American Water Chemicals, Inc.

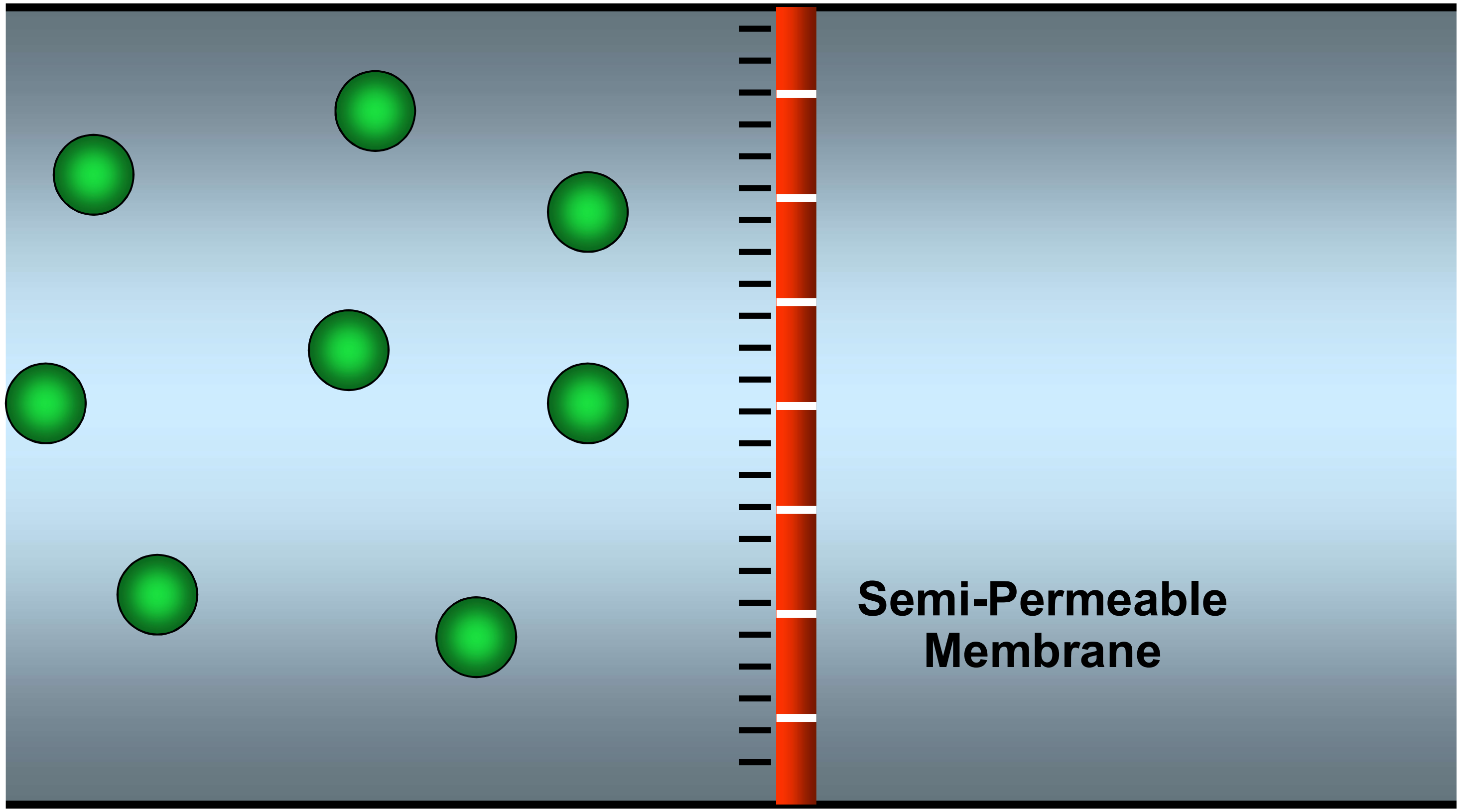
High Performance Membrane Antiscalants and Cleaning Chemicals

ISO 9001:2000 Certified Company

Fundamentals of Reverse Osmosis

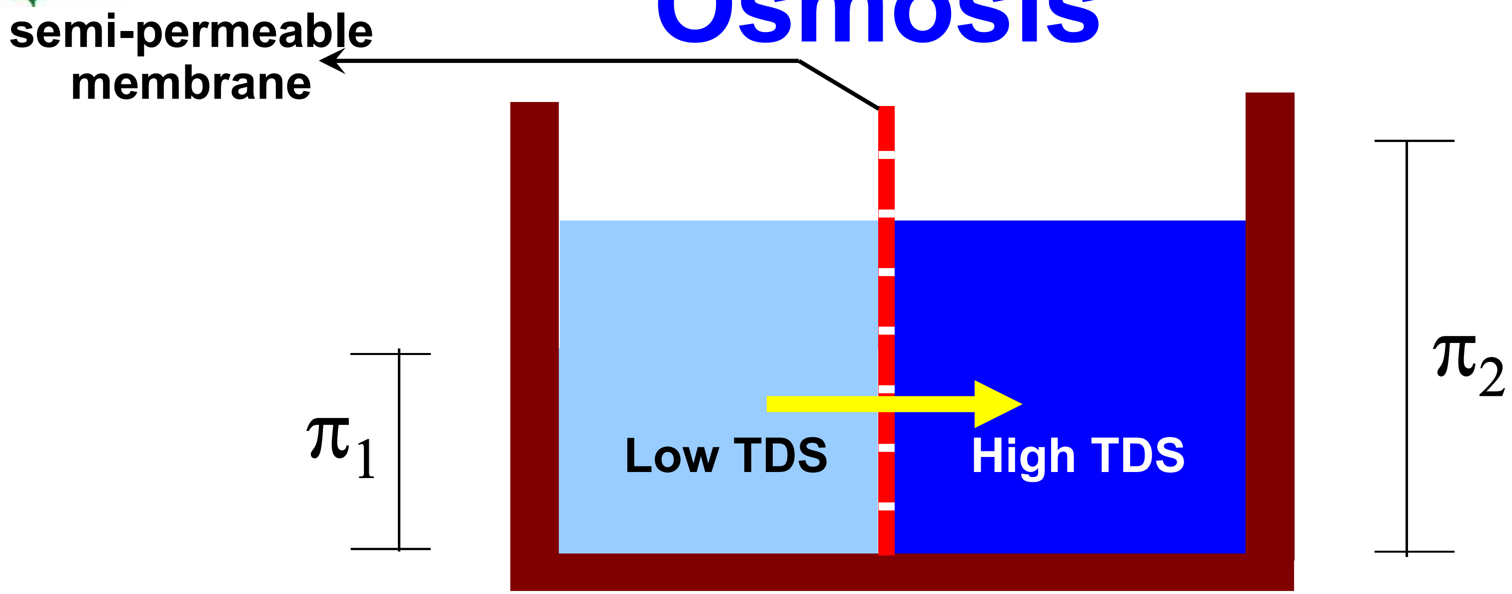
The Concept of Reverse Osmosis

Semi-Permeable Membrane



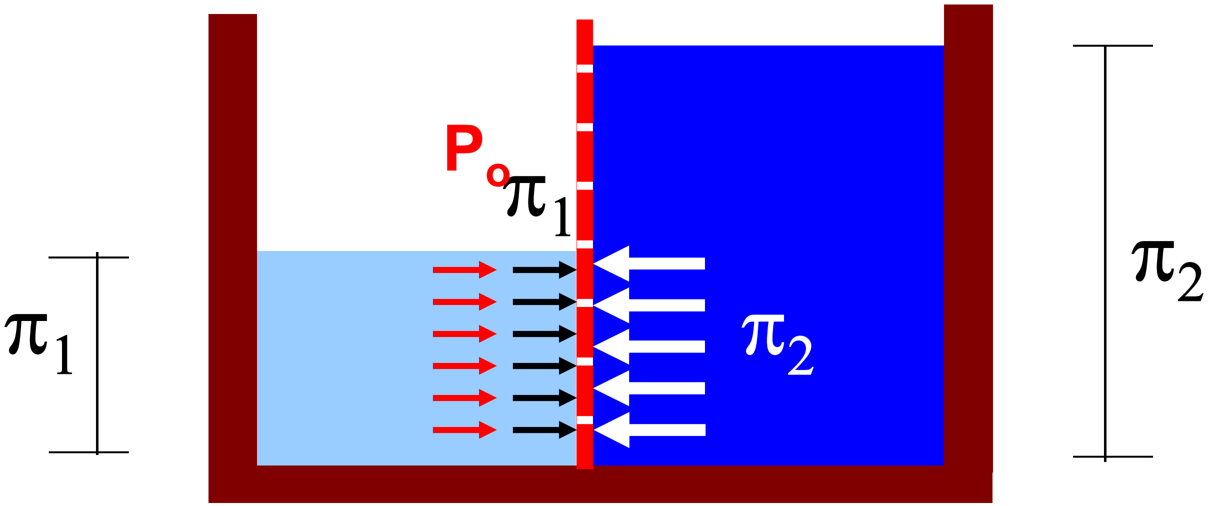
- **Allows only water and gas to pass through**
- **Does not allow dissolved Salts to pass through**

Osmosis



- The Laws of Nature dictate that concentrations are always equal in solutions that are in contact with each other.
- Water will pass from the low TDS side through the semi-permeable membrane in order to dilute the salts on the high TDS side. This phenomenon is known as **osmosis**.
- The concentration of dissolved salts is now equal on both sides of the membrane.

Osmosis



$$P_o + \pi_1 = \pi_2$$

$$P_o = (\pi_2 - \pi_1) = \Delta\pi$$

- Osmosis requires an increase in volume of water on the higher salinity side while reducing the volume on the lower salinity side.
- Since the higher volume of water will be heavier, a force is created in the direction of the lower salinity side.
- Nature overcomes this force through a phenomenon known as osmotic pressure (Po)

Osmosis

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

$$= \left[\frac{\text{Pound}}{\text{Inches}^2}\right] = \text{PSI}$$

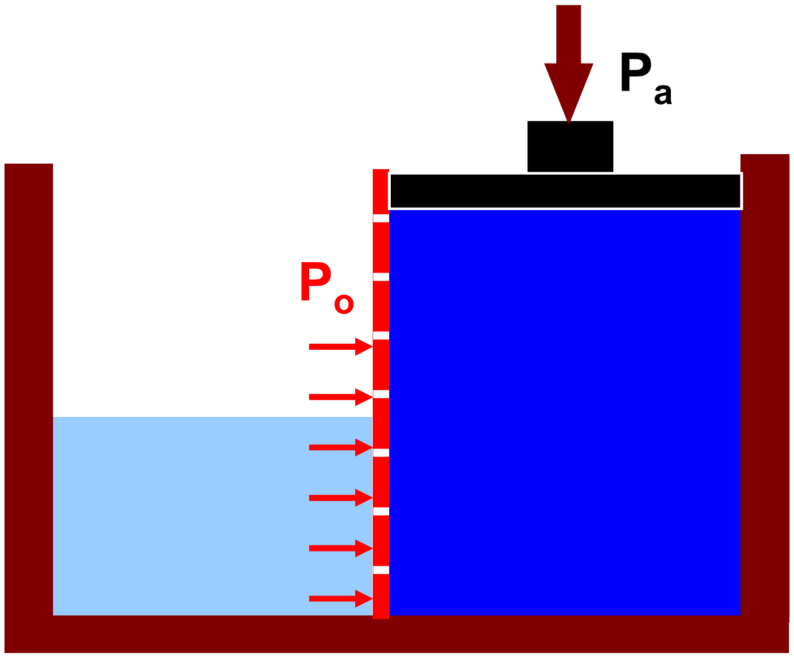
$$\text{Head} = \pi = \text{Height x Density}$$

$$= (\text{Inches}) \frac{(\text{Pound})}{(\text{Inches})(\text{Inches})^2}$$

$$= \left[\frac{\text{Pound}}{\text{Inches}^2}\right] = \text{PSI}$$

Pressure = Head = π

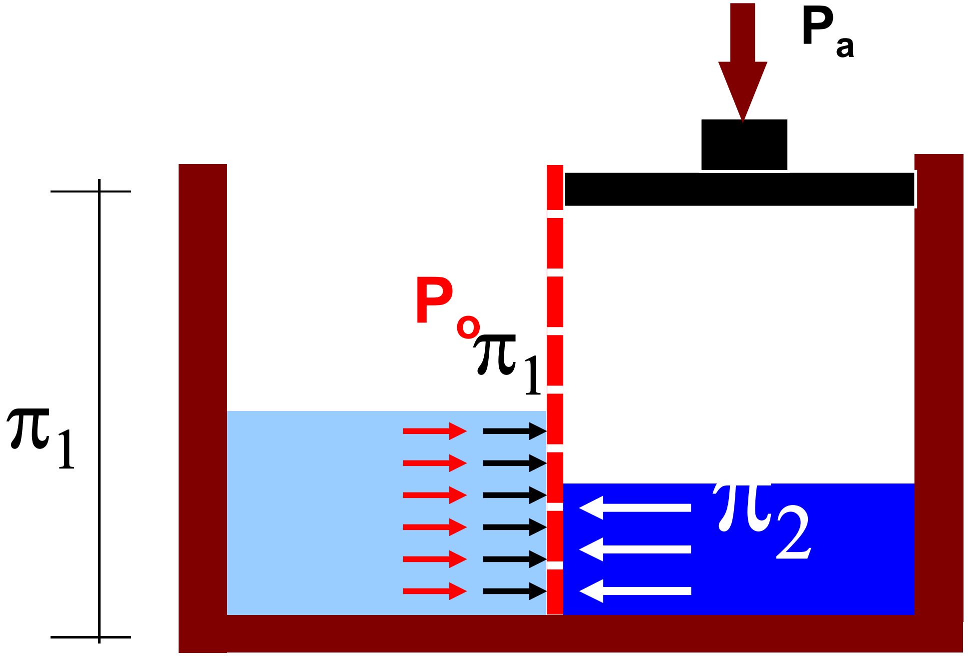
Osmotic Pressure



$$P_a = P_o$$

The pressure (P_a) applied to the concentrated solution to prevent Osmosis must be equal to the osmotic pressure (P_o)

Reverse Osmotic Flow



$P_o + \pi_1 = \pi_2$

$P_a > P_o$

$P_o = (\pi_2 - \pi_1)$

$P_{net} = (P_a - \Delta\pi - \Delta P - P_p)$

where: P_{net} = Net Driving Pressure

P_a = Applied Pressure

$\Delta\pi$ = Osmotic Pressure Differential

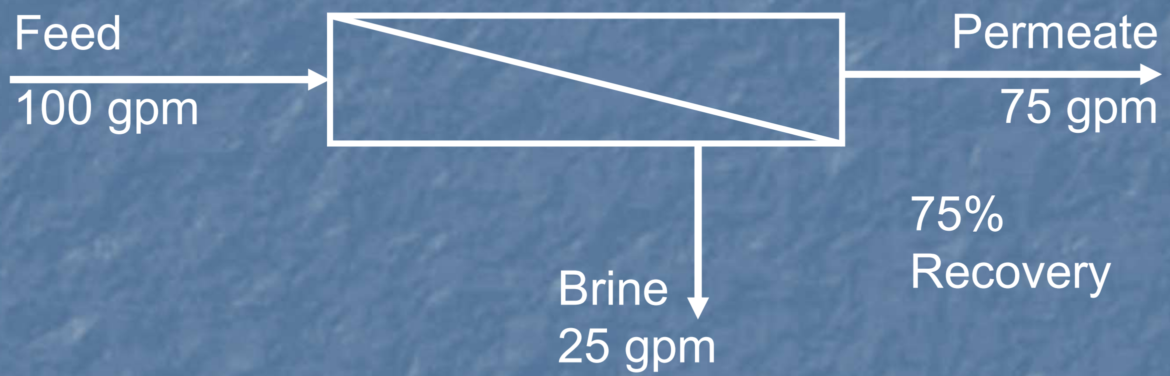
ΔP = Hydraulic Pressure Losses

P_p = π_1 = Permeate Back Pressure

Relative Osmotic Pressures

Material	Concentration (ppm)	Osmotic Pressure (psi)
Sugar	1,000	1.5
NaCl	1,000	11.5
$NaHCO_3$	1,000	12.8
Brackish Water	5,000	52.0
Seawater	35,000	355.0

Flow Balance



$$Q_F = Q_P + Q_C$$

where: Q_F = Flow of Feed Water

Q_P = Flow of Permeate

Q_C = Flow of Concentrate

Permeate Flow

$$Q_p = K_p \cdot S \cdot P_{net} \cdot K_t$$

where: Q_p = Permeate Flow Rate

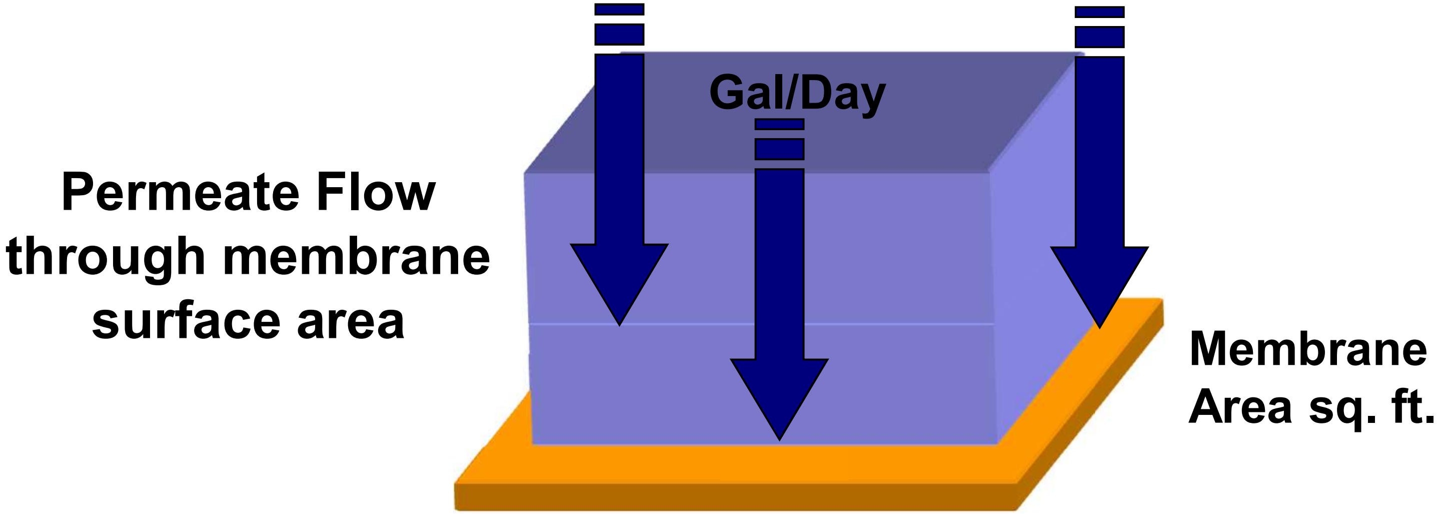
K_p = Water Permeation Coefficient of Membrane

S = Membrane Surface Area

P_{net} = Net Driving Pressure

K_t = Temperature Constant

Effect of Membrane Surface Area on Permeate Flow



$$\text{Flux} = \frac{\text{Permeate Flow}}{\text{Membrane Area}} = \frac{(\text{Gallon})}{(\text{ft}^2)\ (\text{Day})} = \text{GFD}$$

The flow of permeate water through a unit surface area of membrane per unit of time.

Effect of Water Permeation Coefficient on Permeate Flow

Water Permeation Coefficient is also knows as the **(K_p)** Value

Sometimes it is called the "**Specific Productivity**."

Usual units of measure are: **ml / cm2 / sec / bar**

The Kp value is a characteristic of the membrane that determines how easily water can pass through the membrane.

Flux Decline

The Water Permeation Coefficient (K_p) should be expected to decrease with time due to compression and irreversible fouling

This is usually accounted for in all Membrane Projection Programs

Effect of Net Driving Pressure on Permeate Flow

Permeate Flow Rate increases with Increased Net Driving Pressure

Effect of Temperature on Permeate Flow

Permeate Flow Rate increases with Increased Water Temperature due to reduced viscosity

Permeate Flow

$Q_p \propto$ **Water Permeation Coefficient**

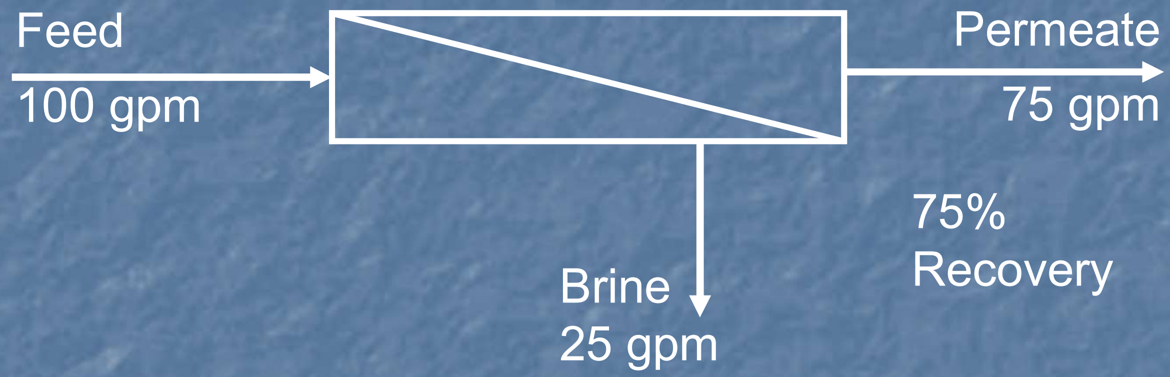
$Q_p \propto$ **Membrane Surface Area**

$Q_p \propto$ **Net Driving Pressure**

$Q_p \propto$ **Water Temperature**

$\propto$ ~ Directly proportional to

System Recovery



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

The Ratio of the Permeate Flow to the Feed Flow, expressed as a percentage.

Cross Flow

- Cross-Flow is the velocity of the concentrate stream across the membrane surface.
- At lower recoveries, less of the feedwater goes to the permeate side
- This means that the water in the reject stream flows across the membrane surface at a higher velocity
- The higher velocity reduces rate of deposition of foulants, scalants and buildup of biofilm due to its aggressive flushing action

Salt Passage

RO program licensed to:
Calculation created by: Tarek El-Shafie
Project name: 2 MGD BWRO

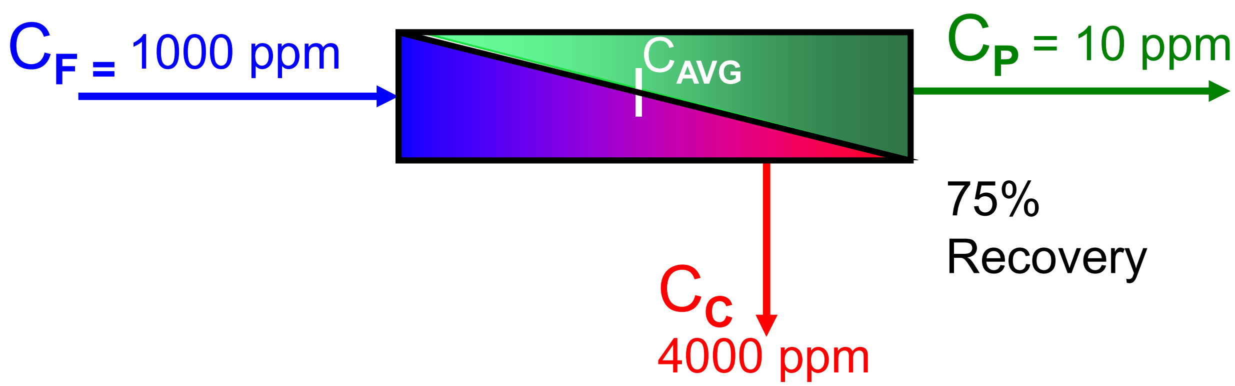
HP Pump flow:	1851.9	gpm	Permeate flow:	2000000.0 0	gpd
Recommended pump press.:	212.8	psi	Raw water flow:	2666666.7	gpd
Feed pressure:	195.5	psi	Permeate recovery:	75.0	%
Feedwater Temperature:	25.0	C(77F)	Element age:	3.0	years
Feed water pH:	7.0		Flux decline % per year:	7.0	
Chem dose, ppm (100%):	0.0	H2SO4	Salt passage increase, %/yr:	10.0	
Acidified feed CO2:	17.72		Feed type:	Well Water	
Average flux rate:	15.4	gfd			

Stage	Perm. Flow gpm	Flow/Vessel Feed gpm	Flow/Vessel Conc gpm	Flux gfd	Beta	Conc.&Throt. Pressures psi	Conc.&Throt. Pressures psi	Element Type	Elem. No.	Array
1-1	1036.6	51.4	22.6	17.3	1.17	170.3	0.0	CPA3	216	36x6
1-2	352.3	45.3	25.7	11.7	1.10	143.8	0.0	CPA3	108	18x6

	Raw water		Feed water		Permeate		Concentrate	
Ion	mg/l	CaCO3	mg/l	CaCO3	mg/l	CaCO3	mg/l	CaCO3
Ca	120.0	299.3	120.0	299.3	0.583	1.5	478.3	1192.6
Mg	35.0	144.0	35.0	144.0	0.170	0.7	139.5	574.0
Na	350.0	760.9	350.0	760.9	8.090	17.6	1375.7	2990.7
K	12.0	15.4	12.0	15.4	0.346	0.4	47.0	60.2
NH4	0.0	0.0	0.0	0.0	0.000	0.0	0.0	0.0
Ba	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0
Sr	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0
CO3	0.1	0.2	0.1	0.2	0.000	0.0	0.4	0.7
HCO3	120.0	98.4	120.0	98.4	3.575	2.9	469.3	384.7
SO4	110.0	114.6	110.0	114.6	0.461	0.5	438.6	456.9
Cl	713.9	1006.9	713.9	1006.9	11.892	16.8	2819.9	3977.3
F	0.0	0.0	0.0	0.0	0.000	0.0	0.0	0.0
NO3	0.0	0.0	0.0	0.0	0.000	0.0	0.0	0.0
B	0.00		0.00		0.000		0.00	
SiO2	0.0		0.0		0.00		0.0	
TDS	1461.0		1461.0		25.1		5768.7	
pH	7.0		7.0		5.6		7.5	

	Raw water	Feed water	Concentrate
CaSO4 / Ksp * 100:	3%	3%	15%
SrSO4 / Ksp * 100:	0%	0%	0%
BaSO4 / Ksp * 100:	0%	0%	0%
SiO2 saturation:	0%	0%	0%
Langelier Saturation Index	-0.46	-0.46	1.23
Stiff & Davis Saturation Index	-0.46	-0.46	0.96
Ionic strength	0.03	0.03	0.12
Osmotic pressure	14.6 psi	14.6 psi	57.5 psi

Salt Passage



$$\textbf{\% Salt Passage} = \frac{C_P}{C_{AVG}} \times 100$$

where: C_{AVG} = Average Concentration of Feed
C_{P} = Concentration of Permeate

The ratio of TDS in the permeate water to the average TDS across the feed side of the membrane, expressed as a percentage.

Average Concentration

Arithmetic Average

$$C_{AVG} = \frac{C_F + C_C}{2}$$

where : C_{AVG} = Average Concentration in System

C_F = Feed Water Concentration

C_C = Concentrate Concentration

- Satisfactory for recovery rates less than 20%.
- It might result in large errors at higher recoveries.

Average Concentration

Log Mean

$$C_{AVG} = \frac{C_F \times \ln\left(\frac{C_C}{C_F}\right)}{1 - \left(\frac{C_F}{C_C}\right)}$$

where : C_{AVG} = Average Concentration in System

C_F = Feed Water Concentration

C_C = Concentrate Concentration

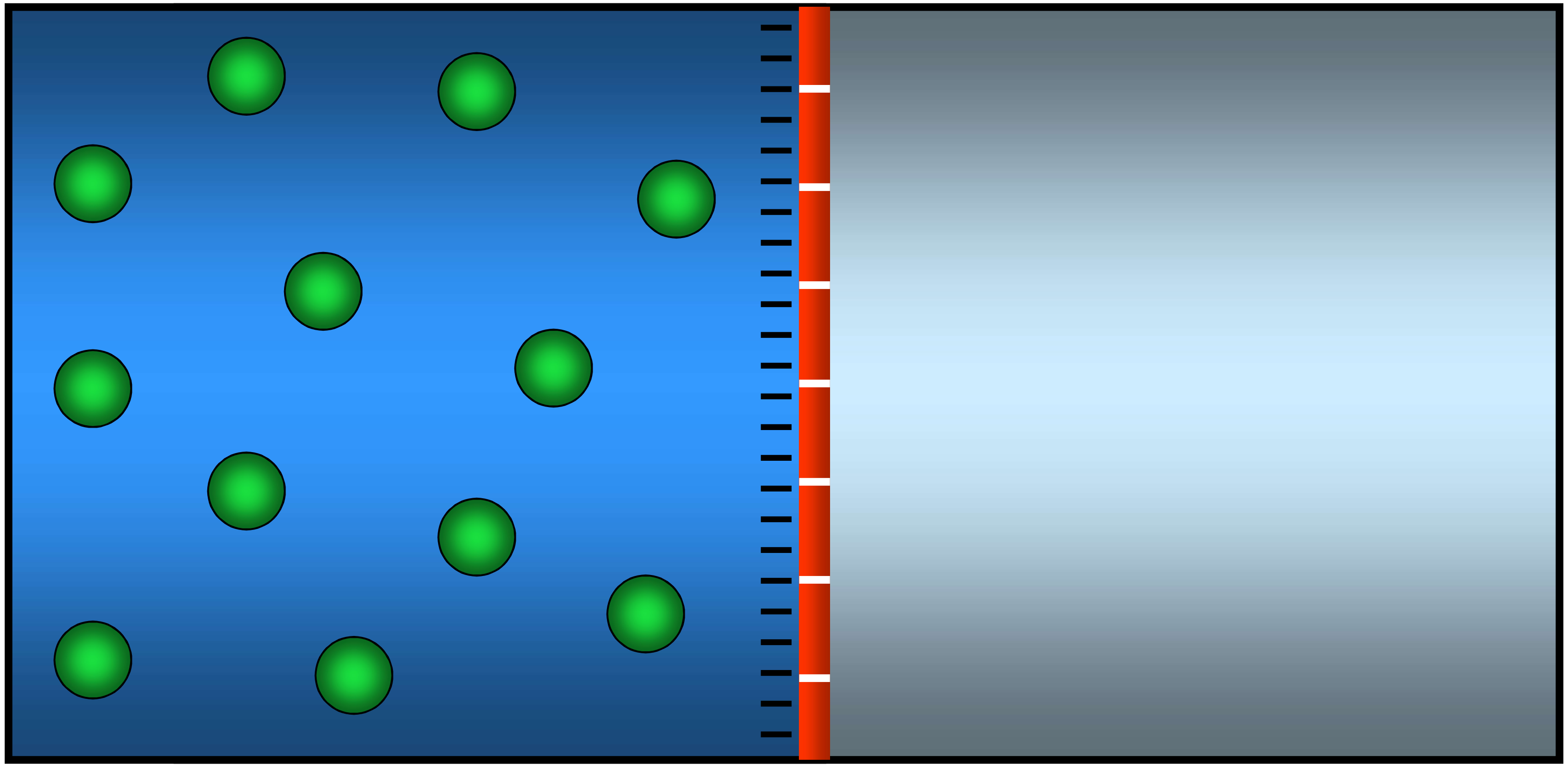
The most accurate method of calculating the average concentration in the system.

Salt Rejection

% Rejection = 100% - % Salt Passage

The ratio of Total Dissolved Solids (TDS) in the feed water that do not pass through the membrane to the Feed TDS.

Salt Diffusion



The movement of molecules from a high area of concentration to a low area of concentration due to random Motion.

Salt Diffusion

$$D_s = K_s \, . \, S \, . \, \Delta C \, . \, K_t$$

where:

D_S = Salt Diffusion

K_S = Salt Permeation Coefficient

S = Membrane Surface Area

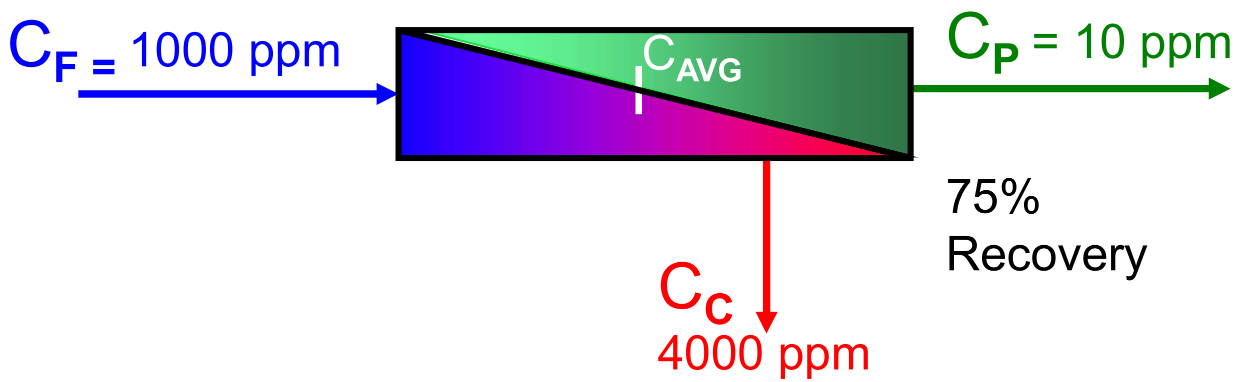
K_t = Temperature Constant

ΔC = Average Concentration Difference across the Membrane ($C_{AVG} - C_{Permeate}$)

Effect of Temperature on Salt Diffusion

As temperature rises, salt molecules gain energy and move at a faster speed. This increases the rate of diffusion across the membrane

Effect of Average Dissolved Solids Concentration on Salt Diffusion



Salt Diffusion is directly proportional to the Average Dissolved Solids Concentration (ppm) across the membrane

Improved Salt Rejection with Increased Feed Pressure

Salt Diffusion is Independent of Applied Pressure. As permeate production increases diffused salts are diluted

Salt Diffusion

$D_s \propto$ Feed Temperature (F or C)

Ds $\propto$ Average Dissolved Solids Concentration (ppm)

Ds $\not\propto$ Applied Pressure (PSI or Bar)

Ds $\propto$ Salt Permeation Coefficient (cm/sec)

$\not\propto$ ~ Independent from
$\propto$ ~ Directly proportional to

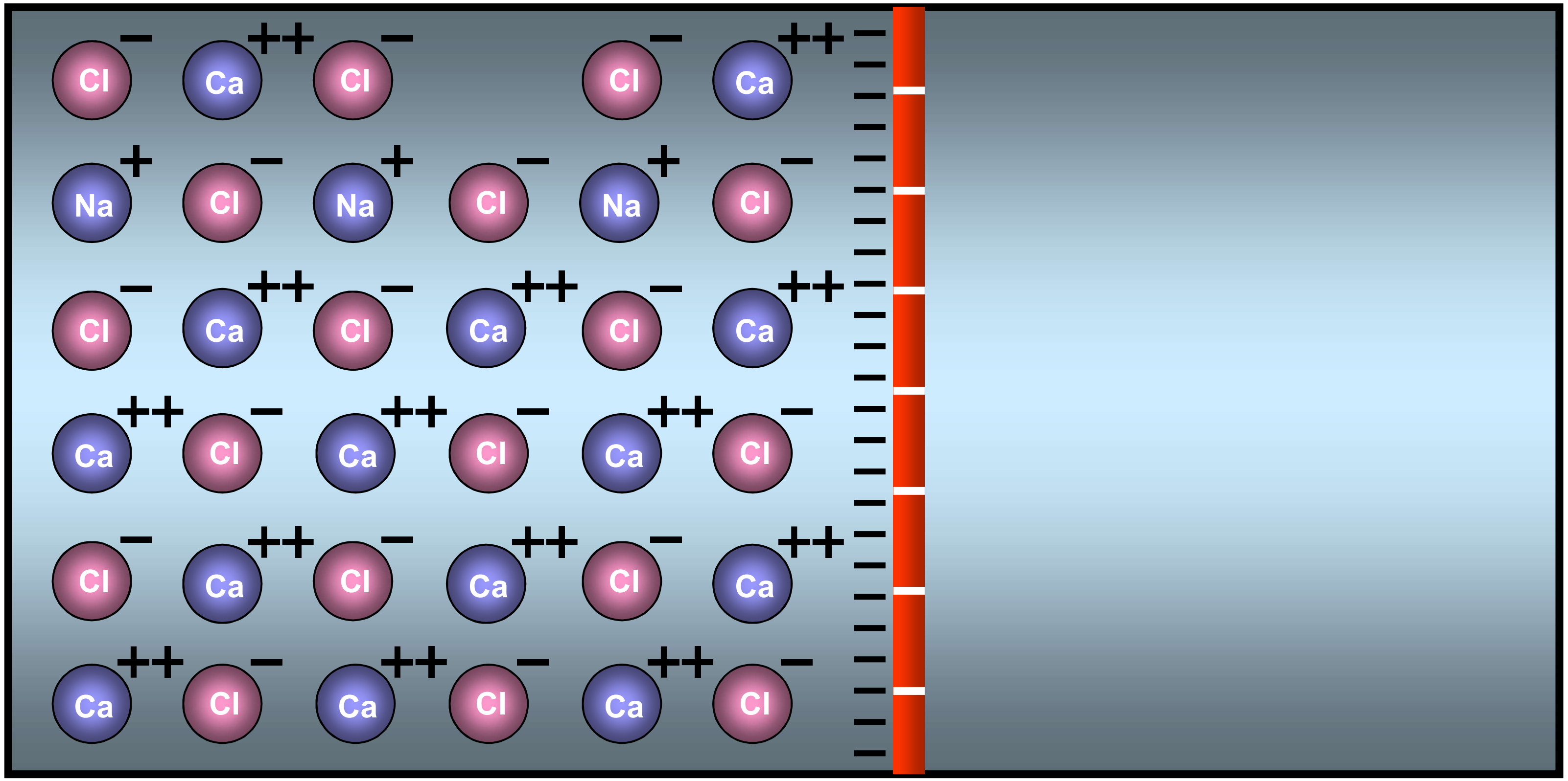
Salt Permeation Coefficient

- The Salt Permeation Coefficient is also known as (**K_s**) value.
- The Salt Permeation Coefficient is a characteristic of the membrane that determines the rate of diffusion of dissolved solids across membrane.

Factors Affecting Salt Permeation

Greatest Influence:	Electrical Charge
Moderate Influence:	Molecular Weight
Slight Influence:	Molecular Structure

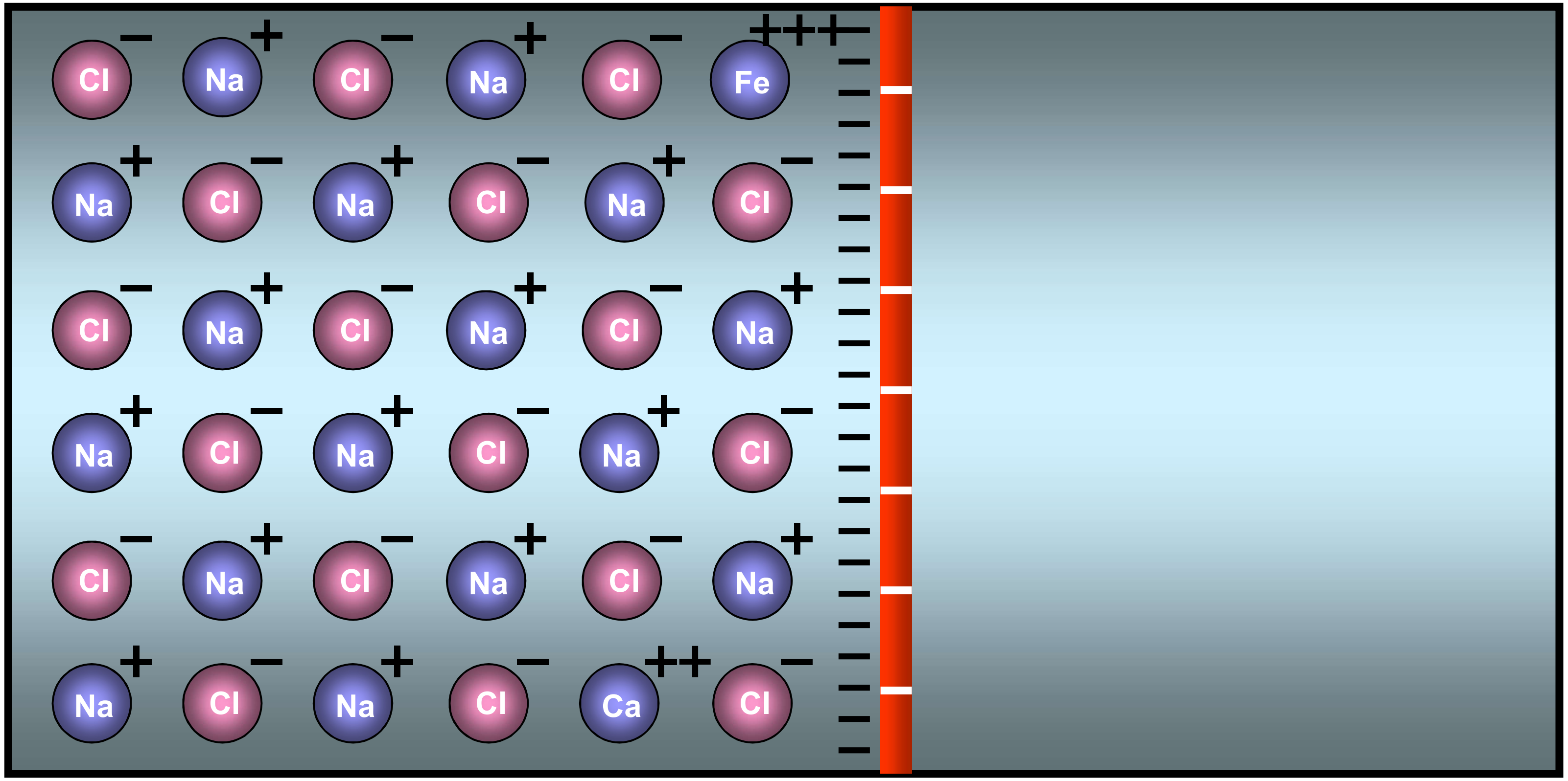
Charge Balance



- For each positive charge that passes through the membrane, a negative charge must also pass.
- The permeate water will always be electrically neutral, <u>there will be a charge balance.</u>

Factors Affecting Salt Permeation

Influence of Electrical Charge



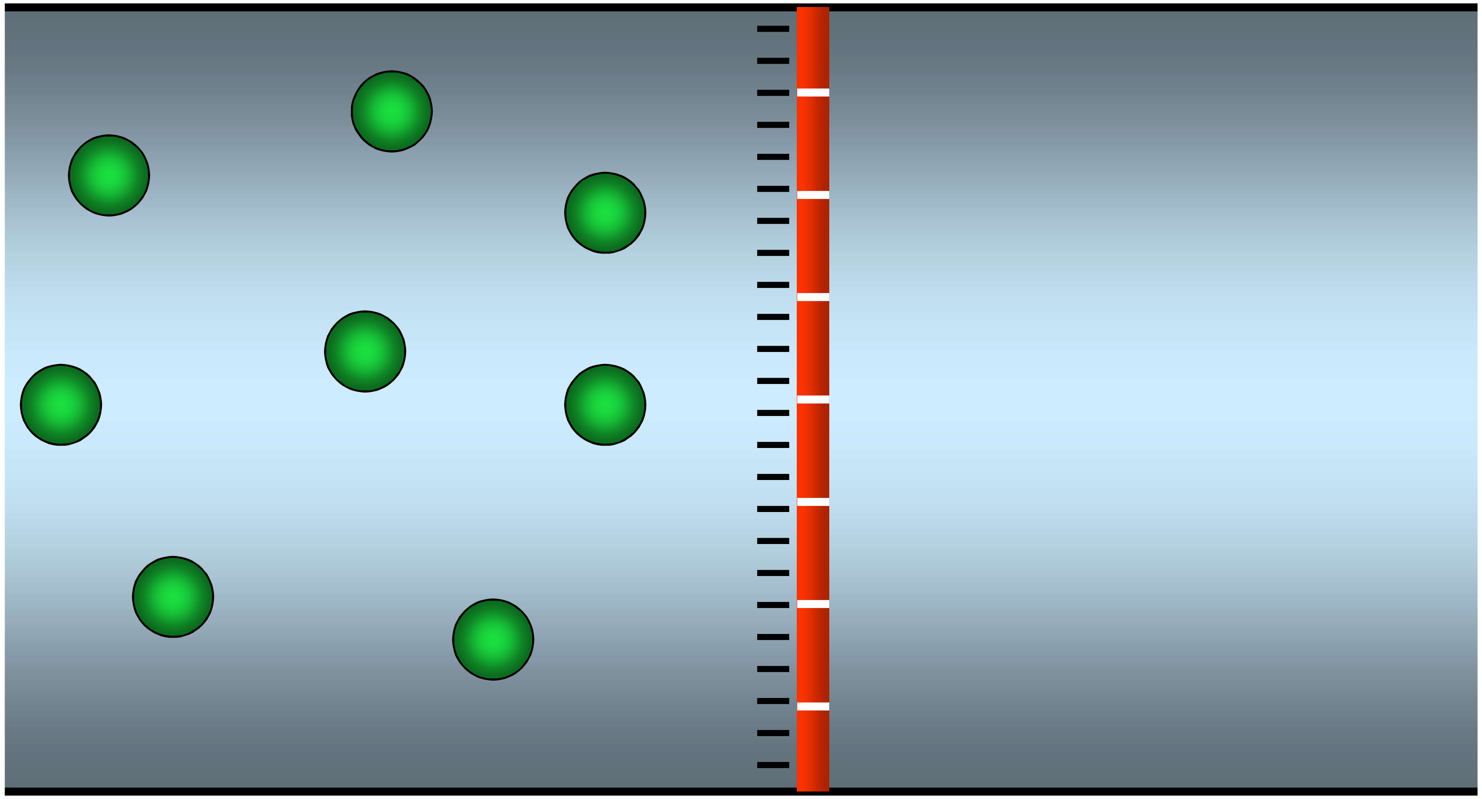
Monovalent Ions = 1 X 10^{-5} cm/sec

Divalent Ions = 1 X 10^{-6} cm/sec

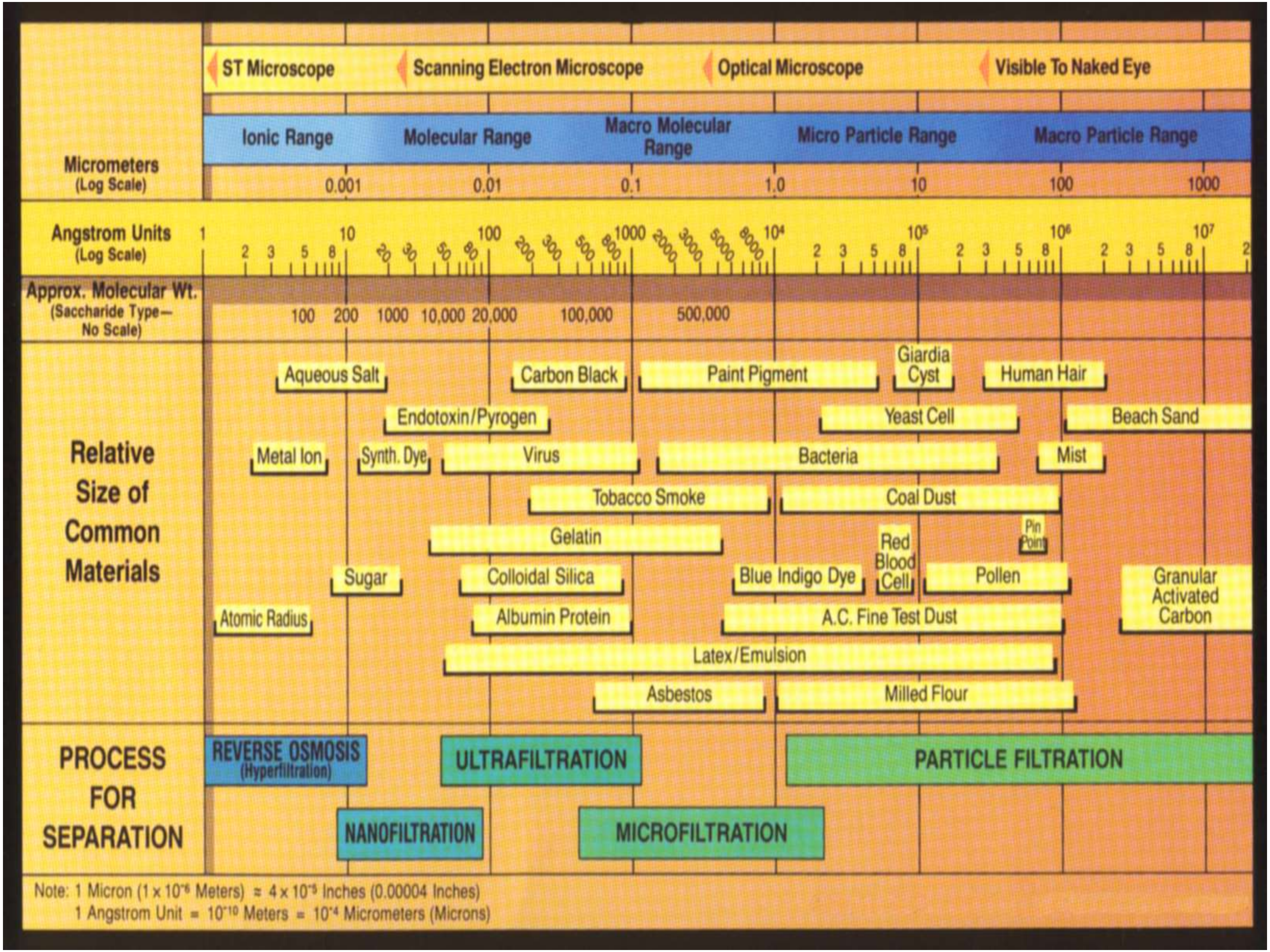
Trivalent Ions = 1 X 10^{-7} cm/sec

Factors Affecting Permeation

Influence of Molecular Weight



- Dissolved non-ionized molecules are not easily rejected by the membrane
- Only molecules with a molecular weight greater than the MW cut off will be rejected


ST Microscope
Scanning Electron Microscope
Optical Microscope
Visible To Naked Eye
Micrometers
(Log Scale)
Ionic Range
Molecular Range
Macro Molecular Range
Micro Particle Range
Macro Particle Range
0.001
0.01
0.1
1.0
10
100
1000
Angstrom Units
(Log Scale)
Approx. Molecular Wt.
(Saccharide Type—No Scale)
100 200 1000 10,000 20,000 100,000 500,000
Relative Size of Common Materials
Aqueous Salt
Carbon Black
Paint Pigment
Giardia Cyst
Human Hair
Endotoxin/Pyrogen
Yeast Cell
Beach Sand
Metal Ion
Synth. Dye
Virus
Bacteria
Mist
Tobacco Smoke
Coal Dust
Gelatin
Red Blood Cell
Pin Point
Sugar
Colloidal Silica
Blue Indigo Dye
Pollen
Granular Activated Carbon
Atomic Radius
Albumin Protein
A.C. Fine Test Dust
Latex/Emulsion
Asbestos
Milled Flour
PROCESS FOR SEPARATION
REVERSE OSMOSIS
(Hyperfiltration)
ULTRAFILTRATION
PARTICLE FILTRATION
NANOFILTRATION
MICROFILTRATION
Note: 1 Micron (1 x 10⁻⁶ Meters) ≈ 4 x 10⁻⁵ Inches (0.00004 Inches)
1 Angstrom Unit = 10⁻¹⁰ Meters = 10⁻⁴ Micrometers (Microns)

Permeation Coefficient of Weak Acids

- Many Dissolved Organics are weak acids.
- Weak acids are those acids that do not become completely ionized in water
- Rate of permeation of weak acids will depend on degree of ionization.
- Boric Acid is an example of an inorganic weak acid

$$H_3BO_3 \rightleftharpoons H^+ + H_2BO_3^-$$

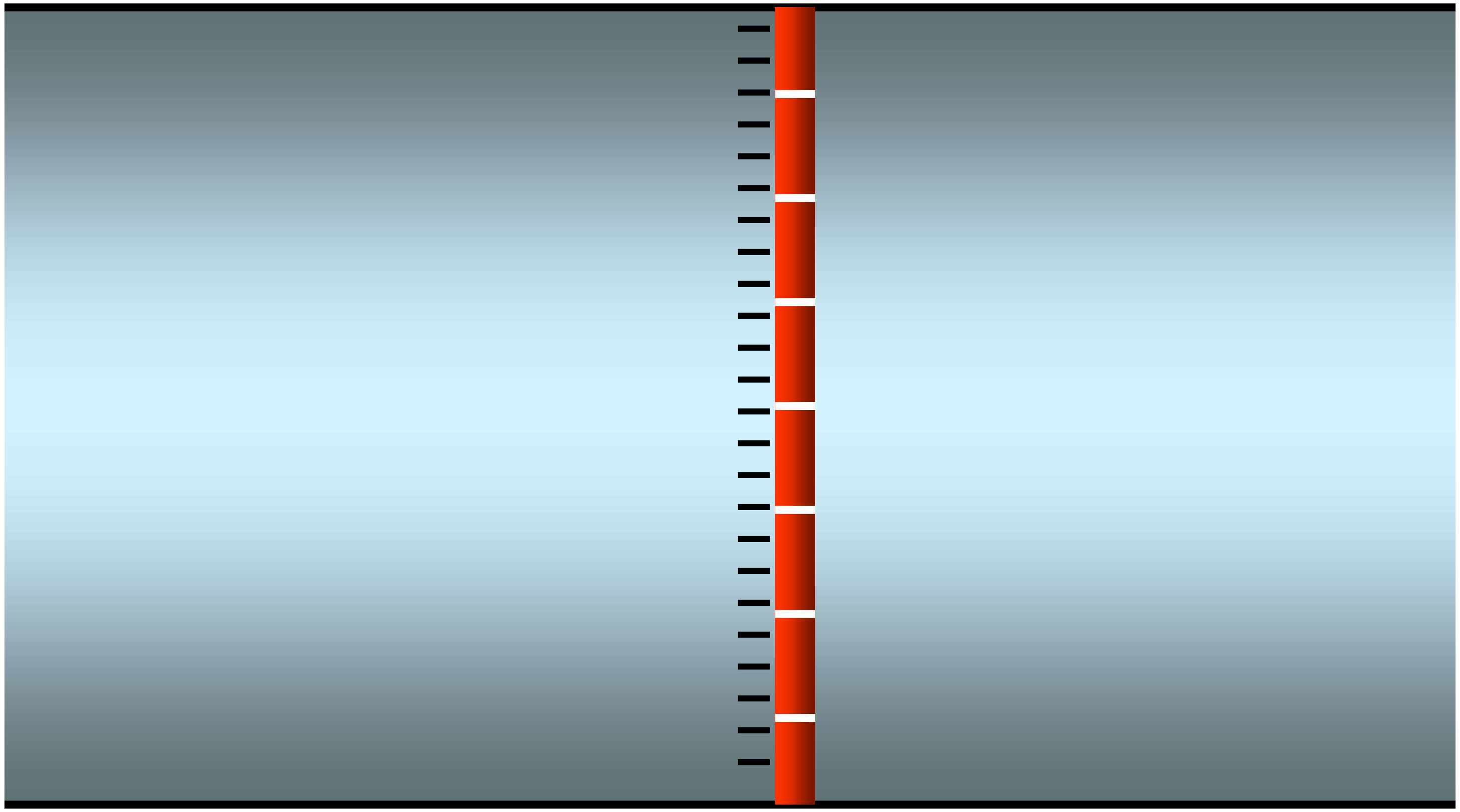
(MW = 62)

- Acetic Acid is an example of an organic weak acid

$$HC_2H_3O_2 \rightleftharpoons H^+ + C_2H_3O^{2-}$$

(MW = 60)

Permeation Coefficient of Gases



Dissolved Gases such as CO_2 and H_2S pass freely through the membrane

Concentration Factor

RO program licensed to:
Calculation created by: Tarek El-Shafie
Project name: 2 MGD BWRO

HP Pump flow:	1851.9	gpm	Permeate flow:	2000000.0 0	gpd
Recommended pump press.:	212.8	psi	Raw water flow:	2666666.7	gpd
Feed pressure:	195.5	psi	Permeate recovery:	75.0	%
Feedwater Temperature:	25.0	C(77F)			
Feed water pH:	7.0		Element age:	3.0	years
Chem dose, ppm (100%):	0.0	H2SO4	Flux decline % per year:	7.0	
Acidified feed CO2:	17.72		Salt passage increase, %/yr:	10.0	
Average flux rate:	15.4	gfd	Feed type:	Well Water	

Stage	Perm. Flow gpm	Flow/Vessel Feed gpm	Flow/Vessel Conc gpm	Flux gfd	Beta	Conc.&Throt. Pressures psi	Conc.&Throt. Pressures psi	Element Type	Elem. No.	Array
1-1	1036.6	51.4	22.6	17.3	1.17	170.3	0.0	CPA3	216	36x6
1-2	352.3	45.3	25.7	11.7	1.10	143.8	0.0	CPA3	108	18x6

	Raw water		Feed water		Permeate		Concentrate	
Ion	mg/l	CaCO3	mg/l	CaCO3	mg/l	CaCO3	mg/l	CaCO3
Ca	120.0	299.3	120.0	299.3	0.583	1.5	478.3	1192.6
Mg	35.0	144.0	35.0	144.0	0.170	0.7	139.5	574.0
Na	350.0	760.9	350.0	760.9	8.090	17.6	1375.7	2990.7
K	12.0	15.4	12.0	15.4	0.346	0.4	47.0	60.2
NH4	0.0	0.0	0.0	0.0	0.000	0.0	0.0	0.0
Ba	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0
Sr	0.000	0.0	0.000	0.0	0.000	0.0	0.000	0.0
CO3	0.1	0.2	0.1	0.2	0.000	0.0	0.4	0.7
HCO3	120.0	98.4	120.0	98.4	3.575	2.9	469.3	384.7
SO4	110.0	114.6	110.0	114.6	0.461	0.5	438.6	456.9
Cl	713.9	1006.9	713.9	1006.9	11.892	16.8	2819.9	3977.3
F	0.0	0.0	0.0	0.0	0.000	0.0	0.0	0.0
NO3	0.0	0.0	0.0	0.0	0.000	0.0	0.0	0.0
B	0.00		0.00		0.000		0.00	
SiO2	0.0		0.0		0.00		0.0	
TDS	1461.0		1461.0		25.1		5768.7	
pH	7.0		7.0		5.6		7.5	

	Raw water	Feed water	Concentrate
CaSO4 / Ksp * 100:	3%	3%	15%
SrSO4 / Ksp * 100:	0%	0%	0%
BaSO4 / Ksp * 100:	0%	0%	0%
SiO2 saturation:	0%	0%	0%
Langelier Saturation Index	-0.46	-0.46	1.23
Stiff & Davis Saturation Index	-0.46	-0.46	0.96
Ionic strength	0.03	0.03	0.12
Osmotic pressure	14.6 psi	14.6 psi	57.5 psi

Concentration Factor

$$CF = \frac{C_C}{C_F} \approx \frac{Q_F}{Q_C}$$

$$= \frac{100\%}{100\% - \%\ Recovery}$$

where: C_F = Concentration Factor

C_C = Concentration of Brine

C_F = Concentration of Feed Water

Q_F = Feed Flow Rate

Q_C = Brine Flow Rate

Mass Balance

$$Q_F \cdot C_F = Q_P \cdot C_P + Q_C \cdot C_C$$

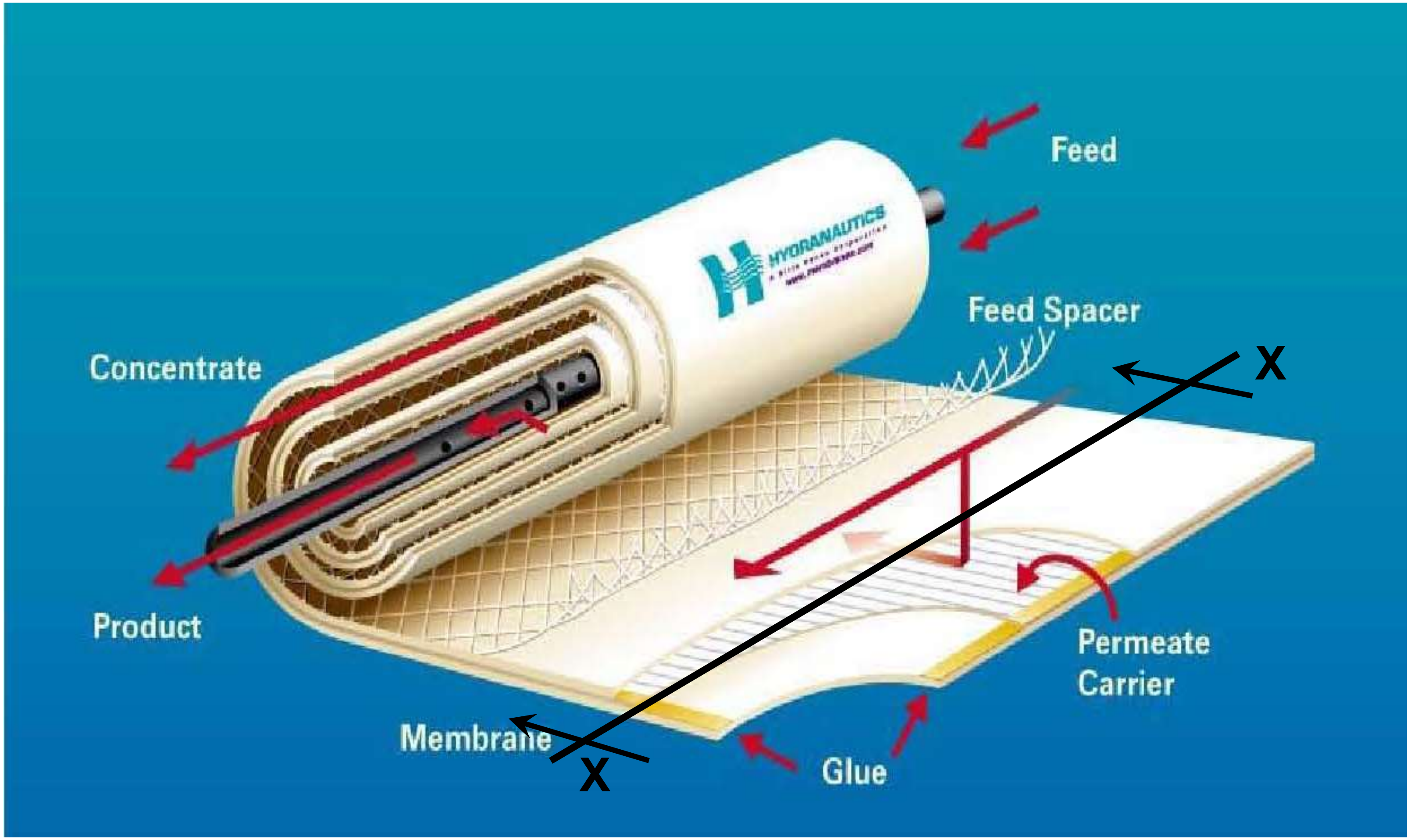
$$\left[\frac{\cancel{L}}{min}\right]\left[\frac{mg}{\cancel{L}}\right] = \left[\frac{\cancel{L}}{min}\right]\left[\frac{mg}{\cancel{L}}\right] + \left[\frac{\cancel{L}}{min}\right]\left[\frac{mg}{\cancel{L}}\right]$$

Assuming 1 min, units will be in mg

where: Q_F = Flow of Feed Water
C_F = Concentration of Feed Water
Q_P = Flow of Permeate
C_P = Concentration of Permeate
Q_C = Flow of Concentrate
C_C = Concentration of Concentrate

Spiral Wound Membranes

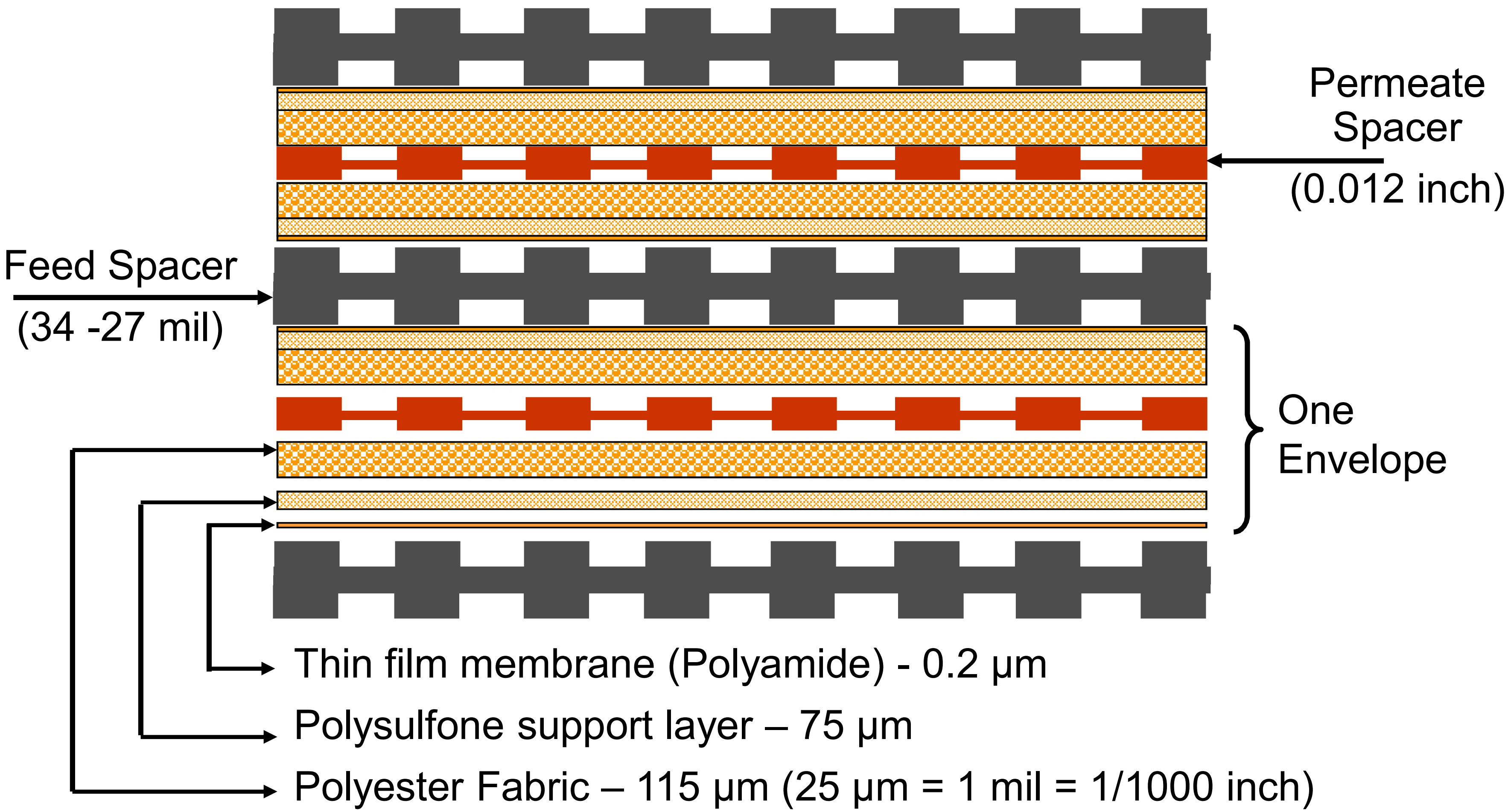
Membrane Structure



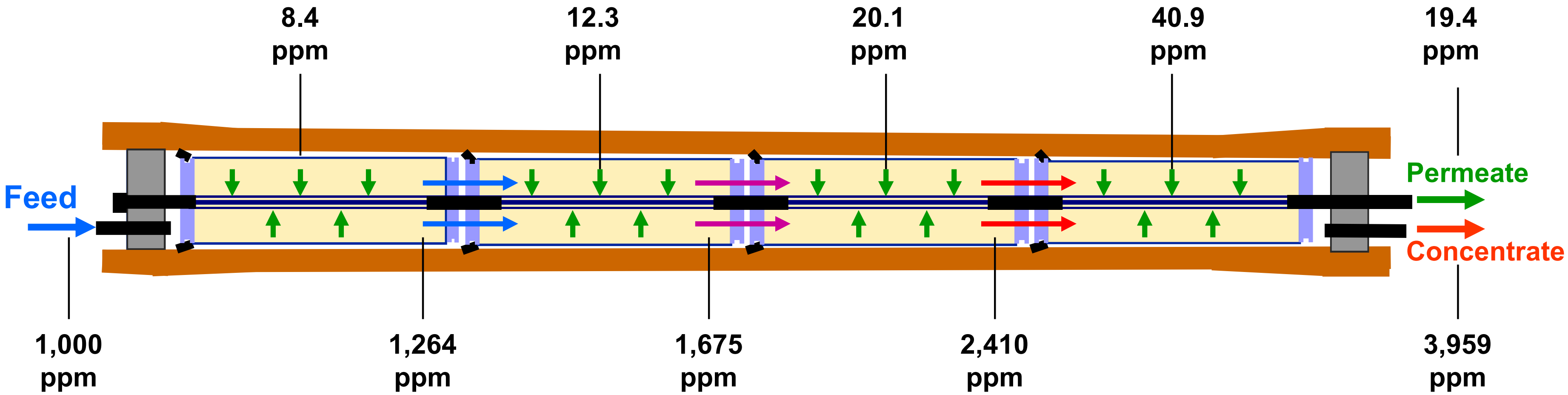
Membrane Structure

Thin Film Composite (TFC)

Cross Sectional View



Flow Directions



(Based on 75% Recovery)