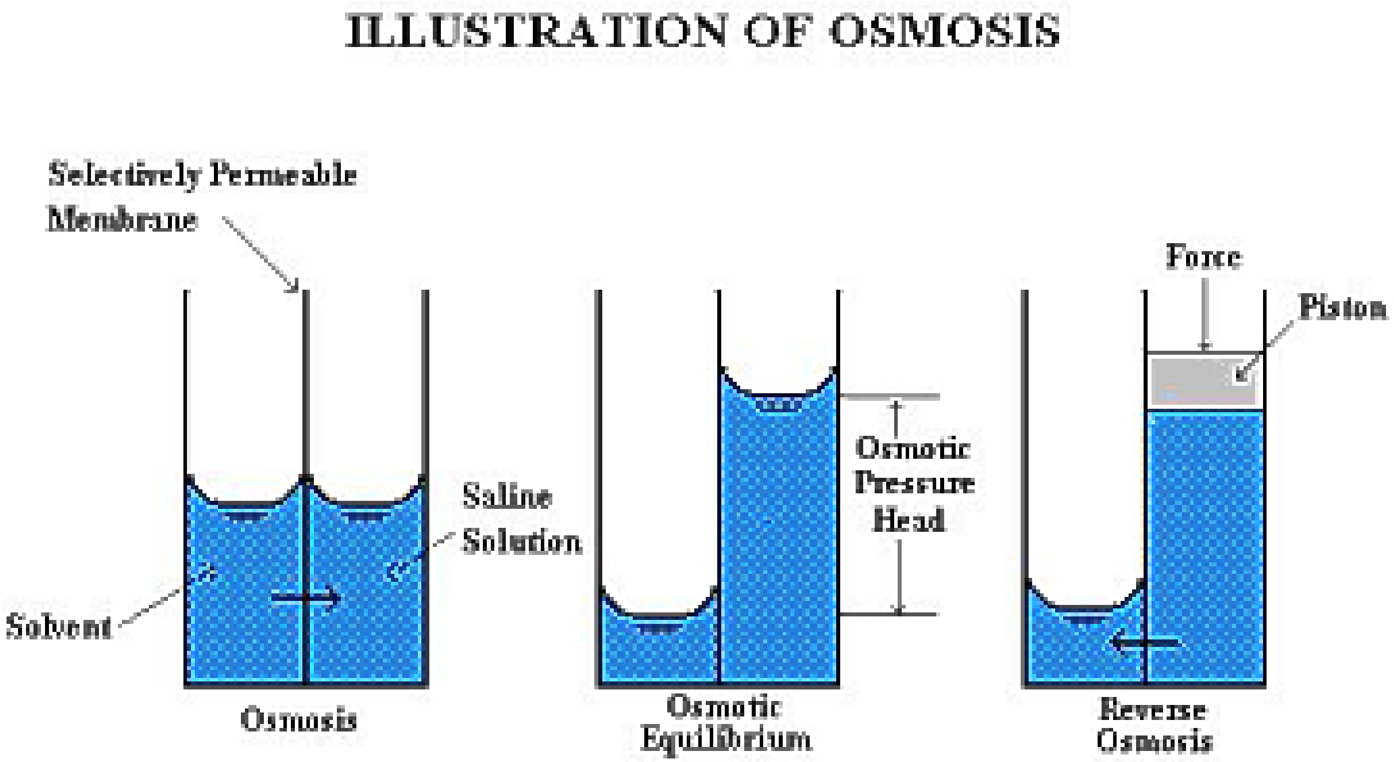
- Reverse Osmosis (RO) [Hyperfiltration]

- Developed in the 50's.
- Very popular and used.
- Ions and low molecular weight species (MW < 200).
- Pore size < 1 nm.
- Water molecules freely pass (0.2 nm).
- Driving force: pressure difference.
- Operating pressure between 10-25 (brackish) and 40-80 bar (seawater).
- Average flux: 5-40 L m^{-2} h^{-1}.

Membrane Separations

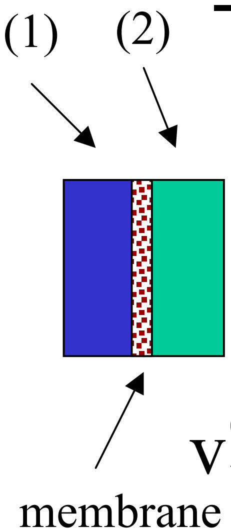
- Reverse Osmosis (RO)



Membrane Separations

- Reverse Osmosis (RO)

  - Why does water cross the membrane ?



$$\mu_i = \mu_i^o(T) + v_i \cdot P + R \cdot T \cdot \ln(\gamma_i \cdot c_i)$$

$$\mu_w^{(1)} = \mu_w^{(2)}$$

$$v_w^{(1)} \cdot P^{(1)} + R \cdot T \cdot \ln a_w^{(1)} = v_w^{(2)} \cdot P^{(2)} + R \cdot T \cdot \ln a_w^{(2)}$$

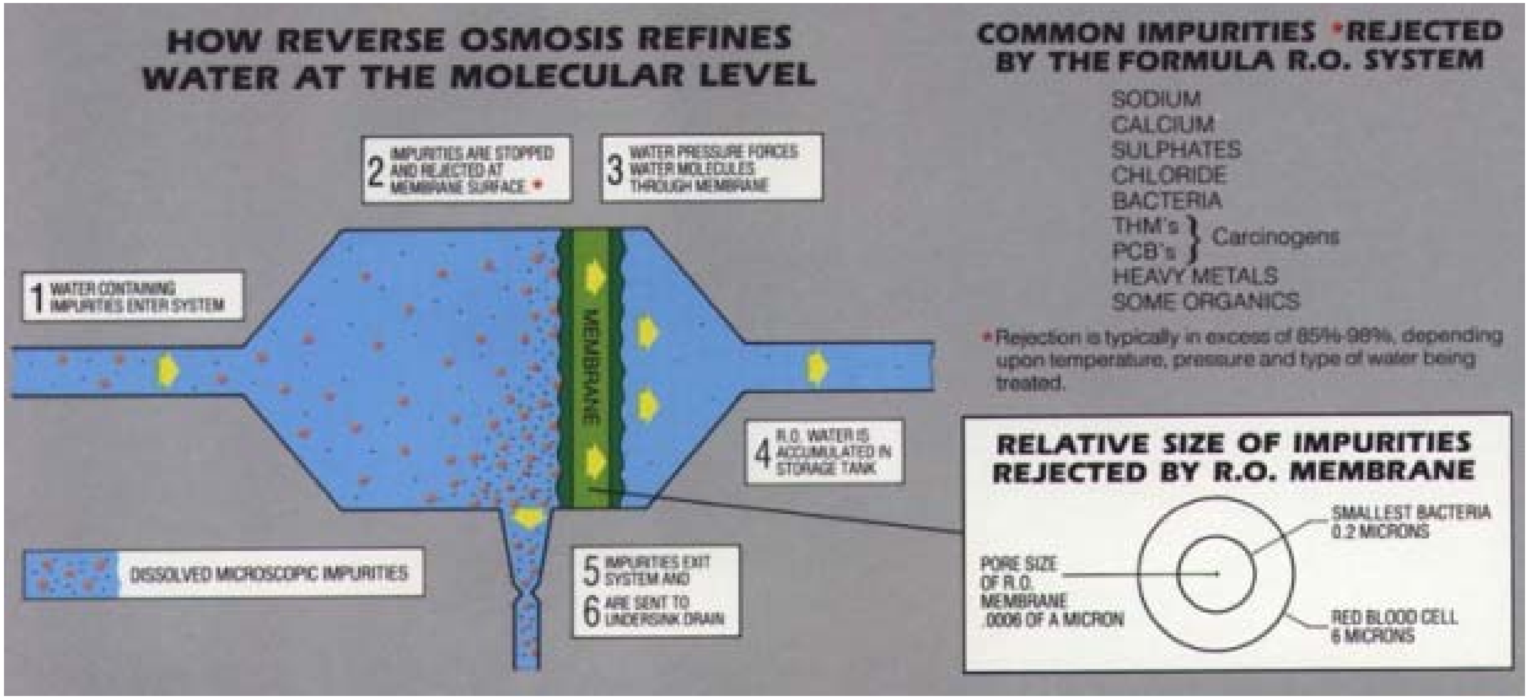
$$v_w \cdot \left(P^{(1)} - P^{(2)}\right) = R \cdot T \cdot \ln a_w^{(2)} - R \cdot T \cdot \ln a_w^{(1)}$$

Definition

$$\pi = -\frac{R \cdot T}{v_w} \cdot \ln a_w \Rightarrow \Delta P = \Delta \pi$$

$$\pi \approx \nu \cdot c \cdot R \cdot T \quad \text{if } c_{salts} \Downarrow$$

- Reverse Osmosis (RO)



- Reverse Osmosis (RO)

- The water freely flows through the membrane due to the pressure difference corrected by the $\Delta\pi$.

$$J_w = \frac{Q_w}{A_m} = A \cdot (\Delta P - \Delta\pi)$$

J_w: Solvent volume flux ($m^3/s \cdot m^2$)

Q_w: Solvent volume flowrate (m^3/s)

A_m: Membrane area (m^2)

A: Permeability ($m^3/s \cdot m^2 \cdot Pa$)*

ΔP: Hydraulic pressure difference (Pa)

$\Delta\pi$: Osmotic pressure difference (Pa)

* $A = A_o \cdot K_t \cdot K_c \cdot K_e$ t: temperature; c: compaction; e: fouling

- Reverse Osmosis (RO)

- Salt flux is due to both diffusion and convective transport.

$$J_s = J_w \cdot C_p = B \cdot \left(C_m - C_p\right) + M \cdot J_w \cdot C_m$$

$$C_p = \frac{J_s}{J_w} = \frac{B \cdot \left(C_m - C_p\right)}{A \cdot \left(\Delta P - \Delta\pi\right)} + M \cdot C_m$$

J_s: Solute mass flux (mol/s·m^2)

B_i: Permeability (m/s)

C_m: Solute concentration on the membrane surface (mol/m^3)

C_p: Solute concentration in the permeate (mol/m^3)

M: Distribution constant (~ 0.005)

- Reverse Osmosis (RO)

\- Thus a relation between the local rejection, R_l, and the permeate flux (or applied pressure) can be found.

$$R_l = \frac{C_m - C_p}{C_m} = 1 - \frac{C_p}{C_m}$$

$$\frac{1}{R_l} = \frac{1}{(1-M)} + \frac{B}{(1-M)} \cdot \frac{1}{J_w}$$

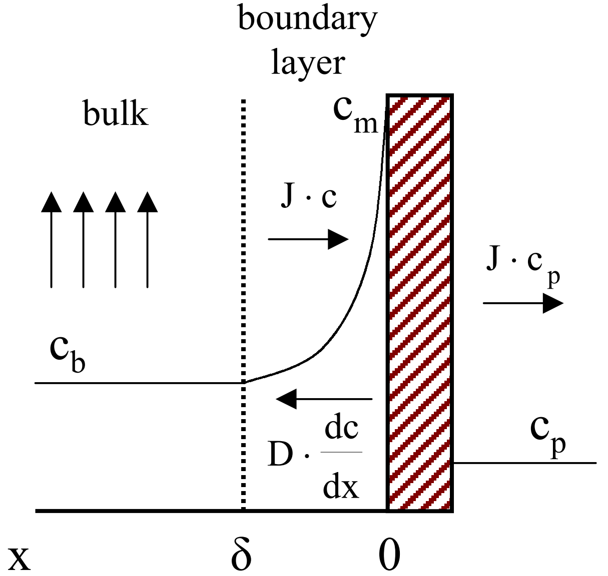
$$\frac{1}{R_l} = \frac{1}{(1-M)} + \frac{B}{(1-M)} \cdot \frac{1}{A \cdot (\Delta P - \Delta \pi)}$$

- Reverse Osmosis (RO)

  - Membranes mostly made of CA or PA.
  - Configuration in spiral-wound or hollow fiber.
  - Typical conversion between 10 and 30%.
  - Flow limited by concentration polarisation.
  - Rejection up to 99% (sometimes higher).
  - Fouling problems and cleaning. Pretreatment.

• Reverse Osmosis (RO)

- Concentration polarisation



$$\ln \frac{c_m - c_p}{c_b - c_p} = \frac{J \cdot \delta}{D}$$

$$\frac{c_m - c_p}{c_b - c_p} = \exp\left(\frac{J \cdot \delta}{D}\right)$$

$$\frac{c_m}{c_b} = \frac{\exp\left(\frac{J}{k}\right)}{R_1 + (1 - R_1) \cdot \exp\left(\frac{J}{k}\right)}$$

D: Diffusion coeficient (m^2/s)

δ: boundary layer thickness (m)

k=D/δ: mass transfer coeficient (m/s)

- Reverse Osmosis (RO)

- Applications: Drinking water, food industry, wastewater treatment. Examples:

√ Desalting of process water.
√ Desalination of brackish or seawater.
√ Production of ultrapure water for laboratories or electronic industry.

√ Concentration wastewater in paper pulping.
√ Concentration of juices, milk or sugar solutions.
√ Concentration of coffee, te or soups.
√ Concentration of aminoacids (and other pharmaceutical substances).

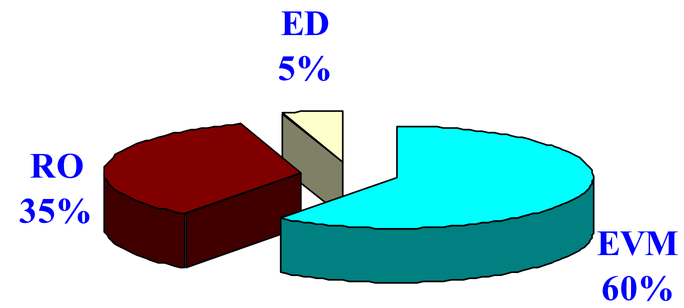
- Reverse Osmosis (RO)

- Seawater desalination:

30-40% market

Very competitive process

Module cascade in series and parallel

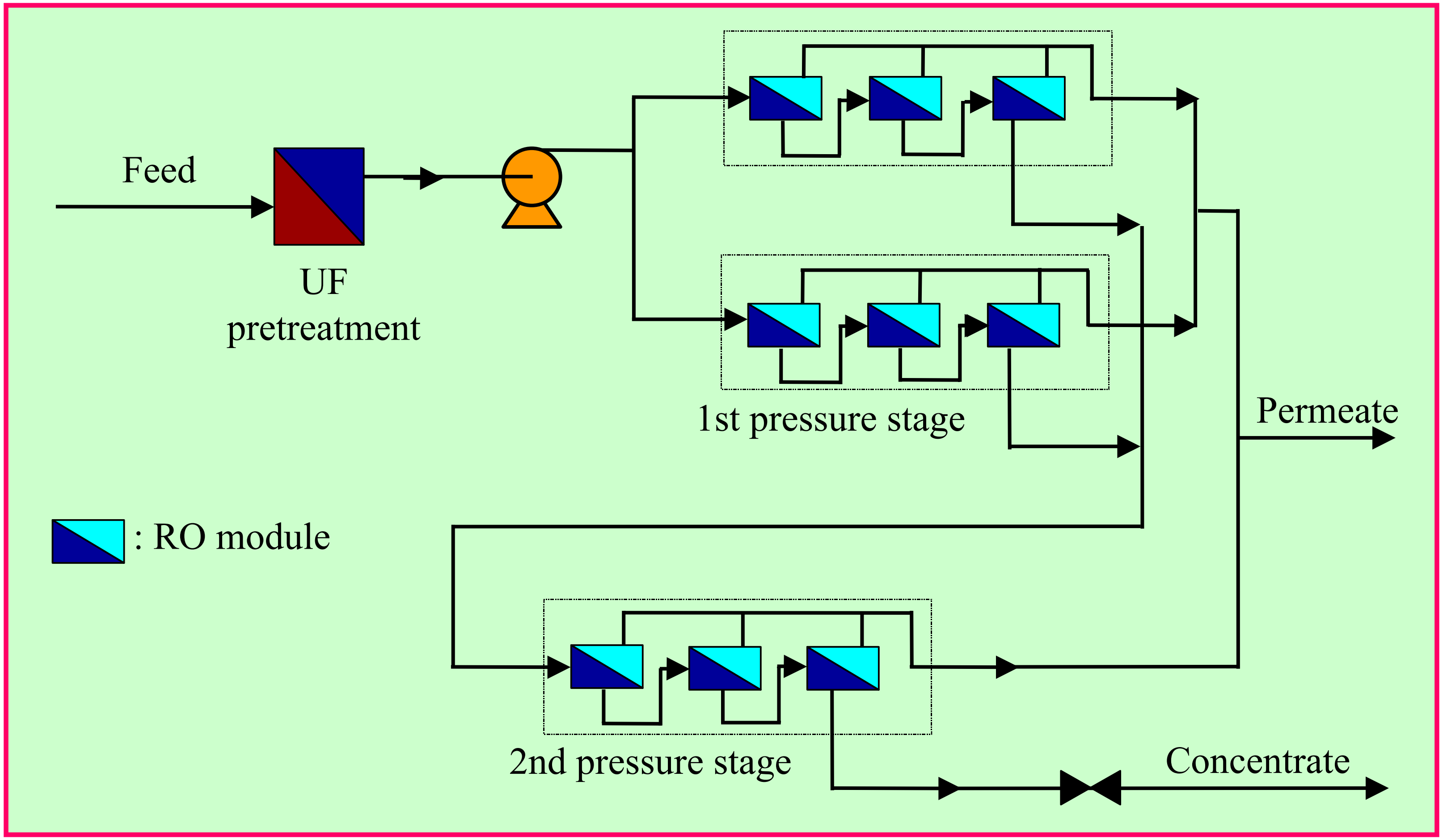


Desalination technologies (1996)

Comparison between the energetic cost for seawater desalination.

Process	Energy (kWh/m^3)
Multiple distillation	15.5
Reverse Osmosis	9
RO with energy recovery	6.5
Electrodialysis	12

- Reverse Osmosis (RO)



Water production plant based on RO.