

A photograph of an industrial Reverse Osmosis (RO) or Nanofiltration (NF) plant. The facility is filled with rows of large, white, cylindrical membrane modules mounted on blue metal frames. The modules are arranged in a grid pattern, and various pipes and valves are visible throughout the system. The background shows a large, well-lit industrial space with a high ceiling and structural beams. The text "REVERSE OSMOSIS NO:2212 1st STAGE" is visible on a large pipe in the upper right. The text "REVERSE OSMOSIS NO:2212 1st STAGE" is also visible on a pipe in the upper left. The text "COOLLINE" is visible on several of the membrane modules.

RO/NF Process Design

April 2009

SYSTEM DESIGN CONSIDERATIONS

- Permeate capacity and quality
- Permeate recovery ratio
- Membrane type
- Average permeate flux rate
- Size of RO trains and array design
- pH adjustment for optimum performance
- Energy Recovery devices

Feedwater and Temperature

1. Complete ion analysis is required. Use maximum concentrations for system sizing
2. Ion charge balance is required, but may not result from provided analysis
3. Special considerations for NH4 and alkalinity
4. Not all water constituents are listed

Hydranautics RO Projection Program - [Analysis]

File Analysis RO Design UF Treatment Calculation Graphs Help

Project: Arabian Gulf SWRO Code: ARBGLF Feed: Seawater - open intake

pH	8.16	Turb	0.0	E cond	66243 uS/cm
Temp	35.0 C	SDI	0.0 15min	H2S	0.0
Ca	497.1 ppm		24.79 meq	CO3	9.2 ppm
Mg	1598.3 ppm		131.55 meq	HCO3	180.2 ppm
Na	13143.0 ppm		571.43 meq	SO4	3354.4 ppm
K	537.1 ppm		13.77 meq	Cl	23699.2 ppm
NH4	0.0 ppm		0.00 meq	F	1.7 ppm
Ba	0.000 ppm		0.00 meq	NO3	0.3 ppm
Sr	9.500 ppm		0.22 meq	B	5.50 ppm
				SiO2	5.2 ppm
Total positive			741.76 meq	Autobalance	Total negative

Calculated TDS	43041 ppm	Ionic strength	0.855	Print
CaSO4 saturation	25.7 %	BaSO4 saturation	0.0 %	Save
Silica saturation	3.3 %	SrSO4 saturation	30.7 %	
Saturation Index	1.6 Langelier	Osmotic pressure	470.4 psi	

Product Water Flow

Hydranautics RO Projection Program - [RO Design]

File Analysis RO Design UF Treatment Calculation Graphs Help

Project: Arabian Gulf SWRO Calculated by: CRB Date: 02/02/07

pH: 8.16 | 10.30 Membrane age: 3.0 years Chem type: H2SO4

Temp: 35.0 C Chem dosing rate: 0.0 ppm Chem concentration: 0.0

Flux decline % per year	7.0	5.0	Feed water type	Seawater
SP increase % per year	10.0	5.0	Permeate blending	
Product recovery, %	40.0	50.0	Concentrate recirc.	
Permeate flow	m3/d	13000.00	11000.00	11777.78
Average flux rate	l/m2-hr	14.5	34.3	Recirculation flow
Feed flow	m3/d	32500.0	12222.2	Permeate pressure
Concentrate flow	m3/d	19500.0	1222.2	

Stage 1

System Specs

Element type	SWC4+	
Elements/vessel	7	
Vessels	144	
Permeate Press	0	

Element type	ESPAB	ESPAB
Elements/vessel	6	6
Vessels	40	20
Permeate Press	2	0

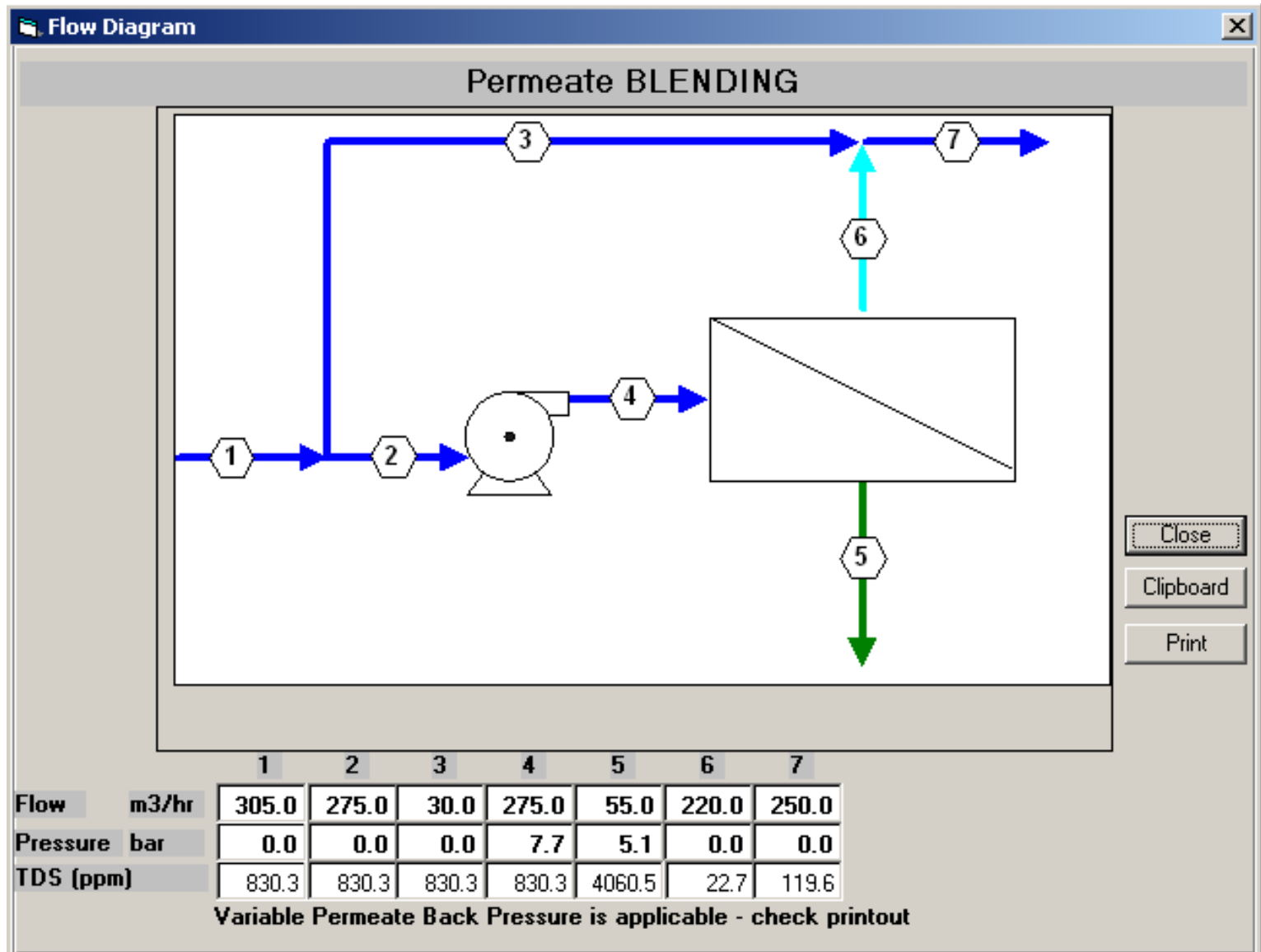
Stages: 2 Pass 2

Recalc Array AutoDisplay

ANAUTICS membranes.com

1. Permeate is entirety of the product water
2. Permeate combined from 1st and full or partial 2nd pass.
3. Permeate plus small amount of feed by-pass

Process Flow Diagram – Feed Bypass



Selecting Your Recovery

Hydranautics RO Projection Program - [RO Design]

File Analysis RO Design UF Treatment Calculation Graphs Help

Project: Arabian Gulf SWRO Calculated by: CRB Date: 02/02/07

pH	8.16	10.30	Membrane age	3.0	years	Chem type	
Temp	35.0	C	Chem dosing rate	0.0	ppm	Chem concentra	
Flux decline % per year		7.0		5.0	Feed water type	Seawater - open	
SP increase % per year		18.8		5.0	Permeate blending	<input type="checkbox"/>	
Product recovery, %		40.0		90.0	Concentrate recirc.	<input checked="" type="checkbox"/>	
Permeate flow	m3/d	13000.00		11000.00		11777.78	
Average flux rate	l/m2-hr	14.5		34.3	Recirculation flow		
Feed flow	m3/d	32500.0		12222.2	Permeate pressure		
Concentrate flow	m3/d	19500.0		1222.2			

Stage 1

System Specs		
Element type	SWC4+	
Elements/vessel	7	
Vessels	144	
Permeate Press	0	

Element type	ESPAB	ESPAB
Elements/vessel	6	6
Vessels	40	20
Permeate Press	2	0

Stage 1 Stage 2

1. Higher Recovery lowers pretreatment costs and saves raw water
2. Limited by scaling indices
3. Limited by Permeate Water Quality
4. Limited by feed pressure and energy optimization
5. Limited by minimum concentrate flow
6. Typical for second pass is 85 to 90%. Concentrate from 2nd reused as feed to the first pass.

Recovery Limitations: Scaling

Hydranautics (warnings in program)

Saturation Limits:

CaSO₄ 230 %

SrSO₄ 800 %

BaSO₄ 6000 %

SiO₂ 100 %

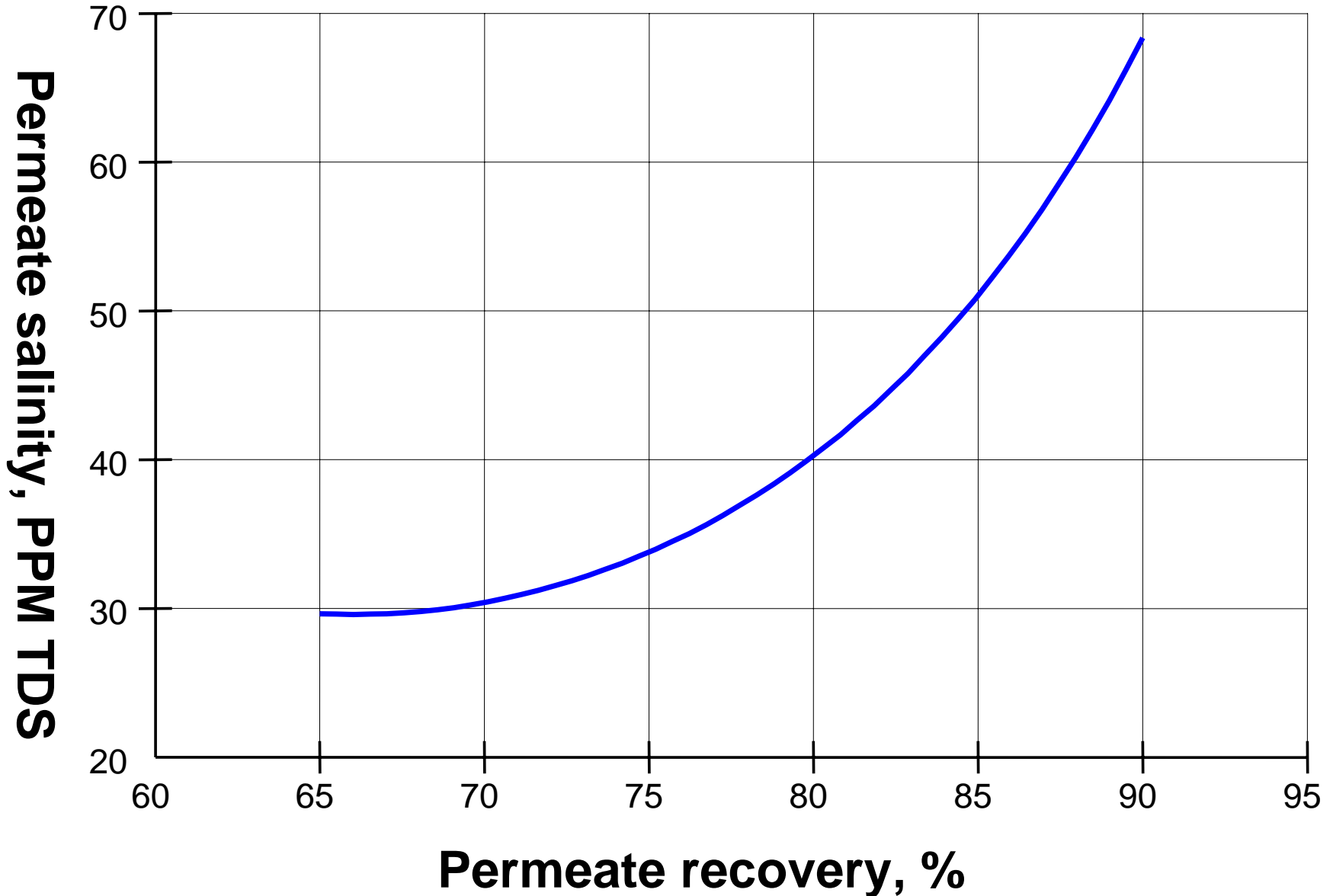
LSI <1.8 (Brackish Feed w. Scale Inhibitor)

Proprietary Chemicals (software provided by vendors)

	Product A	Product B
CaSO ₄	350%	250%
Sr ₂ SO ₄	3500%	3000%
Ba ₂ SO ₄	10500%	6500%
SiO ₂		240 mg/L
CaCO ₃	L.S.I. 3.0	L.S.I. 2.5
CaF ₂	1300000%	10000%

Brackish Water

Salinity vs recovery



Net Driving Pressure (NDP)

NDP - net driving pressure
Driving force of the water
transport (flux) through
the membrane.

$$\text{NDP} = P_f - \bar{P}_{os} - P_p - 0.5 * P_h \quad (+ \text{Permos})$$

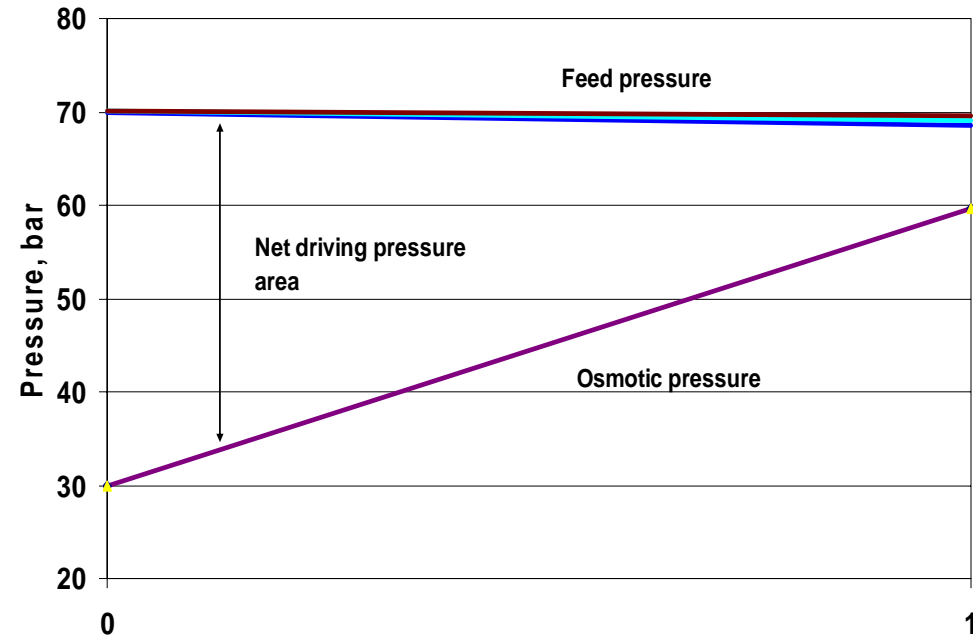
P_f - applied feed pressure

\bar{P}_{os} - osmotic pressure (Avg $F_d P_{os} - \text{Perm } P_{os}$)

P_p - permeate pressure

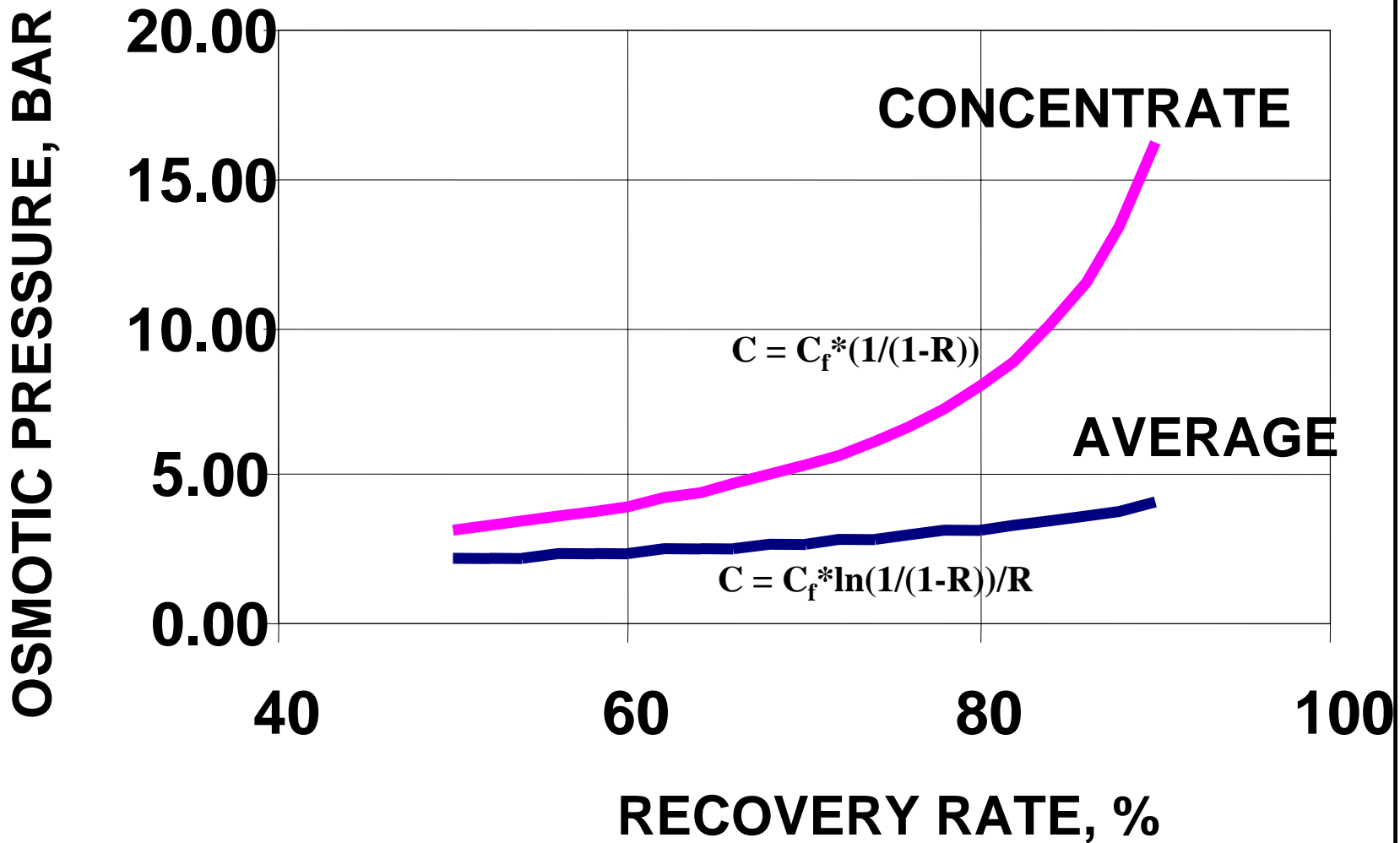
P_h - hydraulic pressure drop across RO element

Mediterranean seawater, 50% recovery



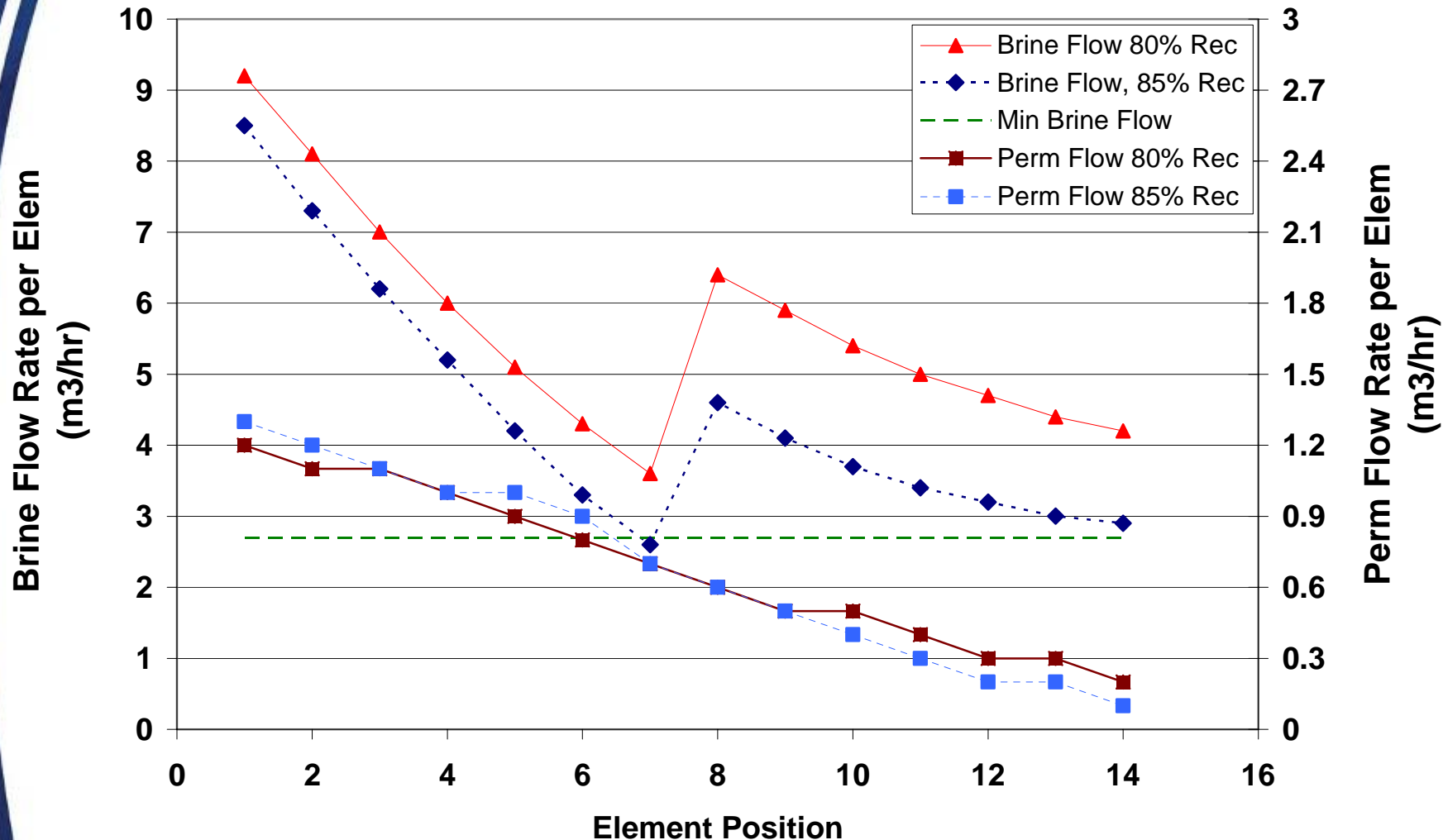
Pressure vessel length

EFFECT OF RECOVERY RATE



Effect of Recovery on Brine Flow

Flow per Element, Brackish Water
(ESPA2, 2100 mg/l TDS, 32 C, 21.4 l/mh)



Selecting Your Flux Rate

Hydraulics RO Projection Program - [RO Design]

File Analysis RO Design UF Treatment Calculation Graphs Help

Project	Arabian Gulf SWRO		Calculated by	CRB	Date	02/02/07
pH	8.16	10.30	Membrane age	3.0 years	Chem type	H2SO4
Temp	35.0	C	Chem dosing rate	0.0 ppm	Chem concentration	
Flux decline % per year		7.0		5.0	Feed water type	Seawater - open intake
SP increase % per year		10.0		5.0	Permeate blending	<input type="checkbox"/>
Product recovery, %		40.0		90.0	Concentrate recirc.	<input checked="" type="checkbox"/>
Permeate flow	m3/d	13098.00		11899.00		11777.78
Average flux rate	l/m2-hr	14.5		34.3	Recirculation flow	
Feed flow	m3/d	32500.0		12222.2	Permeate pressure	
Concentrate flow	m3/d	19500.0		1222.2		

1. Flux rate depends on feedwater type and degree of fouling potential

2. Lead element flux is critical when TOC or particle fouling is likely

3. Hybrid designs, 1st Stage Perm Back pressure, booster pumps can be used to balance flux

Stage 1

System Specs		
Element type	SWC4+	
Elements/vessel	7	
Vessels	144	
Permeate Press	0	
Element type	ESPAB	ESPAB
Elements/vessel	6	6
Vessels	40	20
Permeate Press	2	0

Stage 1 Stage 2

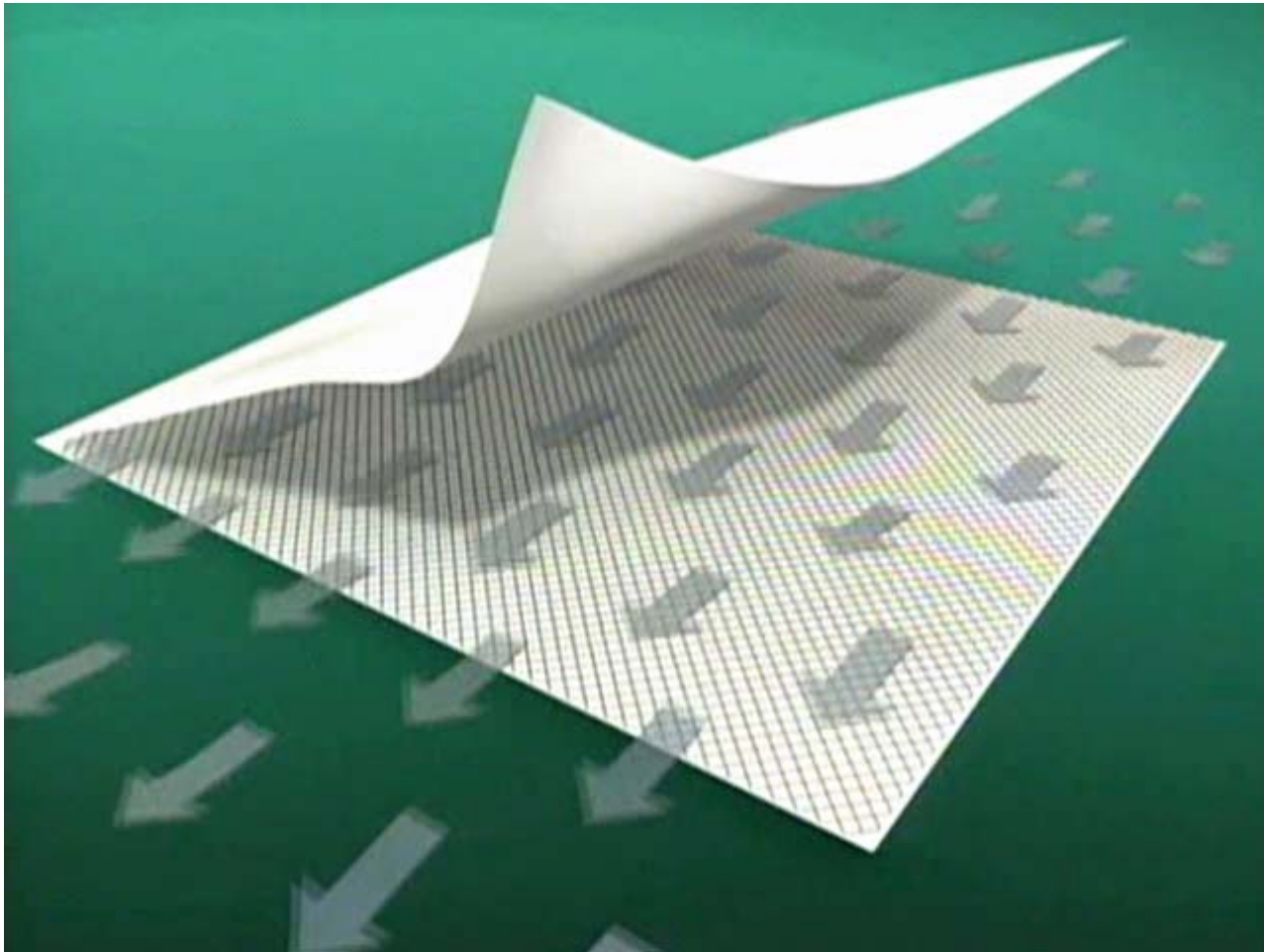
Stages Pass 1

Stages Pass 2

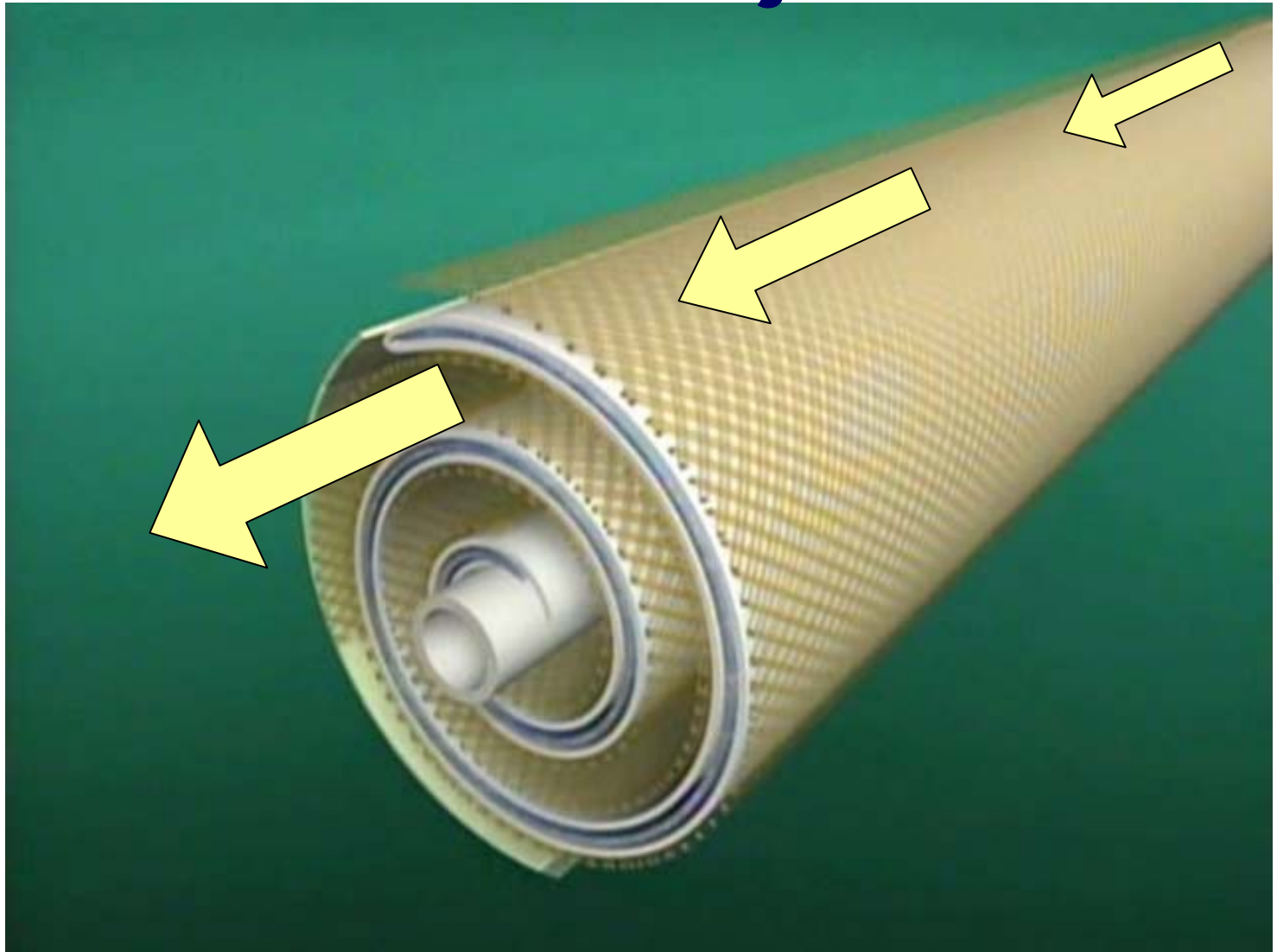
Recalc Array

AutoDisplay
 Summary Calc

Cross Flow in a Spiral Element Sheet



Cross Flow in A Spiral Wound Element Removes Rejected Material



Expected average raw water quality from well, surface intake and secondary effluent

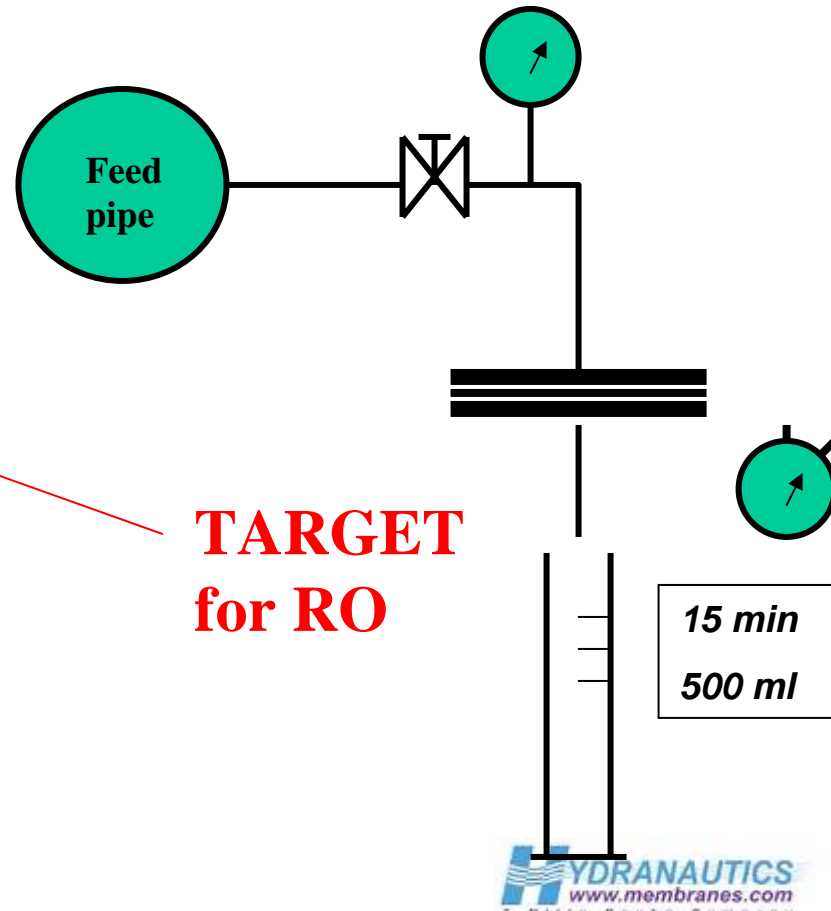
Quality parameter	Well water	Surface water (seawater)	Secondary effluent
Turbidity, NTU	<0.1	<2	<2
SDI	<2	6-12	6-12
Suspended solids, parts per ml	< 1	< 5	< 20
TOC, ppm	< 3	< 5	< 20
Scaling potential	Low to high	Low	Low (except in presence of high concentration of phosphate)

Particles and bacteria cause rapid fouling of RO membranes

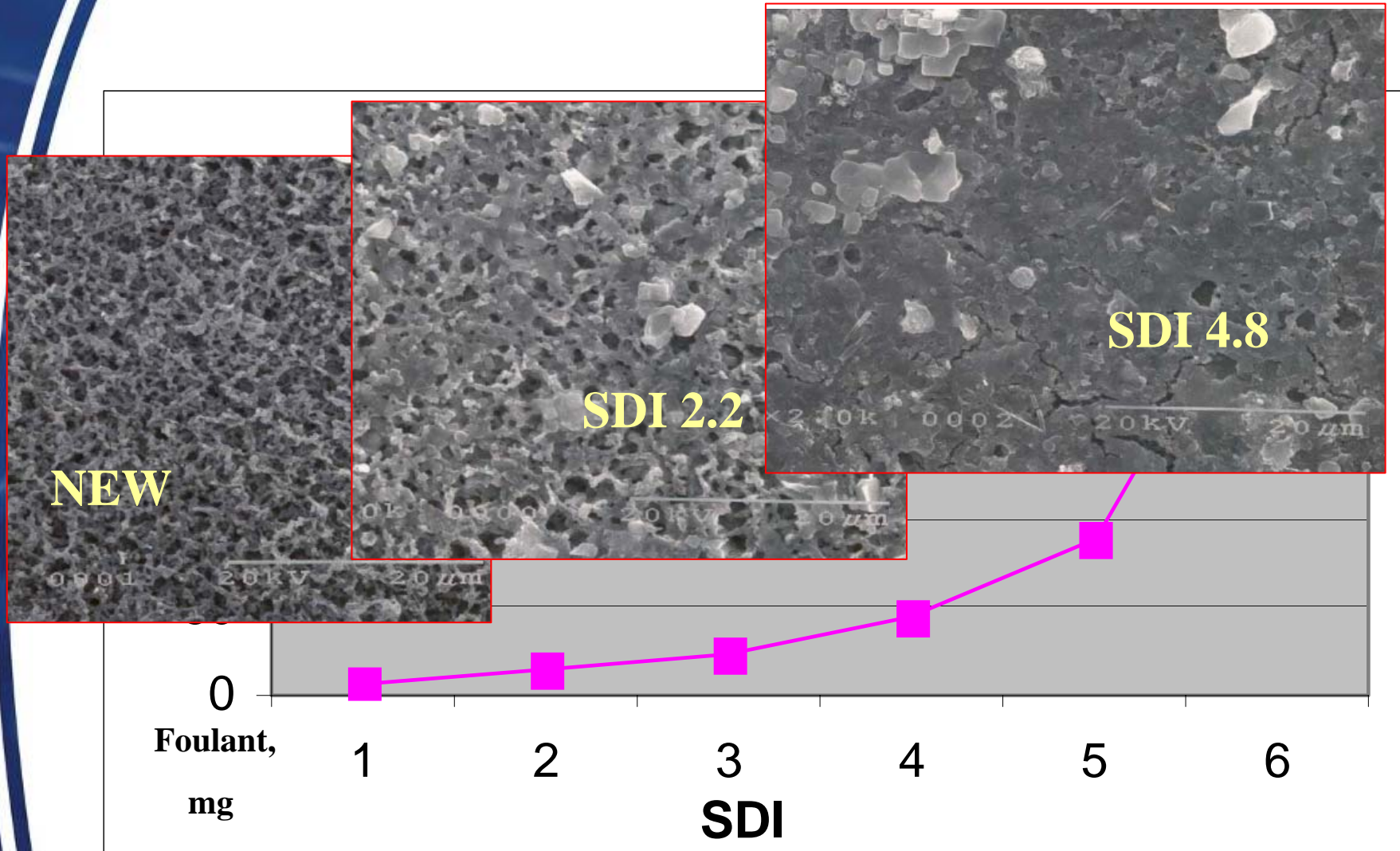
Measurement of Feedwater Quality for SWRO Plants: SDI

Silt Density index : $SDI = 100 * (1 - t_0/t_{15}) / 15$

t_0	t_{15}	SDI (15 min)
18	22	1.2
20	33	2.6
26	73	4.3
46	50	0.5 (?)



Amount of Foulant vs SDI



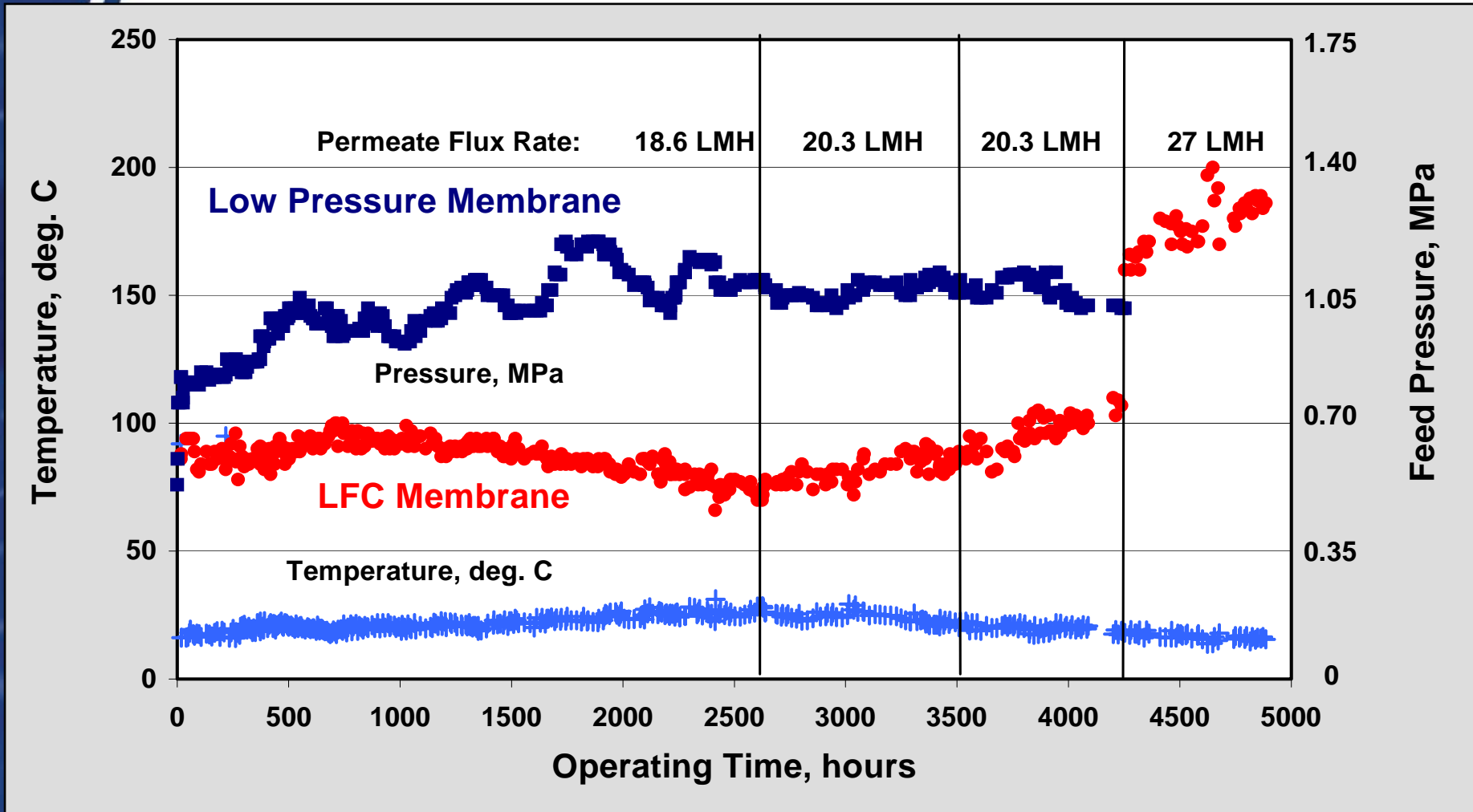
Flux Selection- Brackish, Good Quality

Raw Water source		RO Perm	Brackish Well	Brackish Surface	Brackish Surface
Pretreatment type		RO	Not Soft	Conv.	MF/UF
TOC content		Low	Low	Low	Low
Feedwater Parameters					
Recommended Maximum:					
SDI @ 15 minutes	Maximum	1	3	4	2
Turbidity as NTU	Typical	0.1	0.1	0.1	0.1
TOC ppm as C	Typical	2	2	2	2
BOD ppm as O ₂ (est. as TOC x 2.0)	Maximum	4	4	4	4
COD ppm as O ₂ (est. as TOC x 3.0)	Maximum	6	6	6	6
Particle Count (2um particles / ml)	Typical	100	100	100	100
System Average Flux (in LMH)					
	Conservative	30.6	23.8	17	23.8
	Typical	35.7	27.2	20.4	27.2
	Aggressive	40.8	30.6	23.8	30.6
Lead Element Flux (in LMH)					
	Conservative	49.3	35.7	25.5	30.6
	Typical	51	40.8	30.6	35.7
	Aggressive	59.5	45.9	35.7	40.8

Flux Selection- Brackish, Poor Quality

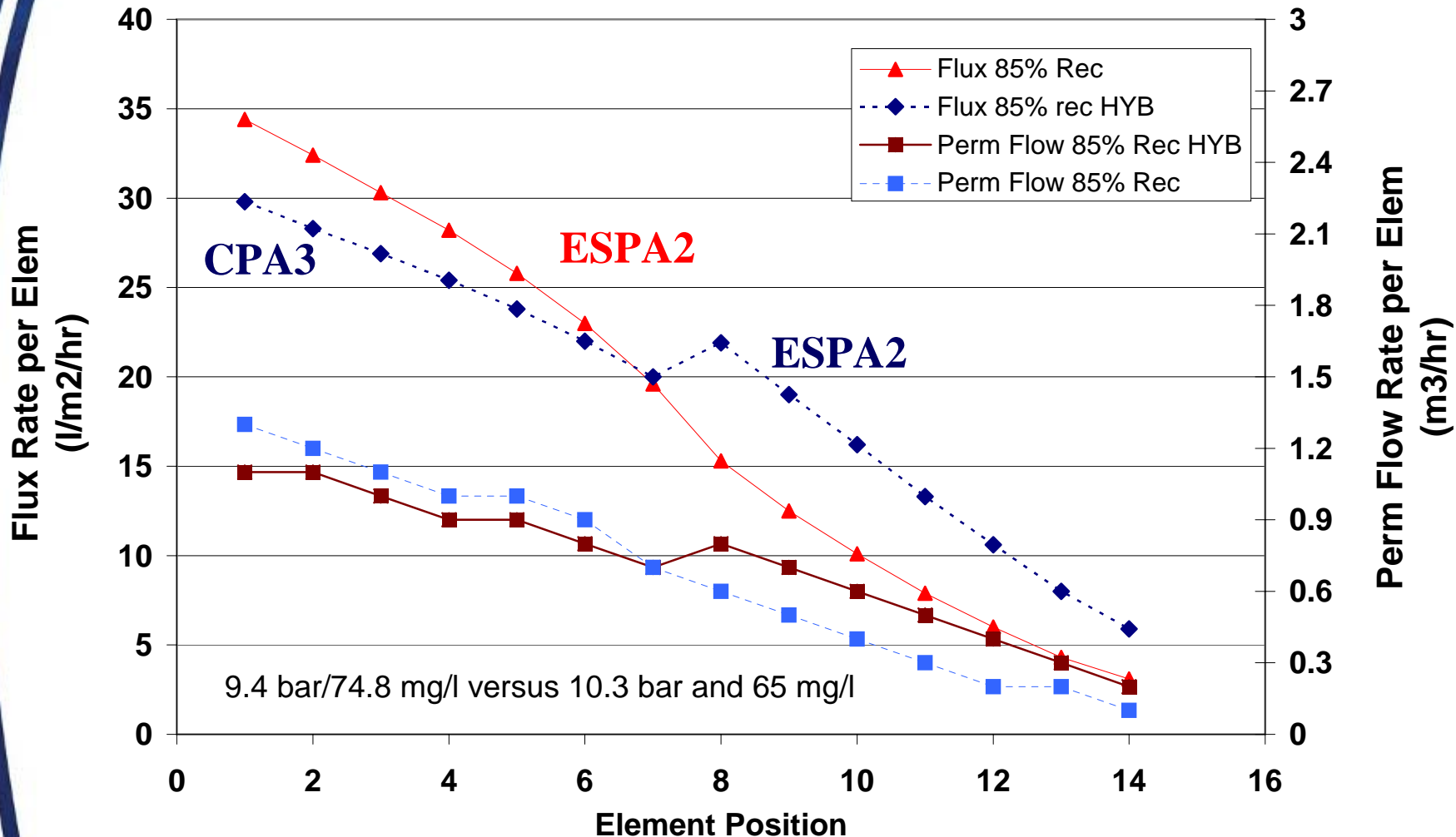
Raw Water source		Brackish Surface	Brackish Surface	Waste Tertiary	Waste Tertiary
Pretreatment type		Conv.	MF/UF	Conv.	MF/UF
TOC content		High	High	High	High
Feedwater Parameters					
Recommended Maximum:					
SDI @ 15 minutes	Maximum	4	2	4	2
Turbidity as NTU	Typical	0	0.1	0.1	0.1
TOC ppm as C	Typical	5	5	5	5
BOD ppm as O ₂ (est. as TOC x 2.0)	Maximum	0	10	10	10
COD ppm as O ₂ (est. as TOC x 3.0)	Maximum	0	15	15	15
Particle Count (2um particles / ml)	Typical	#	100	100	100
System Average Flux (in LMH)	Conservative	17	18.7	11.9	13.6
	Typical	18.7	23.8	17	18.7
	Aggressive	23.8	28.9	20.4	22.1
Lead Element Flux (in LMH)	Conservative	25.5	27.2	18.7	20.4
	Typical	30.6	32.3	25.5	27.2
	Aggressive	35.7	37.4	30.6	32.3

Increased Fouling Rate When Design Flux Rates are Exceeded



Hybrid Designs Balance Flux

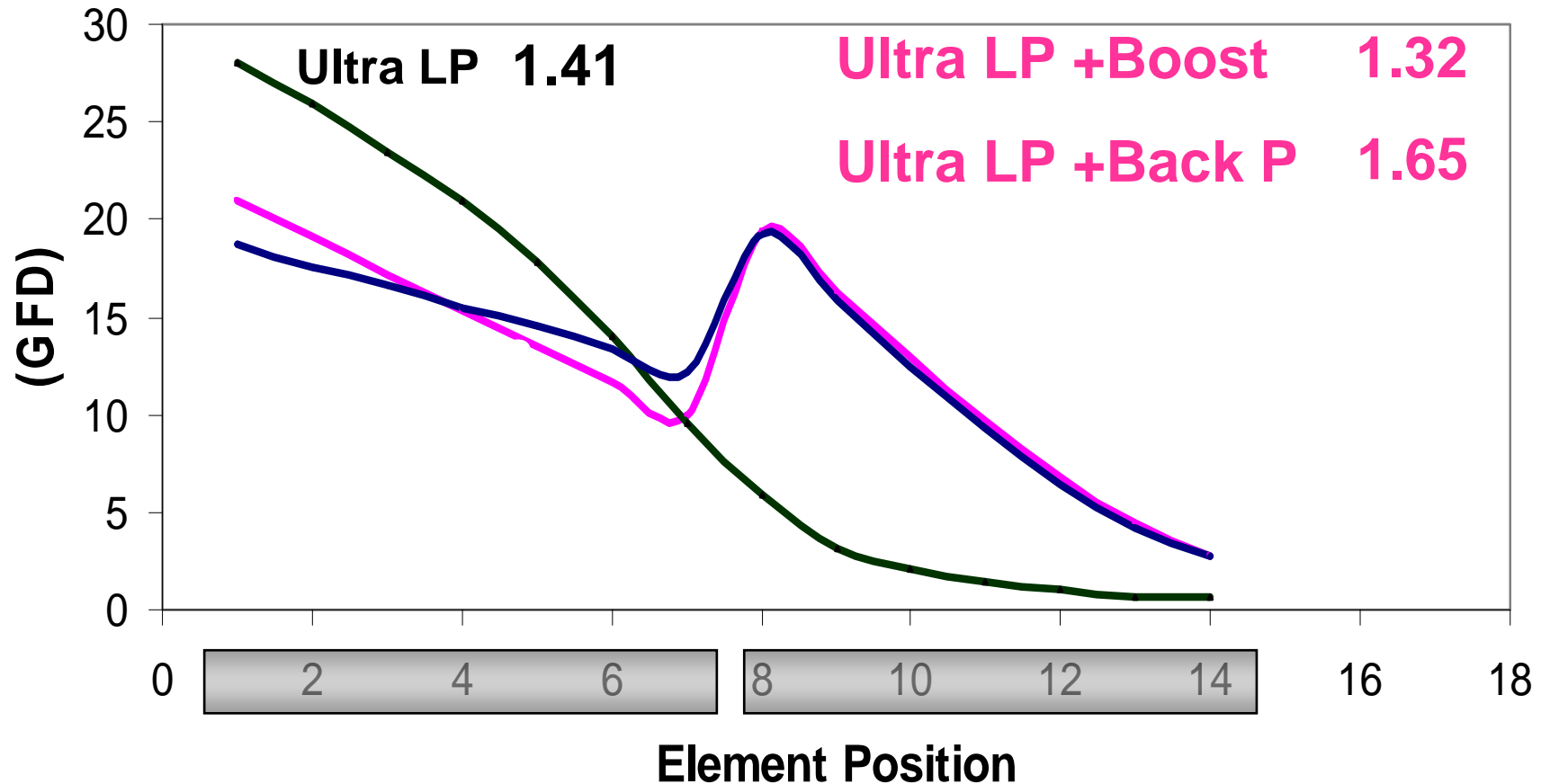
Flux and Flow per Element, Brackish Water
 (ESPA2 versus CPA3/ESPA2 HYBRID)
 2100 mg/l TDS, 32 C, 21.4 l/h



Options to Control Lead Elem Flux

LP 1.84
kWhr / kgal

Specific Power Consumption



Selecting Your Membrane

Hydraulics RO Projection Program - [RO Design]

File Analysis RO Design UF Treatment Calculation Graphs Help

Project: Arabian Gulf SWRO Calculated by: CRB Date: 02/02/07

pH: 8.16, 10.30 Membrane age: 3.0 years Chem type: H2SO4

Temp: 35.0 C Chem dosing rate: 0.0 ppm Chem concentration, %: 98

Flux decline % per year: 7.0, 5.0 Feed water type: Seawater - open intake

SP increase % per year: 10.0, 5.0 Permeate blending: Permeate throttling:

Product recovery, %: 40.0, 90.0 Concentrate recirc.: Booster pump:

Permeate flow: m3/d, 13000.00, 11000.00 Recirculation flow: 11777.78 Split Partial:

Average flux rate: l/m2-hr, 14.5, 34.3 Permeate pressure: 0.0 bar, Variable

Feed flow: m3/d, 32500.0, 12222.2

Concentrate flow: m3/d, 19500.0, 1222.2

System Specs

Stage 1

Element type: SWC4+ (circled)

Elements/vessel: 7

Vessels: 144

Permeate Press: 0

Stage 2

Element type: ESPAB

Elements/vessel: 6

Vessels: 40

Permeate Press: 2

Stages Pass 1: 1

Stages Pass 2: 2

Recalc Array

Recalc Array

Passes: 2

InterPass pump:

Run

Print

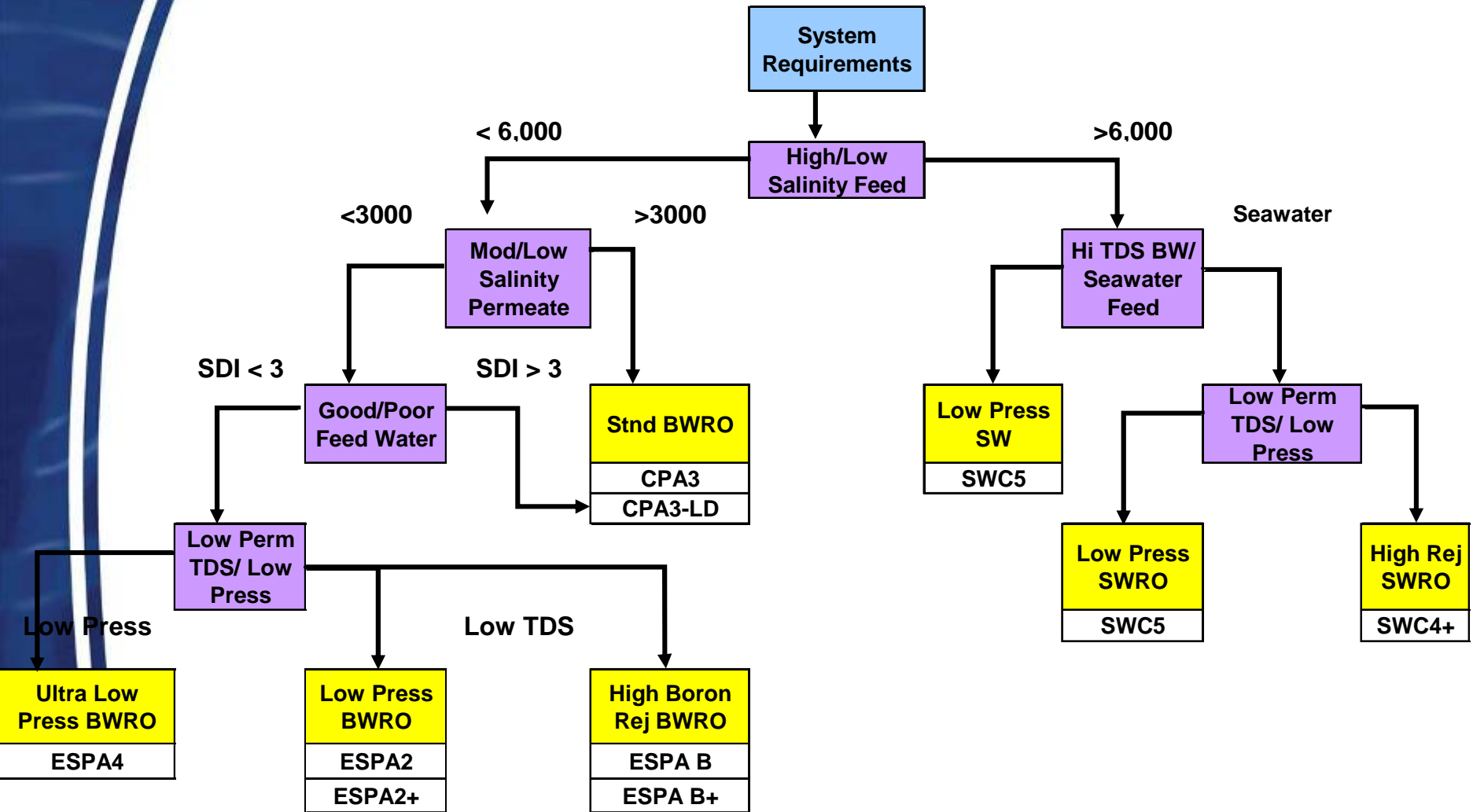
Flow diag.

AutoDisplay

Summary Calc

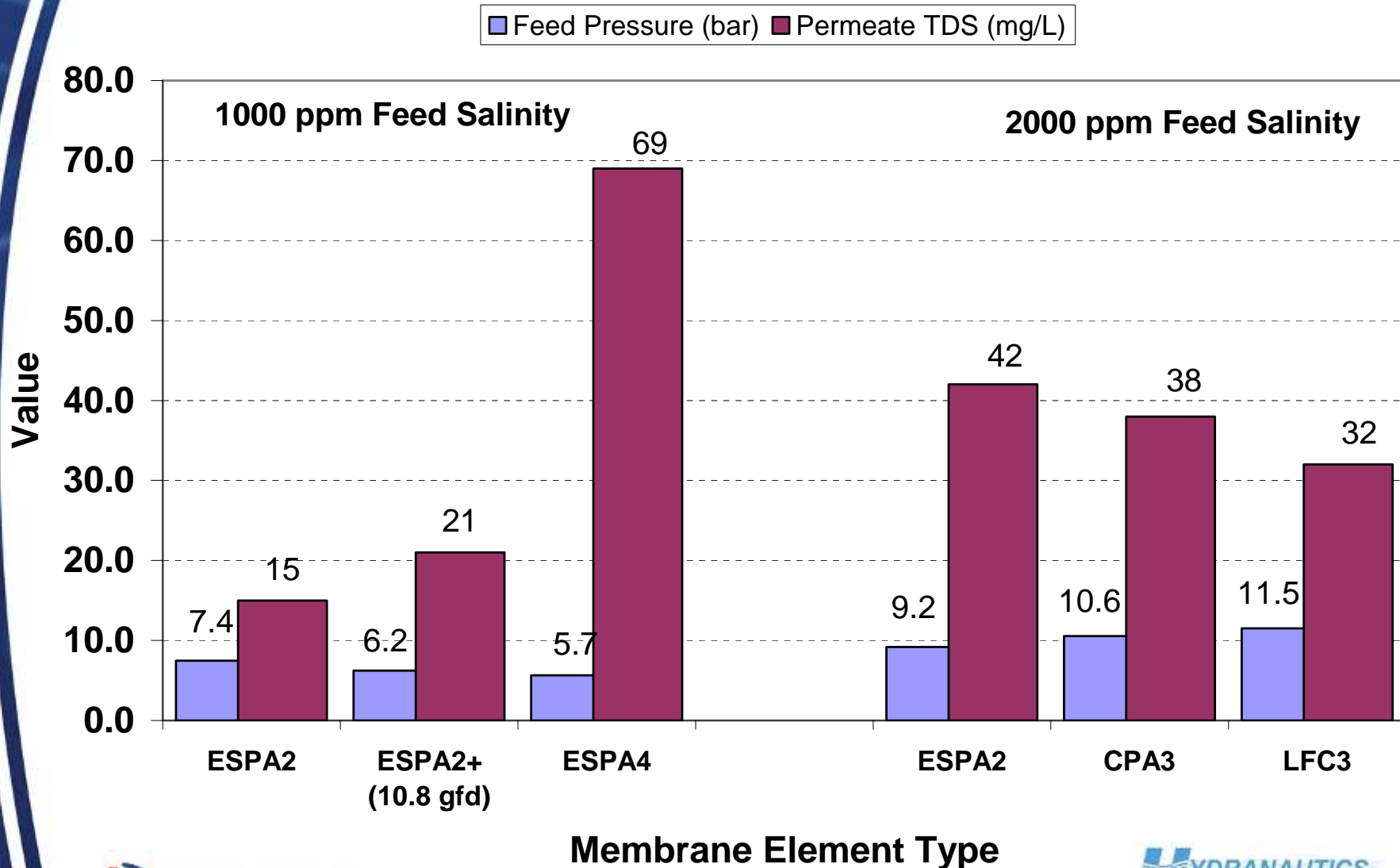
1. Low pressure versus low permeate TDS
2. Select Elements that meet permeate quality, then optimize for pressure
3. NF Membranes

Membrane Selection Logic



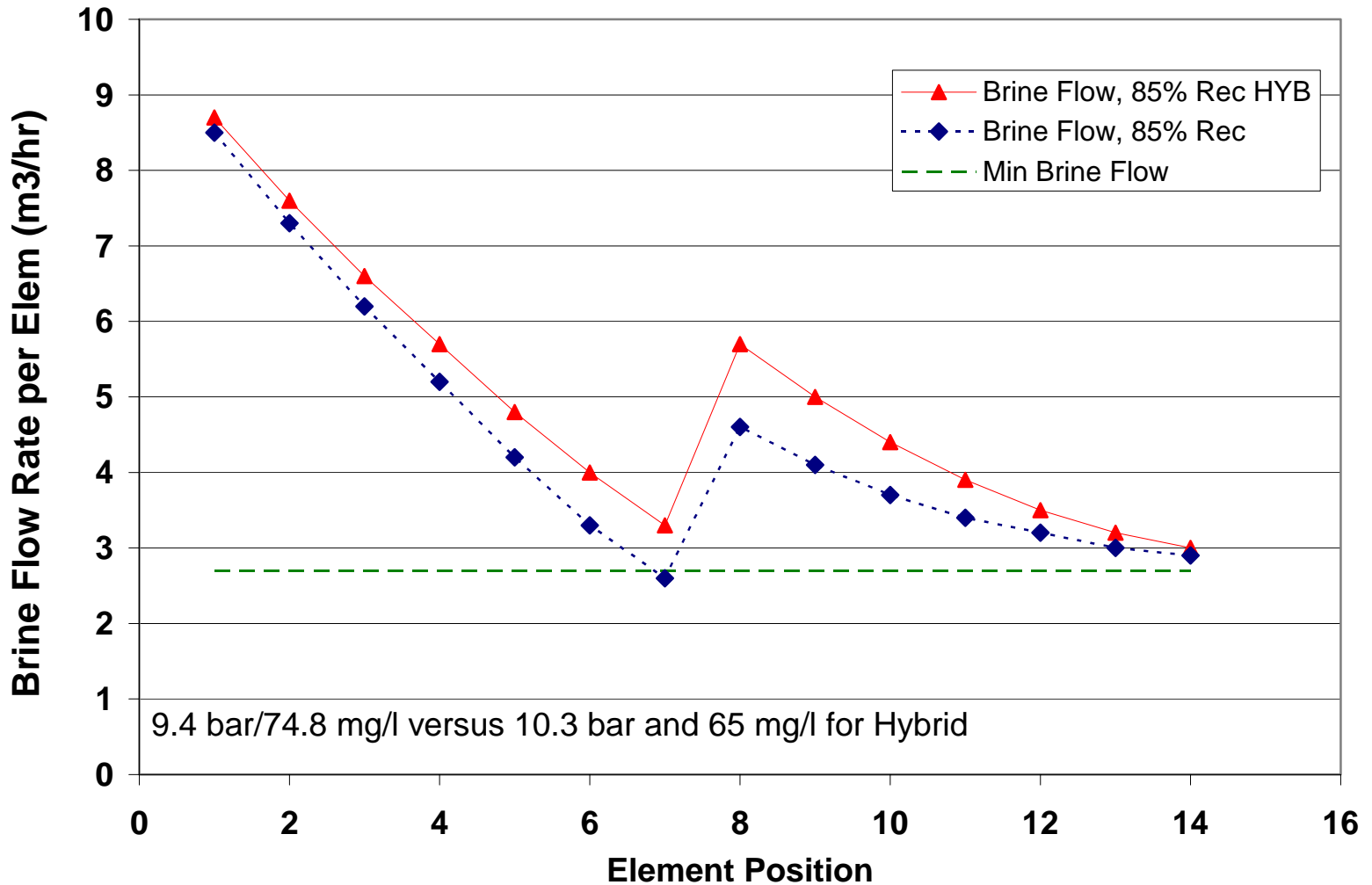
Selection of Brackish Water Membranes

Comparative Performance of Hydranautics Products
(75% recovery, 25 deg C, 12 gfd flux)



Hybrid Element Designs

Flow per Element, Brackish Water
(ESPA2 versus CPA3/ESPA2 HYBRID
2100 mg/l TDS, 32 C, 21.4 l/mh)



Selecting Number of Vessels and Vessel Size

Hydraulics RO Projection Program - [RO Design]

File Analysis RO Design UF Treatment Calculation Graphs Help

Project: Arabian Gulf SWRO Calculated by: CRB Date: 02/02/07

pH	8.16	10.30	Membrane age	3.0	years	Chem type	H2SO4
Temp	35.0	C	Chem dosing rate	0.0	ppm	Chem concentration, %	98

Flux decline % per year: 7.0 5.0
SP increase % per year: 10.0 5.0
Product recovery, %: 40.0 90.0
Permeate flow: m3/d 13000.00 11000.00
Average flux rate: l/m2-hr 14.5 34.3
Feed flow: m3/d 32500.0 12222.2
Concentrate flow: m3/d 19500.0 1222.2

Feed water type: Seawater - open intake
Permeate blending: Permeate throttling:
Concentrate recirc.: Booster pump:
Recirculation flow: 11777.78
Permeate pressure: 0.0 bar Variable

Passes: 2
InterPass pump:

Run
Print
Flow diag.

AutoDisplay
Summary Calc

Stage 1

System Specs
Element type: SWC4+
Elements/vessel: 7
Vessels: 144
Permeate Press: 0

Stages Pass 1: 1
Recalc Array

Element type: ESPAB ESPAB
Elements/vessel: 6 6
Vessels: 40 20
Permeate Press: 2 0

Stages Pass 2: 2
Recalc Array

Stage 1 Stage 2

1. 6-8 Elements per vessel is common
2. Array is chosen to meet operation flexibility and practical size limits. 10-15 MLD current largest train size

Stages and Passes

Hydranautics RO Projection Program - [RO Design]

1. Minimize stages to reduce dP and piping costs
2. One pass treatment with high rej membrane more economical than two passes with moderate rejection elements
3. More stages and/or passes allow greater system flexibility

The screenshot shows the Hydranautics RO Projection Program interface. At the top, there is a menu bar with 'File', 'Analysis', 'Design', 'Calculation', 'Graphs', and 'Help'. Below the menu bar, there are several input fields and controls:

- Project Name:** CRB
- Date:** 02/02/07
- Chem type:** H2SO4
- Chem concentration, %:** 98
- Feed water type:** Seawater - open intake
- Permeate blending:**
- Permeate throttling:**
- Concentrate recirc.:**
- Booster pump:**
- Split Partial:**
- Recirculation flow:** 0.0 m3/d
- Permeate pressure:** 0.0 bar, Variable
- Passes:** 2
- InterPass pump:**
- Stages Pass 1:** 1
- Stages Pass 2:** 2
- Recalc Array** buttons for both Stage 1 and Stage 2.
- Buttons:** Run, Print, Flow diagr.
- Checkboxes:** AutoDisplay, Summary Calc.

At the bottom, there is a table for element specifications:

Element type	Stage 1	Stage 2
Element type	ESPAB	ESPAB
Elements/vessel	6	6
Vessels	40	20
Permeate Press	2	0

Comparison of 1 Pass and 2 Pass Approaches to Same Design

Array, first pass	4:2(7M)	6(7M)
Element type, first pass	ESPA2	SWC3+
Array, second pass	1:1 (5M)	
Element type, second pass	ESPA2	
Feed pressure, first pass, psi	573	776
Interstage booster, first pass, psi	200	
Feed pressure, second pass, psi	214	
Combined recovery rate, %	47.9	47.9
Permeate flow, m ³ /hr	19.2	19.2
Power consumption, 1 st pass, kWhr	41.4	42.9
Power consumption, 2 nd pass, kWhr	7.9	
Total power consumption, kWhr	49.3	42.9
Power consumption, kWhr/m ³	2.57	2.24

pH Adjustment

Hydranautics RO Projection Program - [RO Design]

File Analysis RO Design UF Treatment Calculation Graphs Help

Project: Arabian Gulf SWRO Calculated by: CRB Date: 02/02/07

pH	8.16	10.30	Membrane age	3.0	years	Chem type	H2SO4	
Temp	35.0	C	Chem dosing rate	0.0	ppm	Chem concentration	38	
Flux decline % per year				7.0		5.0	Feed water type	Seawater
SP increase % per year				10.0		5.0	Permeate blending	<input type="checkbox"/>
Product recovery, %				40.0		90.0	Concentrate recirc.	<input checked="" type="checkbox"/>
Permeate flow	m3/d			13000.00		11000.00		11777.78
Average flux rate	l/m2-hr			14.5		34.3	Recirculation flow	
Feed flow	m3/d			32500.0		12222.2	Permeate pressure	0.0
Concentrate flow	m3/d			19500.0		1222.2		

System Specs

Stage 1

Element type	SWC4+	
Elements/vessel	7	
Vessels	144	
Permeate Press	0	

Stage 2

Element type	ESPAB	ESPAB
Elements/vessel	6	6
Vessels	40	20
Permeate Press	2	0

Stages Pass 1 Recalc Array

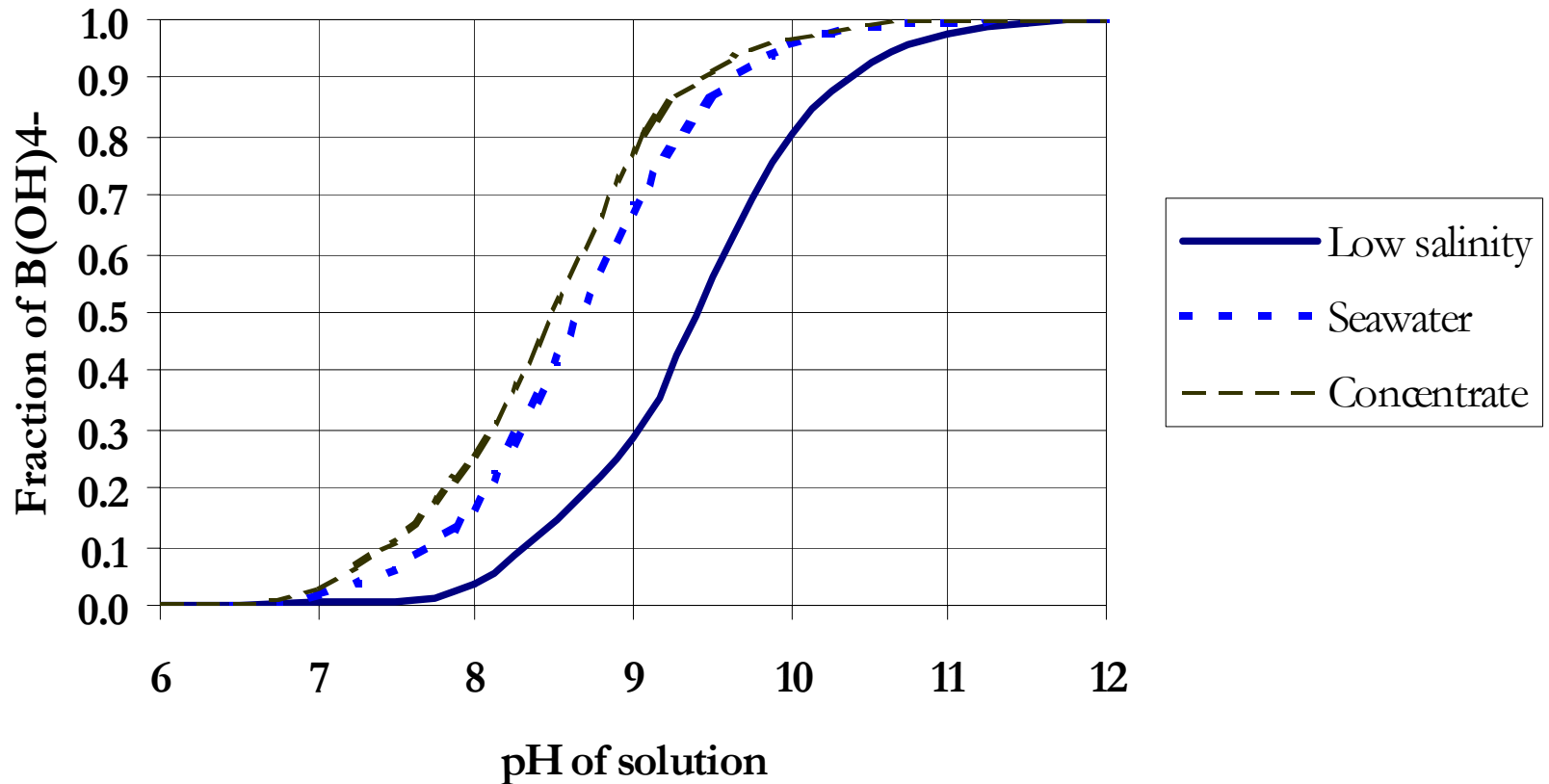
Stages Pass 2 Recalc Array

AutoDisplay
 Summary Calc

1. Lower pH to increase solubility of calcium carbonate or calcium phosphate
2. Increase pH to increase rejection of boron and silica rejection
3. Increase pH to increase solubility of certain organics and silica

Effect of Feed pH on Boric Acid Dissociation

Boron species distribution at 25 C



Conclusions

- Long term experience with RO systems has resulted in optimized performance
- Detailed consideration of all design parameters is necessary to optimize the system performance
- Advances in membrane technology and process design have led to a steady decline in energy consumption and system cost
- Sound operation of RO process should result in 5-8 years of membrane life



THANK YOU