10	$NiSO_4$	99	155
11	$CuSO_4$	99	160
12	Formaldehyde	35	30
13	Methanol	25	32
14	Ethanol	70	46
15	Isopropanol	92	60
16	Urea	70	60
17	Lactic acid (pH2)	94	90
18	Lactic acid (pH5)	99	90
19	Glucose	98	180
20	Sucrose	99	342
21	Chlorinated Pesticides	99	-
22	BOD	95	-
23	COD	97	-

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Specification of CSM

3-1. CSM Element Nomenclature

RE8040-BE

① Types of Element
- RE : Reverse Osmosis Element
- NE : Nanofiltration Element
- UE : Ultrafiltration Element

② Diameter of Element
- 80 : 8.0 inch
- 40 : 4.0 inch
- 25 : 2.5 inch

③ Length of Element
- 40 : 40 inch
- 21 : 21 inch

④ Related to Specification

1) The First Order
- B : Brackish Water Membrane
- T : Tap Water Membrane
- S : Sea Water Membrane
- F : Fouling Resistant Membrane

2) The Second Order
- N : Normal grade
- E : Extended effective area
- R : High salt rejection
- L : Low pressure use

3) In case of BL grade(three orders)
- BLN : Normal grade
- BLR : High salt rejection grade
- BLF : High flux grade

4) In case of NE element
- 40 : NaCl Rejection 40%
- 90 : NaCl Rejection 85～90%

5) In case of UE element : PF

3-2. Representative CSM Installations

1. Boiler Feed Water Use

Customers	Location	Model No.	Capacity	Date	Remarks
Kia Motors	Asan	RE8040-BN	400m^3/hr	Dec.1999	
Dongbu Steel	Dangjin	RE8040-BE	400m^3/hr	Mar.2002	
Veolia	Daesan	RE8040-BE	300m^3/hr	Jan.2003	
SK Corporation	Ulsan	RE8040-BN	350m^3/hr	Oct.2002	
Samsung General Chemical	Daesan	RE8040-FE	420m^3/hr	Jul.2003	
SK Corporation	Ulsan	RE8040-BE	200m^3/hr	Oct.2002	
POSCO	Pohang	RE8040-BN	60m^3/hr	Jan.1999	
Hyundai Motors R&D Center	Namyang	RE8040-BE	100m^3/hr	Mar.1998	
Saehan Industries Inc	Gyungsan	RE8040-BN	100m^3/hr	Apr.2000	
Saehan Industries Inc	Gumi	RE8040-BN	150m^3/hr	Oct.2000	
Hyndai Steel	Dangjin	RE8040-FEN RE8040-FLR	300m^3/hr	Oct.2012	
Hyndai Hysco	Dangjin	RE8040-FE	210m^3/hr	May.2005	
DWChem	Pyung teak	RE8040-FEN	580m^3/hr	Oct.2010	
Hyndai Oil Bank	Daesan	RE8040-FD	650m^3/hr	Sep.2005	

2. Ultra Pure Water/Pure Water Use

Customers	Location	Model No.	Capacity	Date	Remarks
Samsung Electronics	Onyang	RE8040-BE	100m^3/hr	Oct.1997	
Anam S&T	Cheonan	RE8040-BN	30m^3/hr	Sep.1996	
Hankuk Electronics	Kumi	RE8040-BN	100m^3/hr	Jan.1998	Replace CA with PA
Hyundai Electronics	Shanghai	RE8040-BN	50m^3/hr	Oct.1997	
LG Siltron	Kumi	RE8040-BE	120m^3/hr	Aug.2001	UPW 2nd pass
Samsung SDI	Kachun	RE8040-BN	420m^3/hr	Jul.1997	
Samsung SDI	CheonAn	RE8040-HUE	40m^3/hr	Jul.2010	
LG Dispay M5	Kumi	RE8040-BE	570m^3/hr	May.2012	BLR 2nd pass
LG Display P7	Paju	RE8040-UL	130m^3/hr	Feb.2010	
Veolia	Icheon	RE8040-HUE	56m^3/hr	Feb.2012	

3. Brackwish water/ Overseas

Customers	Location	Model No.	Capacity	Date	Remarks
Chesapeake	Virginia	RE8040-BE	310m^3/hr	May.2012	
Gloucester	Virginia	RE8040-BE	315m^3/hr	Aug.2009	
Torrance	California	RE8040-BE	315m^3/hr	Mar.2012	
Dumai	Indonesia	RE8040-BLF	93m^3/hr	Jun.2010	
Karabuk	Turkey	RE8040-BLF	430m^3/hr	May.2012	
FAJR	Iran	RE8040-BR	3,900m^3/hr	Jul.2006	

4. Process Water Use

Customers	Location	Model No.	Capacity	Date	Remarks
Samyang Kasei	Chunju	RE8040-BE	200m^3/hr	Oct.1999	
Samyang Kasei	Chunju	RE8040-BF	200m^3/hr	Aug.2001	
Samsung Motor	Busan	RE8040-BE	220m^3/hr	May.2000	

5. Power Plant Use

Customers	Location	Model No.	Capacity	Date	Remarks
Busan Cogeneration	Busan	RE8040-BN	100m^3/hr	Apr.1999	
KEPCO	Pyungtaek	RE8040-BE	100m^3/hr	Jan.1998	

6. Zero Discharge System Use

Customers	Location	Model No.	Capacity	Date	Remarks
Doosan Electronics	Jeungpyung	RE8040-BE RE4040-SN	30m^3/hr	Jul.1997	
Hyundai Motors	Asan	RE8040-BE	300m^3/hr	Sep.1998	
Hyundai Motors	Asan	RE8040-BF	200m^3/hr	Apr.2001	
Hyundai Motors	Asan	RE8040-SF	20m^3/hr	Jun.2001	

7. Waste Water Recycle Use

Customers	Location	Model No.	Capacity	Date	Remarks
LG Siltron	Ichun	RE8040-BE	30m^3/hr	Jul.1998	
Samsung Electro-Mechanics	Jochiwon	RE8040-BE	120m^3/hr	May.1999	
Capro	Ulsan	RE8040-BE RE8040-SN RE8040-SR	180m^3/hr	Aug.2002	
Samnam Petrochemical	Ulsan	RE8040-BF	100m^3/hr	Aug.2002	
LG Siltron	Kumi	RE8040-BN	120m^3/hr	May.1999	

DWchem	Pyeng Taek	RE8040-FEN	600m^3/hr	Jul.2009	
Samsung Electro-Mechanics	Hwaseong	RE8040-FEN	60m^3/hr	Jun.2009	

8. Waste Water Recycle Use / Overseas

Customers	Location	Model No.	Capacity	Date	Remarks
Kranji	Singapore	RE8040-FE	286m^3/hr	Jun.2006	
Bedok	Singapore	RE16040-BLR	2,318m^3/hr	Feb.2008	
Wollongong	Australia	RE8040-FEN	950m^3/hr	Aug.2007	
Brisbane	Australia	RE8040-FEN	500m^3/hr	Mar.2008	
Scottsdale	Arizona	RE16040-FE	1,161m^3/hr	Jun.2012	
West Basin	Pillippine	RE8040-FE	612m^3/hr	Jul.2008	
EBMUD	USA	RE8040-FE	630m^3/hr	Dec.2008	
Exxon Mobil	USA	RE8040-FE	156m^3/hr	Jul.2009	

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9. Sea Water Desalination Use

Customers	Location	Model No.	Capacity	Date	Remarks
EAST PARS	Iran	RE8040-SN RE8040-BE	1,800m^3/hr	Aug.2000	
Korea Navy Force	Jinhae	RE4040-SR	500pcs	Jun.1998	
KROSIS	S. Korea	RE8040-SN RE4040-SN RE2540-SN	1,000pcs/yr		Plant Manufacturer
Korea Navy Force	Jinhae	RE4040-SR	255pcs	May.2002	
SOUTH PARS	Iran	RE8040-SR RE8040-BE	70m^3/hr	Aug.2002	
Korea Navy Force	Jinhae	RE4040-SR	730pcs	Aug.2002	
Shinan-Gun	Hongdo	RE8040-SN	100m^3/hr	May.1999	
Woodo	S. Korea	RE8040-SN RE8040-SHN	15m^3/hr	Apr.2010	
Chujado	S.Korea	RE8040-SHN	9m^3/hr	Apr.2009	
Dokdo	S.Korea	RE4040-SR	15pcs	Nov.2007	
GiJang	S.Korea	RE16040-SHF RE16040-BLR	1,875m^3/hr	May.2014	BLR 2nd pass
Shuwaikh	Kuwait	RE8040-SHA	0.8m^3/hr	Dec.2011	

10. Potable Water with NF

Customers	Location	Model No.	Capacity	Date	Remarks
Mapyeong	Samcheok	NE4040-90	3.2m^3/day	Feb.2010	
Yeongwol	Yeongwol	NE4040-90	2.0m^3/day	Nov.2011	
Cheonggye	Anyang	NE4040-90	6.3m^3/hr	Dec.2009	
Siheung	Ansan	NE4040-90	13m^3/hr	Jul.2010	
Hanrim	Jeju	NE4040-90	2.3m^3/hr	Jun.2012	

3-3. Brackish Water Elements

Parameter		Unit	Brackish Water Elements			
			RE8040-BE	RE8040-BE34	RE8040-CE	RE4040-BE
Performance (Nominal)	Permeate Flux	GPD	11000	11000	12000	2400
		m^3/d	39.7	36	45.4	9.1
	Salt Rejection	%	99.7	99.7	99.0	99.7
Test Conditions	Operating Pressure	psig	225	225	225	225
	Temperature	℃	25	25	25	25
	NaCl Concentration	ppm	2000	2000	2000	2000
	pH	-	6.5～7.0	6.5～7.0	6.5~7.0	6.5～7.0
	Recovery	%	15	15	15	15
Operating Limits	Max. SDI(15min.)	-	5	5	5	5
	Max. Turbidity	NTU	1	1	1	1
	Max. Chlorine Concentration	ppm	0.1	0.1	0.1	0.1
	Max. Feed Flow Rate	m^3/hr	17	17	17	4.0
	Min. Concentration Flow Rate	m^3/hr	3.6	3.6	3.6	0.91
	Max. Pressure Drop/Element	psig	15	15	15	15
	Max. Operating Temperature	℃	45	45	45	45
	pH Range	Normal	2 ~11	2 ~11	2 ~11	2 ~11
		Cleaning	1～13	1～13	1～13	1～13
Size	Effective Area	ft^2	400	365	400	85
		m^2	37.2	33.9	37.2	7.9
	Element Length	inch	40	40	40	40
	Element Diameter	inch	8.0	8.0	8.0	4.0
	Permeate Tube Inner Dia.	inch	1.125	1.125	1.125	-
	Permeate Tube Outer Dia.	inch	-	-	-	0.75
	Permeate Tube Protrusion	inch	0	0	0	1.0
Maximum Permeate Flow Rate	Surface Water	GPD	7180	6180	4078	1530
		m^3/d	27.3	23.5	15.5	5.8
	Softened Water	GPD	9160	7890	5207	1950
		m^3/d	34.8	30.0	20.0	7.4
	RO/UF Permeate	GPD	11200	9630	6355	2370
		m^3/d	42.4	36.6	24.2	9.0

3-4. Fouling Resistant Elements

Parameter		Unit	Fouling Resistant Elements			
			RE8040-FEN	RE8040-FLR	RE4040-FEN	RE4040-FLR
Performance (Norminal)	Permeate Flux	GPD	11000	10000	2400	2400
		m^3/d	41.6	37.9	9.1	9.1
	Salt Rejection	%	99.7	99.6	99.7	99.7
Test Conditions	Operating Pressure	psig	150	150	225	225
	Temperature	℃	25	25	25	25
	NaCl Concentration	ppm	2000	1500	1500	2000
	pH	-	6.5～7.0	6.5～7.0	6.5～7.0	6.5～7.0
	Recovery	%	15	15	15	15
Operating Limits	Max. SDI(15min.)	-	5	5	5	5
	Max. Turbidity	NTU	1	1	1	1
	Max. Chlorine Concentration	ppm	0.1	0.1	0.1	0.1
	Max. Feed Flow Rate	m^3/hr	17	17	4.0	4.0
	Min. Concentration Flow Rate	m^3/hr	3.6	3.6	0.91	0.91
	Max. Pressure Drop/Element	psig	15	15	15	15
	Max. Operating Temperature	℃	45	45	45	45
	pH Range	Normal	2 ~11	2 ~11	2 ~11	2 ~11
		Cleaning	1～13	1～13	1～13	1～13
Size	Effective Area	ft^2	400	400	85	85
		m^2	37.2	37.2	7.9	7.9
	Element Length	inch	40	40	40	40
	Element Diameter	inch	8.0	8.0	4.0	4.0
	Permeate Tube Inner Dia.	inch	1.125	1.125	-	-
	Permeate Tube Outer Dia.	inch	-	-	0.75	0.75
	Permeate Tube Protrusion	inch	0	0	1.0	1.0
Maximum Permeate Flow Rate	Surface Water	GPD	6180	6180	1530	1530
		m^3/d	23.5	23.5	23.5	5.8
	Softened Water	GPD	7890	7890	1950	1950
		m^3/d	30.0	30.0	7.4	7.4
	RO/UF Permeate	GPD	9630	9630	2370	2370
		m^3/d	36.6	36.6	9.0	9.0

3-5. Low Pressure Elements

Parameter		Unit	Low Pressure Elements			
			RE8040-BLF	RE8040-BLN	RE8040-BLR	RE4040-BLF
Performance (Norminal)	Permeate Flux	GPD	11500	12000	10000	2500
		m^3/d	43.5	45.4	37.9	9.5
	Salt Rejection	%	99.2	99.2	99.6	99.2
Test Conditions	Operating Pressure	psig	100	150	150	100
	Temperature	℃	25	25	25	25
	NaCl Concentration	ppm	500	1500	1500	500
	pH	-	6.5～7.0	6.5～7.0	6.5～7.0	6.5～7.0
	Recovery	%	15	15	15	15
Operating Limits	Max. SDI(15min.)	-	5	5	5	5
	Max. Turbidity	NTU	1	1	1	1
	Max. Chlorine Concentration	ppm	0.1	0.1	0.1	0.1
	Max. Feed Flow Rate	m^3/hr	17	17	17	4.0
	Min. Concentration Flow Rate	m^3/hr	3.6	3.6	3.6	0.91
	Max. Pressure Drop/Element	psig	15	15	15	15
	Max. Operating Temperature	℃	45	45	45	45
	pH Range	Normal	2 ~11	2 ~11	2 ~11	2 ~11
		Cleaning	1～13	1～13	1～13	1～13
Size	Effective Area	ft^2	400	400	400	85
		m^2	37.2	37.2	37.2	7.9
	Element Length	inch	40	40	40	40
	Element Diameter	inch	8.0	8.0	8.0	4.0
	Permeate Tube Inner Dia.	inch	1.125	1.125	1.125	-
	Permeate Tube Outer Dia.	inch	-	-	-	0.75
	Permeate Tube Protrusion	inch	0	0	0	1.0
Maximum Permeate Flow Rate	Surface Water	GPD	8484	8484	8484	1808
		m^3/d	32.1	32.1	32.1	6.4
	Softened Water	GPD	10822	10822	10822	2304
		m^3/d	40.9	40.9	40.9	6.7
	RO/UF Permeate	GPD	13216	13216	13216	2413
		m^3/d	50.0	50.0	50.0	9.1

3-6. Sea Water Elements

Parameter		Unit	Sea Water element			
			RE8040-SHF	RE8040-SHN	RE4040-SHF	RE4040-SHN
Performance (Norminal)	Permeate Flux	GPD	6500	1900	1200	1200
		m^3/d	24.6	7.2	4.5	4.5
	Salt Rejection	%	99.75	99.7	99.75	99.2
Test Conditions	Operating Pressure	psig	800	800	800	800
	Temperature	℃	25	25	25	25
	NaCl Concentration	ppm	32000	32000	32000	32000
	pH	-	6.5～7.0	6.5～7.0	6.5～7.0	6.5～7.0
	Recovery	%	8	8	8	8
Operating Limits	Max. SDI(15min.)	-	5	5	5	5
	Max. Turbidity	NTU	1	1	1	1
	Max. Chlorine Concentration	ppm	0.1	0.1	0.1	0.1
	Max. Feed Flow Rate	m^3/hr	17	4.0	4.0	4.0
	Min. Concentration Flow Rate	m^3/hr	3.6	0.91	0.91	0.91
	Max. Pressure Drop/Element	psig	15	15	15	15
	Max. Operating Temperature	℃	45	45	45	45
	pH Range	Normal	2 ~11	2 ~11	2 ~11	2 ~11
		Cleaning	1～13	1～13	1～13	1～13
Size	Effective Area	ft^2	400	75	75	75
		m^2	34.4	6.9	6.9	6.9
	Element Length	inch	40	40	40	40
	Element Diameter	inch	8.0	4.0	4.0	4.0
	Permeate Tube Inner Dia.	inch	1.125	-	-	-
	Permeate Tube Outer Dia.	inch		0.75	0.75	0.75
	Permeate Tube Protrusion	inch	0	1.0	1.0	1.0
Maximum Permeate Flow Rate	Surface Water	GPD	5932	1100	1100	1100
		m^3/d	22.5	4.2	4.2	4.2
	Softened Water	GPD	6790	1530	1530	1530
		m^3/d	25.8	5.8	5.8	5.8
	RO/UF Permeate	GPD	8660	1950	1950	1950
		m^3/d	32.9	7.4	7.4	7.4

3-7. Nanofiltration(NF) Elements

Parameter		Unit	Nanofiltration(NF) Elements			
			NE8040-90	NE8040-70	NE8040-40	NE4040-90
Performance (Norminal)	Permeate Flux	GPD	8000	7000	10000	1700
		m^3/d	30.3	26.5	37.9	6.0
	Salt Rejection [$MgSO_4$(NaCl)]	%	97(85～95)	97(40~70)	97(40~70)	97(85～90)
Test Conditions	Operating Pressure	psig	75	75	75	75
	Temperature	℃	25	25	25	25
	$MgSO_4$(NaCl) Concentration	ppm	2000(2000)	2000(2000)	2000(2000)	2000(2000)
	pH	-	6.5～7.0	6.5～7.0	6.5～7.0	6.5～7.0
	Recovery	%	15	15	15	15
Operating Limits	Max. SDI(15min.)	-	5	5	5	5
	Max. Turbidity	NTU	1	1	1	1
	Max. Chlorine Concentration	ppm	0.1	0.1	0.1	0.1
	Max. Feed Flow Rate	m^3/hr	15	15	15	4.0
	Min. Concentration Flow Rate	m^3/hr	3.6	3.6	3.6	0.91
	Max. Pressure Drop/Element	psig	15	15	15	15
	Max. Operating Temperature	℃	45	45	45	45
	pH Range	Normal	2 ~11	2 ~11	2 ~11	2 ~11
		Cleaning	1～13	1～13	1～13	1～13
Size	Effective Area	ft^2	400	400	400	85
		m^2	37.2	37.2	37.2	7.9
	Element Length	inch	40	40	40	40
	Element Diameter	inch	8.0	8.0	8.0	4.0
	Permeate Tube Inner Dia.	inch	1.125	1.125	1.125	-
	Permeate Tube Outer Dia.	inch	-	-	-	0.75
	Permeate Tube Protrusion	inch	0	0	0	1.0
Maximum Permeate Flow Rate	Surface Water	GPD	6180	6180	6180	1340
		m^3/d	23.5	23.5	23.5	5.1
	Softened Water	GPD	7890	7890	7890	1710
		m^3/d	30.0	30.0	30.0	6.5
	RO/UF Permeate	GPD	9630	9630	9630	2080
		m^3/d	36.6	36.6	36.6	7.9

3-8. Tap Water Elements

Parameter		Unit	Tap Water Elements			
			RE4040-TL	RE2540-TL	RE4021-TL	RE2521-TL
Performance (Norminal)	Permeate Flux	GPD	2600	800	1050	350
		m^3/d	9.8	3.0	4.0	1.3
	Salt Rejection	%	99.2	99.2	99.2	99.2
Test Conditions	Operating Pressure	psig	150	150	150	150
	Temperature	℃	25	25	25	25
	NaCl Concentration	ppm	1500	1500	1500	1500
	pH	-	6.5～7.0	6.5～7.0	6.5～7.0	6.5～7.0
	Recovery	%	15	15	15	15
Operating Limits	Max. SDI(15min.)	-	5	5	5	5
	Max. Turbidity	NTU	1	1	1	1
	Max. Chlorine Concentration	ppm	0.1	0.1	0.1	0.1
	Max. Feed Flow Rate	m^3/hr	4.0	1.3	4.0	1.3
	Min. Concentration Flow Rate	m^3/hr	0.91	0.22	0.91	0.22
	Max. Pressure Drop/Element	psig	15	15	15	15
	Max. Operating Temperature	℃	45	45	45	45
	pH Range	Normal	2 ~11	2 ~11	2 ~11	2 ~11
		Cleaning	1～13	1～13	1～13	1～13
Size	Effective Area	ft^2	85	27	35	12
		m^2	7.9	2.5	3.3	1.1
	Element Length	inch	40	40	21	21
	Element Diameter	inch	4.0	2.5	4.0	2.5
	Permeate Tube Inner Dia.	inch	-	-	-	-
	Permeate Tube Outer Dia.	inch	0.75	0.75	0.75	0.75
	Permeate Tube Protrusion	inch	1.0	1.0	1.0	1.0
Maximum Permeate Flow Rate	Surface Water	GPD	1808	574	744	255
		m^3/d	6.4	2.2	2.8	1.0
	Softened Water	GPD	2304	732	949	325
		m^3/d	6.7	2.8	3.6	1.2
	RO/UF Permeate	GPD	2413	766	994	340
		m^3/d	9.1	2.9	3.8	1.3

Parameter		Unit	Tap Water Elements			
			RE4040-TE	RE2540-TE	RE4021-TE	RE2521-TE
Performance (Norminal)	Permeate Flux	GPD	2400	800	1050	300
		m^3/d	9.1	3.0	4.0	1.1
	Salt Rejection	%	99.5	99.5	99.5	99.5
Test Conditions	Operating Pressure	psig	225	225	225	225
	Temperature	℃	25	25	25	25
	NaCl Concentration	ppm	2000	2000	2000	2000
	pH	-	6.5～7.0	6.5～7.0	6.5～7.0	6.5～7.0
	Recovery	%	15	15	8	8
Operating Limits	Max. SDI(15min.)	-	5	5	5	5
	Max. Turbidity	NTU	1	1	1	1
	Max. Chlorine Concentration	ppm	0.1	0.1	0.1	0.1
	Max. Feed Flow Rate	m^3/hr	4.0	1.3	4.0	1.3
	Min. Concentration Flow Rate	m^3/hr	0.91	0.22	0.91	0.22
	Max. Pressure Drop/Element	psig	15	15	15	15
	Max. Operating Temperature	℃	45	45	45	45
	pH Range	Normal	2 ~11	2 ~11	2 ~11	2 ~11
		Cleaning	1～13	1～13	1～13	1～13
Size	Effective Area	ft^2	85	27	35	12
		m^2	7.9	2.5	3.3	1.1
	Element Length	inch	40	40	21	21
	Element Diameter	inch	4.0	2.5	4.0	2.5
	Permeate Tube Inner Dia.	inch	-	-	-	-
	Permeate Tube Outer Dia.	inch	0.75	0.75	0.75	0.75
	Permeate Tube Protrusion	inch	1.0	1.0	1.0	1.0
Maximum Permeate Flow Rate	Surface Water	GPD	1530	470	630	210
		m^3/d	5.8	1.8	2.4	0.8
	Softened Water	GPD	1950	630	790	260
		m^3/d	7.4	2.4	3.0	1.0
	RO/UF Permeate	GPD	2370	760	970	340
		m^3/d	9.0	2.9	3.7	1.3

3-9. Ultrafiltration(UF) Elements

Parameter		Unit	Ultrafiltration(UF) Elements		
			UE8040-ES10	UE8040-CEP	UE4040-CEP
Performance (Norminal)	Permeate Flux	GPD	7200	6500	1400
		m^3/d	27.2	24.6	5.3
	Salt Rejection		10k		
Test Conditions	Operating Pressure	psig	20	14.5	14.5
	Temperature	℃	25	25	25
	Feed Water	-	Pure water	Pure water	Pure water
	pH	-	6.5～7.0	6.5～7.0	6.5～7.0
	Recovery	%			
Operating Limits	Max. SDI(15min.)	-			
	Max. Turbidity	NTU			
	Max. Chlorine Concentration	ppm			
	Max. Feed Flow Rate	m^3/hr	17	17	4.0
	Min. Concentration Flow Rate	m^3/hr	3.6	3.6	0.91
	Max. Pressure Drop/Element	psig	15	15	15
	Max. Operating Temperature	℃	45	45	45
	pH Range	Normal			
		Cleaning			
Size	Effective Area	ft^2	400	400	85
		m^2	37.2	37.2	7.9
	Element Length	inch	40	40	40
	Element Diameter	inch	8.0	8.0	4.0
	Permeate Tube Inner Dia.	inch	1.125	1.125	-
	Permeate Tube Outer Dia.	inch	-	-	0.75
	Permeate Tube Protrusion	inch	0	0	1.0
Maximum Permeate Flow Rate	Surface Water	GPD	12653	12653	2600
		m^3/d	47.9	47.9	9.8
	Softened Water	GPD	17700	17700	3000
		m^3/d	67.0	67.0	11.4
	RO/UF Permeate	GPD	19900	19900	3360
		m^3/d	75.3	75.3	12.7

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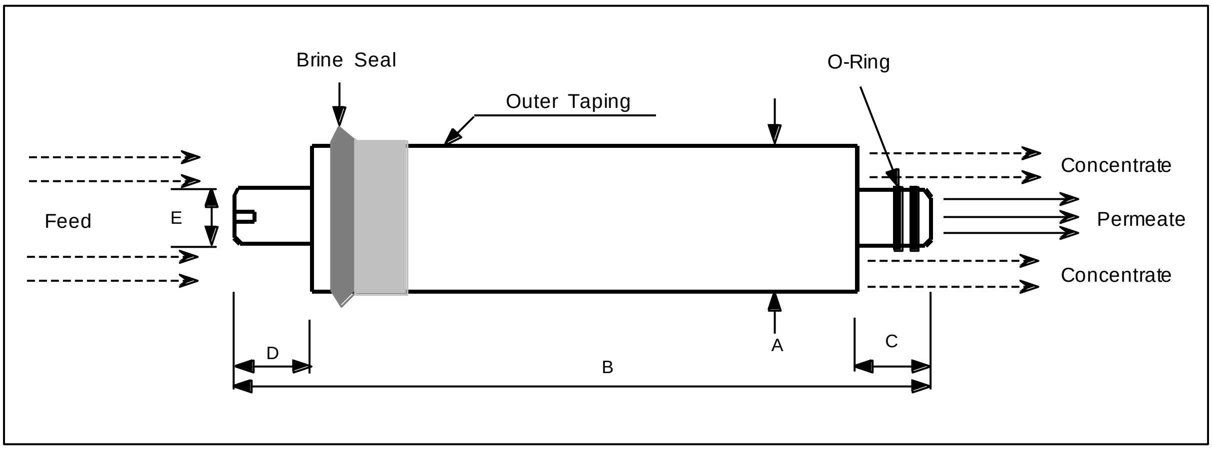
Model No.	Flux (GPD)	Salt Rej' (%)	Test Conditions				Size(mm)				
			Pressure (psig)	Temp. (℃)	Feed Conc. (ppm)	Recovery (%)	A	B	C	D	E
RE1810-30	30	98	60	25	200	15	45.0±0.5	256	25	14	17
RE1810-50	50	98	60	25	200	15	45.0±0.5	256	25	14	17
RE1810-80	80	98	60	25	200	15	45.0±0.5	298	22	22	17
RE1812-50	50	98	60	25	200	15	48.5±0.5	298	23	12	17
RE1812-60	60	98	60	25	200	15	48.5±0.5	298	23	12	17
RE1812-80	80	98	60	25	200	15	48.5±0.5	298	23	12	17
RE2012-LP	50	93	20	25	100	15	50.0±0.5	298	23	12	17
RE2012-LPF	60	93	20	25	100	15	50.0±0.5	298	23	12	17

■ Operating Limits

· Maximum Operating Pressure	125psig
· Maximum Feed Flow Rate	2gpm
· Maximum Operating Temperature	45℃
· Feed Water pH Range	3.0~10.0
· Maximum Turbidity	1.0NTU
· Maximum Silt Density Index	5.0
· Free Chlorine Tolerance	<0.1ppm

※ Consult CSM for other operating conditions.



4-1. Introduction

The efficiency and lifetime of a reverse osmosis (RO) process depends on effective pretreatment of the feed water. The pretreatment includes any process which can minimize fouling, scaling and membrane degradation to maintain product flow, salt rejection, product recovery and economical operating costs.

Fouling is the entrapment of particulates such as inorganic and organic colloids. Examples of the inorganic colloids are iron floc, silica, clay and silt. The organic colloids are mostly consisted of organic polymers and microorganisms. Scaling is the precipitation and deposition within the RO system of sparingly soluble salts such as calcium carbonate ($CaCO_3$), calcium sulfate ($CaSO_4$) and barium sulfate ($BaSO_4$).

A proper pretreatment scheme for the feed water mainly depend on feed water source, feed water composition and application. There are three types of feed water. Well water contains a low Silt Density Index (SDI) (typically < 2) and low bacteria count, thus requiring a simple pretreatment scheme. Surface water, on the other hand, is characterized by a high SDI and can have a high bacteria count. Pretreatment for surface water is more elaborate than for well water, requiring the addition of a coagulant, clarification, and multimedia filtration.

Once the feed water source has been determined, an accurate analysis of the feed water composition including bacteria count should be conducted to determine the dosage size of a coagulant, a scale inhibitor (antiscalant) and a biocide for the disinfection.

4-2. Feed Water Analysis

A complete and accurate feed water analysis must be performed prior to RO system design. The water analysis report should contain the type and the concentration of all constituents in the water. The constituents are consisted of dissolved ions, silica, colloids, and organic (TOC)

■ **Typical dissolved anions are as follows :**

bicarbonate(HCO^{3-}), carbonate(CO_3^{2-}), hydroxide(OH^-), sulfate(SO_4^{2-}), chloride(Cl^-), fluoride(F^-), nitrate(NO_3^-), sulfide(S^{2-}) and phosphate(PO_4^{2-})

■ **Typical dissolved cations are shown below :**

calcium(Ca^{2+}), magnesium(Mg^{2+}), sodium(Na^+), potassium(K^+), iron(Fe^{2+} or Fe^{3+}), manganese(Mn^{2+}), aluminum(Al^{3+}), barium(Ba^{2+}), strontium(Sr^{2+}), copper(Cu^{2+}) and zinc (Zn^{2+}).

Certain combinations of cations and anions form sparingly soluble salts in water and scaling of RO membrane may occur when the salts are concentrated within the RO element beyond their solubility limit. Typical sparingly soluble salts and their solubility product limit are shown in Table 1.

Substance	Formula	Temp.(℃)	Solubility Product
Aluminum Hydroxide	$Al(OH)_3$	20	1.9×10^{-33}
Barium Carbonate	$BaCO_3$	16	7×10^{-9}
Barium Sulfate	$BaSO_4$	25	1.08×10^{-10}
Calcium Carbonate	$CaCO_3$	25	8.7×10^{-9}
Calcium Fluoride	CaF_2	26	3.95×10^{-11}
Calcium Sulfate	$CaSO_4$	10	6.1×10^{-5}
Cupric Sulfide	CuS	18	3.5×10^{-45}
Ferric Hydroxide	$Fe(OH)_3$	18	1.1×10^{-36}
Ferrous Hydroxide	$Fe(OH)_2$	18	1.64×10^{-14}
Magnesium Ammonium Phosphate	$MgNH_4PO_4$	25	2.5×10^{-13}
Magnesium Carbonate	$MgCO_3$	12	2.6×10^{-5}
Magnesium Hydroxide	$Mg(OH)_2$	18	1.2×10^{-11}
Manganese Hydroxide	$Mn(OH)_2$	18	4×10^{-14}
Strontium Carbonate	$SrCO_3$	25	1.6×10^{-9}
Strontium Sulfate	$SrSO_4$	17.4	2.81×10^{-7}
Zinc Hydroxide	$Zn(OH)_2$	20	1.8×10^{-14}

Table 1 : Solubility Products of Sparingly Soluble Inorganic Compounds

In the RO system the most common sparingly soluble salts encountered are $CaSO_4$, $CaCO_3$ and silica. Other salts creating a potential scaling problem are CaF_2, $BaSO_4$ and $SrSO_4$, though less prevalent. Other ions causing problems are described below. Sulfates are present in relatively large concentrations in most raw waters. Their concentration can be artificially increased when sulfuric acid is added to water to adjust pH. In this case, Ba^{2+} and Sr^{2+} must be analyzed accurately at 1㎍/ℓ(ppb) and 1㎎/ℓ(ppm) level of detection, respectively, since $BaSO_4$ and $SrSO_4$ are much less soluble in water than $CaSO_4$ and moreover, barium and strontium sulfate scales are extremely difficult to redissolve.

Alkalinity consists of negative ions which include bicarbonate, carbonate and hydroxide. Most of the alkalinity in naturally occurring water sources is in the form of bicarbonate alkalinity (HCO_3^-). Below a pH of 8.3, the bicarbonate alkalinity will be in equilibrium with a certain concentration of dissolved carbon dioxide. At a pH greater than 8.3, HCO_3^- will be converted to the carbonate form (CO_3^{2-}). With water sources of pH above 11.3, hydroxide (OH^-) will be present.

Water can dissolve carbon dioxide from the air, forming carbonic acid (H_2CO_3). The acidic water will tend to dissolve calcium carbonate from the ground as it passes over or through the calcium carbonate rock. Most naturally occurring water sources are close to saturation in calcium carbonate which is in equilibrium with calcium bicarbonate, depending on the pH of the water. Calcium bicarbonate is much more soluble in water than calcium carbonate. If the water is concentrated in the RO system, calcium carbonate salt is likely to precipitate in the system. Thus the use of a scale inhibitor or lowering the pH below 8 by an acid injection is required in most RO systems.

Nitrates are very soluble in water and thus will not precipitate in an RO system, Nitrates are a health concern since, when ingested by mammals including humans, they are converted to nitrites which interfere with hemoglobins to exchange oxygen in blood. This can cause serious problems especially for fetus and children. For this reason, it is desirable to maintain a nitrate concentration below 40 ㎎/ℓ in drinking water. Typical nitrate removal rate by RO is in the range of 90-96%.

Iron and manganese are present in water either in a divalent state, which is soluble in water, or in a trivalent state, which forms insoluble hydroxides. The soluble iron (Fe^{2+}) can come from either a well water or the rust of pump, piping and tanks, especially if acid is injected upstream of the equipment. If the iron or manganese concentration is greater than 0.05 ㎎/ℓ in RO feed water and they are oxidized by air or an oxidizing agent to the trivalent state, then the insoluble hydroxides $Fe(OH)_3$ and $Mn(OH)_3$ will precipitate in the system, when the water pH is neutral or higher. They can also catalyze the oxidative effects of residual oxidizing agents, possibly accelerating the membrane degradation. Thus iron and manganese must be removed at the pretreatment step (see the pretreatment section).

Aluminum is usually not noticeably present in naturally occurring water sources. With its valence of 3+ like iron (Fe^{3+}), aluminum will form very insoluble hydroxide [$Al(OH)_3$] at the normal operating pH range of 5.3 to 8.5 in an RO system. Because of the high charge characteristics, alum [$Al_2(SO_4)_3$] or sodium aluminate ($NaAlO_2$) is used to coagulate negatively charged colloids in the pretreatment of surface waters. Care must be taken not to employ the coagulant excessively to result in carrying the residual aluminum over to the membranes.

A concentration of aluminum greater than 0.01mg/l in the dialysis water is a health concern for kidney dialysis patients. In this regard, iron [$FeCl_3$ or $Fe_2(SO_4)_3$] may be preferred as a coagulant.

Copper and Zinc are not appreciably detected in natural water sources. Sometimes, it is possible to pick up trace amounts from piping materials. Their hydroxides $Cu(OH)_2$ and $Zn(OH)_2$) will drop out of solution over the operating pH range of 5.3 to 8.5. Because of the low concentrations of copper and zinc, their precipitants will foul the RO system only if allowed to precipitate over an extended period of time without cleaning the system. However, more serious situation may develop, when an oxidizing agent such as hydrogen peroxide is present together with copper or zinc, to degrade the membranes rapidly.

Sulfides are present as a dissolved gas, hydrogen sulfide (H_2S). Hydrogen sulfides oxidizes and releases elemental sulfur which can cause irreversible fouling of RO membranes, Hydrogen sulfide gas can be removed by running the water through a degasifier. Oxidizing sulfides by chlorine or air to insoluble elemental sulfur followed by media filtration also can be used to address the sulfides issue.

Phosphates have a strongly negative charge (3-) and a tendency to react with multivalent cations such as Ca^{2+}, Mg^{2+} ,Fe^{2+} , Fe^{3+} to give insoluble salts. Calcium phosphate has a very limited solubility at neutral pH and an even lower solubility at higher pH. The use of a scale inhibitor or lowering the pH of the feed water below 7 is a measure to control the phosphate precipitate.

Silica is naturally present in most feed waters in the range of 1-100㎎/ℓ and exists mostly in the silicic acid form [$Si(OH)_4$] below a pH of 9. At low pH, Silicic acid can polymerize to form a colloid (colloidal silica). At high pH above 9, it dissociates into the silicate anion (SiO_3^{2-}) and can precipitate as a salt with calcium, magnesium, iron or aluminum. Silica and silicates are difficult to redissolve. Ammonium bifluoride solutions are somewhat successful at cleaning silica scaling. However, ammonium bifluoride is considered a hazardous chemical posing problems for disposal. Silica present in an RO feed water at a concentration greater than 20㎎/ℓ may pose a potential for silica scaling.

Silt density index (SDI), also known as the Fouling Index (FI), is a good indicative to determine the colloidal fouling potential of RO feed water. The source of colloids in RO feed waters is varied and often includes bacteria, clay, colloidal silica and iron corrosion products. Pretreatment chemicals used in a clarifier such as alum, ferric chloride or cationic polyelectrolytes can also cause colloidal fouling if not removed in the clarifier or through proper media filtration.

SDI measurement should be done prior to designing the RO pretreatment system and on a regular basis during RO operation (at least once a day for surface waters). The test measures the rate of fouling of a 0.45㎛ membrane filter by the following procedure.

Place the membrane filter (47㎜, 0.45㎛) on its support, bleed water pressure on carefully, tighten the O-ring seal and fix the support vertically.

Adjust feed pressure to 2.1bar (30psi) and measure initial time t_0, necessary to filter 500㎖ of sample water (feed pressure to be kept constant by continuous adjustment).

Continue filtering the water for 15 min at 2.1bar (30psi). If the filter is plugged up in 15min, use the 10 or 5min measurement. After 15 minutes, measure again time, t_1, necessary to filter additional 500㎖ sample water.

SDI is calculated as follows ;

$$SDI = 100 \times \frac{(1-t_0/t_1)}{T}$$

T is the time before the second flow measurement (5,10 or 15 minutes).

The guideline is to maintain SDI at less than or equal to 5 for RO feed water.

Turbidity is another guideline as an indicator for the rate of RO membrane fouling. Turbidometers (also called nephelometers) measure the scattering of light caused by various suspended solids in the water sample. Water samples having turbidity value greater than 1NTU (Nephelometric Turbidity Units) regarded as high fouling potential feed water for RO membranes. Like the SDI test, turbidity is only an indicator of fouling potential. High turbidity does not necessarily mean that the suspended solid is going to deposit on the RO membrane.

In fact, there are some membrane foulants such as surfactants and soluble polymers that do not scatter light to register a turbidity reading. Although turbidity and SDI are not perfect in predicting the behavior of the colloidal foulants, they are useful for characterizing the RO feed water. For examples, SDI greater than 5 and NTU greater than 1 strongly suggest that some coagulants should be used in the clarifier step of the feed water pretreatment, followed by media filtration. The feed water with SDI less than 5 and NTU less than 1 may just require media filtration or cartridge filters without the necessity of coagulation of the colloids.

It is also necessary to have some guidelines for controlling the amount of the coagulant added to the clarifier, since excessive addition of the coagulant should be avoided. Two feasible guidelines are zeta potential measurement and streaming current detector.

Zeta Potential is a measurement of the overall charge characteristics of the suspended solids in the water, when the water containing the charged colloids flows in one direction between the oppositely charged electrodes. Most colloids in natural water sources have negative charges which help to repel each other to keep them suspended in solution. In overall, the colloidal water will show negative zeta potential. These negative charges can be neutralized by the addition of cationic coagulants such as aluminum sulfate (alum) and ferric chloride. The coagulants are portionwise added until zeta potential reached to zero (neutral). The colloids without charges do not repel each other and are more likely to coagulate into larger particulate groups which can be easily filtered out by media filters.

Streaming Current Detector uses a mechanical plunger to create a high water velocity, which causes movement of the ions surrounding negatively charged suspended colloids. It measures the eletrical current generated by the moving ions. If the charge of the colloids has been neutralized by the addition of a coagulant, there will be very little current generated by the streaming current detector.

The last constituents in the feed water to be analyzed are bacteria count and organic compounds. There are two ways to count bacteria in the water. One method is to collect bacteria by filtering a measured quantity of water through a membrane filter followed by culturing the retained organisms and counting the developed colonies under low power magnification. The second method is to count the retained microorganisms on the filter plate directly under a fluorescent microscope after staining the microorganisms with dyes such as acridine orange. Direct count methods should be preferred, because they are much faster and more accurate than culture techniques.

Examples of organic compounds in the feed water are oils, surfactants, water soluble polymers, and humic acid. The organic compounds are collectively analyzed by Total Organic Carbon (TOC), Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD). Identification of individual organic substance may require more elaborate analytical tools such as chromatography (HPLC) and GC-Mass spectrometry. Removal of the organic compounds from the feed water at the pretreatment step should be considered when TOC exceeds 3㎎/ℓ.

4-3. Prevention of Scale Formation

Scaling of an RO membrane may occur when sparingly soluble salts are concentrated in the RO element beyond their solubility limit. Sparingly soluble salts are listed below in the order of decreasing scaling problem:

$CaCO_3 > CaSO_4 > Silica > SrCO_3 > BaSO_4 > SrSO_4 > CaF_2 > CaSiO_3 > MgSiO_3 > MgSiO_3 > Ca_3(PO4)_2 > Fe(OH)_2$

Calcium sulfate ($CaSO_4$) is more soluble than $BaSO_4$ and $SrSO_4$. However, calcium ion (Ca^{2+}) is present in natural water sources more abundantly than Ba^{2+} and Sr^{2+} and thus $CaSO_4$ will cause more scaling problem than $BaSO_4$ and $SrSO_4$. On the other hand, $BaSO_4$ and $SrSO_4$ are difficult to redissolve once precipitated. Hence, scaling of the two salts should be avoided.

The most frequent scaling problems come from calcium carbonate ($CaCO_3$) because it precipitates fast, once concentrated beyond its solubility limit and also most natural waters are almost saturated with respect to $CaCO_3$. $CaCO_3$ scaling including $SrCO_3$ and $BaCO_3$ can be prevented by acid addition, a scale inhibitor, softening of the feed water, preventive cleaning and low system recovery.

$CaSO_4$ scaling including $BaSO_4$, $SrSO_4$ and CaF_2 is preventable by the same methods as $CaCO_3$ scaling except the acid addition. In fact, using sulfuric acid to lower pH for the prevention of $CaCO_3$ scaling would increase the probability of the sulfate scaling.

Acid Addition

The solubility of CaCO3 depends on the pH as shown in the following equation.

$$CaCO_3 + H \rightleftarrows Ca^{2+} + HCO_3^-$$

The equilibrium can be shifted to the right side to convert $CaCO_3$ to soluble $Ca(HCO_3)_2$ by adding an acid (lowering pH). The acid used should be of food grade quality. Sulfuric acid is commonly employed, but hydrochloric acid is preferred in the case of high scaling potential due to $CaSO_4$, $SrSO_4$ and $BaSO_4$ were also considered.

In order to avoid calcium carbonate scaling, the pH of the concentrate stream in an RO system should be lower than the pH of saturation (pH_s) where the concentrate stream is in equilibrium with $CaCO_3$. This relationship is expressed by the Langelier Saturation Index (LSI) for brackish waters and Stiff & Davis Saturation Index (S&DSI) for sea waters.

$$LSI = pH - pH_S \qquad (TDS < 10{,}000\ mg/\ell)$$

$pH_s = (9.3 + A + B) - (C + D)$

where ; $A = (\mathrm{Log}_{10}[TDS] - 1) / 10$
$B = -13.12 \times \mathrm{Log}_{10}(℃ + 273) + 34.55$
$C = \mathrm{Log}_{10}[Ca^{2+}] - 0.4$, where $[Ca^{2+}]$ is in ppm as $CaCO_3$
$D = \mathrm{Log}_{10}$ [alkalinity], where [alkalinity] is in ppm as $CaCO_3$

(Reference : ASTM D3739-88 Calculation and Adjustment of the Langelier Saturation Index for Reverse Osmosis)

S & DSI = pH - pCa - pAlk - K

Where : pCa is the negative log of the calcium concentration in moles/ℓ.
pAlk is the negative log of the total alkalinity concentration in moles/ℓ.
K is a constant which is a function of water temperature and ionic strength.

(Reference : ASTM D4582-86 Calculation and Adjustment of the Stiff and Davis Saturation Index for Reverse Osmosis)

Concentration factor is used to calculate the concentration of the constituents in the concentrate stream from that in the feed water.

$$\text{Concentration factor} = \frac{1}{1 - \text{recovery}}$$

Where recovery = permeate flow rate / feed flow rate

In reality, concentration polarization should be taken into account to get more accurate scaling potential as shown below.

$$\text{Concentration factor} = \frac{\text{concentration polarization}}{1 - \text{recovery}}$$

The concentration polarization value depends on the turbulence of the bulk stream in the RO element and varies from 1.13 to 1.2, meaning that the concentration of salts at the membrane surface is 13% to 20% higher than in the bulk stream.

To control calcium carbonate scaling by acid addition alone, the LSI or S & DSI in the concentrate stream must be negative. A rule of thumb is to lower the feed water pH to 6.0. If a high quality scale inhibitor is used, the LSI in the concentrate stream can be as high as 1.8 (refer to the inhibitor manufacturer's literature for reference points). This will reduce or eliminate the acid consumption, and also could decrease the potential for corrosion due to the acid addition.

Scale Inhibitor Addition

Scale inhibitors (antiscalants) slow the precipitation process of sparingly soluble salts by being absorbed on the forming salt crystals to prevent the attraction of the supersaturated salt to the crystal surfaces. In this situation the crystals never grow to a size or concentration sufficient to fall out of suspension. Furthermore, many scale inhibitors have some dispersive qualities which involve surrounding particles of suspended salt or organic solids with the anionically charged scale inhibitor. Now the anionically charged particles will repel each other to prevent the agglomeration of the particles to larger particles that may precipitate.

Scale inhibitors effective in controlling carbonate scaling, sulfate scaling and calcium fluoride scaling are listed below.

Sodiumhexametaphostphate(SHMP) is most widely used because it offered good inhibition at a low cost. However, care must be taken in order to avoid hydrolysis of SHMP in the dosing feed tank (a fresh solution should be made every 3 days). Hydrolysis would not only decrease the scale inhibition efficiency, but also create a calcium phosphate scaling risk.

SHMP should be dosed to give a concentration in the concentrate stream of 20㎎/ℓ. The dosage into the feed stream can be calculated by the equation :

SHMP dosing rate = 20mg × (1 - Y).

Where Y is a fraction of recovery

Organophosphonates are more resistant to hydrolysis compared to SHMP even though they are more expensive. They offer scale inhibition and dispersion ability similar to SHMP.

Polyacrylic acids (PAA) are good at both scale inhibition and dispersion. The usual molecular weight of PAA is 2000 to 5000. PAA with higher molecular weight distribution in the range of 6000 to 25000 showed the best dispersion ability at the sacrifice of scale inhibition ability. In general, PAA are more effective than SHMP. However, precipitation reactions may occur with cationic polyelectrolytes or multivalent cations such as aluminum or iron to foul the membrane.

Blend Inhibitors are a combination of low and high molecular weight of PAA or a blend of low molecular weight PAA and organophosphonates for excellent dispersive and inhibitor performance.

There are many manufacturers of scale inhibitors such as BF Goodrich, Arrowhead, Betz, Grace Dearborn, Calgon, FMC, Degremont, Nalco, King-Lee and Maxwell Chemicals, etc. (antiscalant manufacturer list re-check needed) Please, consult with them for the chemical identity of the scale inhibitor brands and their compatibility with RO membranes. They can usually be considered compatible with polyamide RO membranes up to 50 ppm concentration in the concentrate.

Additionally, RO permeate should be used when diluting the scale inhibitors, since calcium present in the feed water may form a precipitate with the scale inhibitors at high concentrations. Precautions must also be taken so that there is no microbial growth in the inhibitor dilution tank. Make certain that no significant amounts of cationic polymers are present when adding an anionic scale inhibitor.

Softening with a Strong Acid Cation Exchange Resin

The scale forming cations such as Ca^{2+}, Ba^{2+}, Sr^{2+}, Mg^{2+}, and Fe^{2+} can be removed by a cation exchange resin which could be a good alternative way to prevent scale formation for small or medium size brackish water RO systems. The resin has to be regenerated with NaCl at the saturation point. A drawback of this process is its relatively high sodium chloride consumption, which might cause an environmental (disposing the brine) or an economic problem.

Softening with a Weak Acid Cation Exchange Resin

The weak acid cation exchange resin can remove only Ca^{2+}, Ba^{2+} and Sr^{2+} linked to bicarbonate and release H^+, thus lowering the pH to a minimum value of 4.2 where the carboxylic acid groups of the resin are no longer dissociated. Therefore, it is only a partial softening and ideal for waters with high bicarbonate content.

The advantages of softening with a weak acid cation exchange resin are :

- Almost stoichiometrical consumption (105%) of acid for regeneration to minimize the operating costs and the environmental impact
- Reduction of the TDS value of the water by the removal of bicarbonate salts to result in the lower permeate TDS.

The disadvantages are :

- Residual hardness due to incomplete softening
- Variable pH of the treated water from 3.5 to 6.5 depending on the degree of exhaustion of the resin

At $pH < 4.2$, the passage of mineral acid may increase the permeate TDS. It is therefore recommended to use more than one resin column in parallel and to regenerate them at different times in order to level out the pH. Other possibilities to avoid extremely low pH values are CO_2 removal or pH adjustment by NaOH.

Lime Softening

Lime [$Ca(OH)_2$] reacts with soluble calcium or magnesium bicarbonate to remove carbonate hardness as shown in the following equations ;

$$Ca(HCO_3)_2 + Ca(OH)_2 \rightarrow 2CaCO_3\downarrow + 2H_2O$$
$$Mg(HCO_3)_2 + 2Ca(OH)_2 \rightarrow Mg(OH)_2 + 2CaCO_3\downarrow + 2H_2O$$

The non-carbonate calcium hardness can be further reduced by adding sodium carbonate (soda ash) :

$$CaCl_2 + Na_2CO_3 \rightarrow 2NaCl + CaCO_3$$

The lime-soda ash process can also reduce the silica concentration. When sodium aluminate and ferric chloride are added as coagulants, the lime-soda ash will precipitate calcium carbonate and a complex consisted of calcium, aluminum and iron silicate. Silica can be reduced to 1㎎/ℓ by adding a mixture of lime and porous magnesium oxide. The lime softening can also reduce barium, strontium and organic substances such as humic acid significantly. The effluent from this process needs media filtration and pH adjustment prior to the RO elements. Lime softening should be considered for brackish water plants larger than $200m^3/h$ (1.2 million gpd).

Preventive Cleaning

In some applications such as small systems, preventive membrane cleaning allows the system to run without dosage of acids or scale inhibitors or softening. Typically, those systems operate at low recovery in the range of 25% and the membrane elements are replaced after 1-2 years. The simplest way of cleaning is a forward flush at low pressure by opening the concentrate valve. Short cleaning intervals are more effective than long cleaning times, e.g. 30seconds every 30 minutes. Cleaning can also be performed with cleaning chemicals, which may be done occasionally between the short cleaning intervals.

Adjustment of System Recovery, pH and Temperature

The precipitation of dissolved salts can be avoided by keeping their concentration in the concentrate stream below the solubility limit, which can be achieved by reducing the system recovery, raising temperature, and adjusting pH.

To be more quantitative for the above operation, solubility product (limit) for each sparingly soluble solute should be calculated under conditions in the concentrate stream as discussed in the following sections. Silica is usually the only reason for adjusting the above three operating variables as a scale control method, since these adjustments have high energy consumption due to low system recovery or other scaling risks such as $CaCO_3$ scaling at high pH. For small systems, a low recovery combined with a preventive cleaning program might be a convenient way to control scaling.

4-4. Solubility Product Calculations

To determine the scaling potential, the ion product IP_c of a sparingly soluble salt in the concentrate stream should be compared with the solubility product K_{sp} of the salt under conditions in the concentrate stream (K_{sp} is a function of temperature and ionic strength). If $IP_c < K_{sp}$, no scale control is necessary.

The concentration of ion species in the concentrate stream is usually not known unless measured experimentally, but can easily be estimated from the concentration in the feed stream by multiplication with the concentration factor CF= 1 / (1 - r). Where r is recovery ratio (expressed as a decimal).

The ionic strength of the feed water is :

$$I_f = \tfrac{1}{2}\Sigma(m_i \times Z_i^2)$$

Where m_i = molar concentration of ion i (mol/kg)

Z_i = ionic charge of ion i

Where the water analysis is not given in molar concentrations, the conversion is as follows :

$$m_i = \frac{1000Ci}{MW_i}$$

Where C_i = concentration of ion i in mg/ℓ

MW_i = molecular weight of ion i

The ionic strength I_c of the concentrate stream is obtained from :

$$I_c = I_f \times \frac{1}{(1 - r)}$$

With the ionic strength of the concentrate stream, the solubility product K_{sp} of the sparingly soluble salt can be obtained.

To make sure that scaling will not occur, the IP_c for $CaSO_4$, $BaSO_4$, $SrSO_4$ and CaF_2 should be less than 0.8 K_{sp} of the corresponding salts, respectively. If $IP_c > 0.8K_{sp}$, one of the scale preventing methods discussed in the previous section must be applied.

If proper scale inhibitors are used, IP_c could be greater than K_{sp} as shown in the following equation.

$IP_c \leq 2.0\ K_{sp}$ for $CaSO_4$ if PAA or organophosphonates are employed
$IP_c \leq 1.5\ K_{sp}$ for $CaSO_4$ if SHMP is used
$IP_c \leq 50\ K_{sp}$ for $BaSO_4$
$IP_c \leq 10\ K_{sp}$ for $SrSO_4$
$IP_c \leq 100\ K_{sp}$ for CaF_2

Barium sulfate is the most insoluble of all alkaline-earth sulfates. In most natural waters, barium is present at a level close to precipitation in the concentrate stream. The critical feed concentration of $BaSO_4$ may be as low as 15㎍/ℓ in sea waters, 5㎍/ℓin brackish waters or even 2㎍/ℓ if sulfuric acid is added to brackish waters.

4-5. Silica Scale Prevention

In addition to $BaSO_4$ scaling, silica scale is also difficult to redissolve. Thus silica scaling has to be prevented. The presence of Al^{3+} and Fe^{3+} complicates the silica scaling via formation of insoluble aluminum and iron silicates. Therefore, if a silica scaling potential exists, aluminum and iron must be removed by 1㎛ cartridge filtration and preventive acid cleanings.

The calculation of the silica scaling potential requires the following data of the feed solution : SiO_2 concentration, temperature, pH and total alkalinity.

The SiO_2 concentration in the concentrate stream is calculated from the SiO_2 concentration in the feed solution and the recovery of the RO system :

$$SiO_{2c} = SiO_{2f} \times \frac{1}{1 \quad r}$$

Where : SiO_{2c} = silica concentration in concentrate as SiO_2 in ㎎/ℓ
SiO_{2f} = silica concentration in feed as SiO_2 in ㎎/ℓ
r = recovery of the RO system expressed as a decimal

Calculate the pH of the concentrate stream from the pH of the feed stream using the following equation.

$$pH = Log_{10}\ ([\text{alkalinity as } CaCO_3] / [CO_2]) + 6.3$$

$$\text{Alkalinity of concentrate} = \frac{\text{Alkalinity of feed}}{1 - r}$$

(need to revised same as SiO_{2C} calculation equation

Obtain the solubility of SiO_2 as a function of temperature. Temperature of the concentrate is assumed equal to temperature of feed solution.

Example are shown in the following table :

T(°C)	Solubility of SiO_2 (mg/ℓ)
5	85
10	96
15	106
20	118
25	128
30	138
35	148

Obtain the pH correction factor for the concentrate pH

Since the solubility of silica increases below a pH of about 7.0 and above a pH of about 7.8, the actual solubility of SiO_2 in the concentrate stream can be further affected by the pH of the concentrate stream and thus is obtained by multiplying the solubility of SiO_2 at a specific temperature by the pH correction factor to give the corrected solubility (SiO_{2cor}).

For examples, pH correction factor are 1.0 at pH 7.8 and 1.5 at pH 8.5, respectively. See ASTM D4993-89 for more details. Compare the silica concentration in the concentrate (SiO_{2c}) of the RO system with the pH corrected silica solubility (SiO_{2cor}). If SiO_{2c} is greater than SiO_{2cor}, silica scaling can occur and adjustment is required.

The easiest way to prevent the silica scaling is to lower recovery. Reiteration of the calculations can be used to optimize recovery with respect to silica scaling, once a reverse osmosis system is operating.

Lime plus soda ash softening can be used in the pretreatment system to decease the SiO_2 concentration in the feed stream. The maximum allowable recovery against silica scaling can be increased significantly by increasing the water temperature using a heat exchanger.

A dispersant such as high molecular weight polyacrylate scale inhibitor is helpful in silica scale control by slowing agglomeration of scale particulate.

Silica solubility as a function of pH (pH correction factor) need to be included..!

4-6. Colloidal Fouling Control

The removal of suspended and colloidal particles can be done by media filtration, crossflow microfiltration and cartridge microfiltration only for the raw waters with an SDI slightly above 5. For raw waters containing high concentrations of colloidal matter showing SDI well above 5, the coagulation and flocculation process is necessary before media filtration.

Ferric sulfate or ferric chloride is usually used as a coagulant to destabilize the negative surface charge of the colloids to result in coagulation and further to entrap them into the freshly formed ferric hydroxide microflocs. Aluminum coagulants are also effective, but not recommended because of possible fouling problems with residual aluminum. Cationic polymers may be used as both coagulants and flocculants.

To further agglomerate the hydroxide microflocs for better filterability, flocculants can be used in combination with coagulants. Flocculants are soluble high molecular weight polymers such as polyacrylamides which may contain cationic, anionic, or neutral active groups.

The hydroxide flocs are allowed to grow and to settle in specifically designed reaction chambers or clarifiers. The hydroxide sludge is removed, and the supernatant water is further treated by media filtration.

Care must be taken not to allow coagulants and flocculants or the hydroxide flocs to escape from media filters to reach the RO membranes. Furthermore, reaction of the residual coagulants and flocculants with a scale inhibitor added after the media filter can cause a precipitate to form, which is very hard to be cleaned. Several RO plants have been heavily fouled by a gel formed from cationic polyelectrolytes and scale inhibitors.

Media filtration

Media filters use a filtration bed consisting of one or more layers of media granules which are sand and anthracite. The grain size for fine sand filter is in the range of 0.35 to 0.5㎜ or 8×12 mesh to 60 mesh and for anthracite filter 0.6 to 0.9 ㎜.

A multimedia filter is designed to make better use of the bed depth in the removal of a greater volume of suspended solids. This is achieved by loading larger (irregular shaped) media granules of lower density such as anthracite over smaller media granules of higher density such as sand. The larger granules at the top remove the larger suspended particles, leaving the smaller particles to be filtered by the finer media, thus to result in more efficient filtration and longer runs between cleaning.

The design depth of the filter media is normally about 0.8m (31 inches) minimum with a 50% freeboard for the media expansion during backwashing. The multimedia filters are usually filled with 0.5m (20 inches) of sand covered with 0.3m (12 inches) of anthracite.

The multimedia filters can be operated by either gravity or a pressure. A higher pressure drop can be applied for higher filter beds or smaller filter grains or higher filtration velocities. The design filtration flow rates are usually 10-20 m/h, and the backwash rates are in the range of 40-50 m/h.

For feed waters with a high fouling potential, flow rates of less than 10m/h and / or second pass media filtration is preferred.

The available pressure is usually about 5m of head for gravity filter and 2 bar (30 psi) to 4 bar (60 psi) for pressure filters. Periodically, the filter is backwashed and rinsed to remove the deposited matter, when the differential pressure increase between the inlet and outlet of the filter is 0.3 to 0.6 bar (4 to 9 psi) for the pressure filter and about 1.4m for the gravity filter. Backwash time is normally about 10min.

Frequent shut-downs and start-ups should be avoided, because a velocity shock will release previously deposited particulate matter.

Oxidation Filtration

Some well waters, usually brackish waters, contain divalent iron (Fe^{2+}), manganese (Mn^{2+}) and sometimes sulfide in the absence of oxygen. If such a water is exposed to air or is chlorinated, Fe^{2+}, Mn^{2+} and sulfide are oxydized to Fe^{3+}, Mn^{3+} and elemental sulfur, respectively, which form insoluble colloidal hydroxides and elemental sulfur as shown in the following equations :

$$4Fe(HCO_3)_2 + O_2 + 2H_2O \rightarrow 4Fe(OH)_3 + 8CO_2$$

$$4Mn(HCO_3)_2 + O_2 + 2H_2O \rightarrow 4Mn(OH)_3 + 8CO_2$$

$$2H_2S + O_2 \rightarrow 2S + 2H_2O$$

Iron fouling occurs more frequently than manganese fouling, since iron is present in the raw waters more abundantly than manganese and the oxidation of iron occurs at a much lower pH. Thus iron fouling is still possible even if the SDI is below 5 and the level of iron in the RO feed water is below 0.1mg/ℓ.

An RO system can treat the well water containing iron (Fe^{2+}) in a closed system without exposure to air or to any oxidizing agent, e.g. chlorine. A low pH is favorable to retard Fe^{2+} oxidation. At pH <6 and oxygen <0.5mg/ℓ, the maximum permissible Fe^{2+} concentration is 4mg/ℓ.

Oxidation and filtration can be done in one step by using a filter media greensand coated with MnO_2 to oxidize Fe^{2+}. Greensand is a green (when dry) mineral glauconite and can be regenerated with $KMnO_4$ when its oxidizing capability is exhausted. After the regeneration, the residual $KMnO_4$ has to be thoroughly rinsed out in order to avoid an oxidation damage of the membranes. This technique is used when Fe^{2+} is present in the raw water in less than 2mg/mℓ.

An alternative to the greensand is a product called Birm (a registered trademark of Clack

Corporation) which is a light silica coated with manganese dioxide. It catalyzes the oxidation of iron and manganese by dissolved oxygen. It does not lose the catalytic activity and thus does not need to be regenerated using $KMnO_4$. However, Birm requires a certain concentration of dissolved oxygen in the feed water at an alkaline pH. The alkaline condition may increase a possibility of $CaCO_3$ precipitation. Birm is less expensive than greensand.

Crossflow Microfiltration and Ultrafiltration

Crossflow microfiltration can effectively remove most suspended matter, depending on the pore size of the membranes. Normally microfiltration MF membranes with a pore size in the range of 1 to 10㎛ are used, depending on the feed water quality. When the silica concentration in the concentrate stream exceeds the calculated solubility, MF membranes with 1㎛ pore size are recommended to minimize the interaction with other colloids such as iron and aluminum colloids.

Now the fouling problem due to colloid deposit is transferred from the RO membrane to the MF membrane. In fact, the fouling of MF membranes is more severe and more often than RO membranes because of a high specific permeate flow. However, it is easier to clean a fouled MF membrane than an RO membrane, using periodic backflush cleanings which have been proven very effective for cleaning MF membranes, not for RO membranes. Chlorine can be added to the wash water in order to prevent biological fouling. Continuous microfiltration membranes (CMF) equipped with an automated backflush washing mechanism are available in the market . It is usually economical to employ multimedia filters prior to MF membranes since the cheaper media filters will take a majority of suspended matter to reduce the costly cleaning frequency of MF membranes and thus to extend the membrane life time.

Cheaper disposable cartridge filters may be an alternative to the MF membranes and replaced before the pressure drop has increased to the permitted limit, but latest after 3 months. Replacing cartridge filters more often than every 1 to 3 months usually indicates a problem with the pretreatment. If it is desirable to remove soluble organic or inorganic polymers, then ultrafiltration (UF) membranes could be used.

4-7. Biological Fouling Prevention

All raw waters contain microorganisms such as bacteria, algae, fungi, viruses and various organisms. Microorganisms can be regarded as colloidal matter and removed by the pretreatment. However, it is very difficult to remove all the microorganisms and a few of them may escape the pretreatment to reproduce and form a biofilm in the downstream processes. MF membranes could remove most of the microorganisms, but still some will escape through the pores or defects of the membranes to reach the RO membranes. The symptoms of the biologically fouled RO system are an increase of the differential pressure accompanied by membrane flux decline.

The potential for biological fouling is more pronounced with surface water than well water. The concentration of bacteria in water is directly related to the biological fouling potential.

Total Bacteria Count (TBC) is a method to determine the total number of viable microorganisms in a water sample according to ASTM F60 by filtering a measured quantity of water through a membrane filter. Subsequently, the organisms retained on the filter surface are cultured on the proper nutrient medium for several days to develop colonies, which are then observed and counted at low power magnification.

This culture technique can be applied to monitor the microbial activity from the intake through the subsequent treatment steps up to the concentrate stream and the permeate.

Direct Bacteria Count techniques employ filtration of the water sample and counting the retained microorganisms on the filter plate directly under a fluorescent microscope after they are stained with acridine orange or INT stain. INT stain can tell the difference between living cells and dead cells.

The germicidal efficiency of free residual chlorine is directly related to the concentration of undissociated hypochlorous acid HOCl which is 100 times more effective than the hypochlorite ion OCl^-.

The fraction of undissociated HOCl increases with decreasing pH and temperture.

At pH = 7.5(25℃), 50% HOCl
At pH = 6.5(25℃), 90% HOCl
At pH = 7.5(5℃), 62% HOCl

In case of existence of any ammonia in the water being treated, chlorine can react with ammonia to give various chloramines in a series of stepwise reactions :

$HOCl + NH_3 \rightarrow NH_2Cl + H_2O$
$HOCl + NH_2Cl \rightarrow NHCl_2 + H_2O$
$HOCl + NHCl_2 \rightarrow NCl_3 + H_2O$

Chloramines also have a germicidal effect, albeit lower than that of chlorine. One advantage with the chloramines is that they do not oxidize the RO membranes. However, there will be always some residual unreacted HOCl which can still oxidize the membranes and thus care must still be taken when chloramines are used as a disinfectant.

To determine the optimum chlorine dosage, best point of injection, pH and contact time to prevent biofouling, the ASTM D1291, Standard Practice for Determining Chlorine Requirement of water should be applied to a representative water sample.

Dechlorination

The residual chlorine has to be dechlorinated before it reaches the RO membrane. CSM RO membrane has some chlorine tolerance, but eventual degradation may occur after 200-1000 hours of exposure to 1 ㎎/ℓ of free chlorine, depending on the pH, temperature and residual transition metals such as iron in the feed water. Under alkaline pH conditions, chlorine degrades the membrane faster than at neutral or acidic pH. At an acidic pH, chlorine becomes more effective as a disinfectant. The influent of RO must be dechlorinated to maintain the residual free chlorine concentration below 0.05ppm.

Activated carbon(AC) bed is very effective in dechlorination of the residual chlorine in RO feed water according to the following reaction :

$C + 2HOCl \rightarrow CO_2 + 2HCl$

Sodium Metabisulfite (SMBS) or sodium Bisulfite (SBS) is most commonly used for removal of free chlorine and as a biostatic, as shown in the following reaction.

$Na_2S_2O_5 + H_2O \rightarrow 2NaHSO_3$
$2NaHSO_3 + 2HOCl \rightarrow H_2SO_4 + 2HCl + Na_2SO_4$

Based on the equivalent weight estimation, 1.34㎎ of sodium metabisulfite will react with 1.0㎎ of free chlorine. In practice 3.0mg of sodium metabisulfite is normally used to remove

1.0㎎ of chlorine to make sure that all the chlorine is reduced.

The injection point of the SMBS solution is preferably upstream of the cartridge filters in order to keep the residual chlorine up to the filters to prevent microbial growth in the filters.

The SMBS solution should be filtered through a separate cartridge and injected through static mixers for good mixing into the RO feed line. The absence of chlorine should be monitored using an oxidation - reduction potential (ORP) electrode downstream of the mixing line.

Disinfection by Ultraviolet (UV) Irradiation

UV at 254㎚ is known to have a germicidal effect and has been used especially for small-scale plants. No chemicals are added and the equipment needs little attention other than periodic cleanings or replacement of the mercury lamps. However, UV treatment is limited to relatively clean waters, because colloids and organic matter interfere with the penetration of UV into depth of the turbid water.

Biological Activity Control by Sodium Bisulfite

Sodium bisulfite (SBS) concentrations in the range of up to 50㎎/ℓ in the feed stream of sea water RO plants have proven effective to control biological fouling. Colloidal fouling has also been reduced by the method. SBS is also helpful in controlling calcium carbonate scaling by supplying protonium (H^+) ions as shown below.

$$2NaHSO_3 + CaCO_3 \rightarrow Na_2SO_3 + Ca^{2+} + HCO_3^- + HSO_3^-$$

4-8. Organic Fouling Prevention

Adsorption of organic substances on the membrane surface causesflux loss. Sometimes the adsorption is irreversible when the organic substances are hydrophobic or positively charged polymers with high molecular weight. Such organic substances including organics present as an emulsion must be removed in the pretreatment.

Organics occuring in natural waters are usually humic substances in concentrations between 0.5 and 20㎎/ℓ as TOC. Pretreatment should be considered when TOC exceeds 3㎎/ℓ. Humic substances can be removed by a coagulation process with hydroxide flocs or by ultrafiltration or by adsorption on activated carbon.

Oils (hydrocarbon or silicon-based) and greases contaminating the RO feed water at levels above 0.1㎎/ℓ should be removed by coagulation or activated carbon. Once the membranes are fouled by oils and greases, they can be cleaned off with alkaline cleaning agents if the flux has not declined by more than 15%.

Trihalomethane (THM)

THMs (e.g. chloroform) are produced from a chemical reaction between free chlorine and trace organics. THMs are considered potentially carcinogenic, so are a concern when found in drinking water. And also trace THMs can be a major concern in the semiconductor industry, if present in feed water.

About 90% of THMs can be rejected by RO membranes. Activated carbon can also adsorb THMs well. A complete removal of THMs is possible by using both activated carbon and RO membranes.

5-1. Introduction

After the pretreatment of the raw water, the treated feed water enters the RO desalination system. The goal of an efficient RO system for a certain required permeate flow is to minimize feed pressure and membrane costs (number of elements) while salt rejection and recovery should be maximized. The optimum design is influenced by the relative importance of these aspects (e.g. recovery vs. membrane costs) related to operating parameters. The desired salt rejection is usually achievable but the recovery determined by a permeate flow is affected by many factors.

An RO system design starts with prioritizing the relationship between the desired permeate flow and operating parameters followed by optimizing the parameters within physical limits levied by both RO membrane elements and the feed water possessing a potential of scaling and fouling. For examples, the recovery of brackish water systems is limited by the solubility of sparingly soluble salts and colloidal fouling potential of the feed water up to 87.5% (achievable only by multi-array system). The recovery by a single brackish water element is limited to 15% by the scaling and fouling potential of the feed water with SDI of 3 to 5.

On the other hand, in seawater desalination, the limit of 30 to 45% recovery (achievable only by multiple elements in series) is mainly imposed by the enhanced osmotic pressure of the concentrate stream, because a typical sea water element is durable only up to 69 bar (1000psi). The recovery by a single seawater element is limited to 10% of the seawater feed with SDI less than 5.

While in seawater desalination systems, the permeate flux is relatively low even at maximum allowed pressure, the permeate flux could be very high in brackish water systems without reaching the limit of 41 bar (595 psi) for brackish water elements. Although it is tempting to increase the permeate flux in order to minimize the costs for membrane elements, the flux has to be limited in order to avoid fouling and scaling. From experience, the flux limit in system design depends on the fouling tendency of the feed water.

5-2. System Design Guidelines

As mentioned above, the main factors influencing seawater system designs are the osmotic pressure and the physical durability of seawater elements, while those affecting brackish water system designs are scaling and fouling potential of the feed water. Hence, seawater systems could be built relatively easily by designing the permeate flow rate within the limit of the two factors with a minimal attention to scaling and fouling potential of seawater. The usual sea water recovery of 30 to 50% can be obtained from single-array systems.

Comparatively, brackish water systems require more elaborate designs mainly due to various scaling and fouling potentials of the feed waters and additionally due to multi-array systems when more than 50% recovery is desired. The system designed with high permeate flux rates is likely to experience higher fouling rates and more frequent chemical cleaning. The silt density index (SDI) value of the pretreated feed water correlates well with the amount of fouling material present.

Experience from the correlation of the SDI value with the membrane fouling trend can set the limits on permeate flux and element recovery for different types of waters, which can be the starting point of the system design guidelines shown in Table 1 below.

Table 1. System Design Guidelines

Feed Source		Well Water/ Softened Water	Softened Surface Water	Surface Water	Sea Water
Feed Water SDI		< 3	3 - 5	3 - 5	< 5
Max, % Recovery per Element		19	17	15	10
Max, Permeate Flow Rate per Element, gpd(m^3/h)	**2.5" Diameter**	710(0.11)	500(0.08)	500(0.08)	500(0.08)
	4" Diameter	2100(0.33)	1870(0.3)	1740(0.27)	1500(0.23)
	8" Diameter	7400(1.16)	6600(1.04)	5800(0.92)	5800(0.92)
Max. Feed Flow Rate per Element, gpm(m^3/h)	**2.5" Diameter**	5.7(1.3)	5.7(1.3)	5.7(1.3)	5.7(1.3)
	4" Diameter	18(4.1)	18(4.1)	18(4.1)	18(4.1)
	8" Diameter	62(14.1)	60(13.7)	55(12.6)	60(13.7)
Min. Concentrate Flow Rate per Element, gpm(m^3/h)	**2.5" Diameter**	1(0.22)	1(0.22)	1(0.22)	1(0.22)
	4" Diameter	4(0.91)	4(0.91)	4(0.91)	4(0.91)
	8" Diameter	16(3.6)	16(3.6)	16(3.6)	16(3.6)

The guidelines in Table 1 are based on a continuous process with a well-designed and operated pretreatment system. Exceeding the limits will result in more frequent cleanings than about four times a year, and a reduced membrane lifetime Consequently, this is not only increase capital and operating costs, but also result in additional operating cost due to increased membrane cleaning replacement frequencies.

5-3. Batch vs. Continuous Process

The majority of RO systems are designed for continuous operation with constant permeate flow and constant system recovery as shown in Figure 1. Variations in feed water temperature and fouling effects are compensated by adjusting the feed pressure.

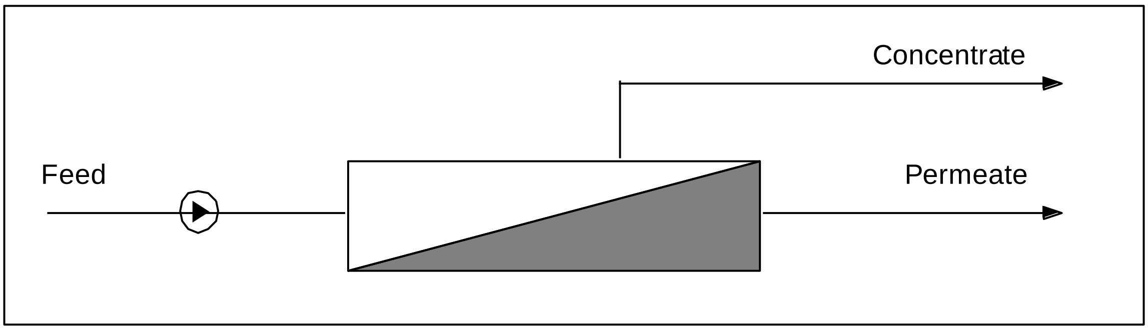


Figure 1 : Continuous RO Process

In certain applications, when relatively small volumes (batches) of special feed waters occur discontinuously, e.g. wastewater or industrial process solutions, the batch operation mode is preferred. The feed water is collected in a tank and treated subsequently. The permeate is removed and the concentrate is recycled back to the tank. At the end of the batch process, a small volume of concentrate remains in the feed tank. After this has been drained, the membranes are typically cleaned before the tank is filled again with a new batch. Figure 2 shows the batch operation mode.

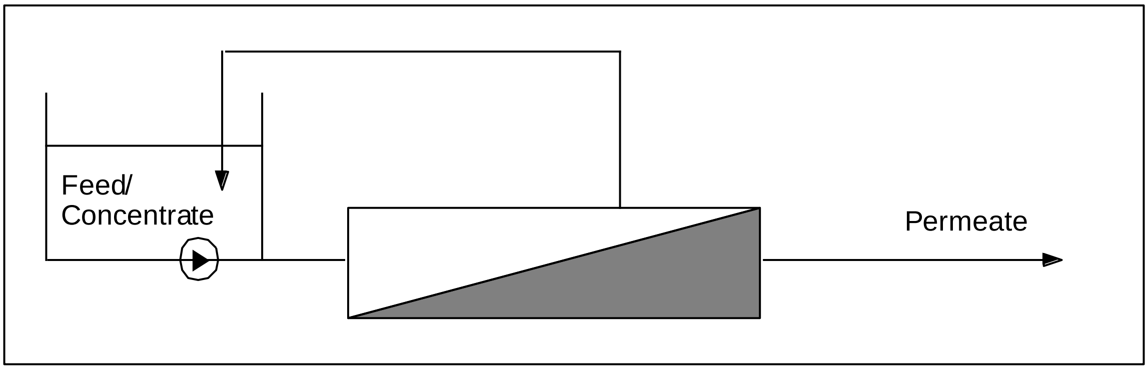


Figure 2 : Batch RO Process

A modification of the batch mode is the semi-batch mode. The feed tank is refilled with feed water already during operation. The batch is terminated with the feed tank full of concentrate. This allows a smaller tank to be used.

Batch systems are usually designed with a constant feed pressure and a declining permeate flow while the feed becomes more concentrated. The guidelines given in Table 1 should be applied to batch systems as well. The permeate flow limits however, are conservative and may be exceeded, if an appropriate cleaning frequency is taken into account.

Some advantages of the batch process over the continuous process are :

- System recovery can be maximized batch by batch
- Cleaning is easily implemented

The disadvantages are :

- No constant permeate quality;
- Larger pump required;
- Higher total running costs.

5-4. Single Pressure Vessel System

A Single Pressure Vessel System consists of a pressure vessel with up to seven membrane elements, which are connected in series. The concentrate of the first element becomes the feed to the second, and so on. The product tubes of all elements are coupled and connected to the vessel permeate port. The permeate port may be located on the feed and or on the concentrate end of the vessel.

Single Pressure Vessel Systems are chosen when only one or few membrane elements are needed for the specified permeate flow.

Feed water enters the system through the shut-off valve and flows through the cartridge filter to the high pressure pump.

From the high pressure pump, the feed water flows to the feed inlet connection of the vessel. The product stream should leave the vessel at no more than 0.3 bar(5 PSI) over atmospheric pressure.

In other words, in any event, the back pressure of the permeate must not be greater than the feed pressure in order not to damage the membranes.

The concentrate leaves the concentrate outlet connection at essentially the feed pressure.

Pressure drop will usually amount to 0.3 to 2 bar (5~30 PSI) from feed inlet to concentrate outlet, depending on the number of membrane elements, the feed flow velocity and the temperature. The concentrate flow is controlled by the concentrate flow control value.

The system recovery is controlled by this valve and must never exceed the design value.

5-5. Single Array System

In a single array system, two or more modules are arranged in parallel. Feed product and concentrate are connected to manifolds. Other aspects of the system are the same as in a single-pressure vessel system. Single-array systems are typically used where the system recovery is less than 50%. e.g. in sea water desalination.

An example of a single-array system is outlined in Figure 3. Each of the three pressure vessels houses six CSM elements RE8040-SHN.

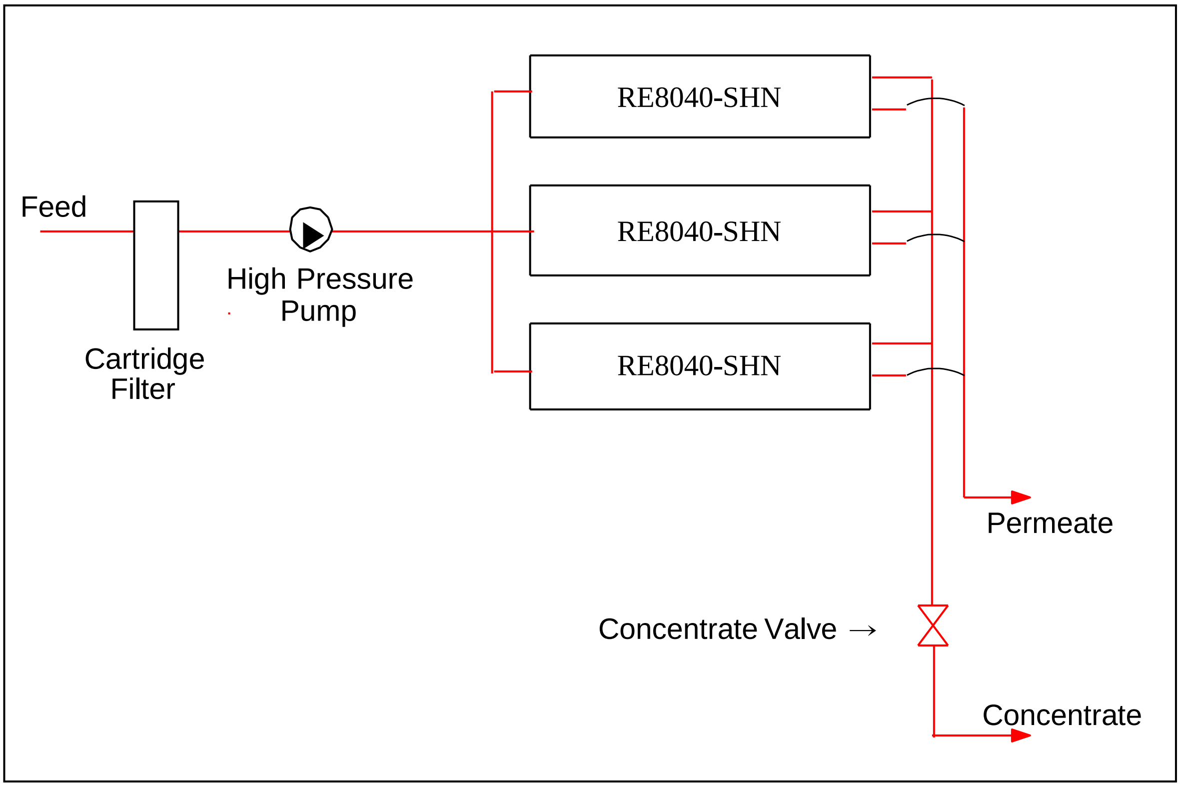


Figure 3 : Single Array System

5-6. Multi Array system

Systems with more than one array or stage are used for higher system recoveries without exceeding the single element recovery limits. Usually two arrays will suffice for recoveries up to 75%, and three must be used for higher recoveries 87.5%. These numbers are based on the assumption that standard pressure vessels with six elements are used. Higher recoveries can be achieved if feed water contains less suspended solids and scale potential.

Generally speaking, the higher the system recovery, the more membrane elements have to be connected in series. In order to compensate for the permeate that is removed and to maintain a uniform feed flow to each array, the number of pressure vessels per array decreases in the direction of feed flow.

A typical two-array system using a staging ratio of 2:1 is shown in Figure 4. The staging ratio is defined as the ratio of pressure vessels in two adjacent arrays, upstream vessels: downstream vessels.

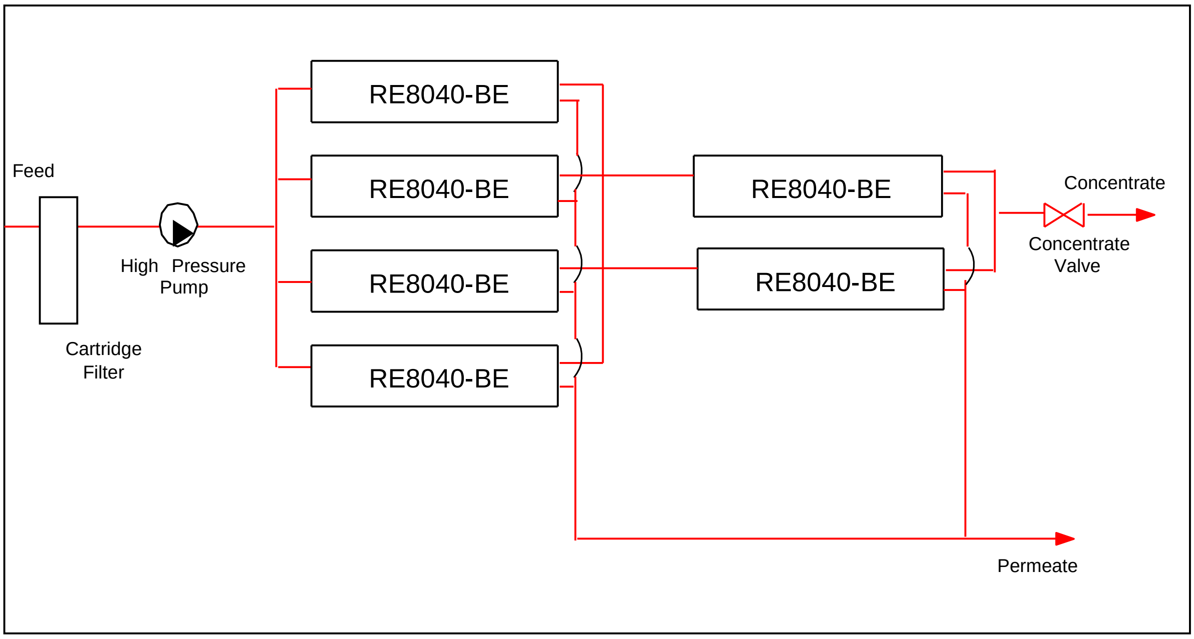


Figure 4 : Two Array System

5-7. Double Pass System

A double pass system is the combination of two RO systems where the permeate of the first system (first pass) becomes the feed for the second system (second pass). Both RO system may be of the single-array or multi-array type, either with continuous flow or with concentrate recirculation. With this concept, a product conductivity of < 1㎲/㎝ can be achieved without any contamination from organic matter and pyrogens including bacteria. Thus applications of double pass systems can be found in the production of pure water for pharmaceutical, medical and semiconductor industries.

Figure 5 shows a schematic flow diagram of a double pass system.

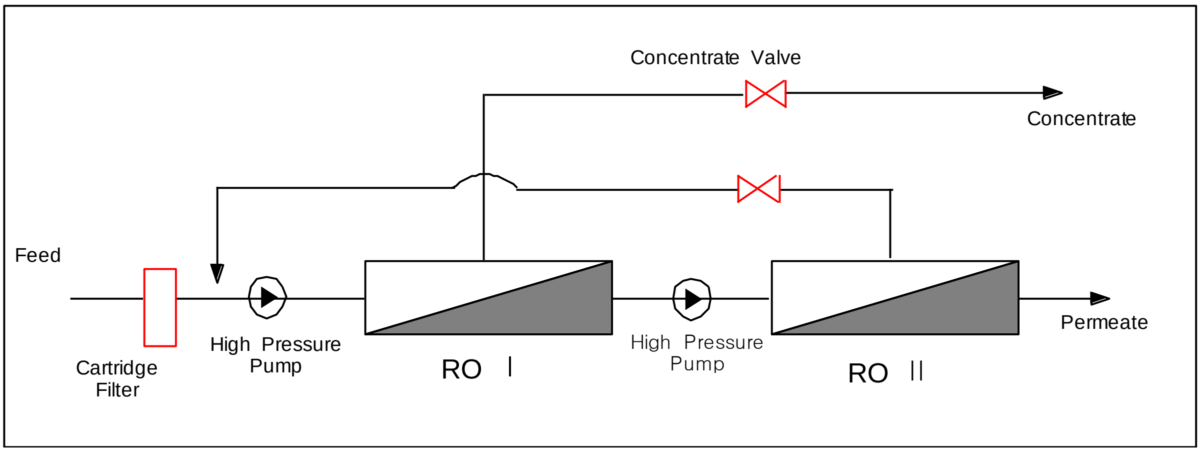


Figure 5 : Double Pass System

The concentrate of RO II is recycled back to the feed of RO l, because its quality is usually better than the system rawfeed water.

The high quality of RO II feed water (RO l permeate) enable the RO II can be designed for a higher recovery than RO I and with fewer membrane elements.

Instead of having a separate high pressure pump for the second pass, the whole system can also be operated with one single high pressure pump, provided the maximum permissible feed pressure of the membrane element is not exceeded (41 bar (600psi) for brackish water elements).

The second pass is then operated with the permeate backpressure from RO I. Care must be exercised that the permeate backpressure at no time exceeds the feed pressure by more than 0.3 bar (5psi)

5-8. Number of Elements and Pressure Vessels for System Design

As mentioned in the introduction, RO systems are usually designed for a specified amount of water production per day (total permeate flow Q_T). Then a number of membrane elements (N_E) required to produce Q_T is estimated from dividing Q_T by average permeate flow per element (Q_A)

$$N_E = \frac{Q_T}{Q_A} \qquad (1)$$

In most standard applications, the average permeate flow per element (Q_A) is about 75% of the maximum permeate flow per element (Q_M) which is shown in Table 1 in the section of system design guidelines.

$$Q_A = 0.75\ Q_M \qquad (2)$$

Thus equation (1) can be converted to equation 3.

$$N_E = \frac{Q_T}{0.75Q_M} \qquad (3)$$

And also the number of pressure vessels, N_V is obtained from dividing N_E by P_E which is the number of elements per pressure vessel.

$$N_v = \frac{N_E}{P_E} \qquad (4)$$

Standard vessels contain six elements. N_v is rounded to the next highest whole number.

With Q_T , N_E , N_V and the analysis of the feed water source, a system can be selected. The selected system must then be verified using CSM Pro5 computer simulation program. This program calculates the feed pressure and the permeate quality of the system including the operating data of all individual elements. Furthermore, the system design can easily be optimized by adjusting the number and type of elements and their arrangement (e.g. single array or multi array). However, the optimization should be conducted within the physical limit of the elements and the empirical limit of the recovery rate according to the guidelines of the fouling potential of the feed waters.

For examples, Two-array systems with 6-element vessels effectively employ twelve spiral wound elements in series and are generally capable of operating at an overall recovery rate of 60 to 75%. For such systems the average individual recovery rate per element will vary from 7 to 12%. To operate a two-array system at an overall recovery much higher than 75% will cause an individual element to exceed the maximum recovery limits (e.g. 15% for a feed water with SDI in the range of 3 to 5). Then, a third array will have to be employed to place eighteen elements in series for a recovery rate lower than 15% per element.

If two-array systems are operated at too low a recovery (e.g. <60%), the feed flow rates to the first-array vessels can be too high causing excessive feed/concentrate-side pressure drops and potentially damaging the elements. As a result, systems with lower than 60% recovery will typically utilize single array configurations.

Table 1. Recommended average permeate flux vs various water source

Water Source	Recommended permeate flux
Waste Water (SDI<5)	8 ~ 12 gfd
Waste Water pretreated by UF(SDI<3)	10 ~ 14 gfd
Seawater, open intake(SDI<5)	7 ~ 10 gfd
High walinity well water(SDI<3)	8 ~ 12 gfd
Surface water(SDI<5)	12 ~ 16 gfd
Surface water(SDI<3)	13 ~ 17 gfd
Well water(SDI<3)	13 ~ 17 gfd
RO/UF permeate(SDI<1)	21 ~ 30 gfd

5-9. Important Parameters for System Design

The performance of an RO system is usually defined by its feed pressure, its permeate flow and its salt passage (salt rejection). Two simple equations show the relationship among the parameters.

$$\mathrm{Q} = \mathrm{A} \times \mathrm{S} \times \left(P_f - \frac{\Delta P_{fc}}{2} - P_p - \pi_{ave}\right) \qquad (1)$$

Q = permeate flow
A = membrane permeability coefficient
S = membrane surface area
P_f = feed pressure
ΔP_{fc} = concentrate side pressure drop
P_p = permeate pressure
π_{ave} = average osmotic pressure

Equation 1 indicates that the permeate flow Q is directly proportional to the surface area S times a net permeation driving force.

$$\left(P_f - \frac{\Delta P_{fc}}{2} - P_p - \pi_{ave}\right)$$

On the other hand, the salt passage is mainly governed by diffusion and thus the salt flux N is proportional to the difference in salt concentration between both sides of the membrane as shown in equation 2.

$$N = B \times (C_{fc} - C_P) \qquad (2)$$

B = salt diffusion coefficient
C_{fc} = feed - concentrate average concentration
C_P = permeate concentration

The equations 1 and 2 can be used to calculate the performance of a single RO element and also of a multi RO element system if average values for $(P_f - \Delta P_{fc} / 2 – P_p - \pi_{ave})$ and $(C_{fc} - C_p)$, temperature, and number of elements are known.

When a large number of elements are combined in a system with a complex series-parallel-series configuration and only inlet operating variables are known, system performance calculation becomes more complex and tedious. However, if all the operating conditions for first element can be confirmed, then, the operation variables including flow, pressure, concentration, etc., for following elementcan be calculated by a computer simulation program.

The first step is to guess the applied pressure P_f needed to produce the water flow rate (Q) required. Equation 1 can be converted to equation 3.

$$P_f = \frac{Q}{A \times S} + \pi_{ave} + \frac{\Delta P_{fc}}{2} + P_p \qquad (3)$$

To solve equation 3 for the feed pressure, the total area of the membrane from the total number of elements is summed to give S. The average osmotic pressure (π_{ave}) is calculated from the average concentration of the feed and the concentrate which is obtained from the nominal recovery and salt rejection of the element. The differential pressure ΔP_{fc} may be estimated from the average of ΔP_{fc} calculated from flow to the first element in series and the last element in the array.

The membrane permeability coefficient (A) is provided by the manufacturer or obtained from the slope of the curve of the permeate flow (Q) versus the operating pressure ($P_f - \Delta\pi$).

Now using the guessed applied pressure (P_f), the computer calculates feed flow rates, permeate flow rates and salt concentrations on an element by element basis through the system. The total calculated permeate flow (Q) is lower than the target flow, then the pressure is raised proportionally and if Q is higher than the target flow, then the pressure is lowered proportionally.

The estimated water qualities of the concentrate exiting the last array is then checked for solubility and pH limits for various scaling forming salts. If the solubility limits are exceeded, Q or the pressure may be decreased, but not so low to drop below the minimum concentrate flow rate. If it does, then more staging (number of arrays) is required.

Another limiting factor is that in any event, the maximum feed flow rate and permeate flow rate of the first element in the first array must not be exceeded. If they do, then a physical damage to the element and rapid fouling would occur. Controlling the feed pressure or adding more elements may be necessary to avoid such problems.

To be accurate and closer to the real situation, equation 1 could have several additional variables as shown in equation 4.

$$\mathrm{Q} = \mathrm{A} \times \mathrm{S} \times \mathrm{TCF} \times \mathrm{FF} \times \left(P_f - \frac{\Delta P_{fc}}{2} - P_p - \pi_{ave}\right) \qquad (4)$$

$$C_p = B \times C_{fc} \times Pf \times TCF \times \frac{S}{Q} \qquad (5)$$

$$\mathrm{TCF} = \exp\left[U \times \left(\frac{1}{298} - \frac{1}{273 + T}\right)\right] \qquad (6)$$

$$\Delta\pi = \pi - \pi_p \qquad (7)$$

$$\pi = \pi_f \times \frac{C_{fc}}{C_f} \times Pf \qquad (8)$$

$$\mathrm{Pf} = \exp[0.7 \times \mathrm{Y}] \qquad (9)$$

Q = permeate flow
A = membrane permeability coefficient
S = membrane surface area
TCF = temperature correction factor
FF = fouling Factor, about 0.8
P_f = feed pressure
ΔP_{fc} = feed-concentrate side pressure drop
P_p = permeate pressure
$\Delta\pi$ = driving osmotic pressure
C_p = permeate concentration
B = salt diffusion coefficient
C_{fc} = concentration of the concentrate
C_f = concentration of the feed
Pf = concentration polarization
U = temperature correction factor coefficient which depends on membrane sheet
π = average feed - concentrate osmotic pressure
π_f = osmotic pressure of feed
π_p = permeate side osmotic pressure
π_f = feed osmotic pressure
Y = recovery of the element

's CSM PRO5 computer program utilizes equations 4 and 9. Through the iterative trial and error process, it projects the performance of given systems, and optimizes the design of the system.

5-10. Testing of System Designs for Unusual Applications

For the desalination of well characterized waters with known SDI and composition, the RO performance can be projected with reliable accuracy by the computer program. However, testing is recommended to support the proper system design in special situations such as :

- Unknown feed water quality
- Waste waters
- Special permeate quality requirements
- Very high system recoveries
- Very large plants

First, a screening test is demanded to select the right membrane and to obtain an idea about flux and rejection properties of this membrane in the special situations. Usually a small piece of flat sheet coupon membrane is used for the screening test.

Second, using a 2540 size element, scale up data such as permeate flow and salt rejection as a function of feed pressure and system recovery are obtained. In subsequent batch mode test, leading the permeate into a separate containment and returning the concentrate to the feed tank, permeate flow and salt rejection are monitored until the permeate flow has declined to a very low value such as 0.09 gpm. From the batch tests, an indication of membrane stability and fouling propensities can be revealed.

Third, a pilot test is conducted in the field with a continuous operation mode. The pilot plant has at least contains one 8040 size element, preferably an arrangement of elements similar to the arrangement in a large scale system. The permeate flow of the pilot plant should be at least 1% of the large scale plant flow. The test should be run for more than 30 days. The objective is to confirm the system design reliability and to optimize operating parameters as well as to minimize the risk involved in large scale plants.

5-11. System Components

High Pressure Pump

The high pressure pump must provide smooth and continuous flow to the RO membrane elements and also be sized to provide the necessary flow rate at the desired pressure. Its energy consumption is one of the major expenses of RO system operation. There are two types of high pressure pumps, centrifugal pumps and piston pumps. Centrifugal pumps, which operate by spinning the fluid with the pump impellers are more energy-efficient than piston pumps, which use various numbers of mechanical plungers to create pressure. The centrifugal pumps provide more smooth and continuous flow than the piston pump, and are controlled by a throttling valve on the discharge line. The piston pump cannot be throttled, so pressure is controlled by a back pressure valve installed in a bypass line from the pump discharge to the pump suction. The pressure from piston pumps tends to pulsate, creating surges, which could damage RO membrane elements and therefore should be controlled using a damper (accumulator).

Pressure Vessel

Pressure vessel (membrane element housing) is designed for specific pressure applications. Most pressure vessels are overdesigned for safety reasons to withstand a pressure at 1.5 times the rated operating pressure. The vessel materials are usually FRP (fiber glass reinforced plastic) and sometimes stainless steel (316L) for special applications such as very high pressure applications (>800psi).

Pressure vessels are available with different diameters, lengths, and pressure ratings. The smaller vessels with diameters in the range of 1.5 to 2.5 inch are usually supplied by (need to be checked). All other vessels with diameter in the range of 2.5 to 8 inch and the pressure rating up to 1000psi are manufactured by Advanced Structures Inc (also need to be checked).

Alarms and Shutdowns

There is always the possibility of a malfunction in the RO system or with the pretreatment. Instruments can be used to monitor the quality of the RO feed water as well as the performance of the RO system. The instruments such as flow meters, pressure gauges, pH meters and conductivity meters can be connected with an audible alarm that will sound if some parameter is not within design specifications. Furthermore, if the parameter is significantly out of the specifications to damage the high pressure pumps and the RO elements or to produce an unacceptable permeate water, then the alarm should warrant automatic shutdown of the RO system. Suggested alarms and shutdowns are shown below :

- Low inlet pressure damaging the high pressure pump
- Too high feed pressure damaging the RO elements
- High feed temperature damaging the RO elements
- High permeate pressure damaging the RO elements
- Too high concentration of colloidal matter or sparingly soluble salts in the feed damaging the RO elements
- Oxidizing agents in the feed damaging the RO elements
- Low concentrate flow fouling and/or scaling the RO membranes
- Oil in the feed fouling the RO membranes

Instruments, Valves, and Equipment

As mentioned above, instruments and valves are necessary not only to detect a malfunction in the RO system, but also to ensure proper routine operation of the system. The necessary instruments, valves, and other equipment are listed below in more details.

Pressure gauges to measure the pressure drop across the cartridge filter, the pressure on the pump inlet line and discharge line, the feed pressure to the membrane element(s), the pressure drop between feed and concentrate of each array, and eventually the pressure in the permeate line. Liquid-filled gauges should contain membrane compatible fluids such as water or glycerine in place of oils or other water immiscible liquids.

Flow meters to measure feed, concentrate and total permeate flow rate, also permeate flow rate of each array. pH meter in the feed line after acidification to control carbonate scaling potential. Conductivity meters in the feed line, in the brine line, and in the permeate line to determine permeate quality and salt rejection. Sample ports on the feed, concentrate and permeate line (total permeate and permeate of each array) to be able to evaluate system performance. A sample port on each pressure vessel permeate outlet is recommended to facilitate troubleshooting.

Feed inlet valve to shut down the plant for maintenance and preservation. Valve on the pump discharge line or pump bypass line to control feed pressure during operation and feed pressure increase rate during start-up. Check valve on pump discharge line. Check valve and atmospheric drain valve on permeate line to prevent the permeate pressure from exceeding the feed pressure. Flow control valve on the concentrate line to set the recovery (Caution : back-pressure valve must not be used). Valve in the permeate line to provide permeate drain during cleaning and start-up. Valves in the feed and concentrate line (and between arrays) to connect a cleaning circuit.

A small draw-back tank is necessary in the permeate line to provide enough volume for osmosis backflow when a seawater system shuts down. Without the tank, air could be sucked into the membrane elements to dry the membrane (flux loss) and to contaminate the permeate side by airborn bacteria and fungi.

A shut down flush system flushes the feed-concentrate line with pretreated feed water or with permeate water after shut down, especially when scale inhibitors are used, and also in the case of a seawater system.

Materials of System Construction

The materials of system construction including the RO elements, pumps, pressure vessels, pipes, valves and instruments should be compatible with the pressures, vibrations, and temperatures fluctuations during the RO system operation. The materials must also be resistant to the potential corrosion attacks caused by the high chloride content of the feed water and the concentrate stream, and the chemicals used for membrane cleaning.

Non-metalic materials such as plastics and fiberglass are widely used not only for economic reasons (e.g. pressure vessels and pipes), but also for preventing corrosion and chemical attacks, usually in the low pressure (<10 bar) applications.

However, it is usually necessary to use metals for the high-pressure (10-70 bar/ 200-1,000PSI) parts such as pumps, piping and valves. Carbon and low alloy steels do not have sufficient corrosion resistance, and their corrosion products can foul the membranes.

Stainless steel type AISI 316 L with <0.03% C is recommended for the pipe system for RO plants with concentrate stream TDS below 7000 ppm. For TDS higher than 7000ppm, stainless steel type 904L is preferred for pipes and bends for welding and stainless steel type 254 SMO should be used for flange connections, valves, and pumps where crevices occur.

6-1. Introduction

Successful long term performance of the RO system mainly depends on proper operation and maintenance of the system.

This includes well planned pretreatment and initial plant start-up. Membrane fouling and scaling, which can reduce permeate flow rate and salt rejection significantly, are caused primarily by a poor pretreatment and also an improper system operation. Mechanical and chemical induced damages of the RO system including the membranes may also arise from improper operations. Record keeping and data normalization is indispensably required to analyze the actual plant performance and to localize the source of any problem. Data normalization with reference to the initial start-up system performance is useful to show any performance changes during the sequential operations.

Complete records are required in case of a system performance warranty claim including elements.

6-2. Initial Start-up

1) Checklist before Start-up

Before starting up the RO system, it is important to make sure that the whole pretreatment process is working according to the specifications. If the chemical characteristics of the raw water are changed, then a full analysis of the water entering the RO unit should be conducted so that proper measurements can be made to put the variables under control.

Factors affecting the feed water quality and thus the system design are as follows :

Flow, SDI, Turbidity, Temperature, pH, TDS, residual chlorine, and bacteria counts

And also the following mechanical inspections of the RO system are recommended for the initial start-up.

- Operational conditions of media filters and cartridge filters
- Feed line is purged and flushed before pressure vessels are connected
- Chemical dosing lines and valves
- Proper mixing of chemicals in the feed stream
- Safety shut off of the RO system when the chemical dosage pumps are shut-down
- Complete chlorine removal prior to the membranes
- Instrumentation for proper operation and monitoring of the pretreatment and RO system
- Installation and calibration of such instrumentation
- Installation of pressure relief protection device
- Piping and securing pressure vessels for operation and cleaning mode
- Lubrication and proper rotation of pumps
- Valves for permeate line, feed flow, and reject flow control are in open position
- Initial feed flow should be limited to less than 50% of operating feed flow

2) Start-up Sequence

- Before starting the initial operation sequence, the pretreatment section should be thoroughly rinsed to flush out debris and other contaminants without allowing the feed to enter the elements
- Make sure that all valve settings are correct. The feed pressure control and concentrate control valves should be fully open
- Use the feed water at a low flow rate to expel the air out of the elements and pressure vessels at a gauge pressure of 30 to 60 psi for more than 30 minutes. All permeate and

concentrate flows should be directed to an approved waste collection drain during flushing. At this point, all pipe connections and valves are checked for leaks

- After the system has been flushed, close the feed pressure control valve, but make sure that the concentrate control valve is open. Improper concentrate valve control may cause the recovery to be exceeded which can initiate scaling within the elements.
- Open the feed pressure control valve little by little so that feed pressure does not exceed 4.0 kg/cm^2 (60 psi) and then start the high pressure pump
- Increase opening of the feed pressure valve slowly to elevate the feed pressure and feed flow rate to the elements until the design concentrate flow is reached. Then slowly close the concentrate control valve until the ratio of permeate flow to concentrate flow approaches the designed recovery ratio
- Repeat opening of the feed pressure control valve and closing of the concentrate control valve until the design permeate and concentrate flows are obtained, while checking the system pressure to ensure that it does not exceed the upper design limit
- After adjusting the two valves, calculate the system recovery and compare it to the system design value
- Check chemical additions of acid, scale inhibitor, and sodium metabisulfite. Measure pH, conductivity, calcium hardness and alkalinity levels to calculate the Langelier Saturation Index (LSI) or the Stiff & Davis Saturation Index (S & DSI) for the evaluation of scale formation potential.
- Take the first reading of all operating parameters after allowing the system to run for one hour. Read the permeate conductivity from each pressure vessel and identify any vessel with any malfunction
- After 24 to 48 hours of operation, record all plant performance data such as feed pressure, differential pressure, temperature, flows, recovery ratio and conductivity readings. And also analyze the constituents of feed water, concentrate, and permeate water samples. Compare system performance to design values. Use the initial system performance information as a reference for evaluating future system performance. Measure system performance regularly during the first week of operation

6-3. Record Keeping for Maintenance

All relevant data of the RO system is strongly recommended to be recorded properly. They are not only necessary for monitoring the performance of the system, but also valuable tools for trouble shooting and also needed in the cases of warranty claims.

The RO system performance depends for the most part on the proper operation of the pretreatment and thus the operating characteristics of the pretreatment equipment for the following items should be recorded and maintained.

1) Pre-treatment System

- Discharge pressure of any well or booster pumps and pressure drop of all filters including sand filter, multi media filter, and activated carbon filter. The data of the pressure drop may indicate when a backwash for the filters is needed
- Total residual chlorine concentration in the RO feed
- Regeneration period of water softener if used for the removal of hardness
- Inlet and outlet pressure of microfilters and cartridge filters. An increase in the differential pressure between inlet and outlet pressure may indicate the time for cleaning and backwashing of the microfilters or a replacement of cartridge filters
- Silt Density Index (SDI) and turbidity of the RO feed stream. Measure SDI and the turbidity before and after all the filters
- Consumption of acid and any other chemicals such as coagulants and scale inhibitors. Scale inhibition can also be accomplished by pH control (usually pH 6-7), depending on the amount of hardness in the feed water

2) RO Operating Data

The following data must be recorded frequently, preferably once per shift.

- Complete water analysis of the feed, permeate, and concentrate water and the raw water before pre-treatment once at start-up and every week thereafter
- pH of the feed, permeate and concentrate water and temperature of the feed water
- Langelier Saturation Index (LSI) of the concentrate water from the last array (for concentrate water < 10,000 ppm TDS)
- Stiff and Davis Saturation Index (S & DSI) of the concentrate water from the last array (for concentrate water > 10,000 ppm TDS)
- Feed flow pressure after high pressure pump
- Feed, permeate and concentrate flow pressure of each array. Pressure drop per cartridge

and per array

- Permeate and concentrate flows of each array. Calculate recovery ratio to ensure that it does not exceedthe design limit
- Conductivity/TDS of the feed, permeate, and concentrate streams for each array. The TDS of the RO concentrate can be used along with the feed water TDS to calculate an average concentration which can be used to calculate an average membrane salt rejection as shown in the following equations

()

$$\text{Average salt rejection(\%)} = 1 - \left[\frac{\text{permeate TDS}}{(\text{feed TDS} + \text{concentrate TDS}) / 2} \right] \times 100$$

- Calibration of all gauges and meters based on manufacturer's recommendations at least once every three months. Important gauges include pH meters, flow meters, pressure gauges, and conductivity meters. It is recommended that the water pH is verified weekly andon a weekly schedule, the pH probe should be placed into buffer solutions with particular pH values, calibrating the probe to those values. If the values are drifting every time the pH meter is checked, the reference probe needs to be replaced or have its KCl solution replenished

3) Maintenance Log

- Record regular maintenance
- Record mechanical failures and replacements or additions of RO devices and pre-treatment equipment such as cartridge filters
- Record any change of membrane element locations with element serial numbers
- Record calibration history of all gauges and meters
- Record all details about cleanings of RO membranes including date, duration of cleaning, cleaning agents and concentration, solution pH, temperature, flow rate and pressure

6-4. Data Normalization

The performance of an RO system is influenced by changes in the feed water TDS, feed pressure, temperature and recovery ratio. Data normalization is a process to convert the actual performance of the RO system into a form which can be compared to a given reference performance which may be the designed performance or the measured initial performance.

A difference between the normalized data and the initial or designed performance may indicate there are some problems in the system as shown below.

- Membrane fouling and / or scaling
- Membrane chemical damage - poor salt rejection due to a chemical change and / or degradation in the membrane structure by excessive exposure to chlorine or extreme pH
- Mechanical failure - a broken O-ring or element glue line
- Hydraulic plugging - the presence of foulants (large size colloids) or scale sticked to the flow channel spacing between the membrane leaves of spiral - wound elements

The problems could be identified early when the normalized data are recorded daily. Three representative variables such as, normalized permeate flow rate, normalized differential pressure, and normalized salt rejection are calculated from the RO operating data. Thus, the effects of the above four problems can be directly monitored by the three variables as shown below.

- Normalized permeate flow rate
- Normalized salt rejection
- Normalized differential pressure

1) Normalized Permeate Flow rate

Normalized permeate flow rate is the most important monitoring parameter for an RO system. Normalizing for the effects of pressure, temperature, and solute concentration on permeate flow rate will enable the resulting flow value to reflect changes due to characteristics of the membrane, and the integrity of the membrane elements or vessels. Thus the normalized permeate flow rate can be used to monitor the following problems :

① The extent of fouling and scale formation on the membrane surface, causing a decrease in the permeate flow rate

② Membrane compaction, causing a decrease in the flow rate

③ The integrity of the membrane system such as mechanical leaks in the system, causing an increase in the flow rate

④ The extent of membrane deterioration, causing an increase in the flow rate

The normalized permeate flow rate can be obtained by the following equation :

$$Q_N = Q_O \times \frac{P_i - \dfrac{\Delta P_i}{2} - P_{pi} - \pi_i}{P_o - \dfrac{\Delta P_o}{2} - P_{po} - \pi_o} \times \frac{TCF_i}{TCF_o}$$

Q_N = normalized permeate flow rate.
Q_o = measured (actual) permeate flow rate.
P_i = initial operating pressure,
P_o = actual operating pressure
ΔP_i = initial differential pressure,
ΔP_o = actual differential pressure
P_{pi} = initial permeate pressure,
P_{po} = actual permeate pressure
π_i = initial osmotic pressure of the feed-concentrate,
π_o = actual osmotic pressure of the feed-concentrate
TCF_i = initial temperature correction factor
TCF_o = actual temperature correction factor

The temperature correction factor can be obtained by the following equation :

$TCF = EXP [3140 \times (1 / 298 - 1 / (273 + T))] ; T \geq 25℃$
$TCF = EXP [2750 \times (1 / 298 - 1 / (273 + T))] ; T < 25℃$

The osmotic pressure of the feed-concentrate mixture can be obtained by the following equation :

$$\pi = \frac{0.0385 \times C_{fc} (T + 273)}{14.25 \times (1000 - C_{fc} / 1000)}$$

The concentration of feed-concentrate can be obtained by the following equation :

$$C_{fc} = C_f \times \frac{\ln \dfrac{1}{1-Y}}{Y}$$

C_{fc} = concentration of feed-concentrate as ion in mg/l
C_f = concentration of feed as ion in mg/l
Y = recovery ratio = permeate flow rate / feed flow rate
T = temperature of feed flow

2) Normailized Salt Rejection

Salt rejection is the most widely known method of monitoring the performance of an RO system, though any problem in the system could have been noticed and corrected sooner by monitoring other parameters such as normalized differential pressure and permeate flow rate, before the problem affects the salt rejection.

The normalized salt passage can be obtained by the following equation,and then normalized salt rejection (%) can be easily calculated by substracting normalized salt passage (%) value.from integer 100.

$$\text{Normalized Salt passage (\%)) =} \frac{C_{po} \times NDP_o \times TCF_i \times C_{fci} \times C_{fo}}{C_{fco} \times NDP_i \times TCF_o \times C_{fco} \times C_{fi}}$$

C_{po} = actual concentration of permeate as ion in mg/l
NDP_i = initial net driving pressure
NDP_o = actual net driving pressure
C_{fci} = initial concentration of feed-concentrate as ion in mg/l
C_{fco} = actual concentration of feed-concentrate as ion in mg/l
C_{fi} = initial concentration of feed as ion in mg/l
C_{fo} = actual concentration of feed as ion in mg/l

The net driving pressure can be obtained by the following equation :

$$NDP = P - \Delta P/2 - P_p - \pi$$

P = operating pressure
ΔP = differential pressure
P_p = permeate pressure
π = osmotic pressure of the feed-concentrate

The rate of rejection varies for each of the particular salts in the feed water and thus a variation in the ion composition of an RO feed water will result in a change in the overall percent rejection of the TDS. Hence, it is suggested to record an individual ion rejection in order to have a basis for future performance comparison, when a system starts with a new membrane.

The data on the individual ion rejections is also helpful in diagnosing some system malfunction. For example, a rejection calculated using a divalent ion such as calcium can tell a difference between a mechanical leak in the system and membrane deterioration. Mechanical damages in membranes, glue lines and O-rings will result in a similar decrease in rejection for both monovalent and divalent ions, while, in the case of membrane deterioration, the rejection decline will be more severe for monovalent ions.

3) Normalized Differential Pressure (ΔP)

Differential pressure is the difference between the feed pressure and the concentrate or brine pressure exiting the end of the elements. It is a measure of the pressure drop as the feed water passes through the flow channels of all the elements in the system. At constant flow rate, an increase in the differential pressure indicates that large colloidal particles or physical debris such as pump shavings, inorganic scales and bio-film particulates are blocking the flow channels. The telescoping of spiral wound elements can also cause an increase in the differential pressure, which is a function of the permeate and concentrate flow rates. Since these rates may vary daily due to variation in water temperature or some other changing parameters, the actual differential pressure should be normalized according to the following equation to compare with the initial differential pressure.

$$\text{Normalized Differential Pressure} = \text{actual } \Delta P \times \frac{(2\times\text{initial concentrate flow} + \text{initial permeate flow})^{1.5}}{(2\times\text{concentrate flow} + \text{permeate flow})^{1.5}}$$

A percent change (e.g. 10%) in normalized differential pressure could suggest when to clean an RO system.

7-1. Introduction

Fouling of RO membrane is more or less a normal phenomenon of most RO systems since the pre-treatment of the feed water prior to the RO membrane is basically designed to reduce fouling substances as much as possible and technically could not remove all of them. Fortunately, with correct cleaning frequency, most foulants can be removed from the membrane. The cleaning frequency could be minimized as long as the pre-treatment is well maintained without upset conditions such as an uncontrolled change in feed water composition and uncontrolled biological contamination. Sometimes mistakes in the system operation such as too high recovery and failure of chemical dosing systems could end up with fouling the membrane.

A fouled membrane exhibits two major performance issues, one is higher operating pressure and higher pressure drop. As foulants collect on the surface of the membrane, they form an additional barrier layer to transport through the membrane. Higher pressure drop is a result of the increased resistance to crossflow caused by the layer of foulants. Pressure drop can be converted into axial pressure on the membrane (especially membrane module). High axial pressure caused by membrane fouling can cause membrane and membrane module to fail. Cleaning the fouled membranes can be accomplished by suitable cleaning agents at alkaline (up to pH12) and acidic (pH2) conditions because CSM RO membranes are stable at the pH conditions and at an elevated temperature (45℃). Many foulants, particularly clay-type soils, can compact with time as the foulant layer increases in depth. As the foulants compact, it will become more difficult to remove them during cleaning. Thus the time of cleaning must not be delayed too long.

7-2. Timing for Cleaning

Elements should be cleaned immediately when one of the following symptoms is detected :

- Loss of 10 to 15% in normalized permeate flow rate
- Decrease of 0.5% in salt rejection

The differential pressure (feed pressure - concentrate pressure) ΔP increases by 15% from the reference conditions (initial performance established during the first24 to 48 hours of operation). Ideally, element cleaning is planned when any performance deteriorations by 10% and should be completed prior to the time performance changes by 15%. Missing the proper timing for elements cleaning can lead to irreversible fouling and/or scaling of the membrane.

It should be noted that it is important to normalize flow and salt content of the permeate according to the normalization procedure described in Section 6.

7-3. Cleaning Tank and Other Equipments

The mixing tank for cleaning agents should be made of polypropylene or FRP which is resistant to pH in the range of 1 to 13. The cleaning agents exhibit enhanced cleaning efficiency at an elevated temperature. (e.g. 35-40℃). The cleaning solution temperature should not be below 15℃ at which the cleaning efficiency is very retarded. Cooling may also be required to avoid overheating, so the heating and cooling equipments may be necessary to control the temperature of the cleaning solution adequately.

The size of the tank needs to be large enough to contain the volume of the cleaning solution approximately equivalent to the volume of the pressure vessel plus the volume of the feed and return pipes. If it is difficult to calculate the exact volume of the pipes, it can be assumed to be about 20% of the vessel volume. Appropriate pump, valves, flow meters, and pressure gauge should be installed to control the flow. Especially, pump capacity should be determined enough to handle the maximum recirculation flow rate for the largest stage (generally, 1st stage) in the entire RO skid. Catridge filters should be changed prior to conducting cleaning with every new cleaning solution.

7-4. Cleaning Procedure

1. Fill the cleaning solution tank with RO permeate water. The volume of cleaning solution should be sufficient to fill all the pressure vessels and pipe lines. Add the calculated amount of the cleaning chemicals to the tank. Use a mixer or recirculate the solution with the transfer pump to ensure that all chemicals are completely dissolved and well-mixed before circulating the solution to the RO elements.
2. Drain most of the water from the RO system to prevent the dilution of the cleaning solution by remaining process water in the RO system.
3. Heat the solution to the temperature recommended by the manufacturer to improve cleaning effectiveness.
3. Pump the preheated cleaning solution to the vessel at conditions of low flow rate (about half of that shown in Table 1) and low pressure to displace the process water remaining in the vessel. Dump the displaced water until the presence of the cleaning solution is evident in the RO concentrate system or in the return pipe, indicated by the pH and temperature of the cleaning solution. Adjust flow rate and pressure according to the Table 1. Open the RO concentrate throttling valve completely to minimize operating pressure during cleaning. Use only enough pressure to recirculate the cleaning solution without permeate coming out.

Table 1 : Feed Flow Rate of Cleaning Solution per Pressure Vessel during Recirculation

Element Diameter (in)	**RecommendedFeed Flow Rate**	
	(gpm)	**(m^3/h)**
2.5	3-5	0.7-1.2
4	8-10	1.8-2.3
8	30-45	6.0-10.2

5. Recycle the concentrate to the cleaning solution tank until the desired temperature is maintained throughout the system. Observe any increase in the turbidity to judge efficiency of the cleaning solution, especially in the case of an alkaline cleaning solution or a detergent solution. If the cleaning solution becomes turbid or colored, drain the solution and restart with a freshly prepared cleaning solution. Check the pH during acid cleaning. The acid is gradually consumed when it dissolves inorganic precipitates on membrane surface. If the pH increases more than 0.5 pH unit, add more acid.
6. Turn the pump off and allow the elements to soak. Sometimes a soak period of about 1 hour is sufficient. For intensive fouling, an extended soak period is beneficial; soak the

elements for 10-15 hours. To maintain a high temperature during an extended soak period, use a slow recirculation rate (about 10% of that shown in Table 1).

7. Circulate the cleaning solution at the rates shown in Table 1 for 30-60 minutes. The high flow rate flushes out the foulants loosened from the membrane surfaces by the cleaning. If the elements are heavily fouled, a flow rate which is 50% higher than shown in Table 1 may enhance cleaning efficiency. However, excessive pressure drop may be a problem at higher flow rates. The maximum recommended drops are 1.4 bar (20PSI) per element or 4.1 bar (60PSI) per multi-element vessel. The direction of flow during cleaning must be the same as during normal operation to avoid telescoping of the elements.
8. Drain the used cleaning solution out of the system. Analyze a sample of the used solution to determine the types and the amount of substances (fouling materials) removed from the membrane elements. The results could tell the degree of cleaning and the causes of fouling.
9. RO permeate or good quality water (filtered, SDI < 3), free of bacteria and chlorine, conductivity < 10,000 s/cm is used for flushing out the residual cleaning solution. The minimum flush out temperature is 20℃ to prevent precipitation.
10. The RO plant is started up again at normal operating conditions. However, the permeate at the initial stage of start-up must be drained until conductivity and pH returns to normal. And also the permeate side draining is necessary when another cleaning cycle with another cleaning chemical is to follow. During the rinse out step, the operating parameters should be noted to judge the cleaning efficiency and to decide if another cleaning is required. If the system has to be shut-down after cleaning for longer than 24 hours, the elements should be stored in a preservative solution such as 1% sodium bisulfite and 0.5% formaldehyde. For multi-array systems, cleaning should be carried out separately for each array. This can be accomplished either by using one cleaning pump and operating one array at a time, or using separate cleaning pump for each array.

7-5. Cleaning Chemicals

Choosing right cleaning chemicals is important since harsh and frequent cleaning will shorten the membrane lifetime, and sometimes a inappropriate choice of cleaning chemicals can worsen the fouling situation. The cleaning will be more effective if it is tailored to the specific fouling situation. Therefore, the type of foulants should be determined prior to cleaning, there are helpful ways to determine the type of foulants as shown below :

- Analyze the plant performance data
- Analyze the feed water characteristics to find potential fouling substances
- Check the results of previous cleanings which may indicate specific fouling substances
- Analyze the foulants collected with a membrane filter used for SDI measurement
- Analyze the deposits on the cartridge filter
- Inspect the inner surface of the feed line tubing and the feed end scroll of the RO element. If it is reddish-brown, fouling by iron is possible. Biological fouling or an organic material deposit is often slimy or gelatinous.

Table 2 lists suitable cleaning chemicals depending on the type of foulants. The acid cleaners are to redissolve inorganic deposits including iron, while the alkaline cleaners are to remove organic fouling including biological matter. Sulfuric acid should not be used for cleaning because of the risk of calcium sulfate scaling formation.

For the preparation of the cleaning solutions, RO permeate is preferred, but prefiltered raw water may be used. The raw water could have some buffering ability, so more acid or hydroxide may be needed to reach the desired pH level, which is about 2 for acid cleaning and about 12 for alkaline cleaning at 30℃, respectively. At 35℃, the pH limit is in the range of 2 to 11, and at 50℃ the operable pH range is 3 to 10.

Table 2. Cleaning Chemicals for CSM Membrane

Foulant	Cleaning Chemical	**Comments**
Inorganic salts ($CaCO_3$,$CaSO_4$,$BaSO_4$)	0.2% Hydrochloric Acid. 0.5% Phosphoric Acid. 2.0% Citric Acid.	Best O.K. O.K.
Metal Oxides (Iron)	0.5% Phosphoric Acid. 1.0% Sodium Hydrosulfite.	Good Good
Inorganic Colloids (silt)	0.1% Sodium Hydroxide (NaOH), 30℃ 0.025 Sodium Dodecylsulfate/0.1% NaOH, 30℃	Good Good
Biofilms	0.1% Sodium Hyudroxide, 30℃. 1.0% Sodium Ethylene Diamine Tetra Acetic Acid (Na_4EDTA) and 0.1% NaOH, 30℃	Best Best When biofilm contains inorganic scaling
Organics	0.025%Sodium Dodecylsulfate/0.1% NaOH, 30℃. 0.1% Sodium Triphosphate/1% Na_4EDTA	Good Good
Silica	0.1% Sodium Hydroxide, 30℃. 1.0% Sodium Ethylene Diamine Tetra Acetic Acid (Na_4 EDTA) and 0.1% NaOH, 30℃	O.K. O.K.

Table 2 shows the working formula for cleaning solutions, but commercial cleaning chemicals are frequently used in the field rather than self-made formulations. Most of the commercial chemicals are compatible with CSM membranes in short term test. The long term compatibility test including cleaning efficacy should be carried out. In the meantime, they can be used as long as the membrane performance is carefully monitored to detect any long term effects at an early stage. In any event, make sure that the commercial chemicals do not contain cationic and nonionic surfactants, and the pH of the cleaning solution should not exceed the limits at the specified temperature.

7-6. Disinfection

If the RO system is suspected to be infected by bacteria or mold, e.g. slimy deposit or rotten smell, a disinfection should be performed after the cleaning. The procedure is the same as for cleaning, except the high flow pumping step.

Commonly used disinfectants are formaldehyde, hydrogen peroxide, peracetic acid, and chlorine. Quaternary ammonium disinfectants, iodine, and phenolic compounds should not be used because they cause flux losses.

The effective concentration of formaldehyde is in the range of 0.5 to 3%. Care should be taken in handling this chemical since it is considered as a carcinogen.

A 400ppm peracetic acid solution (also containing 2,000 ppm of hydrogen peroxide) can be used to disinfect the RO system. The biocidal efficacy of peracetic acid is much higher than hydrogen peroxide. Care must be exercised not to exceed the 0.2% concentration as a sum of both compounds. Only periodic use is recommended since continuous exposure at this concentration may damage the membrane. When the peracetic acid is used, pH adjustment is usually not required.

However, when hydrogen peroxide is employed alone up to 0.2% concentration, pH of the solution is preferably adjusted to be 3. This will ensure optimal biocidal effect and minimum damage to the membrane. If an alkaline cleaning has preceded disinfection, an acid rinsing is recommended for both sides of the membrane. Additionally, hydrogen peroxide can attack the membrane more aggressively at temperature above 25℃ and in the presence of transition metals such as iron and manganese.

CSM membranes can withstand short term exposure to free chlorine (hypochlorite). However, eventual degradation may occur after 200-1000 hours of exposure to one ppm chlorine, depending on feed water characteristics, e.g. pH and the presence of heavy metals. Thus chlorine is not recommended for disinfecting the membrane, but can be used in the pre-treatment prior to the RO elements.

Disinfection using chloramine, chloramine-T, and N-chloroiso-cyanurate is not recommended, since their effectiveness as disinfectants at low concentration (<3㎎/ℓ) is limited and the compounds can also slowly damage the membranes.

8-1. Opening Pressure Vessel

STEP 1 RELIEVE PRESSURE

1. Shut off all sources of pressure and relieve residual pressure from the vessel, following the system manufacturer's recommendations.

STEP 2 DISCONNECT PERMEATE PORT

1. Disconnect and remove permeate piping from the permeate port of the vessel.

STEP 3 EXAMINE END CLOSURE

1. Examine end closure of vessel for corrosion. If any is evident, proceed as follows :
   A. Loosen any deposits with a small wire brush and/or a medium grade piece of Scotchbrite.
   B. Flush away loosened deposits with clean water.

STEP 4 REMOVE INTERLOCK

1. Use a 1/4" hex key wrench to remove the three securing screws from the yellow plastic securing ring. Place one of the screws aside for use on reassembly. Thread the other two screws into the threaded jacking holes in the securing ring until they contact the bearing plate. If excessive corrosion build-up prevents threading,
   A. Apply penetrating fluid (such as WD-40® or LPS-1®) to interfacing areas of securing ring. (Securing ring may have become bonded to locking ring set and/or bearing plate.)
   B. With a screwdriver handle or similar tool, tap the securing ring to release the bond.
   C. Again attempt to remove ring by turning the jacking screws an additional 1/4 turn.
2. Grip the two (2) screws firmly and pull the securing ring towards you. Once ring is free, carefully remove it from the bearing plate.
3. If ring cannot be freed by the method, then use the screws as jacking screws by turning 1/4 turn on each screw.
4. Once ring has started to move, repeat procedure in step 2. above.
5. Use a cushioned mallet or hammer in conjunction with a wood block to tap bearing plate face. This should free locking ring segments.
6. Refer to Figure. 1 for locking ring segment identification.

Pressure Vessel of Advanced Structures Inc. for 8040 Elements

7. Rotate locking ring set so that segment A (key segment) is at the 12 o'clock position. Segment A can now be removed. If segments will not rotate, repeat 1A, 1B, and 5.
8. Repeat step 7 above for segments B&C.
9. After removal of segments, remove all debris (corrosion products, dirt, etc.) from the vessel ends.

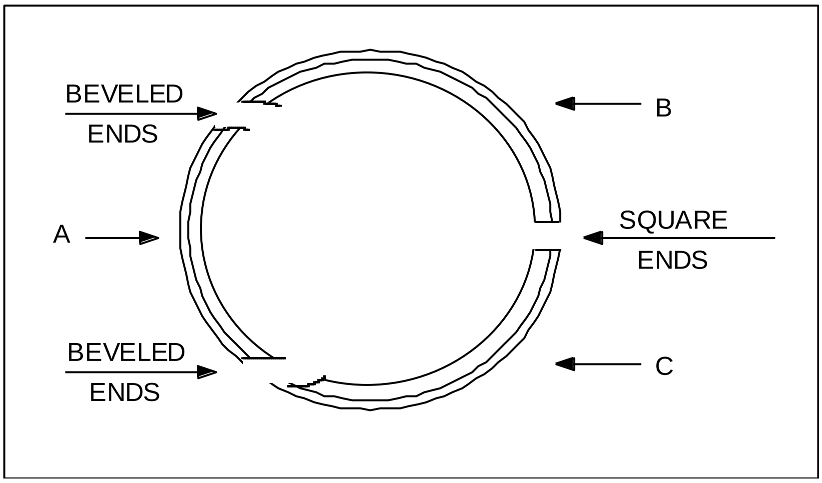


Figure 1.

STEP 5 REMOVE HEAD

STEP 5A REMOVAL BY HAND

1. Thread a short length (12 in.) of 1 in. I.D. pipe into the permeate port and pull the head straight out. A sharp forceful tug may be required to start the head assembly moving.
2. If the head seal remains in the vessel bore, it should be removed at this time.

STEP 5B REMOVAL USING HEAD TOOL

1. Insert the tool into the shell with threaded rods in line with bearing plate holes.
2. Thread the rods into the bearing plate holes and turn until the knobs bottom out.
3. Grasp tool with both hands and pull straight out to remove the head. If the head will not release from the shell,
   A. Thread a 1" ID pipe approximately 2 feet long into the permeate port.
   B. Carefully rock the head assembly back and forth to release the seal.
   C. Once the head seal has been broken, complete removal as instructed in the Opening Vessel section.
4. To remove the tool from the head, reinstall the head part-way into the shell so that the tool is compressed, then unscrew the rods.

8-2. Element Removal and Loading

Do not proceed the steps for removing elements until all pressure has been relieved from the vessel and both heads have been removed from the vessel.

STEP 1 REMOVE ELEMENT INTERFACE HARDWARE

1. Remove thrust ring from downstream (concentrate) end.
2. Remove adapters from elements at each end.

STEP 2 ELEMENT REMOVAL

1. Remove elements from vessel. Clean off any excess lubricant from vessel inside diameter before removing elements. Elements must be removed in direction of feed flow.
2. Flush out the vessel with clean water to remove all dust and debris.
3. Examine membrane element surfaces for any imperfection which could scratch the vessel bore. Pay particular attention to edges of anti-telescope device (ATD/brine seal carrier). If any defects are found which cannot easily be corrected, contact the element manufacturer for corrective action.
4. Using an approximate 50% mixture of glycerine in water, lubricate the inside of the vessel. This may best be accomplished using a suitably sized swab soaked in the mixture. This procedure will ease membrane element loading and reduce chance of scratching the vessel bore.
5. Load the first element into the upstream end of the vessel. Leave a few inches of the element projecting from the vessel to facilitate interconnection to the next element.
6. Apply a light film of a non-petrolium based lubricant, such as Parker Super O-Lube, to the inter connector O-ring. (The amount of O-lube should be just enough to give a luster to the O-ring. Excess O-lube must be removed to prevent possibility of element contamination).
7. Assemble the inter connector to the loaded element.
8. Line up the next element to be loaded and assemble it to the inter connector already assembled on first element.

CAUTION

Maintain element alignment carefully during assembly process. Do not allow element weight to be supported by interconnector.

Misalignment can result in damage to interconnectors or permeate tubes or to element outer surface.

9. Push both elements into the vessel until a few inches are projecting from the vessel. Repeat loading process until all elements are installed.
10. When the final element is installed, push the element stack forward until the face of the first(downstream) element is at dimension D as shown in figure 2.

Take care to avoid pushing elements too far as it can be difficult to push the stack in a reverse direction.

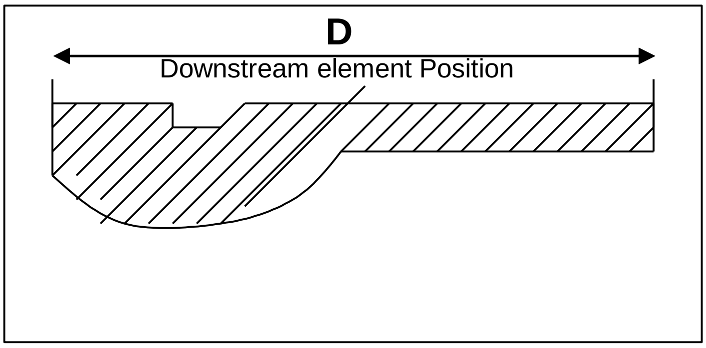


Figure 2

VESSEL TYPE DIMENSION "D"
(see figure 2)

E8U/SP	**8.40 in.**
E8L/SP	**8.65 in.**
E8B/SP	**9.15 in**
E8B/SP	**9.90 in.**

Alternate To Measurement Method

1. Insert a clean thrust ring into downstream end of vessel.
2. Insert head assembly, without quad seal or adapter, into downstream end of vessel.
3. Place the two square ended sections of locking ring into locking ring groove (with squared ends together, stepped side outwards.)
4. Load elements as described in 5 through 9.
5. Install upstream adapter per Step 4 and head assembly per section on "Closing Vessel."

STEP 4 INSTALL ELEMENT INTERFACE HARDWARE

1. Assemble adapter to element permeate tube at each end of vessel.

8-3. Closing Vessel

1. Do not proceed to closing vessel steps until elements and adapters have been installed in vessel.
2. Do not proceed to closing vessel steps until head has been checked for correct component assembly, and vessel has been shimmed to prevent movement of the elements if required

STEP 1 INSPECT SHELL INSIDE SURFACE

1. Inspect the vessel inside surface for any corrosion deposits or other foreign matter. If any are found, clean the surface as follows :
    A. Using a medium or finer grade of Scotchbirter and a mild soap solution, clean each end of the vessel liner surface up to 8" in from each end of vessel.
    B. Rinse away all loosened deposits from the shell inside surface using clean fresh water.
2. Inspect the vessel inside surface for scratches or other damage which could cause leaks. Vessels that leak must be replaced.
3. Inspect feed and concentrate port seals and attachments for internal and external damage or deterioration. Contact Advanced Structures, Inc. for guidance, if damage to the vessel's internal surface or feed / concentrate port, seals or attachments are discovered during inspection.

STEP 2 SHELL AND HEAD SEAL LUBRICATION

1. Work O-ring lubricant glycerin into the shell from half way up the bevel to approximately 1/2" in from the bevel. (See Figure 3)
2. Ensure the entire head seal is covered with a thin layer of O-ring lubricant, with no dirt or dust contamination. Use only glycerin for lubrication.

STEP 3 INSTALL HEAD

STEP 3A INSTALLATION BY HAND

1. Hold the head assembly square to axis of the shell and slide it straight in until a slight resistance is felt. Do not rotate the head assembly after insertion into the vessel as this may cause the head seal to become detached.

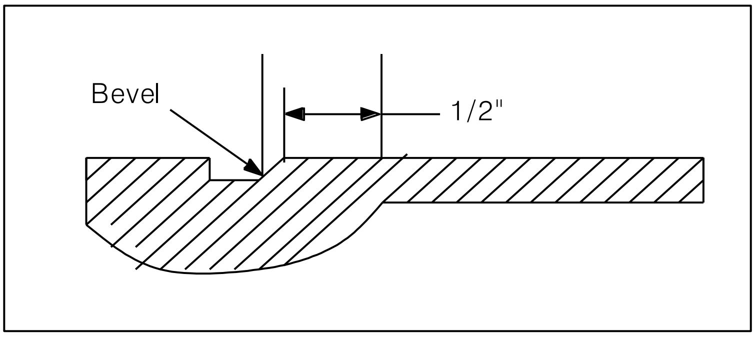


Figure 3

2. Using both hands, firmly push the head in as far as it will go. (A sharp, forceful thrust may be necessary to enter the head seal into the vessel bore). When the head is correctly positioned, approximately 1/2" of the locking ring groove will be exposed.

STEP 3B INSTALLATION USING TOOL

1. Hold the head assembly square to axis of the shell and slide it straight in until a slight resistance is felt.
2. Slide the head tool into the shell just behind the head. Do not engage threaded rods.
3. Give a sharp, forceful thrust on the head tool to enter the head into the vessel bore. Then push into the shell as far as it will go. When the head is correctly positioned, approximately 1/2" of the locking ring groove will be exposed.
4. Remove the tool by pulling straight out. Do not rotate.(The tool can be obtained from Advanced Structures, Inc.)

STEP 4 INSTALL INTERLOCK

1. Refer to Figure 1 for correct segment identification.
2. With the head assembly inserted into the shell, install segment B into the bottom of the shell groove, with the stepped edge facing outwards.
3. Slide segment B counterclockwise making room to install segment C into the bottom of the shell groove.
4. Slide segments B & C in the shell groove until the square ends meet at the 3 o'clock position. Hold these in position while installing segment A (the key segment in the 9 o'clock position).
5. Rotate the installed locking ring set counterclockwise until the square ends of segments B&C are in the 12 o'clock position. (This will prevent the segments from falling out.) Locking ring segments must be installed with stepped edge facing outwards.
6. Install the yellow securing ring with its ends flush. Align the three mounting holes in the ring with their corresponding holes in the bearing plate. Insert the three securing screws and turn them in about two turns.

7. Press the securing ring in until it seats securely on the bearing plate. Before inserting of securing screws, it is advisable to lightly coat the screw threads with anti-seize compound, to ease later disassembly.
8. Tighten all three mounting screws until snug. Over-tightening may cause disassembly problems!
9. Visually inspect locking ring set to ensure it is correctly positioned between shell and bearing plate.
10. Verify that securing ring is fully seated and held in place by securing screws.

WARNING

INTERLOCKING COMPONENTS MUST BE CORRECTLY INSTALLED. INCORRECT ASSEMBLY OR INSTALLATION CAN RESULT IN EXPLOSIVE HEAD FAILURE.

STEP 5 RECONNECT PERMEATE PIPING

1. Reconnect manifold piping to the vessel permeate port. Using Teflon tape on all threaded connections will help ensure a leak-free assembly.

Do not tighten a component into thermoplastic permeate port more than one turn past hand tight.

STEP 6 PRE-PRESSURIZATION CHECKS

It is vitally important that the following checks be carried out before any attempt is made to pressurize the vessel.

HEAD ASSEMBLY

Verify the following at each end of the vessel.

1. Head assembly is in good condition, with no evidence of damage or corrosion.
2. Locking ring set is properly in place and yellow securing ring is snugly held in place by the securing screws.

MEMBRANE ELEMENTS

Verify belows

1. Elements are installed in the vessel.
2. Element adapters are installed at each end of vessel.
3. Thrust ring installed at downstream end of vessel.

PIPING CONNECTIONS

1. Check all piping connections to ensure that they will provide a leak-free seal.

STEP 7 PRESSURIZATION

1. After following the above pre-pressurization checks, pressurize vessel in accordance with the element specifications.
2. Vessels should be filled slowly to assist trapped air to escape.
3. Vessels should be pressurized slowly to avoid damage to membrane elements and vessel components.

9-1. Introduction

Any RO system malfunction manifests itself in a loss of salt rejection, a loss of permeate flow, and an increase in differential pressure, respectively or collectively.

If one of the three parameters or combined ones deviates slowly from the normalized value, it may indicate a normal fouling and scaling which can be removed by proper cleaning.

A fast or an immediate performance decline indicates a defect or mis-operation of the system. It is essential in this case that the proper corrective measure is taken as early as possible because any delay decreases the chance of restoring the system performance and also it may create other problems.

A prerequisite for early detection of potential problems is consistent record keeping and performance normalization, including proper calibration of all instruments. It may not be possible to detect a problem at the early stage without accurate system performance readings

After the problem has been detected, the next step is to localize the problem and to identify the causes of the problem. This can be done using the data of the record keeping log sheet or some additional on-line measurements.

If the data are not sufficient to determine the causes, one or more membrane elements must be taken out of the system and analyzed by either nondestructive or destructive methods.

9-2. Instrument Calibrations

Instrument calibrations are the first thing to check in any troubleshooting operation since wrong instrumentation can miss a real decrease in salt rejection or cause a false alarm.

On-line TDS Meters

Accuracy of on-line TDS meters can be verified by measuring the feed and permeate water TDS with a separate handheld meter.

The percent salt rejection calculated by the handheld meter is compared to the values obtained from the on-line meter. The two values should be relatively close. If a discrepancy arises, recalibrate the on-line meter fbased on the instructions of the manufacturer. Before recalibrating, inspect the probe for the possible accumulation of foreign material that may interfere with the accurate reading. Also, make sure that the probes are mounted properly according the manufacturer's specifications. Improperly mounted probes may trap air bubbles or have inadequate water circulation through the probe, which may cause false readings.

Flowmeters

Flow meter calibration is also important in an RO system, since the correct measurement of permeate and concentrate flow rates is critical to the successful operation of the system. For instance, the concentrate flow rate lower than the system specification may create a situation for the accelerated fouling and scaling, and the normalized permeate flow rate is a critical parameter to monitor any trend in fouling or membrane deterioration.

One method of calibration is to direct the water from the flow meter into a vessel and to measure the time that it takes to fill the known volume. This should be repeated several times for accuracy. If the variation is slight, the values (the volume divided by the time) can be averaged. The other method is to calibrate a flow meter to a known flow meter which has been calibrated previously.

Pressure Sensors

Besides the feed pressure and the permeate pressure, the measurement of the differential pressure is necessary to monitor the build up of deposits on the membrane surface, or within the element flow channels. Inaccuracy in the pressure readings will cause to miss the proper timing for cleaning the system.

The accuracy of mechanical pressure gauges should be periodically verified using a calibrated pressure gauge. Electronic pressure sensors have the potential for greater accuracy. However, they are subject to sensor drift and damage resulting from vibration of the high pressure pumps.

To reduce the effects of vibration, the sensor can be mounted remotely and connected to the high pressure piping with a length of stainless steel or high-pressure nylon tubing.

A calibration pressure gauge mounted with a quick-connect fitting is useful for calibrating pressure sensors.

pH Meters and Temperature

The pH meters should be regularly calibrated using buffer solutions with a known pH. Small variations in feed water temperature do not significantly affect the percent salt rejection. However,

The temperature readings are still important because they are used to determine the normalized permeate flow rate. Therefore the accuracy of the feed water temperature readings should therefore be regularly verified with an accurate thermometer.

9-3. Locating High Salt Passage (Low Salt Rejection)

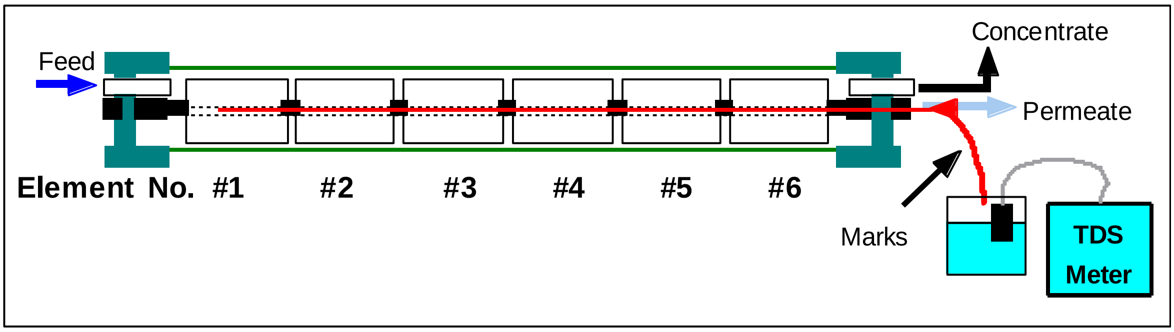
A loss in salt rejection may be uniform throughout the entire system or it could be limited to the front or to the tail end of the system. It could be a general system failure or it could be limited to one or few individual vessels. The location of the high salt passage can be isolated by following three steps :

- Check the individual vessel permeate TDS values.
- Probe the suspected vessel.
- Individually test the performance of each element in the vessel.

A well-designed system contains a sample port located in the permeate stream from each vessel. Care must be taken during sampling to avoid mixing of the permeate sample with permeate from other vessels. All permeate samples are then measured for their concentration of dissolved solids with a TDS meter. Notice that from one array to the next the average permeate TDS usually increases, because the second array is fed with the concentrate from the first array. To determine the salt passage of all vessels from their permeate TDS, the TDS of the feed stream to each array must also be measured. The salt passage is the ratio of the permeate TDS to the feed TDS.

If one pressure vessel shows a significantly higher permeate TDS than the other vessels of the same array, then this vessel should be probed. Probing involves the insertion of a plastic tube (approx. 1/4" for 8" module) into the full length of the permeate tube (see Figure 1).

While the RO system is operating at normal operating conditions, water is diverted from the permeate stream of the vessel in question. A few minutes should be allowed to rinse out the tubing and allow the RO system to equilibrate. The TDS of the permeate sample from the tubing can then be measured with a hand-held meter and the data be recorded. This measurement should reflect the TDS of the permeate being produced by the CSM element at that location.



9-4. Element Analysis

If high salt passage is found only in one or several elements in one or several pressure vessels, then it is most likely that the element(s) could have mechanical damages such as punctures on the membrane surface, glue line failure, a cracked centerfold of the elements and damaged O-rings including brine seals. Damaged O-rings and brine seals can be verified easily by visual inspection of the failed elements.

Damaged membranes and glue line failure can be visualized only by the autopsy of the elements. Alternatively, those physical damages can be verified by a dye test along with the test for salt rejection and flux using a small test line containing methylene blue or rhodamine B. If the dye is detected visually or spectroscopically in the permeate, this proves there is a considerable damage in the membrane or glue line. Then the element can be autopsied to find the causes of the damages.

When there is a general system failure, a front end element or a tail end element should be taken out of the vessels for examination, depending on where the problem is located.

When the problem cannot be located, an element from both ends of the system should be taken for further analysis. Typical front end problems are due to fouling and typical tail-end problems are orginated from scaling. Vessels/elements with these problems usually show low permeate flow rate and sometimes a high salt passage from severe fouling and scaling due to enhanced concentration build-up on membrane surface.

If the membranes are damaged by chemicals such as chlorine and concentrated acid, a high salt passage along with a higher permeate flow rate would occur usually in all the elements of the first array. If the accidental high dosage of the chemicals into the system is not corrected immediately, the membranes of the second array would also be damaged.

9-5. Cleaning Test for Heavily Fouled Elements

The regular cleaning procedure, which is part of the system operation, usually restores a decline in less than 15% of the permeate flow rate of the system back to the normal value. However, when the decline in the flow rate is greater than 15% due to missing the proper cleaning time or an accidental pre-treatment upset, it is usually difficult to recover the lost flow rate fully by the normal cleaning. In this case, an element from the front end or tail end, depending on the location of the problem, should be taken out for cleaning tests using more proper chemicals or more aggressive chemicals. When the cleaning test has proven effective, the treatment can be applied to the whole RO system.

However, cleaning may not be successful when the membrane is damaged, or when the permeate flow of the element is below 50% of specification due to heavy fouling and scaling. Then, the element is autopsied to examine the membrane surface, the glue line, and the fouling deposits by the methods shown in the following section.

9-6. Analytical Methods for Heavily Fouled Elements

Visual Inspection

To a certain degree by a visual inspection of the autopsied element, the appearance of the foulant will provide clues to its nature and to the difficulty in its removal. Large filter media particles like activated carbon will be evident to the sight.

A biological foulant will have a different appearance than an inorganic scale, and smell differently. Other mechanical problems with the element such as the broken glue line and, the damaged feed and product water channel materials can be spotted visually.

Dissolution in Acid

If the deposits on the membrane appear to be crystalline and dissolve in an acidic solution (HCl) of pH 3 to 4 with some gas evolution (carbon dioxide), then it is likely that the deposits are consisted of carbonates such as $CaCO_3$.

Sulfates or silica will only dissolve with difficulty in very low pH(e.g. pH1) solution. If the scale is soluble in 0.1M hydrofluoric acid (HF) solution, it is possibly silica.

Dye Test

A dye such as methylene blue or rhodamine B can be added in a concentration of 0.001 to 0.005% to the feed water of the test element on an individual element test stand. The dye will permeate the membrane through areas of degradation and mechanical leaks in the element. The dye in the permeate water can be detected visually or measured using a spectrophotometer.

After the dye test, the element can be autopsied to visually inspect the specific location of the dye passage. Damaged areas may pick up more dye than unaffected areas. Chemical attack by chlorine or high dosage acid induced hydrolysis of the membrane will tend to result in uniform absorption of the dye.

Optical Microscopy

When the visual inspection of the autopsied element can not reveal enough information about the nature of foulants, a high power light microscope can tell if a foulant is biological or inorganic scale. It can also provide information about the crystalline structure of a scale formation. Using polarized light, the microscope can tell the difference between calcium sulfate and calcium carbonate scales, since calcium sulfate crystal has more than one refractive index to give a unique appearance.

Sometimes it can be recognized under the microscope that a layer of scale sitting on the membrane surface is covered by another layer of organic and biological foulants. In this case, it may be a most effective cleaning to remove the organic and biological foulants first with an alkaline cleaning solution, prior to attempting to remove the scale with an acidic solution.

Fourier Transform Infrared Spectroscopy (FTIR)

FTIR can provide additional information about foulants on the membrane surface. When there is a thick layer of foulants on the membrane, it is preferred to scrape off a sample of foulants from the membrane surface. The sample is dried and FTIR of the dried sample is run. If a suitable size of sample cannot be collected from the membrane surface, an FTIR analysis may be performed directly on the fouled membrane using a technique called attenuated total reflection (ATR). ATR will give FTIR spectrum corresponding to the foulants after it subtracts FTIR spectrum of a fresh membrane from that of the fouled membrane. Sometimes, the subtraction process does not work well to result in a mixture of peaks corresponding to both the foulants and the membrane.

Organic and inorganic compounds have their own specific FTIR peaks which can in turn be used to identify the compounds in a mixture. From the peak intensity, semiquantitative analysis is also possible. If the FTIR spectrum shows peaks originated from Si-O-Si, CO_3, and SO_4, then it indicates there are silica, calcium carbonate, and sulfates, respectively in the foulants. If the spectrum exhibits peaks corresponding to C-H, -CO-, C-C, and C-N, then it indicates the foulant is organic or biological substances. Peaks due to C-H, -CO-, C-C, and phenol groups strongly suggest that the foulant is consisted of humic acid.

Scanning Electron Microscopy (SEM)

SEM can distinguish much smaller objects than the optical microscope. So SEM gives clear photographs of particles as small as 0.1㎛ to identify small crystalline and amorphous inorganic scaling matter, and also the cell structure of microorganisms. SEM could be very helpful in analyzing the foulants in more detail.

Energy Dispersive X-ray (EDX)

During the process of SEM, X-ray radiation is emitted from the sample due to the electron bombardment. The X-ray is low energy and includes the characteristic of the elements in the sample. Thus EDX can identify elemental composition in the sample and even offer a semi-quantitative analysis of the sample. It can detect very small amount of inorganic elements in the sample and also identify carbon, nitrogen and oxygen, though less sensitively. It works the best for analyzing an inorganic scale, but also is useful for organic sample analysis.

The method can also furnish the evidence of halogen damage of the membrane due to chlorine oxidation by detecting the presence of chlorine chemically attached to the polyamide.

9-7. Causes of Element Failures and Corrective Measures

9-7-1. High Salt Passage and High Permeate Flow

Membrane Oxidation

A combination of a high salt passage (low salt rejection) accompanied by high permeate flow is a typical symptom of the damaged membrane oxidized by oxidizing chemicals including chlorine, bromine, and ozone. Other oxidizing chemicals such as peracetic acid, hydrogen peroxide, and N-chloro compounds are less aggressive, but still can damage the membranes when they are present in excessive amount or coexist with transition metals. A neutral to alkaline pH favors the attack to the membrane. At the early stage of the oxidation, the front end elements are usually more affected than the rest.

The oxidation damage can be made visible by a dye test on the element or on membrane coupons after autopsy of the element. Once membrane oxidation occurred no corrective action is possible. Consequently, all damaged elements must be replaced.

Leak

A leak from feed or concentrate to permeate through a mechanical damage of the element or of the permeate tubing can cause high salt passage and high permeate flow. The contribution of the leak to the permeate flow may depend on the magnitude of the damage usually caused by high pressure and vibration. The types of the damages include leaking O-rings, cracked tubes, telescoping, punctured membranes, and centerfold cracking.

9-7-2. High Salt Passage and Normal Permeate Flow

Leaking O-ring

Leaking O-rings can be detected by the probing technique (Section 9-3). Inspect O-rings of couplers, adaptors, and end plugs for correct installation and aging condition. Replace old and damaged O-rings. O-rings may leak after exposure to certain chemicals, or to mechanical stress, e.g. element movement caused by water hammer. Sometimes, they have been improperly installed or moved out of their proper location during element loading.

Telescoping

Telescoping is caused by excessive pressure drop from feed to concentrate. Eight inch elements are more critical because of their greater feed side area. Make sure that a thrust ring is used with eight inch elements to support the elements' outer diameters. Elements with smaller diameter are supported by their permeate tubing. Severe telescoping can rupture the glue line or the membrane itself. Telescoping damage can be identified by probing (section 9-3). The operating conditions leading to excessive pressure drop are detailed in the section of High Differential Pressure. For an example, when the pressure pump is started before a drained system has sufficient time to fill , the front end elements will be exposed to higher than normal water velocities. This can hammer the elements to telescoping which can be prevented by opening the throttling valve slowly.

Membrane Surface Abrasion

The front-end elements are typically most affected by crystalline or sharp-edged metallic suspended solids in the feed water. Check the incoming water for such particles. Microscopic inspection of the membrane surface will also reveal the damage. No corrective action is possible, damaged elements must be replaced. The pretreatment process also must be adequately changed to cope with this kind of problem. Ensure that no particles and debris are released from the high pressure pump and piping.

Permeate Back-pressure

When the permeate pressure exceeds the feed/concentrate pressure by more than 0.3 bar (5 PSI) at any time, the membrane may tear. The damage can be identified by probing and element leak test. Upon autopsy of the damaged element, the outer membrane typically shows creases parallel to the permeate tube, usually close to the outer glue line. The rupture of the membrane occurs mostly in the edges between the feed-sided glue line, the outer glue line, and the concentrate- sided glue line.

Centerfold Cracking

The regular process for making a spiral wound element requires folding a leaf of membrane sheet in the center (centerfold). The creased (folded) membrane can break at the centerfold under certain conditions. Then the salt passage increases with or without an increase in the permeate flow. Centerfold cracking may be caused by :

- Hydraulic shock during start-up (e.g. by air in the system)
- Too fast pressure increase
- Increased shear stress
- Abrasion by scaling and fouling
- Permeate back-pressure

Centerfold cracking typically occurs only after one year or more of improper operation, and only at systems with a high frequency system shut down.

9-7-3. High Salt Passage and Low Permeate Flow

High salt passage combined with low permeate flow is the most commonly occurring system failure, usually induced by colloidal fouling, metal oxide fouling and scaling.

Colloidal Fouling

Colloidal fouling occurs predominantly in the first array. The problem can be more easily located when permeate flow meters have been installed in each array separately. SDI should be checked more frequently to identify the pre-treatment upset.

Inspect SDI filters and cartridge filters for deposits. Clean the elements according to the cleaning procedure and the types of foulants, and correct the pre-treatment process accordingly.

Metal Oxide Fouling

Metal oxide fouling also occurs predominantly in the first array. Check feed water for levels of iron and aluminum. Check the materials of construction upstream of the membranes. Improper construction materials may undergo corrosion to shed iron in the feed water. Inspect SDI filters and cartridge filters for deposits. Clean the membranes with an acidic cleaning solution. Correct the pre-treatment and / or material selection.

Scaling

Scaling is originated from the precipitation and deposition of sparingly soluble salts onto membrane surface. Scaling generally starts in the last array, and then gradually moving to the upstream arrays. Analyze the concentrate for levels of calcium, barium, strontium, sulfate, fluoride, silicate, pH and LSI (S & DSI for sea water). Try to calculate the mass balance for those salts, analyzing also feed water and permeate. Scaling occurs slowly because of the low concentrations involved except $CaCO_3$.

The crystalline structure of the deposits can be observed under the microscope. The type of scaling is identified by a chemical analysis or X-ray analysis. Cleaning with acid and/or an alkaline EDTA solution with subsequent analysis of the spent solution may also help to identify the type of scalant. In the case of carbonate scaling, adjust the pH of the pre-treatment. For the other salts, either use an appropriate scale inhibitor or other suitable pre-treatment techniques, or lower the recovery. Make sure that the design recovery is not exceeded at any time of operation.

9-7-4. Low Permeate Flow and Normal Salt Passage

Biofouling

Biofouling of the membrane occurs predominantly at the front end of the system and affects permeate flow, feed flow, feed pressure, differential pressure, and salt passage in the way as shown below :

- Permeate flow decreases when operated at constant feed pressure and recovery.
- Feed flow decreases when operated at constant feed pressure and recovery.
- Feed pressure has to be increased if the permeate flow is maintained at constant recovery. Increasing the feed pressure will invoke a worse situation, since it increases the fouling, making it more difficult to clean later.
- Differential pressure increases sharply when the bacterial fouling is massive or when it is combined with silt fouling.
- Since pressure drop across the pressure vessels is a sensitive indicator of fouling, installing pressure monitoring devices is strongly recommended for each array.
- Salt passage is normal at the beginning, but may increase when fouling becomes massive.
- High counts of microorganisms in water samples from the feed, concentrate, or permeate stream indicate the beginning or the presence of biofouling.
- Corrective measures require disinfection of the whole system including pre-treatment , and optimization of the pre-treatment system to cope with the microorganism growth in the raw water.
- An incomplete cleaning and disinfection will result in rapid re-growth of the micro- organisms.

Aged Preservation Solution

Elements of RO systems preserved in a bisulfite solution can also become biologically fouled, if the preservation solution is too old, too warm, or oxidized by oxygen. An alkaline cleaning usually helps to restore the permeate flow.

Incomplete Wetting

Elements that have been allowed to dry out, usually give a very low permeate flow with a normal salt passage. The lost permeate flow may be recovered by soaking the elements in a 50:50 mixture of alcohol and water for one or two hours followed by soaking in water.

9-7-5. Low Permeate Flow and Low Salt Passage

Compaction

Membrane compaction usually results in low permeate flow and low permeate salt passage (increased salt rejection). CSM membrane does not undergo considerable compaction at normal operation, but significant compaction may occur at high feed pressure (see section 5 of System Design), high water temperature (> 45℃) and water hammer.

The water hammer can occur when the high pressure pump starts with air in the system and full opening of the throttle valve.

The compaction can also induce intrusions of the membrane into the permeate channel spacer fabric, which are visible. Thus, the permeate flow is not only restricted by the compaction of the polyamide or the polysulfone layer, but also by the reduced cross-section of the permeate spacer that is available for permeate flow. Damaged elements should be replaced, or the flux loss of system must be compensated by the addition of new elements. New elements should be located properly in the system to avoid uneven flow distribution and recovery of the individual vessels.

Organic Fouling

Organic matter in the feed water can deposit on the membrane surface to cause flux loss, mainly in the first array. The deposited organic layer could act as an additional barrier for dissolved solutes, or plug pinholes of the membrane, to increase salt rejection.

Organics with hydrophobic characters or cationic groups can produce such an effect. Examples are hydrocarbons, cationic polyelectrolytes, cationic surfactants, nonionic surfactants, and humic acids.

Analyze the incoming water for oil and organic matter, and check the SDI filter and the cartridge filter for organic deposits. Conduct SDI and TOC measurements on a more frequent basis. Improve the pre-treatment accordingly.

An oil fouling can be removed with an alkaline cleaning agent,. Cationic polyelectrolytes may be cleaned off at an acidic pH, if it is not a precipitation product with other compounds, e.g., antiscalants. Cleaning with alcohol has also proven to be effective in removing adsorbed organic films.

9-7-6 High Differential Pressure

High differential pressure, also called pressure drop from feed to concentrate, generates a high force pushing the feed side of the element in flow direction. This force impacts on the permeate tubes and the fiberglass shells of the elements in the same vessel. The stress on the last element in the vessel is the highest since it has to bear the sum of the forces from the pressure drops of all prior elements.

The upper limit of the differential pressure per multi-element vessel is 4.1 bar (60 PSI), per single element 1.4 bar (20 PSI). When these limits are exceeded, even for a very short time, the elements might be mechanically damaged to result in telescoping and/or breaking the fiberglass shell. This type of damage may not disturb the membrane performance temporarily, but eventually cause flux loss or high salt passage.

An increase in differential pressure at constant flow rates usually arises from the accumulation of debris, foulants and scale within the element flow channels (feed spacer). It usually decreases the permeate flow. An excessive increase in differential pressure can occur from operating mistakes such as exceeding the recommended feed flow (section 5, System Design), and building up the feed pressure too fast during start-up (water hammer).

Water hammer, a hydraulic shock to the membrane element, can also happen when the system is started up before all air has been flushed out. This could be the case at initial start-up or at restart-ups, after the system has been allowed to drain. Ensure that the pressure vessels are not under vacuum when the plant is shut down (e.g. by installation of a vacuum breaker). In starting up a partially empty RO system, the pump may behave as if it had little or no back-pressure. It will suck water at great velocities, thus hammering the elements. Also the high pressure pump can be damaged by cavitation.

The feed-to-concentrate differential pressure is a measure of the resistance to the hydraulic flow of water through the system. It is very dependent on the flow rates through the element flow channels, and on the water temperature. It is therefore suggested that the permeate and concentrate flow rates be maintained as constant as possible in order to notice and monitor any element plugging which causing an increase in differential pressure.

The knowledge of the extent and the location of the differential pressure increase provide a valuable tool to identify the cause(s) of a problem. Therefore it is useful to monitor the differential pressure across each array as well as the overall feed-to-concentrate differential pressure. Some of the common causes and prevention of high differential pressure are discussed below.

Failure of Cartridge Filters

When cartridge filters are loosely installed in the housing or connected without using inter connectors, they can shed debris and particles to block the flow channels in the front end elements. Sometimes cartridge filters deteriorates while in operation due to hydraulic shock or the presence of incompatible materials.

Media Filter Breakthrough

Fines from multimedia, carbon, weak acid cation exchange resin, or diatomaceous earth filters may set loose and enter into the RO feed water. Sometimes some of the coagulated colloids can pass through the channeling of the filters when the filters are not regularly back-washed to result in caking and channeling of the filters. The channeling could occur in very old filters. Cartridge filters should catch most of the larger particles. Smaller particles can pass through a five micron nominally rated cartridge filter to plug the lead elements.

Chemical cleaning is difficult. It can be tried to rinse out the deposits with detergents. Separate single-element cleaning is recommended to avoid the transport of removed particles into other elements. Diatomaceous earth filters should be taken off-line when such problems are encountered. Soft carbons made from coal should be replaced by coconut-shell-based carbons with a hardness rating of 95 or better. New media should be sufficiently back-washed to remove fines before the bed is put into service.

Pump Impeller Deterioration

Most of the multistage centrifugal pumps employ at least one plastic impeller. When a pump problem such as misalignment of the pump shaft develops, the impellers have been known to deteriorate and throw off small plastic shavings. The shavings can enter and physically plug the lead-end RO elements.

Many high pressure pumps are equipped with an optional discharge screen. This screen will catch most of the shavings. Pump discharge screens should be checked regularly for shavings or other debris. The screen may be cleaned or replaced. As part of a routine maintenance schedule, monitoring the discharge pressure of the pumps prior to any control valves is suggested. If not enough pressure, it may be deteriorating.

Scaling

Scaling can cause the tail-end differential pressure to increase. Make sure that scale control is properly taken into account (see Section 4-3), and clean the membranes with the appropriate chemicals (see Section 7-5). Ensure that the designed system recovery will not be exceeded.

Brine Seal Damage

Brine seals can be damaged or turned over during installation or due to hydraulic impacts. A certain amount of feed water will flow through the chasm in the damaged seals to bypass around the element, resulting in less flow and velocity through the element. This will cause to exceed the limit for maximum element recovery to increase the potential for fouling and scaling.

As a fouled element in the multi-element pressure vessels becomes more plugged, there is a greater chance for the downstream elements to become fouled due to insufficient concentrate flow rates within that vessel.

The brine seal damage causing an increase in differential pressure could happen randomly in any pressure vessel. Early detection for the increase in differential pressure is important for an easy correction of system malfunctions.

Biological Fouling

Biological fouling is typically associated with marked increase of the differential pressure at the lead end of RO system. Biofilms are gelatinous and quite thick, thus creating a high flow resistance.

Corrective measures have been described in Section 9-7-4. It is important to frequently clean out the microbial growth and disinfect the system. It is also suggested that water samplesare taken and analyzed on a regular basis from the feed, permeate, and concentrate streams to estimate the microorganism occurence.

Precipitated Antiscalants

When polymeric organic anti-scalants come into contact with multivalent cations like aluminium or residual cationic polymeric flocculants which can heavily foul the lead elements, repeated applications of an alkaline EDTA solution may clean the fouled elements with some difficulties.