Reverse Osmosis/Nanofiltration Membranes 101

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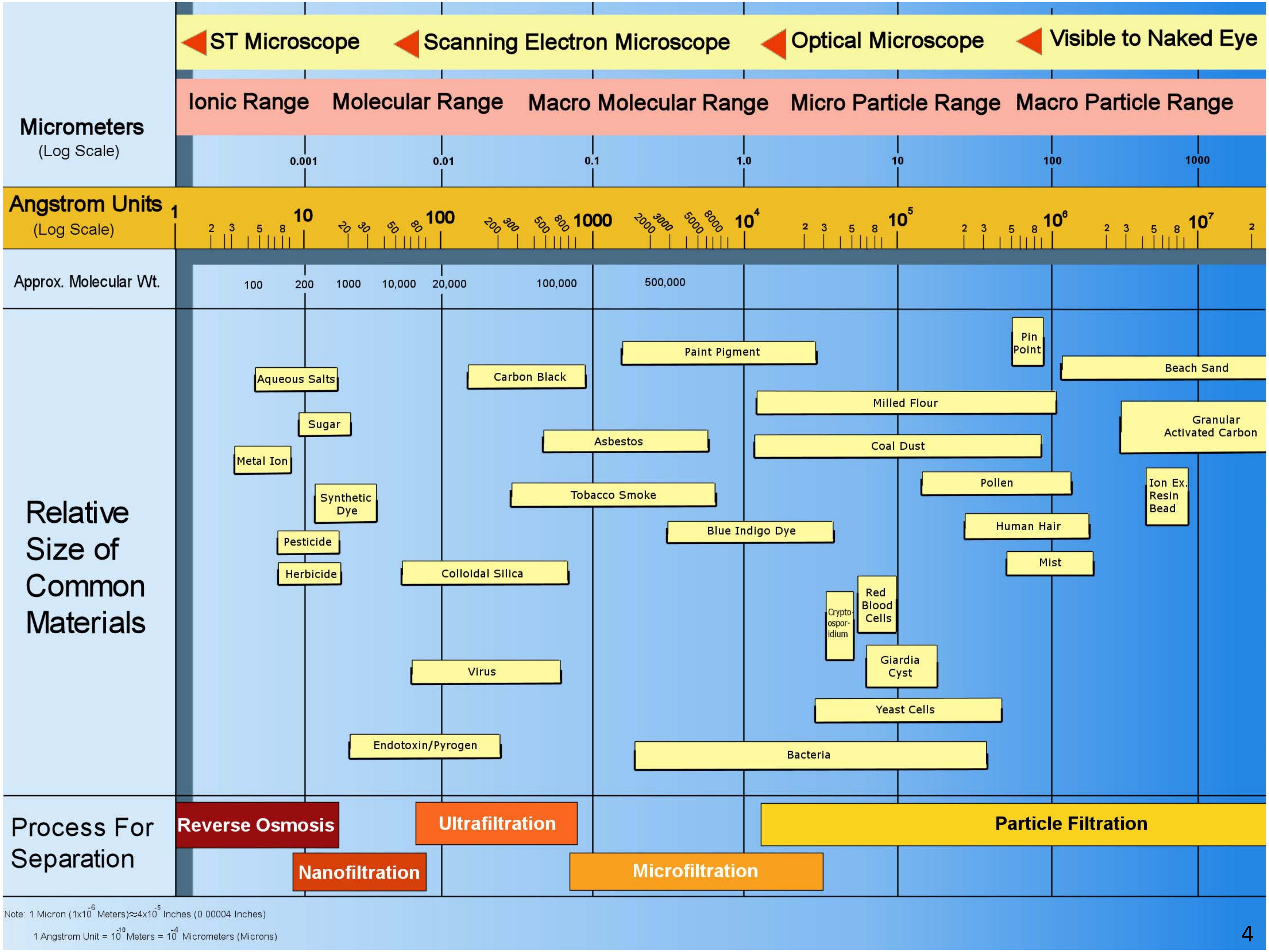
Morning Agenda

I. Introduction to RO / NF
II. Membranes and Modules
III. RO Theory
IV. Operation
V. Monitoring & Optimization

INTRODUCTION TO RO / NF


ST Microscope
Scanning Electron Microscope
Optical Microscope
Visible to Naked Eye
Ionic Range
Molecular Range
Macro Molecular Range
Micro Particle Range
Macro Particle Range
Micrometers (Log Scale)
0.001
0.01
0.1
1.0
10
100
1000
Angstrom Units (Log Scale)
1 2 3 5 8 10 20 30 50 80 100 200 300 500 800 1000 2000 3000 5000 8000 10^4 2 3 5 8 10^5 2 3 5 8 10^6 2 3 5 8 10^7 2
Approx. Molecular Wt.
100 200 1000 10,000 20,000 100,000 500,000
Relative Size of Common Materials
Aqueous Salts
Sugar
Metal Ion
Synthetic Dye
Pesticide
Herbicide
Carbon Black
Asbestos
Tobacco Smoke
Colloidal Silica
Virus
Endotoxin/Pyrogen
Paint Pigment
Blue Indigo Dye
Milled Flour
Coal Dust
Pollen
Human Hair
Mist
Pin Point
Beach Sand
Granular Activated Carbon
Ion Ex. Resin Bead
Crypto-ospor-idium
Red Blood Cells
Giardia Cyst
Yeast Cells
Bacteria
Process For Separation
Reverse Osmosis
Nanofiltration
Ultrafiltration
Microfiltration
Particle Filtration
Note: 1 Micron (1x10^-6 Meters)≈4x10^-5 Inches (0.00004 Inches)
1 Angstrom Unit = 10^-10 Meters = 10^-4 Micrometers (Microns)

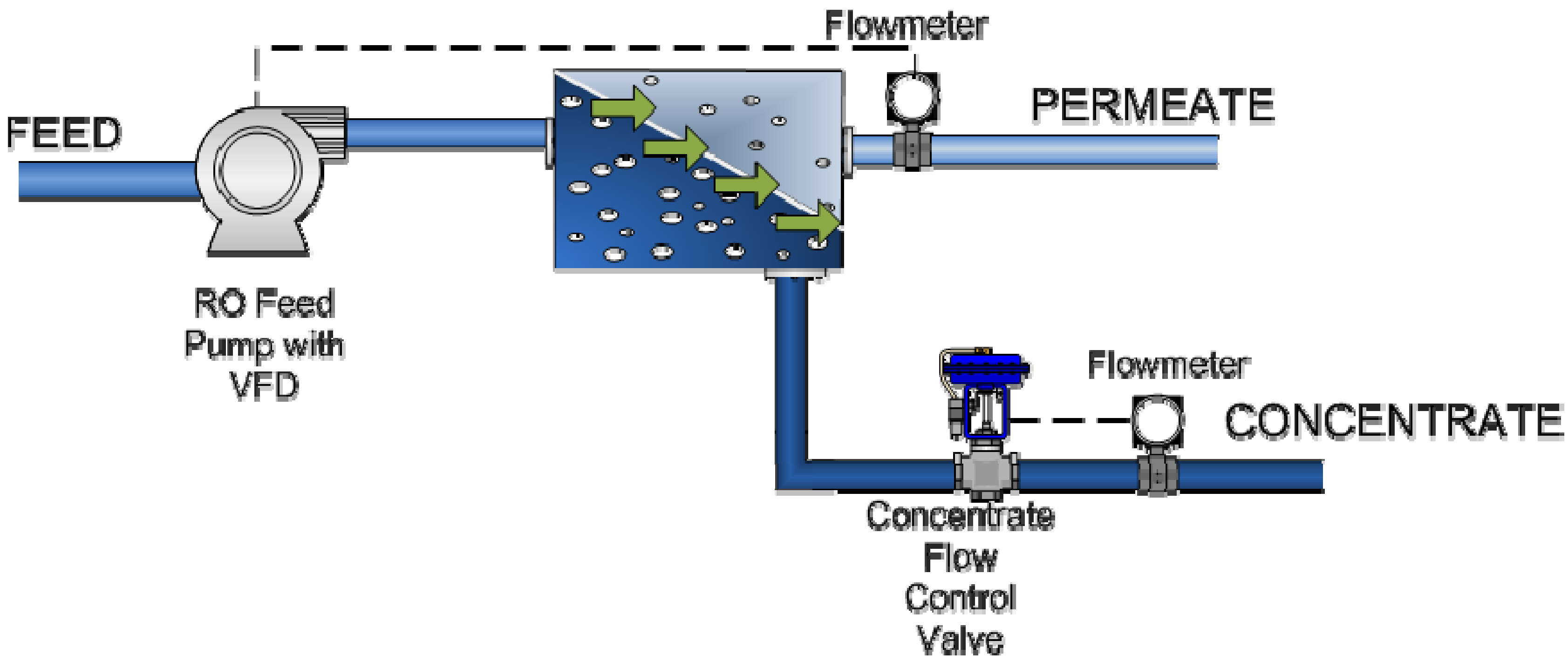
RO and Nanofiltration (NF) Defined

- RO and NF are separation processes that produce purified water (permeate) and reject (concentrate) from a feed stream
- Water under pressure flows through a semi-permeable membrane, while salt is retained and concentrated on the feed side
- The difference between RO and NF is in the membrane rejection
  - RO removes nearly all dissolved ions
  - NF removes color and primarily divalent/multivalent ions (calcium, magnesium, arsenic and sulfate)

RO and Nanofiltration (NF) Applications

- RO - TDS Reduction
  - Potable water
  - Waste reclamation, volume reduction
  - Ultrapure water - Boiler Feed, Electronics Mfg, WFI
- NF - Selective Removal of Low MW Components
  - Color and organic removal
  - Softening (hardness removal)

RO Process Diagram



Reverse Osmosis Terminology

Permeate = Water passing through membrane

Concentrate = Water <u>not</u> passing through membrane

Feed = Total feed to RO (Permeate + Concentrate)

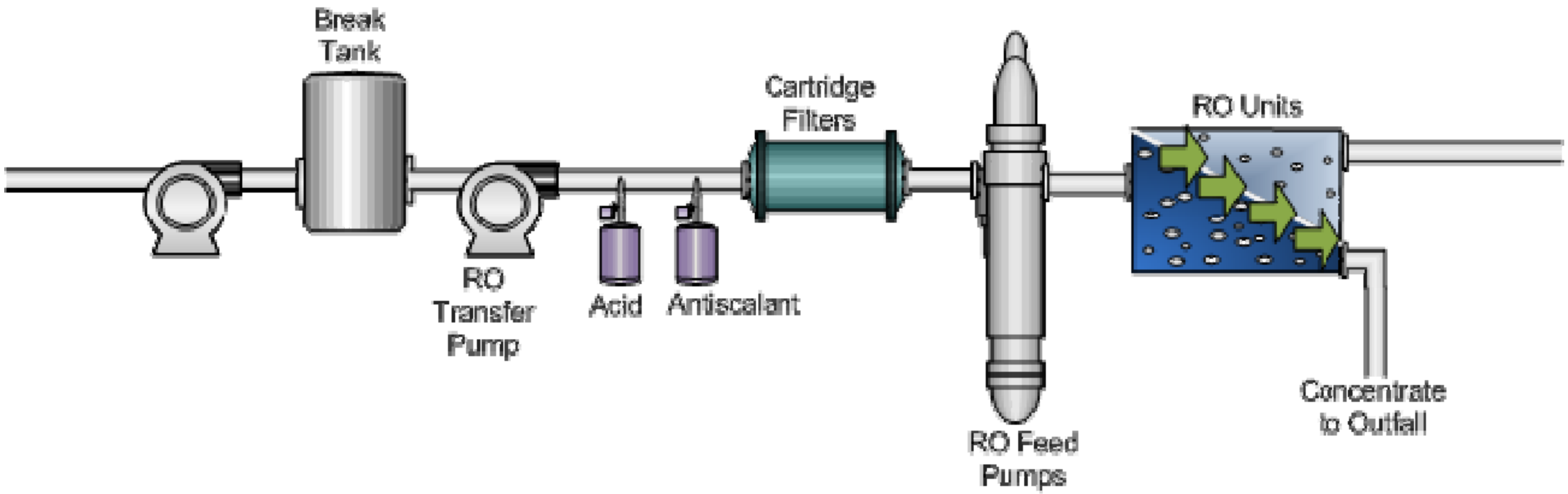
Recovery = Water Recovery (%)

Rejection = Salt Rejection (%)

Reverse Osmosis and Nanofiltration

- The amount of water that can be recovered is limited by chemistry & hydraulics
- Two strategies to increase recovery
  - Addition of acid increases solubility of some scale forming compounds ($CaCO_3$ and $CaPO_4$)
  - Scale Inhibitors to delay or stop formation of scale on the membrane
- RO/NF membranes have important limitations
  - The feed must be essentially free of particles
  - The membrane must not be exposed to strong oxidants (free chlorine, permanganate)
- Staging of membrane elements maintains crossflow velocities within acceptable ranges

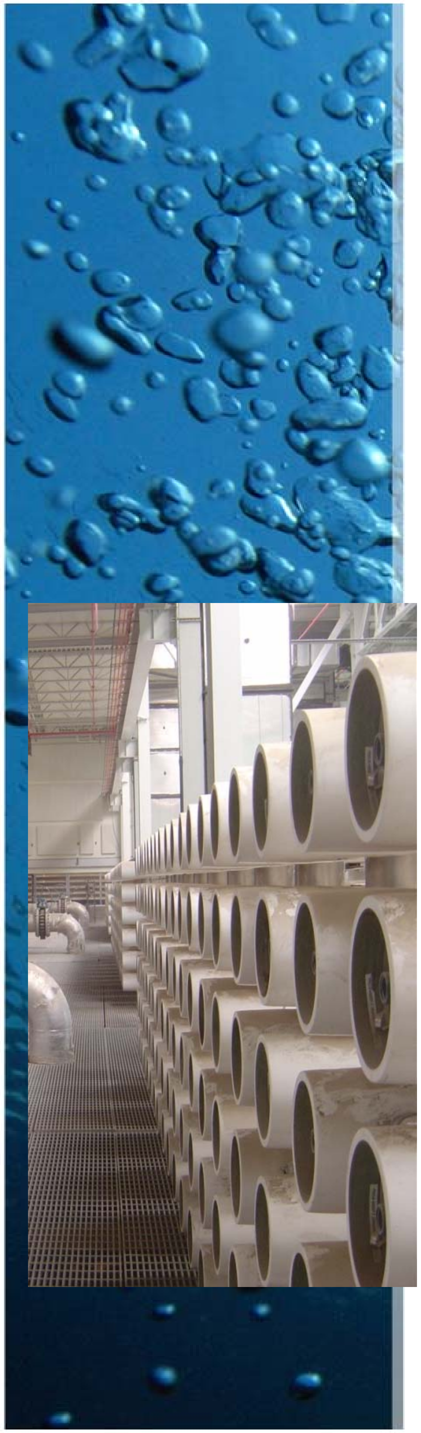
Typical RO System



Reverse Osmosis Trains

5 MGD Train

RO / NF
MEMBRANES & MODULES



RO/NF Process – Overview

- Pressure driven process using membranes
- Purpose: removal of dissolved solids
- RO is one of the few methods that removes dissolved salts
  - Ion exchange, which uses expensive regeneration chemicals
  - Thermal processes which use more energy than modern RO technologies
- NF removes color at lower pressure/energy than RO where high TDS is not a concern

RO /NF Membranes

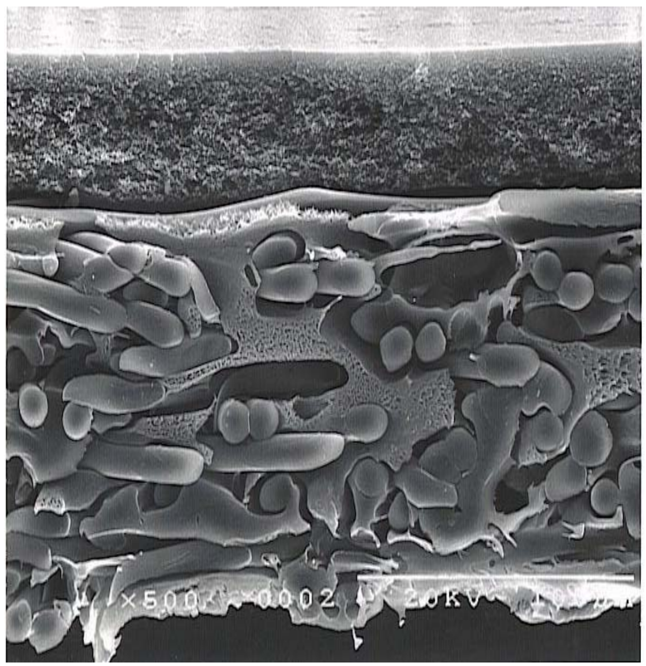
- Membranes are non-porous
- Water and salt passage through the RO membranes are by two different mechanisms (pressure and diffusion)
- Almost universal is the use of flat sheet membrane assembled in spiral wound elements

Thin Film Composite Membrane Cross Section

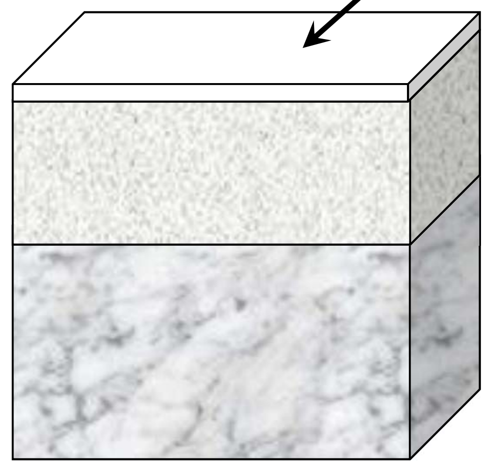
Polyamide
0.04 - 0.1 microns

Polysulfone
75 - 100 microns

Polyester Fabric
2000 microns



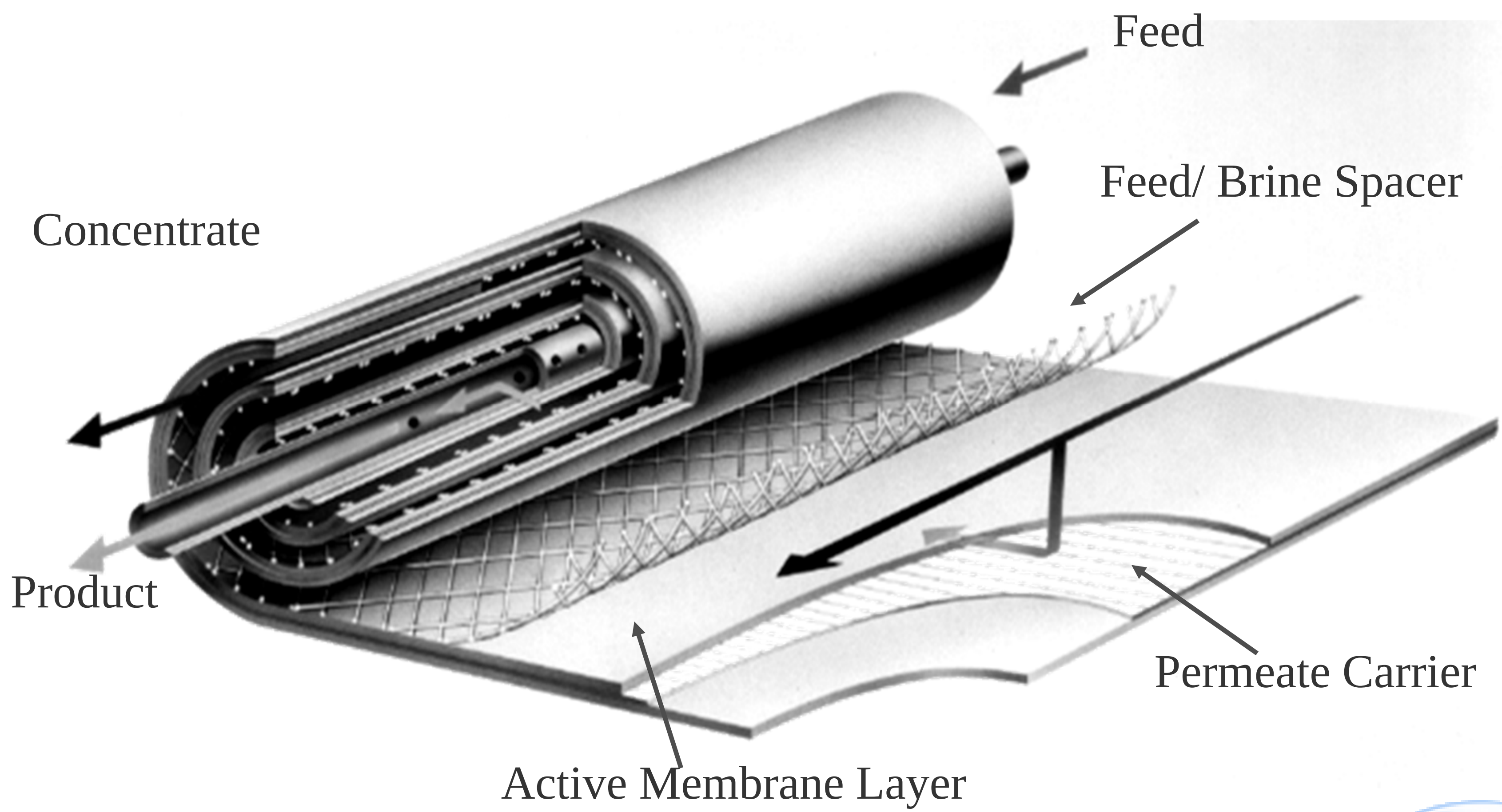
Membrane surface



Thin Film Composite Membrane Characteristics

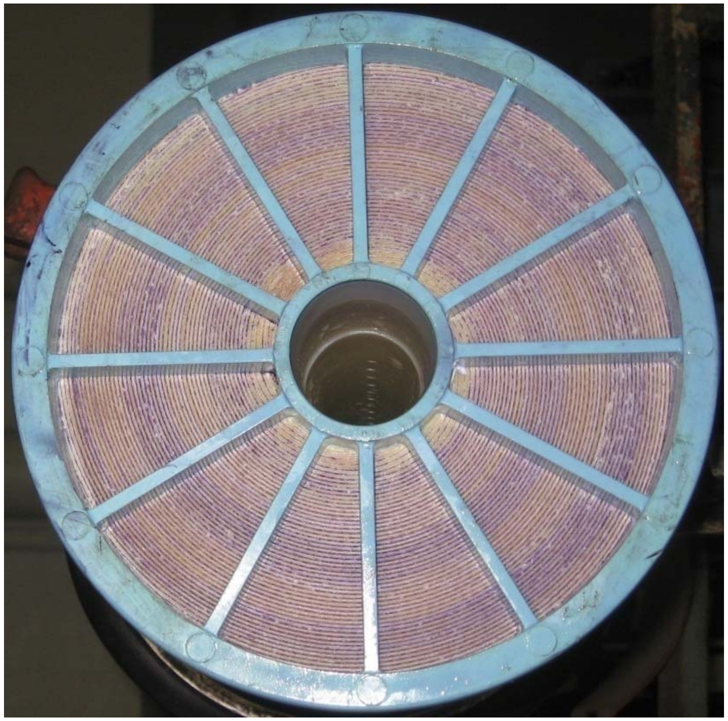
Characteristic	Reverse Osmosis	Nanofiltration
Operating Pressure	100 - 300 psi	50 - 150 psi
NaCl Rejection	up to 99.8%	20% to 70% 99.7% $MgSO_4$ & color removal
pH Tolerance Range	2 - 10	3 - 9
Temperature	113°F Max	113°F Max
Oxidant Sensitivity	All Sensitive to Oxidants Some tolerance to Chloramine	PES (not TFC) Tolerant to Free Chlorine

Spiral Wound Element

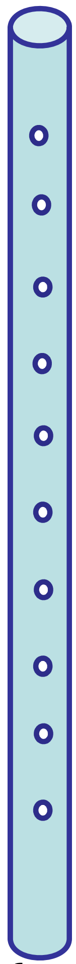


RO Membrane Element Construction

Spiral Wound Membrane Elements

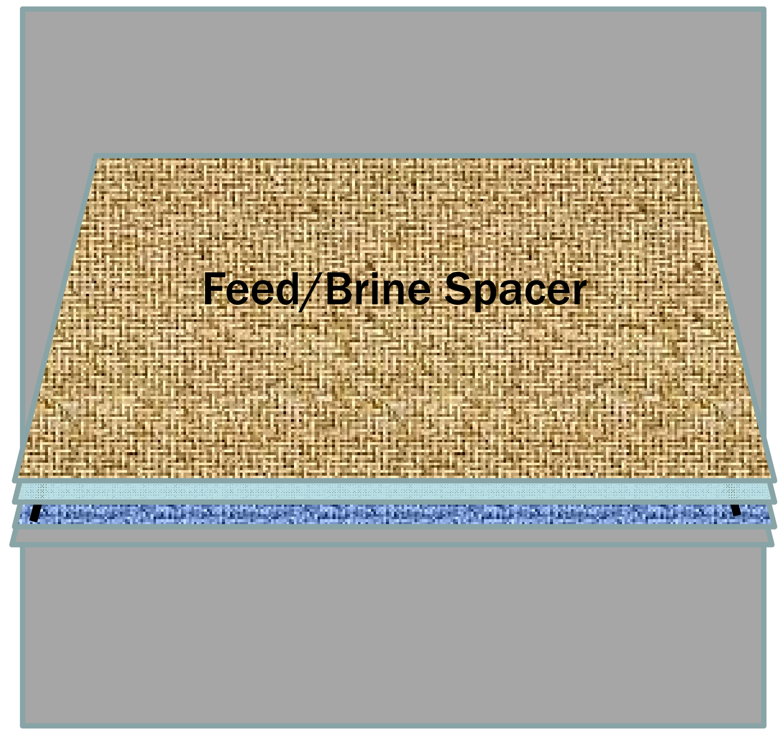


Making a Spiral Wound Element



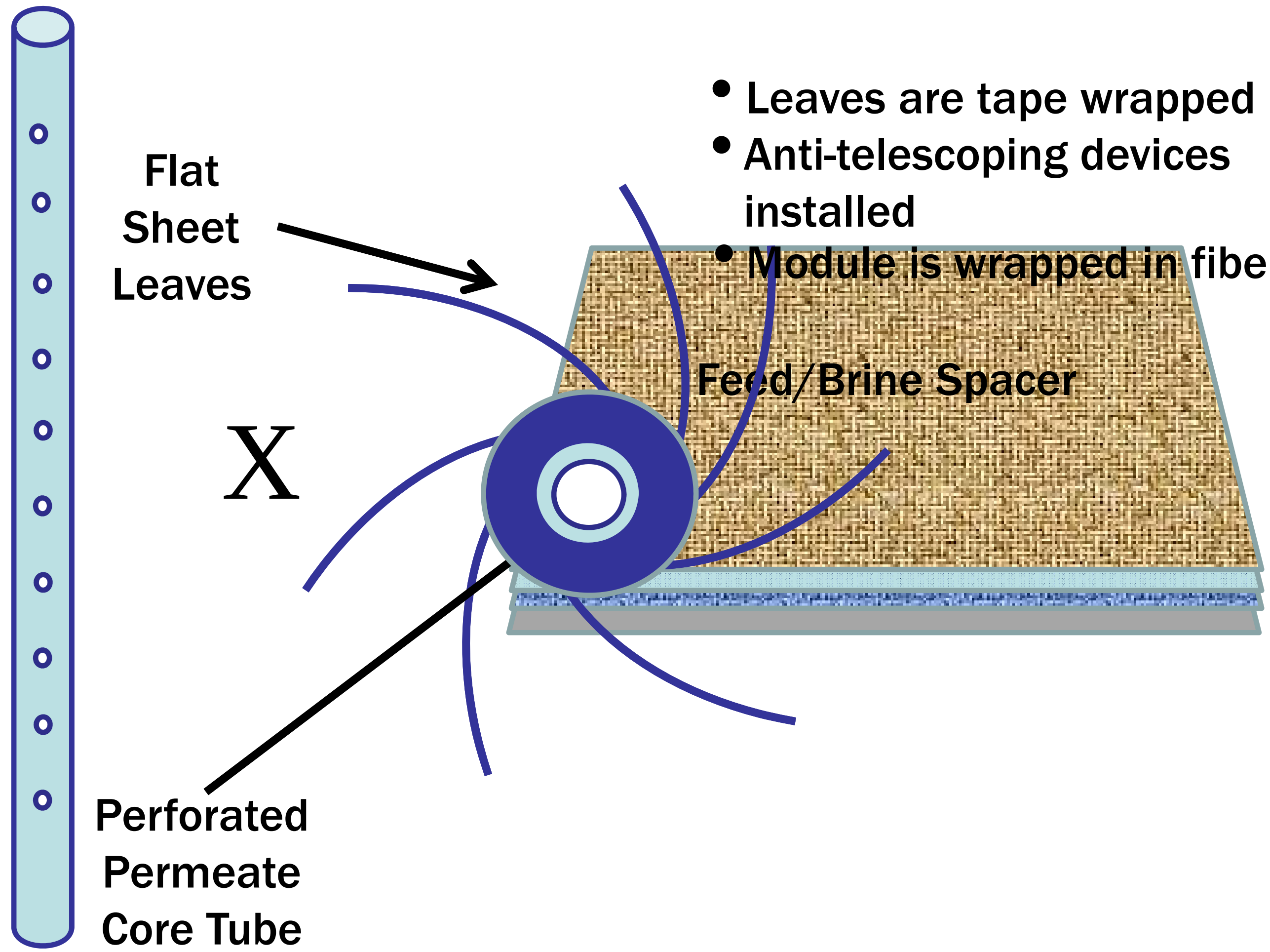
Perforated Permeate Tube

X

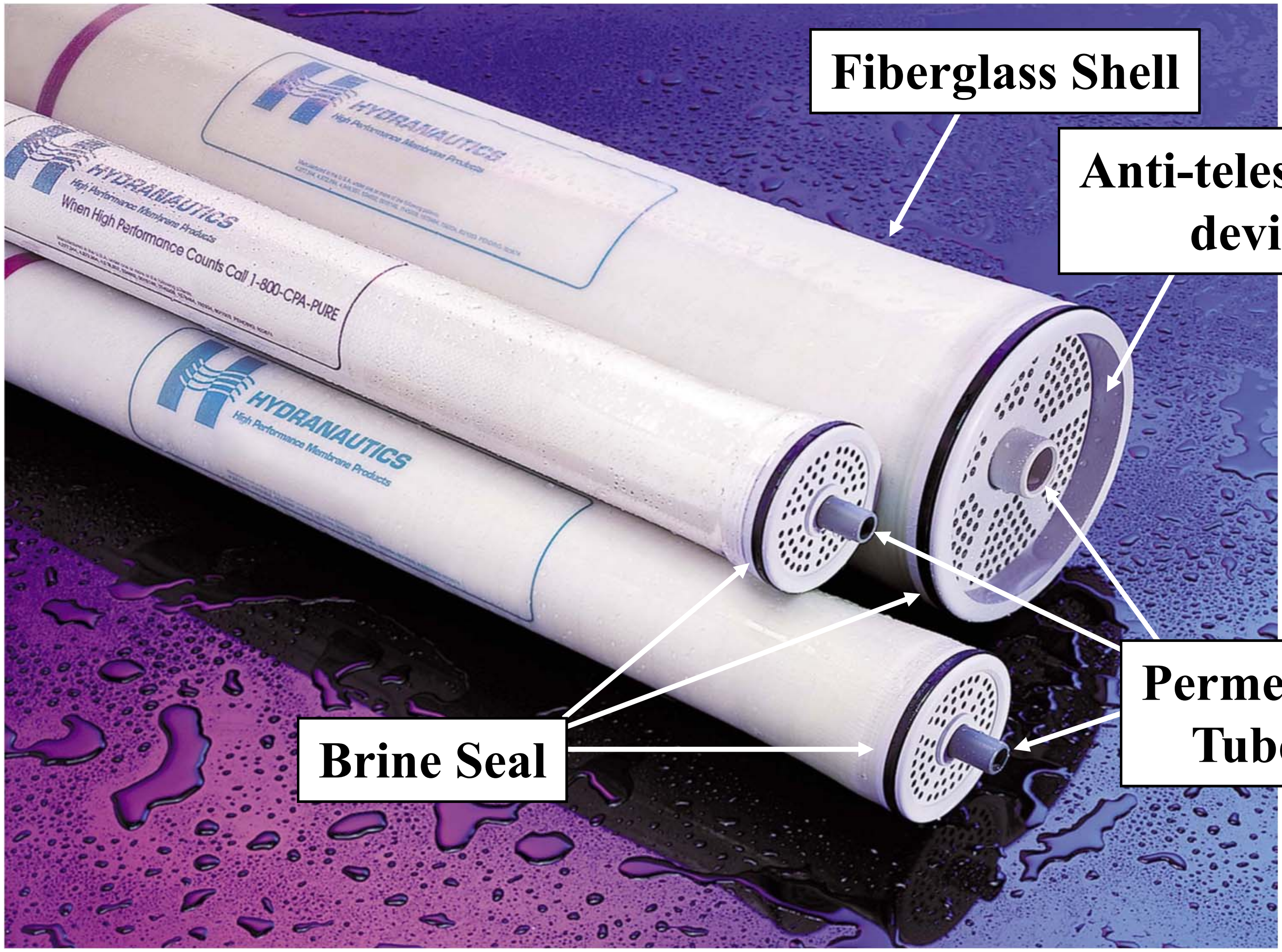


Making a Spiral Wound Element

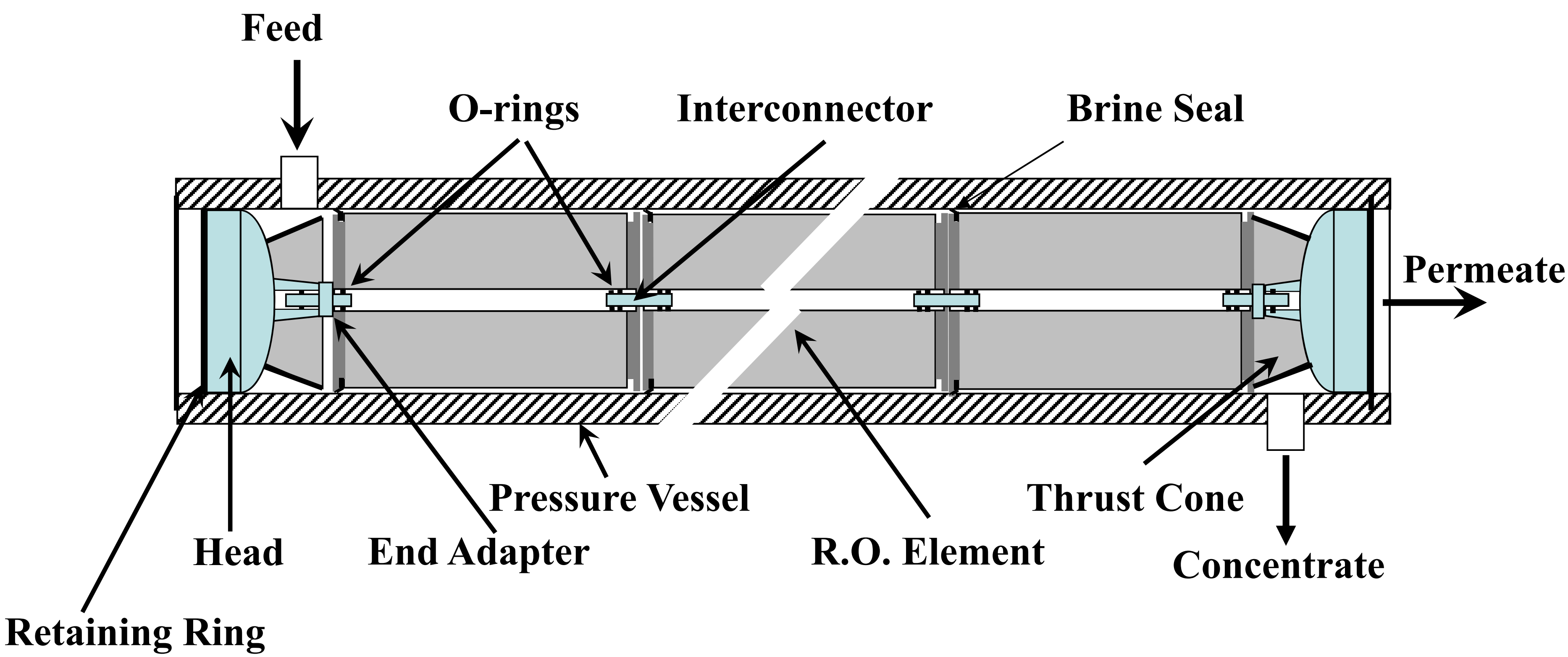
- Leaves are tape wrapped
- Anti-telescoping devices installed
- Module is wrapped in fiberglass



Typical RO Membrane Elements



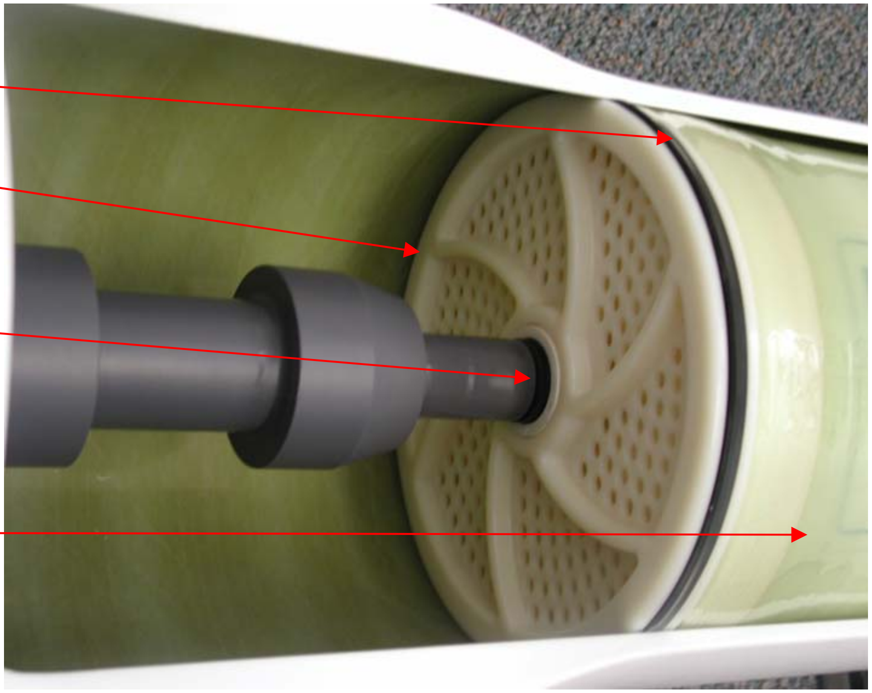
Pressure Vessel Assembly



Spiral Wound Element Components

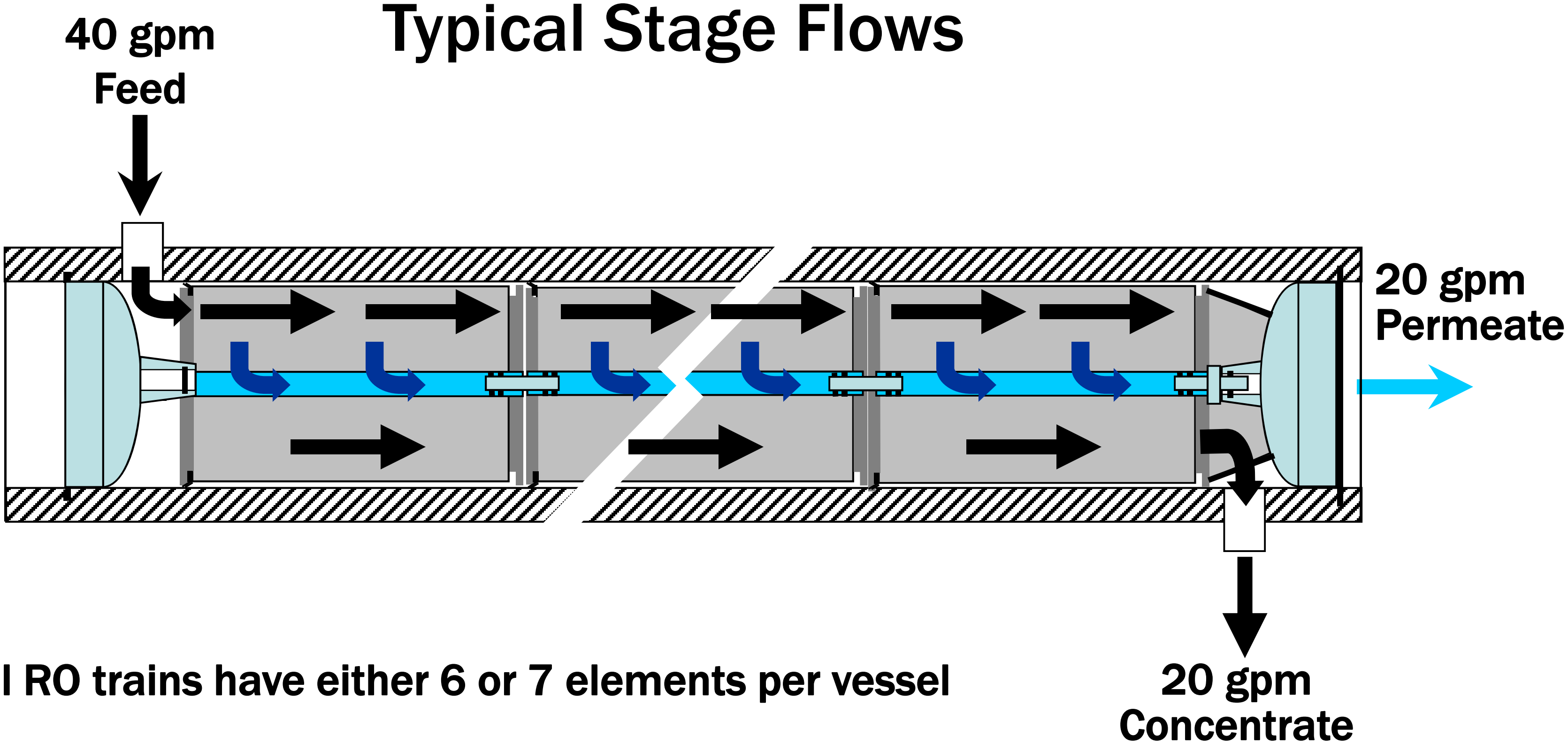
- Brine Seal (EPR)
- ATDs – Anti Telescoping Device (ABS)
- Permeate Core Tube (Noryl or PVC)
- Outer Wrap

  (Fiberglass Reinforced Plastic)



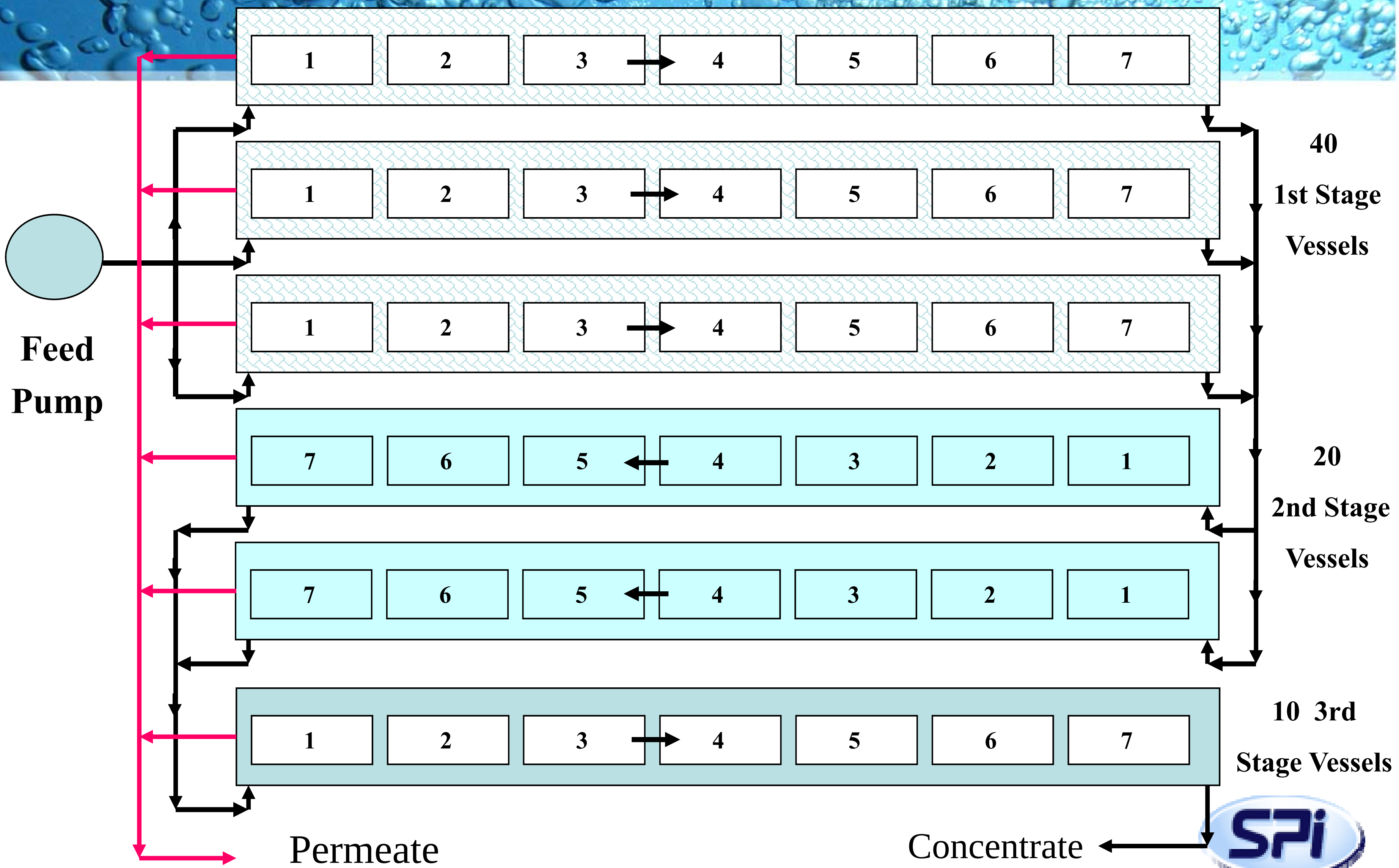
Reverse Osmosis Pressure Vessel Assembly

Typical Stage Flows



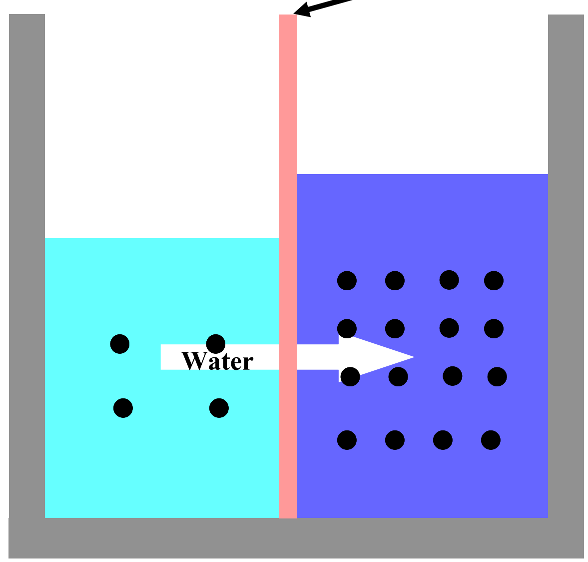
Typical RO trains have either 6 or 7 elements per vessel

Plan View of RO Unit



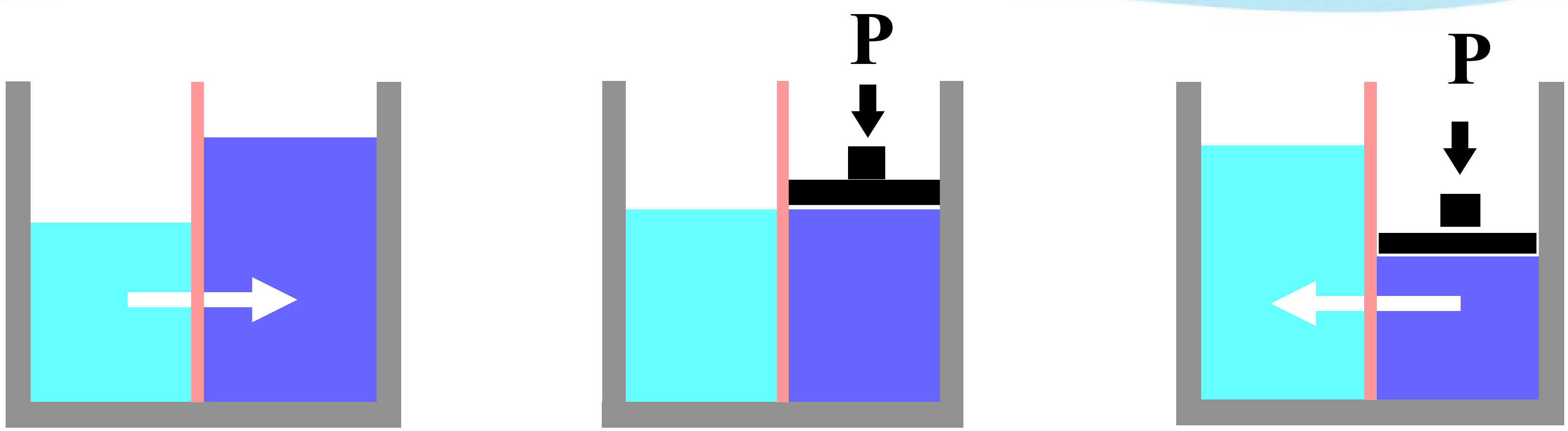
REVERSE OSMOSIS THEORY

Osmosis



Spontaneous flow of water from dilute solution to concentrated solution, when the two solutions are separated by semi-permeable membrane

Three Cases of Osmosis



osmosis

water flow from dilute side to concentrated side

equilibrium

no net water flow
P = osmotic pressure

reverse osmosis

water flow from concentrated side to dilute side

Osmotic Pressure

- Property of a <u>solution</u> dependent upon:
  - Type of contaminants (salts) in solution
  - Concentration of salts in solution
  - Temperature of solution
- Osmotic pressure can be calculated from water chemistry and temperature
- Based on number of molecules, not size of molecule

Typical Osmotic Pressures

Species	Concentration (mg/L)	Osmotic Pressure (psi)
NaCl	1,000	11.4
LiCl	1,000	16
$MgSO_4$	1,000	3.6
Sucrose	1,000	1.5
Seawater	35,000	374

Water Flux

Flow of water through a unit area of membrane

- The most common units of flux are "gfd" (Gallons per Day / Square Foot)

15 gfd = 2 ft/day or 1"/hour velocity through membrane

$$\text{Flux (gfd)} = \frac{\text{Permeate Flow (gpd)}}{\text{Membrane Area } (\text{ft}^2)}$$

Permeate Flow

$$Q_W = A \cdot a \cdot P_{net}$$

where:

Q_W = Permeate Water Flow

A = Water Permeation Coefficient

a = Membrane Area

P_{net} = Net Driving Pressure

Net Driving Pressure

$$P_{NET} = P_{FEED} - \Delta P - \Delta \Pi - P_{PERM}$$

Where:

P_{NET}	=	Net Driving Pressure
P_{FEED}	=	Feed Pressure
ΔP	=	Feed - Concentrate Pressure (delta P)
$\Delta \Pi$	=	Average Osmotic Pressure
P_{PERM}	=	Permeate Pressure

Specific Flux is the Water Permeation Coefficient

$$SF = A = Q_W \,/\, (a)\,(P_{NET})$$

where:

SF	=	Specific Flux
Q_W	=	Permeate Water Flow
A	=	Water Permeation Coefficient
a	=	Membrane Area
P_{NET}	=	Net Driving Pressure

At a given temperature (temp dependent)

Salt Flow

$$F_S = B\,a\left(\Delta C\right)$$

where: F_S = Salt Flow

B = Salt Permeation Coefficient

a = Membrane area

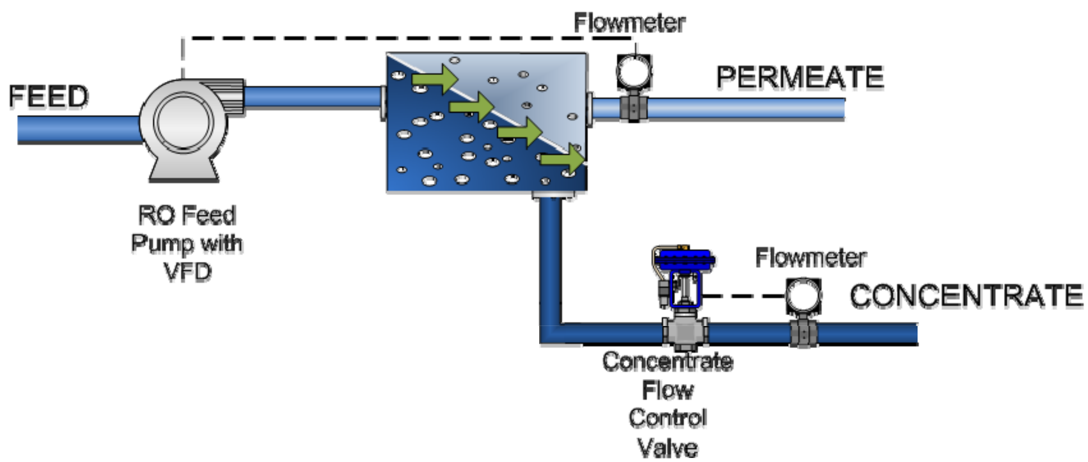
ΔC = Average Concentration Difference Across the Membrane

Temperature dependent

Recovery

Ratio of permeate flow to feed flow expressed as a percentage

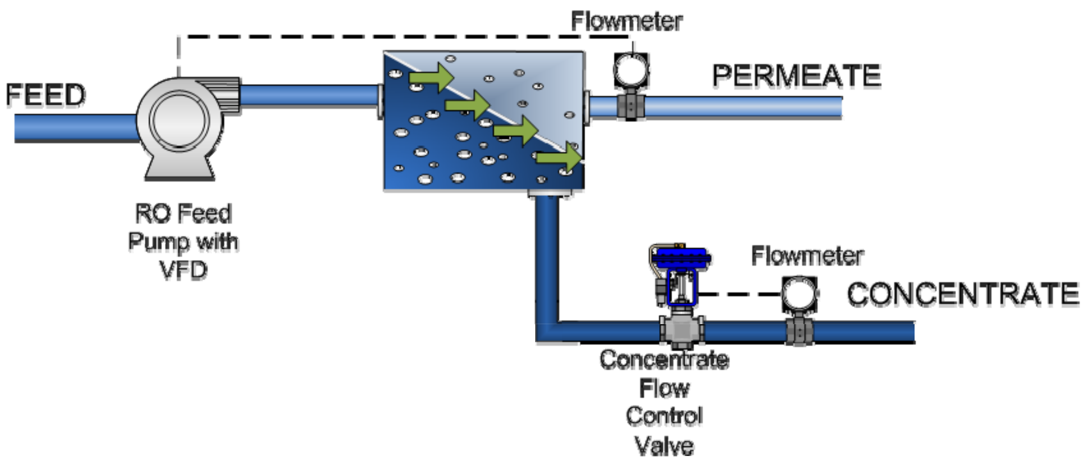
$$\% \text{ Recovery} = \frac{\text{Permeate Flow}}{\text{Feed Flow}} \times 100$$



System Salt Rejection

Percentage of Total Dissolved Solids (TDS) that does not pass through membrane. Based on feed water TDS

$$\% \text{ Rejection} = \left(1 - \frac{\text{Permeate TDS}}{\text{Feed TDS}}\right) \times 100$$



Removal Rates of Constituents by RO

	Feed mg/L	Permeate mg/L	% Rejection*
Ca^{2+}	93	0.01	100.0%
Mg^{2+}	24.9	0.01	100.0%
Na^{+}	214	6.38	97.0%
NH_4^+ (as N)	30.2	1.24	95.9%
Cl^{-}	236	3.64	98.5%
HCO_3^-	287.7	16.45	94.3%
SO_4^{2-}	298.5	0.48	99.8%
TOC	11.1	0.18	98.4%
SiO_2	23.7	0.10	99.6%
Total Nitrogen (as N)	33.5	1.53	95.4%
TDS	991	19.86	98.0%

*** System Rejection: 11gfd @ 85% Recovery**

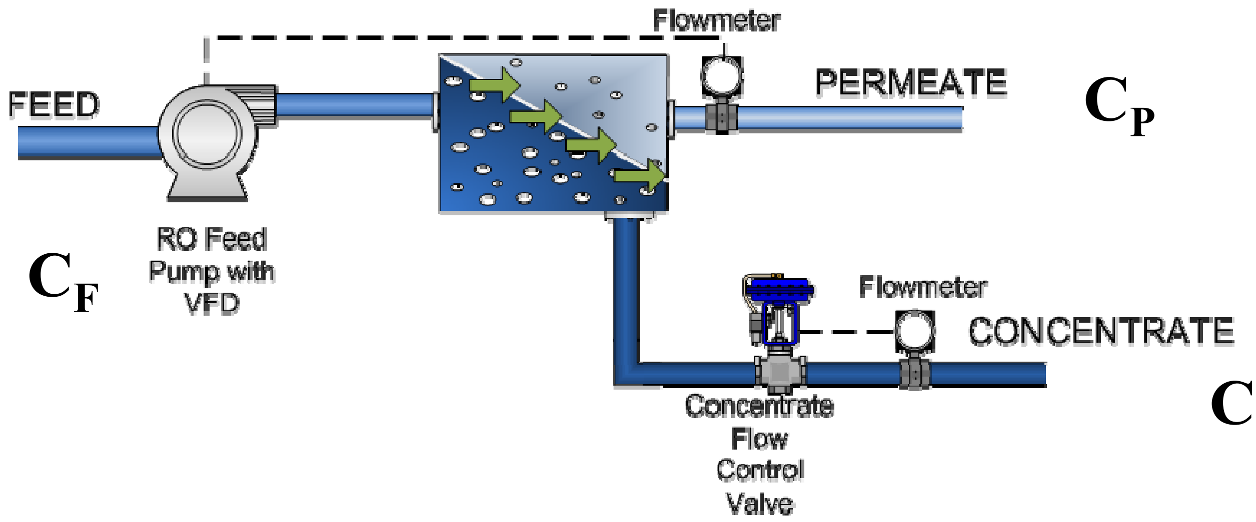
$$\% \text{ Rejection} = \left(1 - \frac{\text{Permeate TDS}}{\text{Feed TDS}}\right) \times 100$$

Concentration Factor

$$CF = \frac{C_C}{C_F}$$

where:

CF	=	Concentration Factor
C_C	=	Concentration of Concentrate
C_F	=	Concentration of Feedwater



C_P

C_F

$C_c = C_F * CF$

CF depends on Recovery and Salt Rejection

How RO Works

at constant $\overline{\Delta C}$ across the membrane

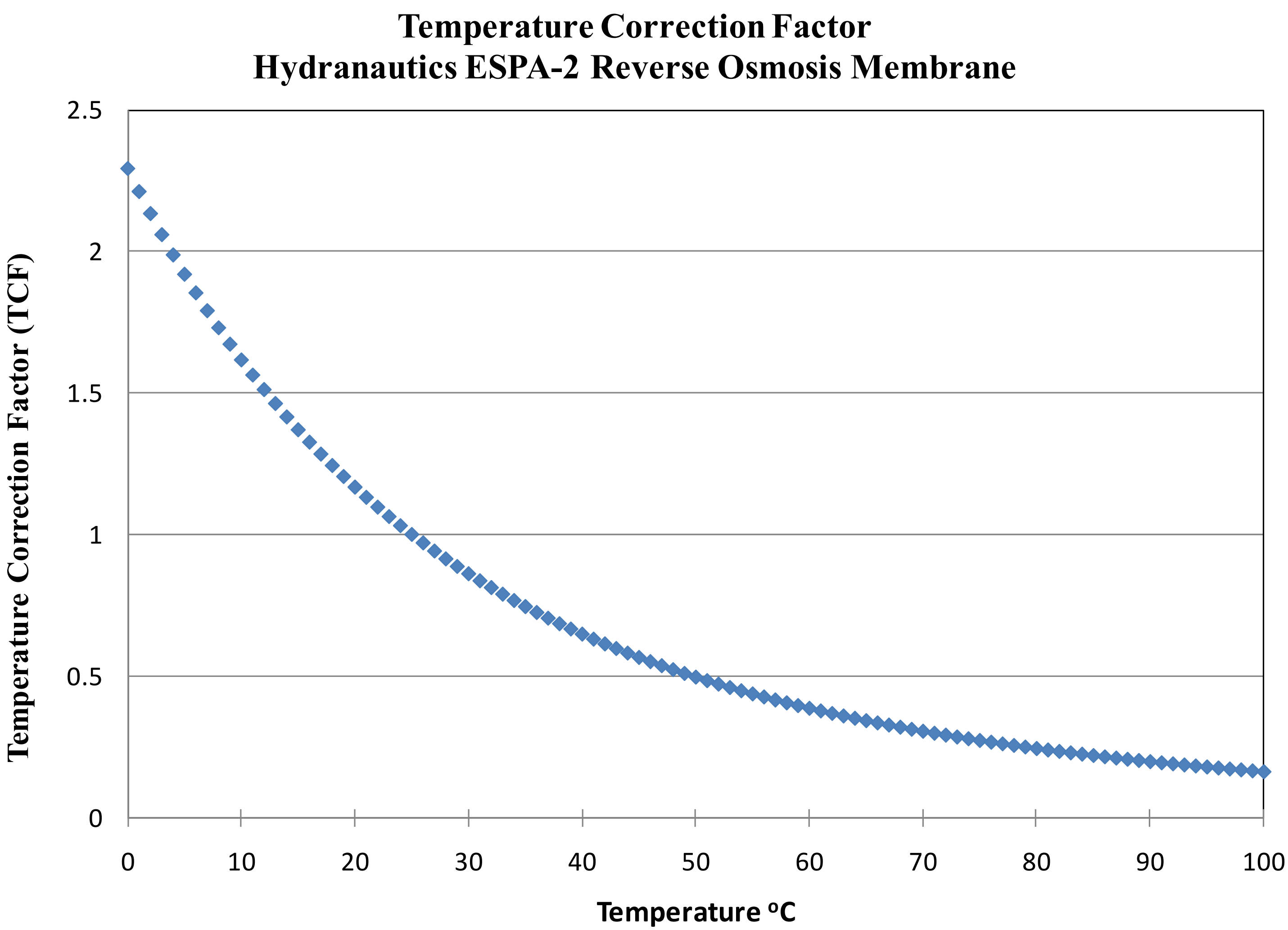
P_{net}	Permeate Water	Permeate Salt	Permeate Concentration
(psi)	(L/min)	(mg/min)	(mg/L)
50	1	1,000	1,000
100	2	?	?

How RO Works

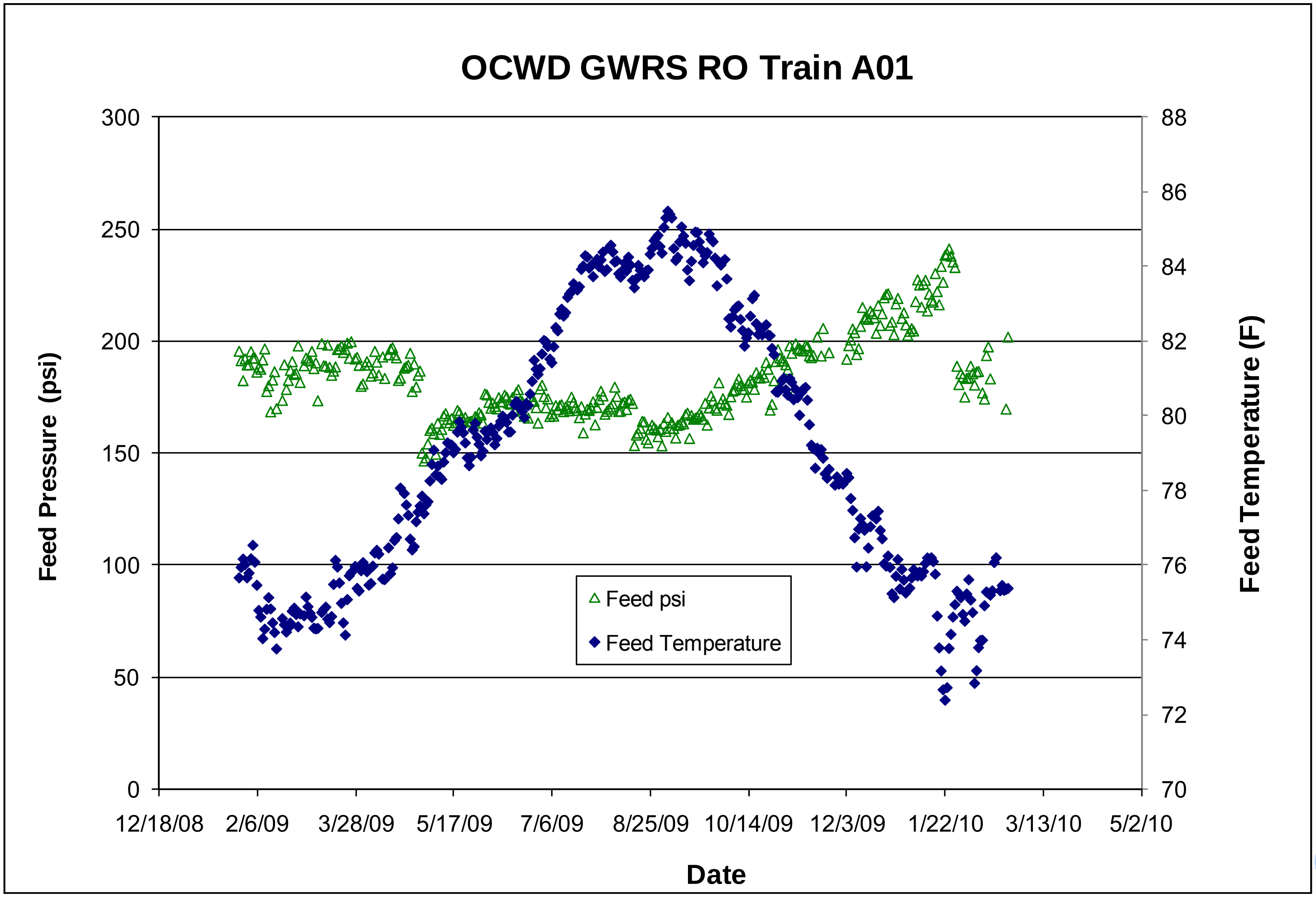
at constant $\overline{\Delta C}$ across the membrane

P_{net}	Permeate Water	Permeate Salt	Permeate Concentration
(psi)	(L/min)	(mg/min)	(mg/L)
50	1	1,000	1,000
100	2	1,000	500
200	4	1,000	250
400	8	1,000	125

Temperature Effect on RO Permeability



Temperature Effect on RO Permeability



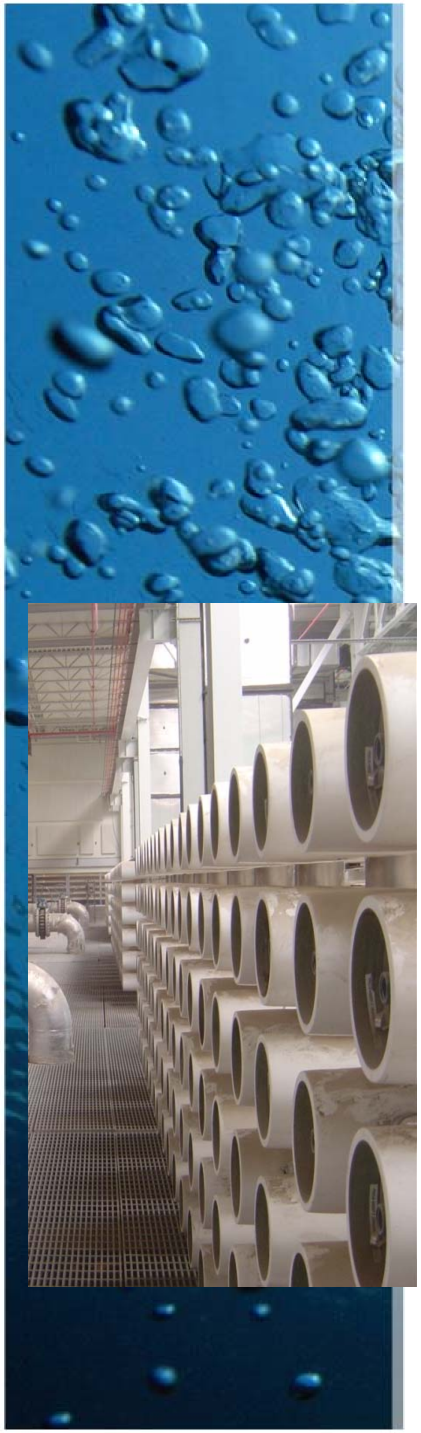
OPERATION

Important points about Reverse Osmosis

- Membrane Performance is local to each element
- Osmotic pressure must be overcome to obtain flow
- Flow of water through membrane is a function of local net driving pressure
- Flow of salt through membrane is a function of local salt concentration
- Osmotic pressure of feed increases as salts are rejected, lowering the net driving pressure
- Increasing water temperature will increase water flow and salt passage

Understanding the two types of Pressure Measurements

- Net Driving Pressure - available to make permeate
- Delta P (dP) – Pressure drop from feed end to concentrate end of vessel
  - System dP: Feed - Concentrate
  - Stage 1 dP: Feed – Stage 1 Out (Interstage)
  - Stage 2 dP: Interstage – Stage 2 Out (Concentrate)



RO Process – Criteria for Successful Operation

- Operate system at design permeate and concentrate setpoints
- Minimize (and monitor) the operating pressure required
- Normalize operating data for overall system and for each stage if possible
  - Specific Flux, Normalized ΔP and Normalized Permeate Conductivity
- Maintain permeate water quality
- Clean based on system limitations and economics (energy vs cleaning cost)

SPi

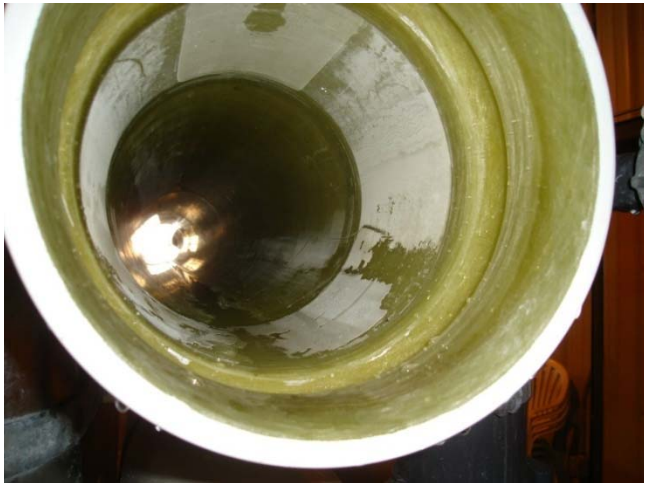
Pretreatment

- Chemical Addition
  - Acid
  - Scale Inhibitor
- Cartridge Filters
- Feedwater Instrumentation

Threshold Inhibitor (Antiscalant) Addition

Function:

- Delay and/or inhibit the precipitation of sparingly soluble salts in the RO concentrate stream
  - Calcium Carbonate ($CaCO_3$)
  - Calcium Phosphate ($CaPO_4$)
  - Calcium Sulfate ($CaSO_4$)
  - Barium Sulfate ($BaSO_4$)
  - Silica (SiO_2)



Cartridge Filters

Function:

- Remove suspended solids/debris
- Protect pumps and RO membranes
- Provides additional mixing for chemicals

RO Process – Minimize System Pressure During Operation

Pressure increases due to one of 3 reasons

- Fouling – Accumulation of biological or organic matter on surface of membrane
- Scaling – Precipitation of inorganic compound at tail end of array
- Deposition – Accumulation of debris on face of first element

Fouling of RO Membranes

- Fouling is a generic term that can consist of one or more of the following:
  - Suspended solids, colloids, microorganisms, and organic chemicals
- Fouling can be difficult to predict
- Fouling can occur at the front end (lead elements), tail end or overall

Scaling of RO Membranes

- Scaling refers to formation of a chemical “scale” similar to what occurs in a water heater or boiler

  Typical scales are:

  - calcium carbonate, calcium phosphate
  - calcium sulfate, barium sulfate or strontium sulfate
  - silica
- Scaling potential can be calculated based on water chemistry
- Scaling initially occurs at tail end of RO system – last few elements

MONITORING AND OPTIMIZATION

Regularly Monitored RO Parameters

- Date and Time
- Feed pH
- Feed conductivity
- Feed temperature
- Feed pressure
- Stage differential pressures
- Concentrate pressure
- Concentrate flow
- Permeate flow
- Permeate conductivity
- Permeate pressure

RO Monitoring Tools

- Conductivity profiles
- Vessel flow tests
- CIP effectiveness
  - Lower feed pressure
  - Lower delta P
  - “Temporary” effect on TDS
- Normalized performance data

Data Normalization

- Calculation of values that describe membrane performance at design conditions even when system is not operated at design conditions (flow, temperature, recovery, etc.)
- Removes influence of variable operating conditions

Data Normalization

Why Normalize Data?

- Allows user to make direct comparison of membrane performance despite changes in operating conditions
- Used to determine if the system performance is stable or developing problems

Types of Normalized Data

- Specific Flux - Membrane productivity on a standard basis
- Normalized ΔP - Pressure drop at standard operating conditions
- Normalized Permeate Conductivity - Permeate conductivity at standard operating conditions

Questions

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