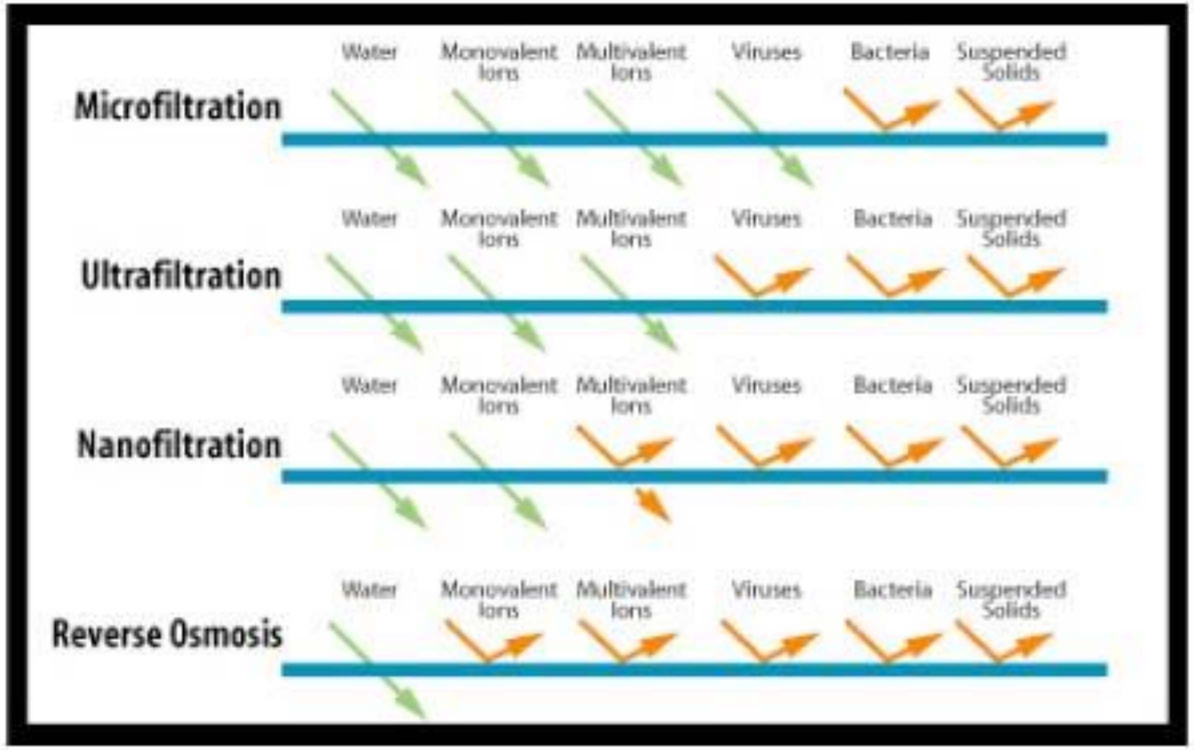
280.371 Process Engineering Operations

Membrane Separation Processes
Lecture 2

Dr Eli Gray-Stuart
Lecture slides by Prof Marie Wong

In this course we will focus on the pressure driven membrane processes

- Reverse Osmosis (Hyperfiltration)
- Ultrafiltration
- Microfiltration

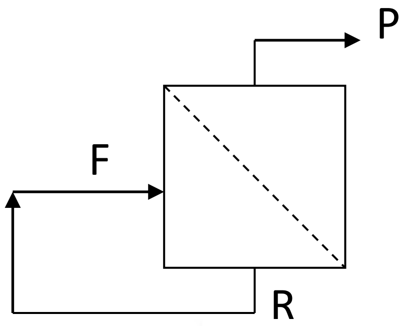


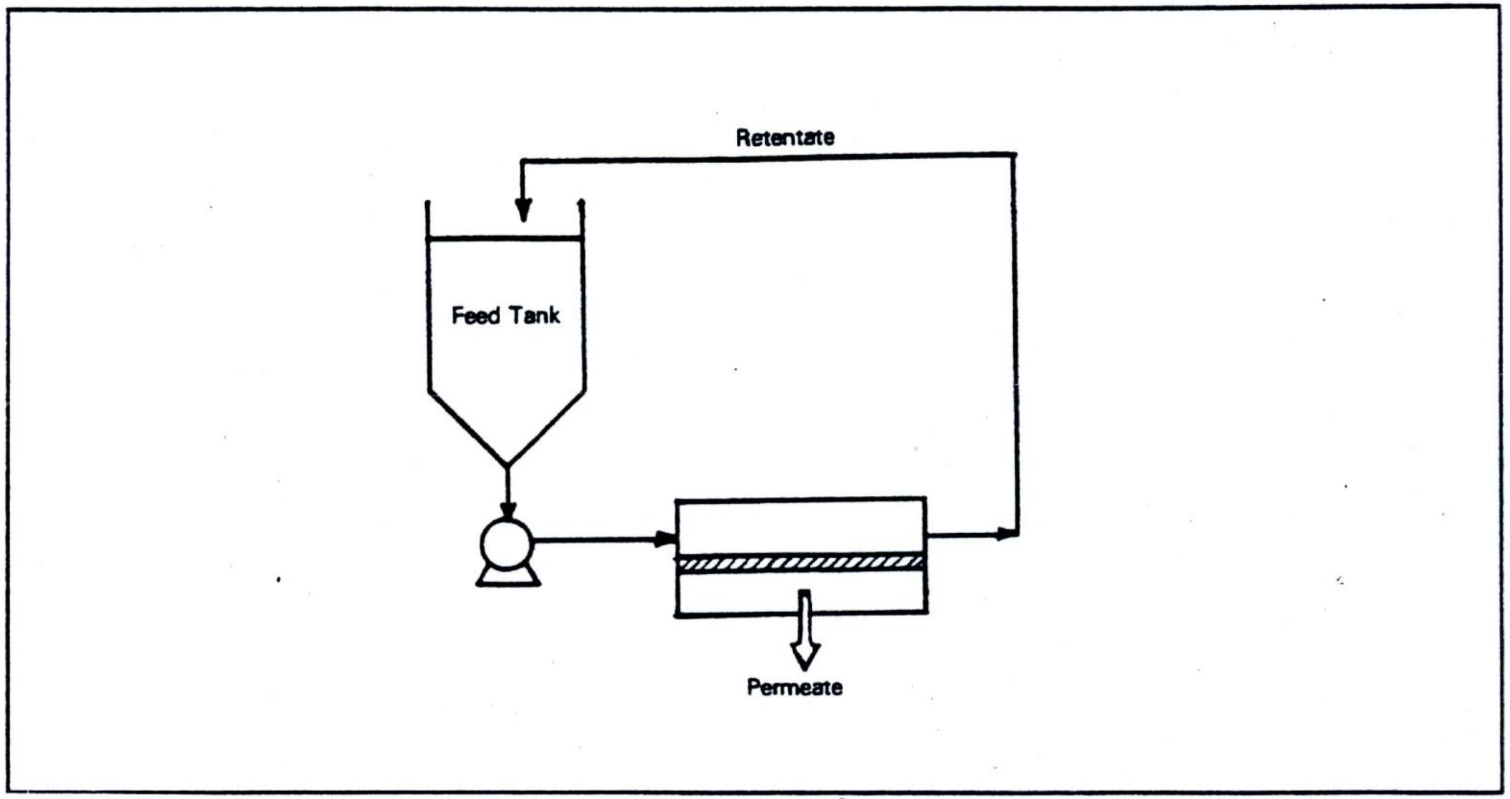
Membrane Process Characteristics

www.kochmembrane.com

Batch Operation

- Concentration increases over time
- Viscosity increases over time
- Flux declines over time

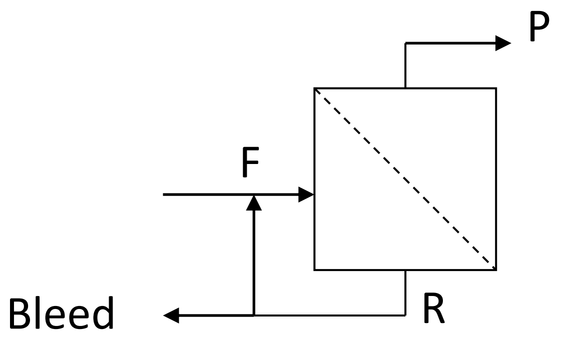


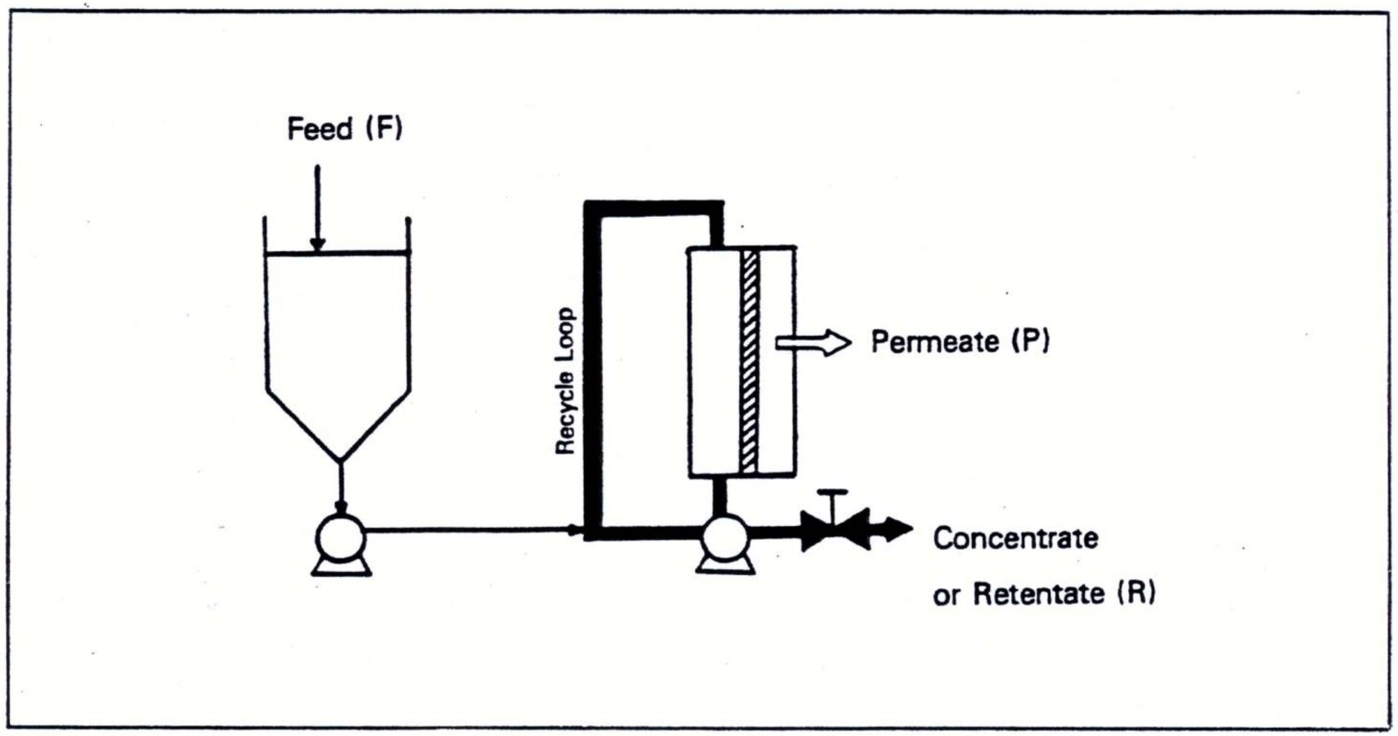


(Cheryan, 1986)

Continuous (feed & bleed) recycle – single stage

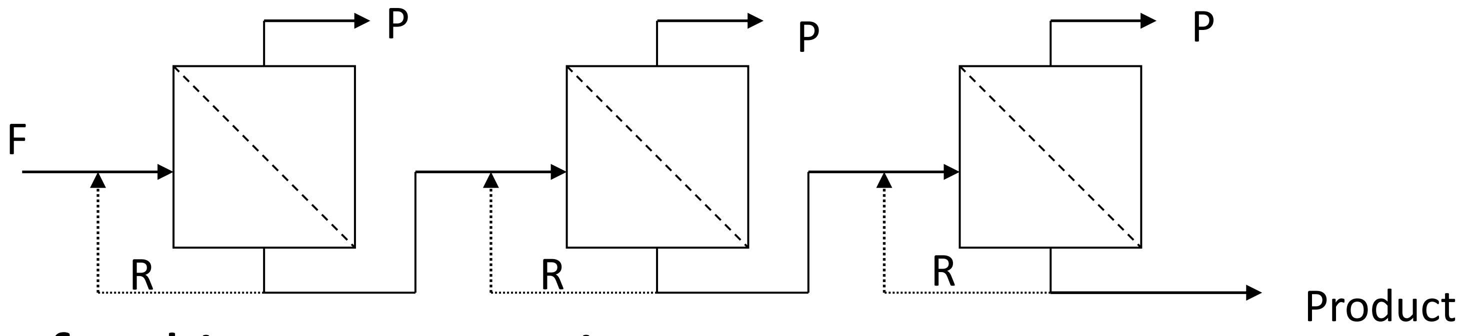
- concentration in recycle loop kept constant
- Initially unsteady state then will reach steady state



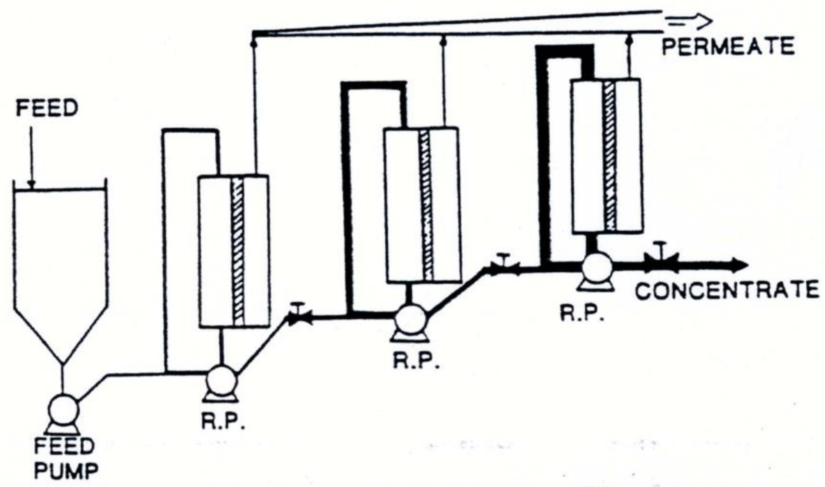


(Cheryan, 1986)

Continuous (feed & bleed) recycle – multi-stage

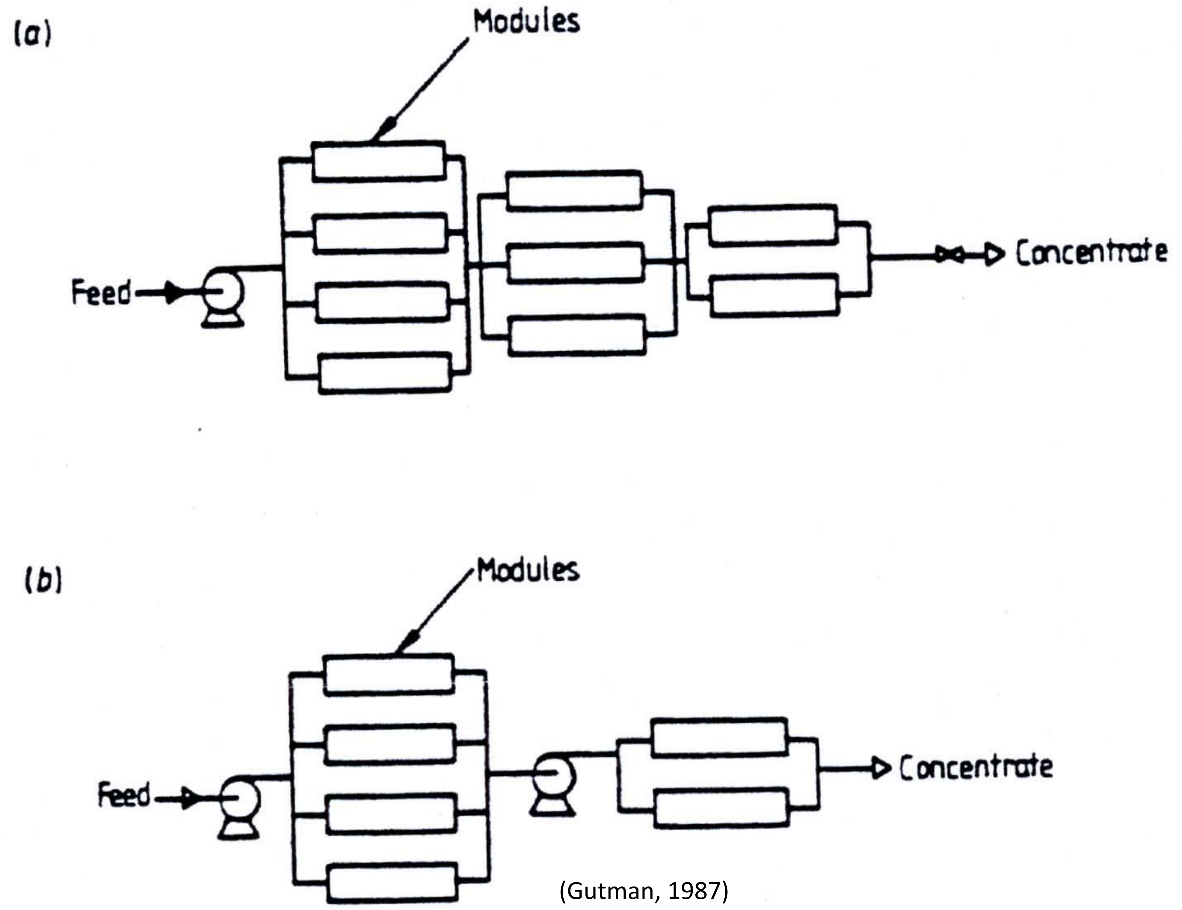


- Concentration of the feed increases as it moves to next stage



(Cheryan, 1986)

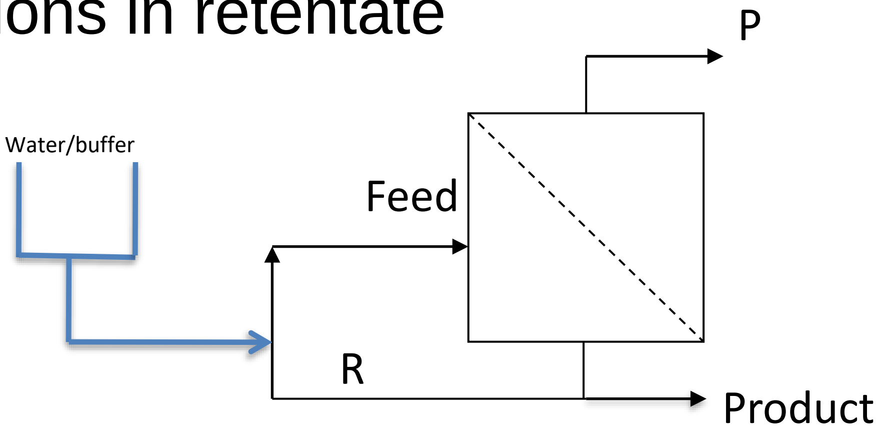
Continuous single-stage systems



(Gutman, 1987)

Diafiltration

- Operating procedure to achieve higher concentrations in retentate
- Addition of water or dilute solution to feed solution
- Washing effect
- Concentration of whey protein example



Product → Composition ↓	Cheddar whey	WPC-35	WPC-60	WPC-80
True protein %	0.60	3.02	10.74	22.48
NPN %	0.20	0.34	0.60	1.52
Total protein %	0.80	3.36	11.34	24.00
Lactose %	4.49	5.01	4.97	1.62
Lactic acid %	0.15	0.15	0.16	0.05
Ash (minerals) %	0.50	0.64	0.88	0.98
Fat %	0.06	0.31	1.09	2.40
Other components* %	-	0.13	0.46	0.95
Total solids %	6.00	9.60	18.90	30.00
Protein/TS %	-	35.00	60.00	80.00
PH	6.0-6.3	-	-	-
Amount kg/h	10,000	1,940	547	250

* 'Other components' in WPC refers to components which are not found in standard WPC analyses. If the N-conversion factor is higher than %N × 6.38, part or all of them may be protein

(APV, 1988)

Flux

- Volumetric or mass flow rate per unit area of membrane

$$J = \frac{volumetric\ \ or\ mass\ permeation\ \ rate}{membrane\ area}$$

- Volumetric flux $m^3\ m^{-2}\ s^{-1}$, $m\ s^{-1}$, LMH

- Mass flux $kg\ m^{-2}\ s^{-1}$

- Flux = f(driving force, system, process fluid, operating parameters)

Determining Flux - theoretical vs empirical

$$J = \frac{driving\ \ force}{\text{resistances}}$$

$$J = k(driving\ \ force)$$

$$J = \frac{\Delta P_{TM}}{\mu(\sum Resistances)}$$

$$J = \frac{volumetric\ or\ mass\ permeation\ rate}{membrane\ area}$$

$$J = \frac{Permeate\ flow\ rate}{membrane\ area} = \frac{P}{A \times t}$$

Solute Retention Coefficient

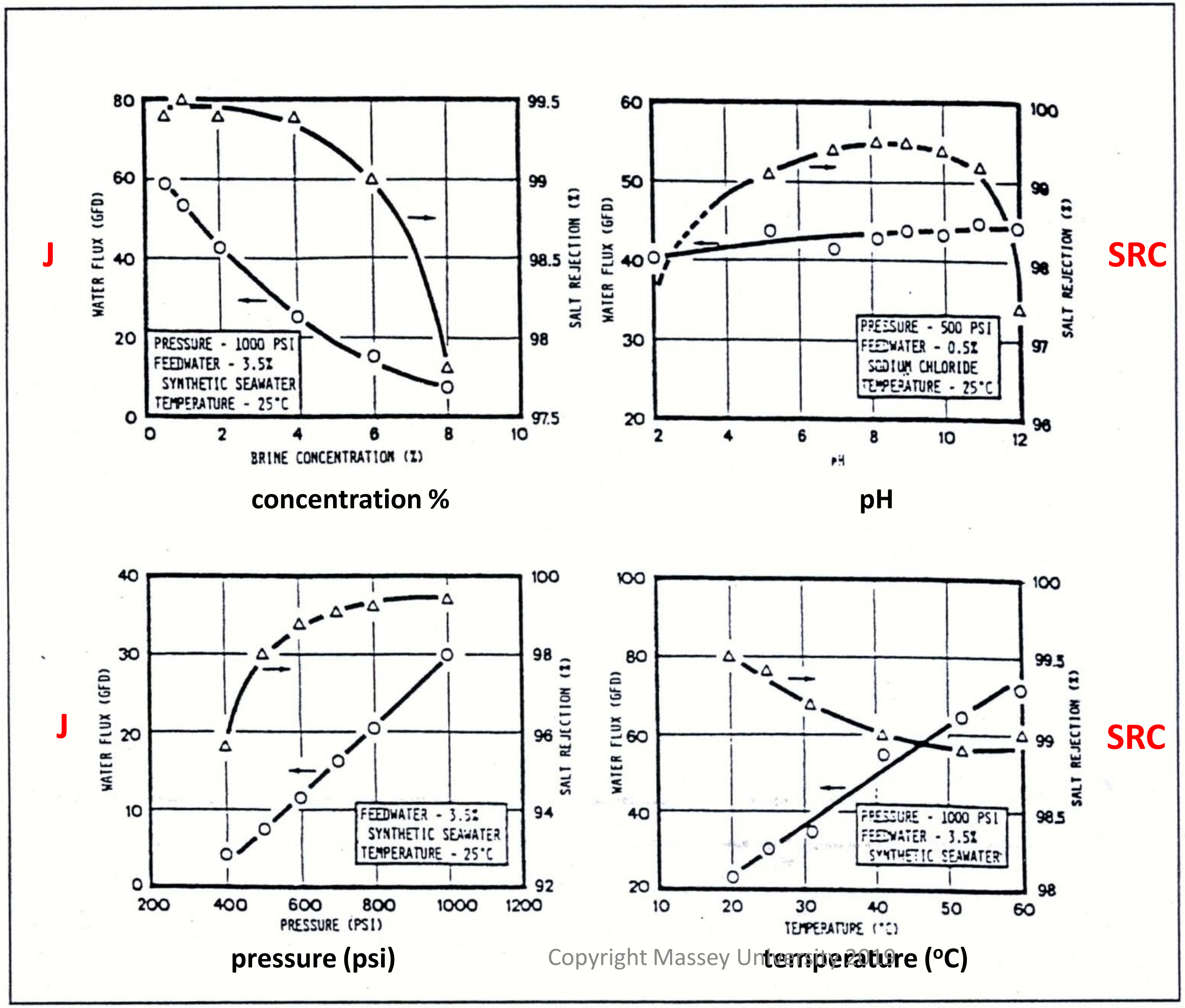
MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

- = Solute Rejection Coefficient
- Measure of a membrane's ability to retain a solute.

$$SRC = \frac{solute\ concentration\ in\ feed\ - solute\ concentration\ in\ permeate}{solution\ concentration\ in\ feed} \quad (1)$$

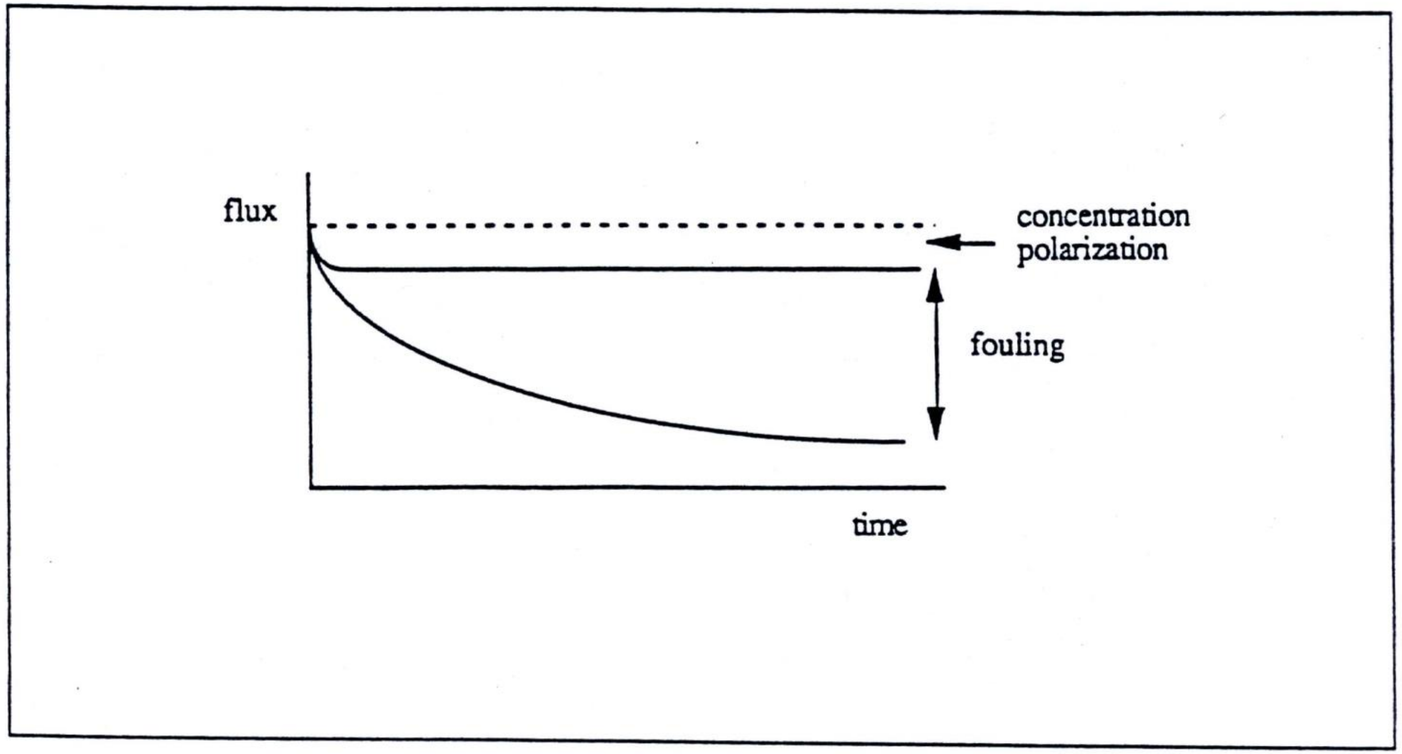
$$SRC = 1 - \frac{c_p}{c_f} = 1 - \frac{c_p}{c_b} \quad (2)$$

Flux (J) and Solute Retention (SRC)



(Belfort, 1984)

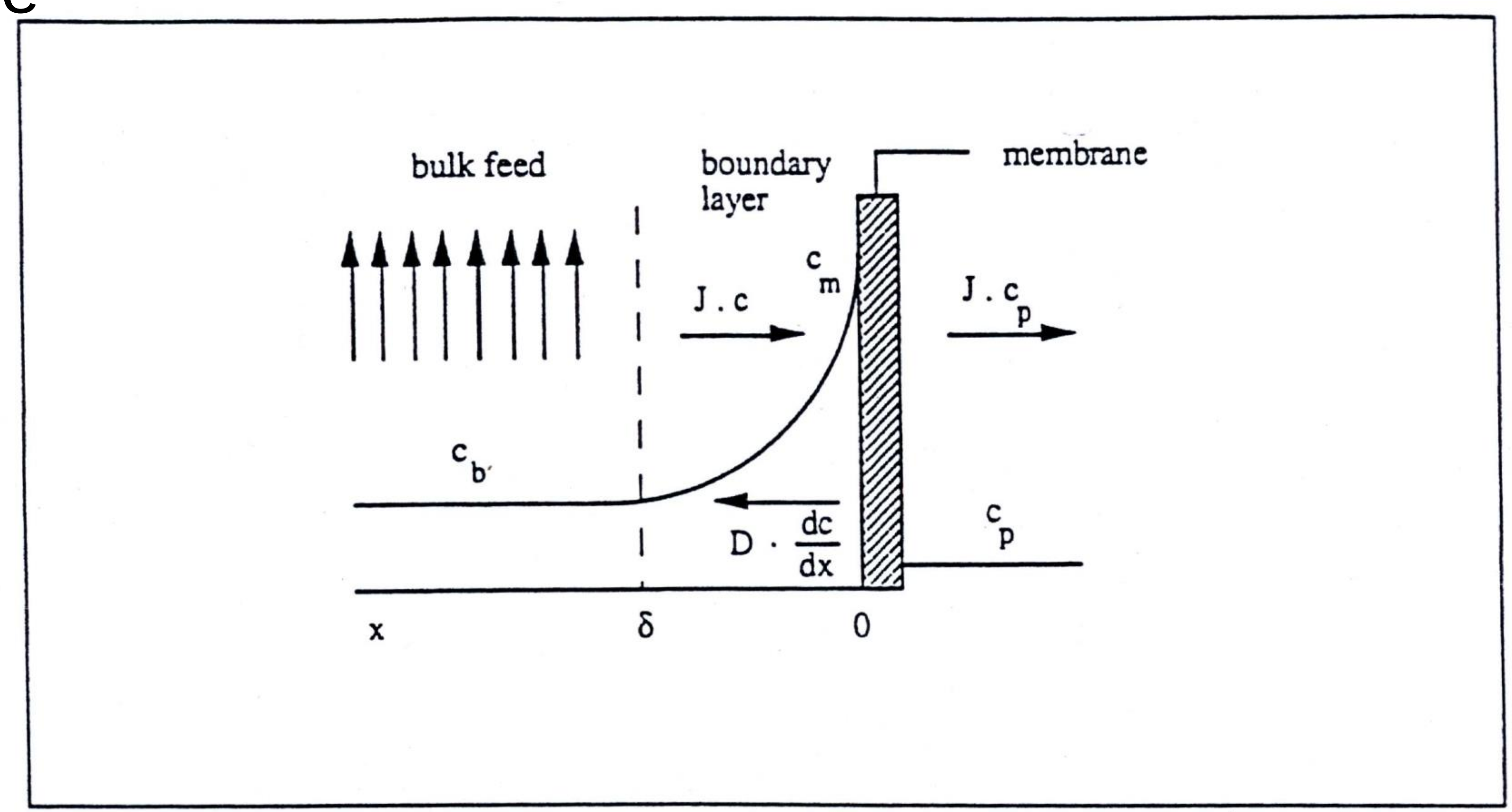
Flux Decline



- Characteristic of pressure driven processes
- Due to concentration polarisation and membrane fouling

Concentration Polarisation

- A result of the increase in solute concentration adjacent to membrane
- Reversible



(Mulder, 1996)

Consequences of concentration polarisation

- Retention can be lower
- Retention can be higher
- Flux will be lower

Factors which increase concentration polarisation

- Increased flux
- Increased solute rejection
- Low shear at membrane surface
- Low diffusivity due to size of solute molecule, temperature or viscosity of feed

Methods to reduce concentration polarisation

- Increase cross-flow velocity
- Reduce channel height
- Increase temperature to increase diffusivity and decrease viscosity
- Increase turbulence through turbulence promoters, pulsating feed flow, back flushing or by using membranes with a corrugated surface.

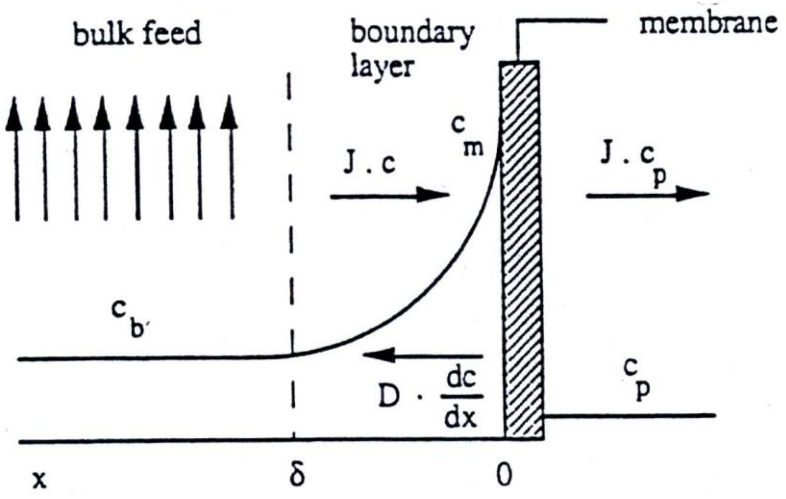
- If a steady state (dynamic equilibrium) is established the following relationship will hold

$$\begin{matrix}\text{Solute transport} \\ \text{to membrane}\end{matrix} + \begin{matrix}\text{back diffusion} \\ \text{of solute}\end{matrix} = \begin{matrix}\text{removal rate of} \\ \text{solute in permeate}\end{matrix}$$

$$Jc + D\frac{dc}{dx} = Jc_p \qquad (3)$$

limits $x \to 0$, $c = c_m$
$x \to \delta$, $c = c_b$

$$\frac{c_m - c_p}{c_b - c_p} = \exp\left(\frac{J\delta}{D}\right) \qquad (4)$$



The mass transfer coefficient is

$$k = \frac{D}{\delta} \tag{5}$$

$$\frac{c_m - c_p}{c_b - c_p} = \exp\left(\frac{J}{k}\right) \tag{6}$$

Recall: Solute retention coefficient (SRC)

$$SRC = 1 - \frac{c_p}{c_b} \tag{2}$$

From Equation (2) and (6) we can obtain

$$\frac{c_m}{c_b} = 1 - SRC + SRC \exp\left(\frac{J}{k}\right) \tag{7}$$

Concentration polarisation may be characterised using the polarisation modulus (M)

$$\mathrm{M} = \frac{\text{solute concentration adjacent to membrane surface}}{\text{solute concentration in bulk stream}} = \frac{c_m}{c_b} \quad (8)$$

If $c_p = 0$, i.e. the solute is completely retained by the membrane, i.e. SRC = 1

Then Equation 7 simplifies to

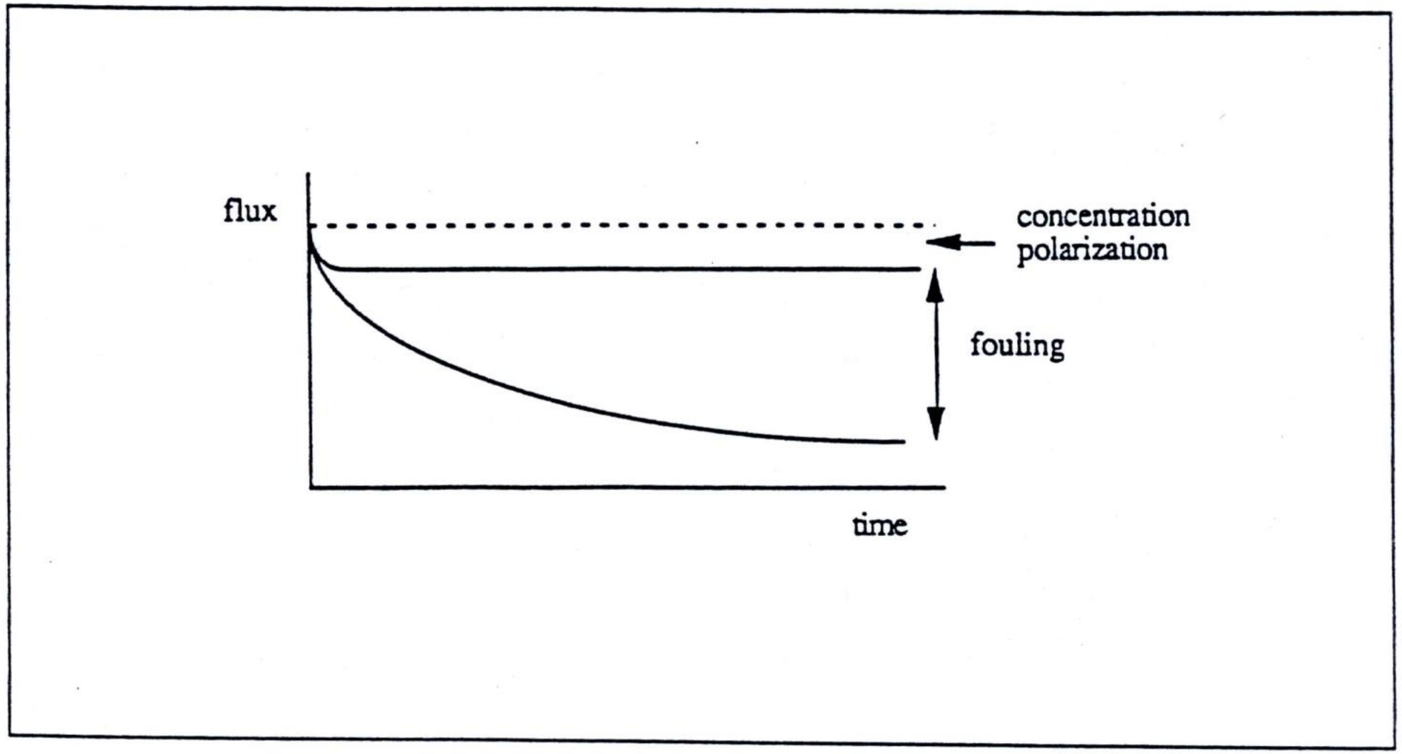
$$M = \frac{c_m}{c_b} = \exp\left(\frac{J}{k}\right) \quad (9)$$

Flux equation from membrane mass balance

$$\frac{c_m}{c_b} = exp\left(\frac{J}{k}\right) \qquad (9)$$

$$J = k\,ln\left(\frac{c_m}{c_b}\right)$$

Flux Decline



- Characteristic of pressure driven processes
- Due to concentration polarisation and membrane fouling

Membrane Fouling

MASSEY UNIVERSITY
TE KUNENGA KI PŪREHUROA
UNIVERSITY OF NEW ZEALAND

- Due to physico-chemical interactions of the process fluid with the membrane or due to water supply
- Characterised by flux decline with increased solute rejection
- Irreversible during operation
- Removed by increasing shear, changing ionic charges or changing surface activity i.e. cleaning
- Caused by protein, cells, polysaccharides, colloidal salts and synthetic polymers
- Silica and other ions in water supply and many antifoaming agents are strong foulants

Fouling mechanisms

- Absorption (into)
- Adsorption (surface only)
- Aggregation
  - Blocking
  - Gelation
  - Polymerisation
  - Flocculation
  - Adhesion
  - Coagulation

Cleaning of membranes

- Water flush – not town supply, RO
- Alkalis (NaOH)
- Acids (H_3PO_4, acetic acid, citric acid)
- Enzymes (proteases, amylases)
- Sanitisers (NaOCl, H_2O_2, NaS_2O_5)
- Detergents
- Depends on type of foulant on membrane
- Must be compatible with membrane
- Water flush between each cleaner
- Contact time and temperature important

Modelling of flux decline

The flux through the membrane can be described the Darcy equation

$$J = \frac{(driving \;\; force)}{(dynamic \;\; viscosity) \; (resistance \;\; to \, flux)}$$

$$J = \frac{\Delta P_{tm}}{\mu R_{tot}}$$

$$J = \frac{\Delta P_{tm}}{\mu \left(R_m + R_{rf} + R_{if} \right)}$$

For a membrane with cake build-up

$$J = \frac{\Delta P}{\mu\left(R_m + R_C\right)}$$

$$Cake\ thickness = \frac{R_C}{\alpha}$$

α = specific cake resistance (m^{-2})

Resistances to flux

R_m resistance of the clean membrane

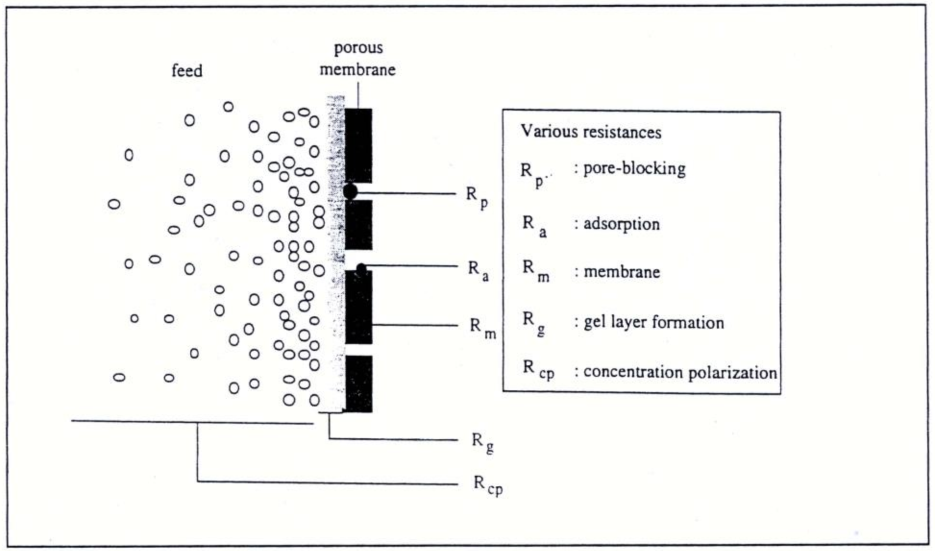
R_g gel layer resistance

R_{cp} concentration polarisation

R_a resistance due to adsorbed material - on surface or in pores

R_p resistance due to plugging of pores

R_c resistance due to cake layer formation



$$J = \frac{\Delta P_{TM}}{\mu(\sum Resistances)}$$

Learning outcomes achieved:

- For applications in Lecture 1, which would be the best system configuration?
- Solve problems for SRC and ΔP_{TM}
- Derive flux equation from mass balance at membrane

$$SRC = 1 - \frac{c_p}{c_f} \qquad = 1 - \frac{c_p}{c_b}$$ where c_b = concentration in the bulk flow

$$\frac{c_m}{c_b} = \exp\left(\frac{J}{k}\right)$$

$$J = k \ln\left(\frac{c_m}{c_b}\right) \qquad k = \frac{D}{\delta}$$

$$J = \frac{\Delta P_{TM}}{\mu R_{Total}}$$

$$J = \frac{Permeate\ flow\ rate}{membrane\ area} \qquad = \frac{P}{A \times t}$$

Problem 2

The permeate flux through a membrane under optimal processing conditions is 6×10^{-4} $m^3m^{-2}s^{-1}$. How much membrane area would you need to produce 1440 m^3 of filtered broth within an 8-h shift, if the flux does not change?

Problem 3

An ultrafiltration membrane has a pure water flux of 5.6×10^{-5} $m^3m^{-2}s^{-1}$ at a transmembrane pressure of 3×10^5 Pa. When the membrane is used to concentrate an aqueous slurry of yeast cells at a transmembrane pressure of 4×10^5 Pa, the steady-state flux is reduced to 8.3×10^{-6} $m^3m^{-2}s^{-1}$ because of the buildup of a cake layer of cells. The specific resistance of the cake is 1.5×10^{18} m^{-2}. Calculate the thickness of the yeast cake. How would you attempt to reduce the resistance offered by the cake? What is the likely result of increasing the processing temperature by 5 °C? (The viscosity of water at the operating conditions was 1.2×10^{-3} Pa.s).

Problem 4

During steady-state concentration of albumin by ultrafiltration, the permeate stream contained albumin at a concentration of 0.002 kg m^{-3}. The concentration of albumin in the bulk feed was 2 kg m^{-3}. Calculate the solute rejection coefficient, *SRC*.