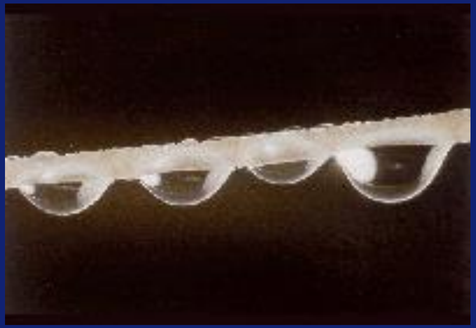
LABORATOIRE DE GÉNIE CHIMIQUE
TOULOUSE • UMR 5503

14TH WORLD FILTRATION CONGRESS
BORDEAUX FRANCE
30 JUNE - 4 JULY 2025

Short courses

Membrane : basics



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Course WFC 2025

www.patricebacchin.fr

www.lgc.cnrs.fr

Université de Toulouse

UNIVERSITÉ TOULOUSE III PAUL SABATIER

Course outline

1: Introduction to Membrane Separation Processes

- **Definition and fundamental principles**
- **Classification of membrane processes**
- **Comparison with other separation technologies**
- **Industrial applications and case studies**

2: Membrane Structures, Operating Parameters, and Characterization

- Relationship between structure and function: pore size, selectivity, permeability
- Definition and measurements of operating parameters characterizing selectivity and performance
- Membrane characterization techniques

3: Limitations of Membrane Processes: Fouling and Solutions

- Types of fouling
- Mechanisms and impact on performance
- Initiation to modeling
- Prevention and cleaning strategies

Round of table

What do you know about membrane processes ?

Specific expectations ?

(not listed in the course outline)

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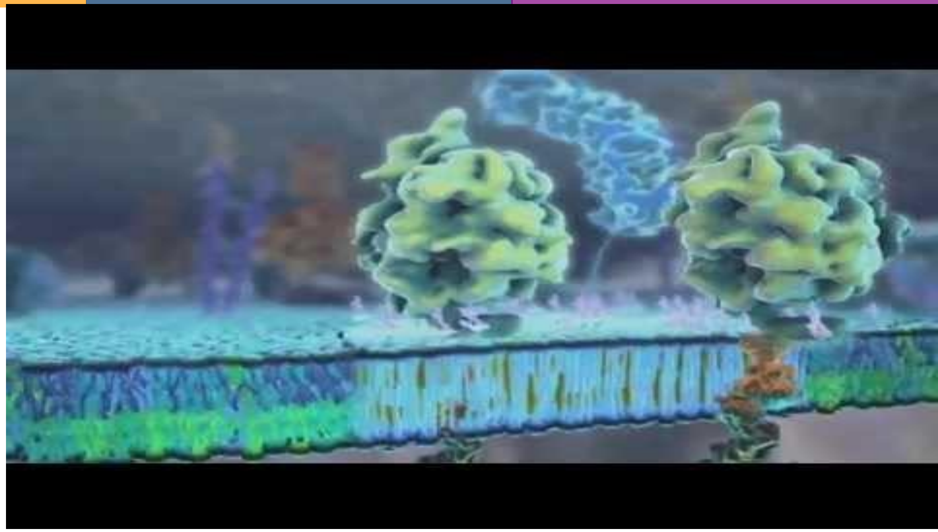
Biological and artificial membranes



https://youtu.be/-TgmrI1y6qc

In biology :

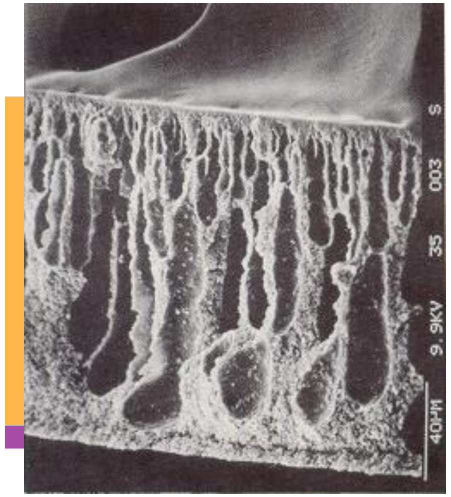
Dynamic lipid bilayer structure with proteins embedded in rigid floating structures (RAFT) over 10-30% of the surface to ensure selectivity between the inside and outside of the cell

Stability thanks to interactions between the various components

Asymmetrical materials (organic or mineral)

macroporous support (for mechanical strength)

skin or surface layer (for selectivity)



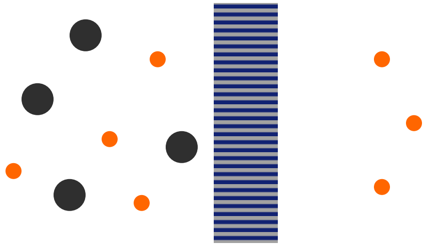
In process :

Stable artificial structure with charged pores
Stability thanks to organic or inorganic chemical bonds

But often bioinspired by natural membranes
The Graal !

Membranes : definition and classification from driving forces

Membrane: permselective barrier between two phases (reducing the movement of a solute or fluid)



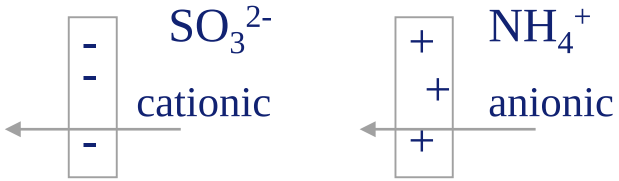
Driving Force →

$$\nabla\mu = RT\nabla \ln a + v\nabla P - zF\nabla E$$

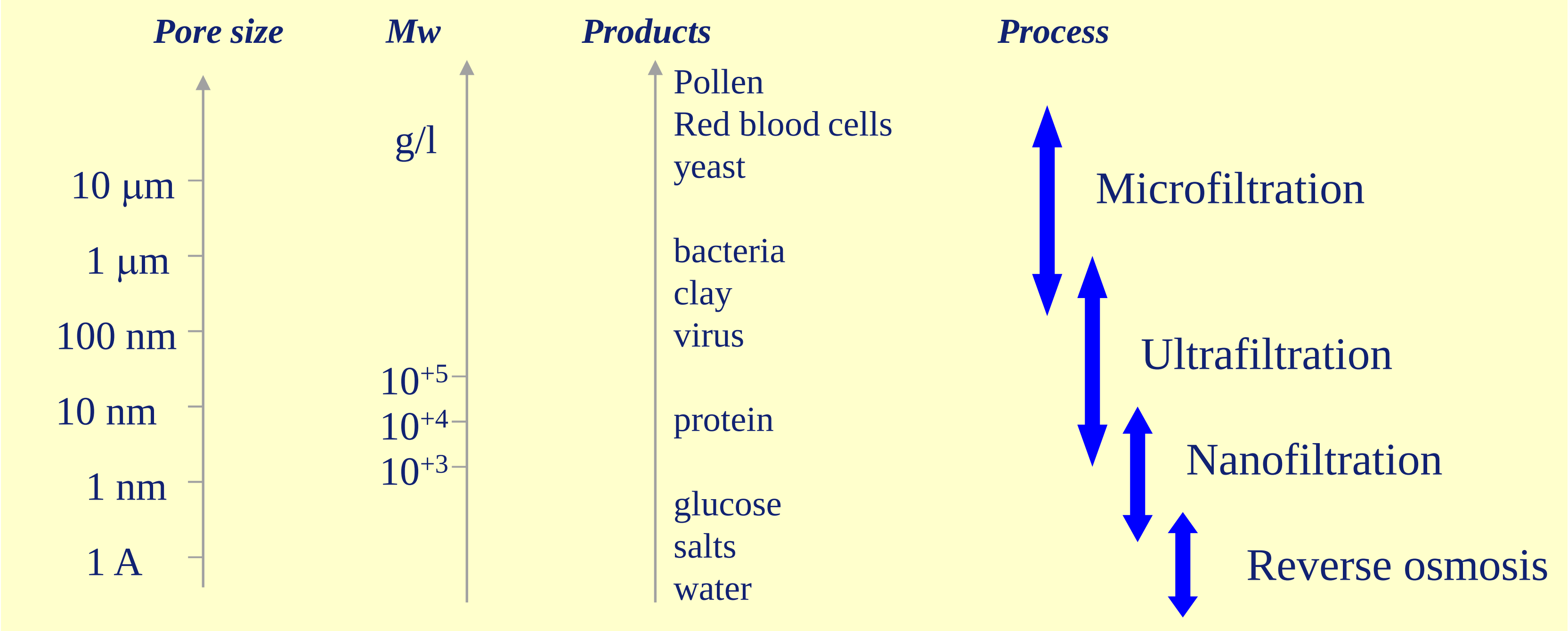
	activity ($RT\nabla \ln a$)	pressure ($v\nabla P$)	Electric field ($zF\nabla E$)
Microfiltration *Ultrafiltration* *Nanofiltration* *Reverse Osmose*	Antagonist force	Driving force	
Electrodialysis	Antagonist force		Driving force
Pervaporation *Dialysis*	Driving force	Antagonist force	

Membranes ... Classification from structure

Structure ➤ Charged



➤ Porous

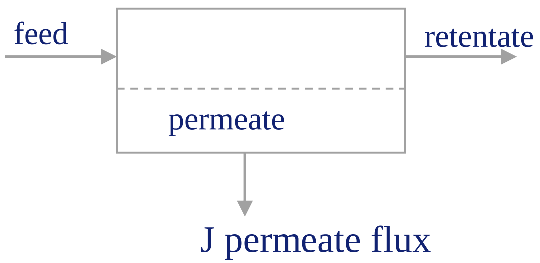


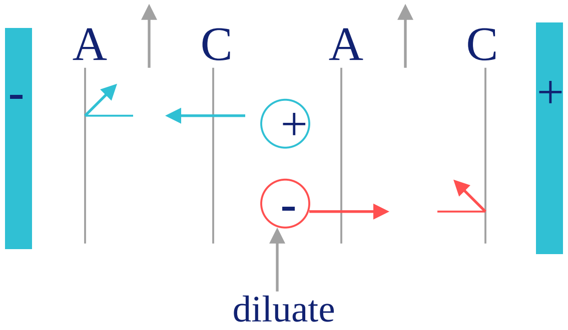
➤ Dense

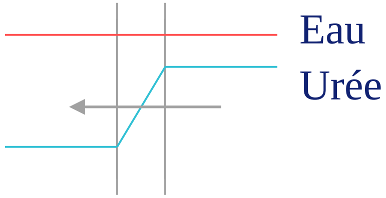
Hydrophilic or hydrophobic material

Membrane processes : applications and competing processes

			Applications	Competing processes
$\nabla\mu = v\nabla P$	***Microfiltration*** ***Ultrafiltration*** ***Nanofiltration*** ***Reverse osmosis***	ΔP= transmembrane pressure (see scheme 1)	Clarification Water and waste water treatment Desalination	Settling Floculation/ settling Distillation
$\nabla\mu = zF\nabla E$	***Electrodialysis*** ***Reverse ED***	(see scheme 2)	Desalination Valorization of food product Energy harvesting	Ionic exchange
$\nabla\mu = RT\nabla \ln a$	***Dialysis*** ***Pervaporation***	(see scheme 3)	Artificial kidney COV Extraction	Precipitation Liquid/liquid Extraction







Food Biomedical Pharmaceutical Environnement Materials

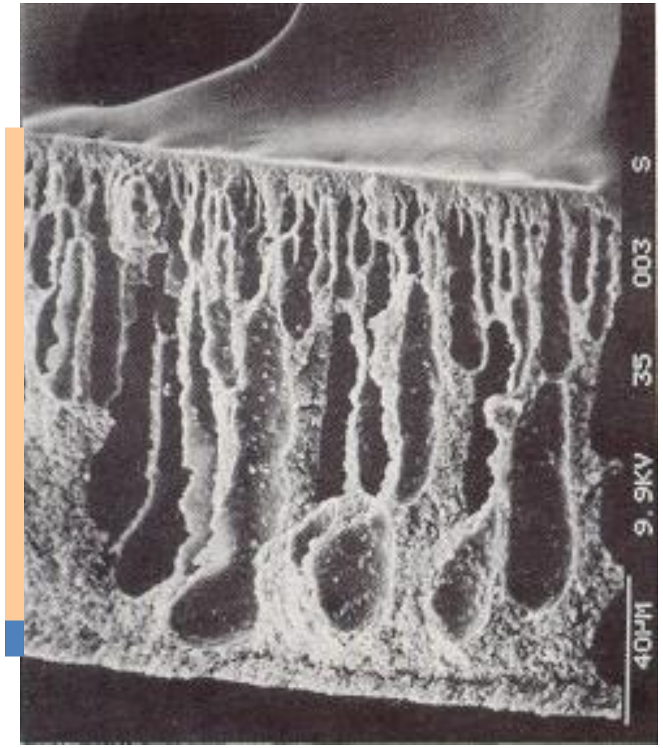
Membrane materials

Synthetic materials organic (cellulose acetate, polysulfone …)
inorganic (ZrO_2, TiO_2, alumine)

Asymmetric materials

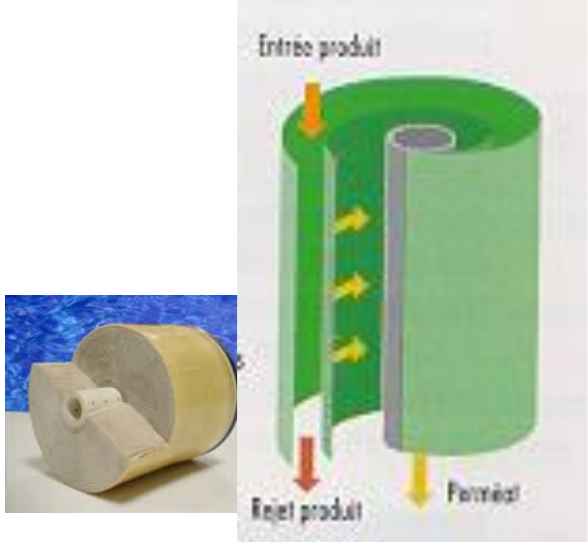
macroporous support
(for mechanical strength)

skin or surface layer
(for selectivity)



Membrane technologies : some examples

Spiral



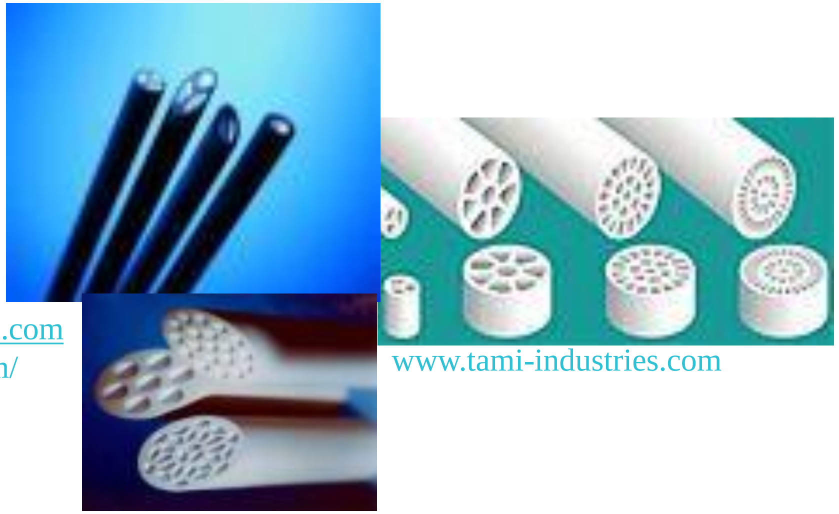
www.dow.com/liquidseps
https://www.lenntech.com/

Planar

www.sterlitech.com/

Tubular

Φ_{int} 1 cm

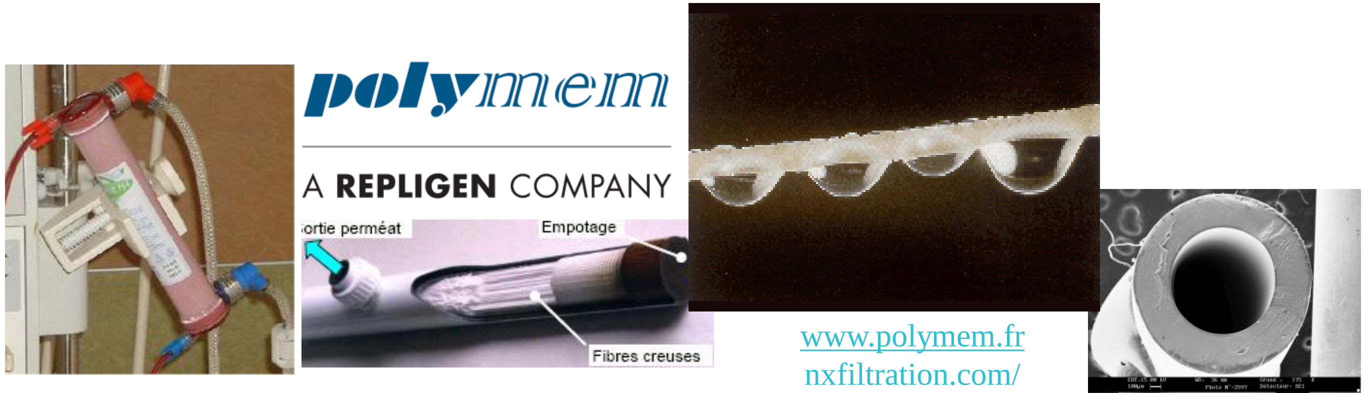


www.alsys-group.com
www.pall.com/
www.tami-industries.com

Hollow fiber

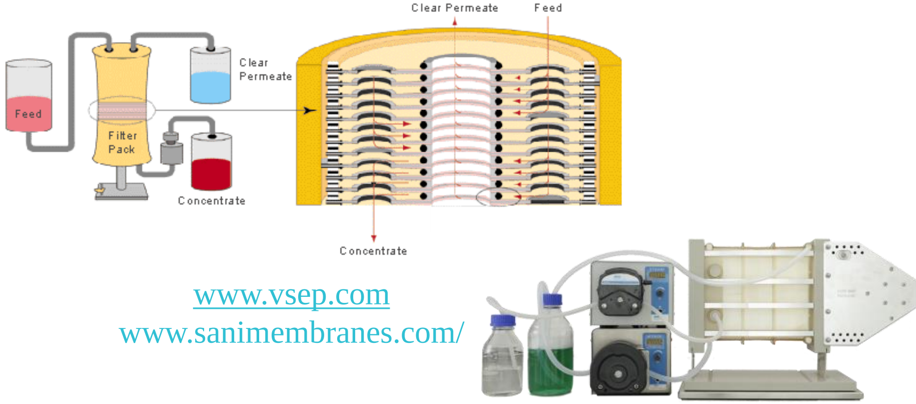
Φ_{int} 0,1-1 mm

hemotech.fr



www.polymem.fr
nxfiltration.com/

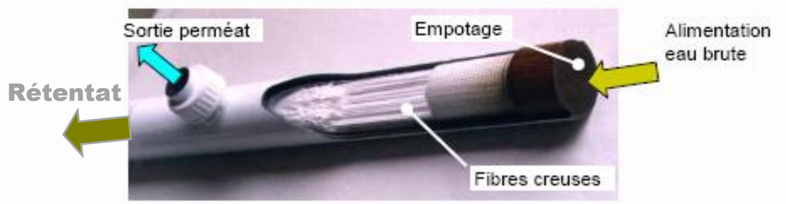
Vibrating disk

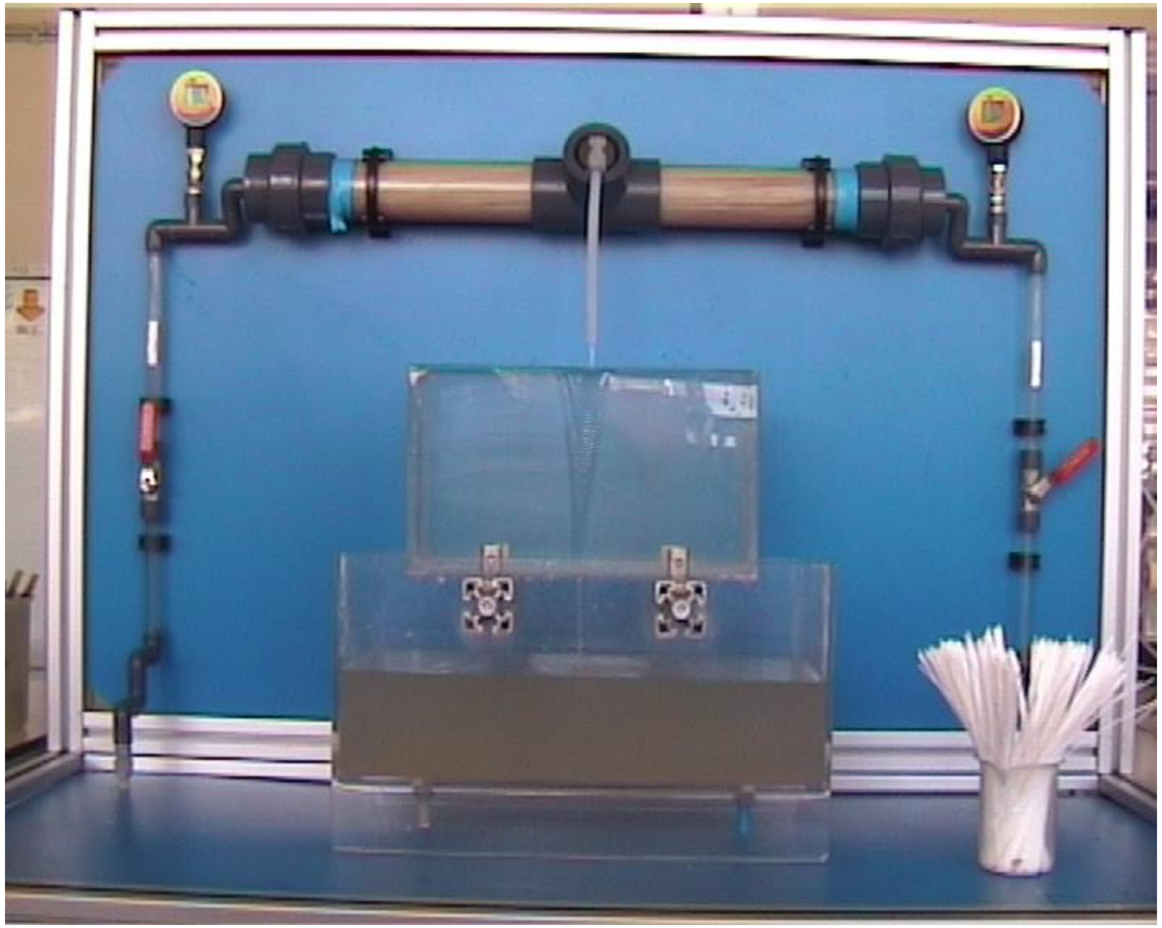


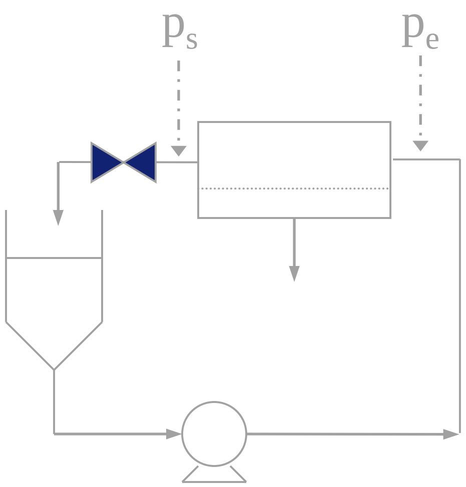
www.vsep.com
www.sanimembranes.com/

Membrane technology : In practice

Illustration: Crossflow ultrafiltration on a hollow-fiber module







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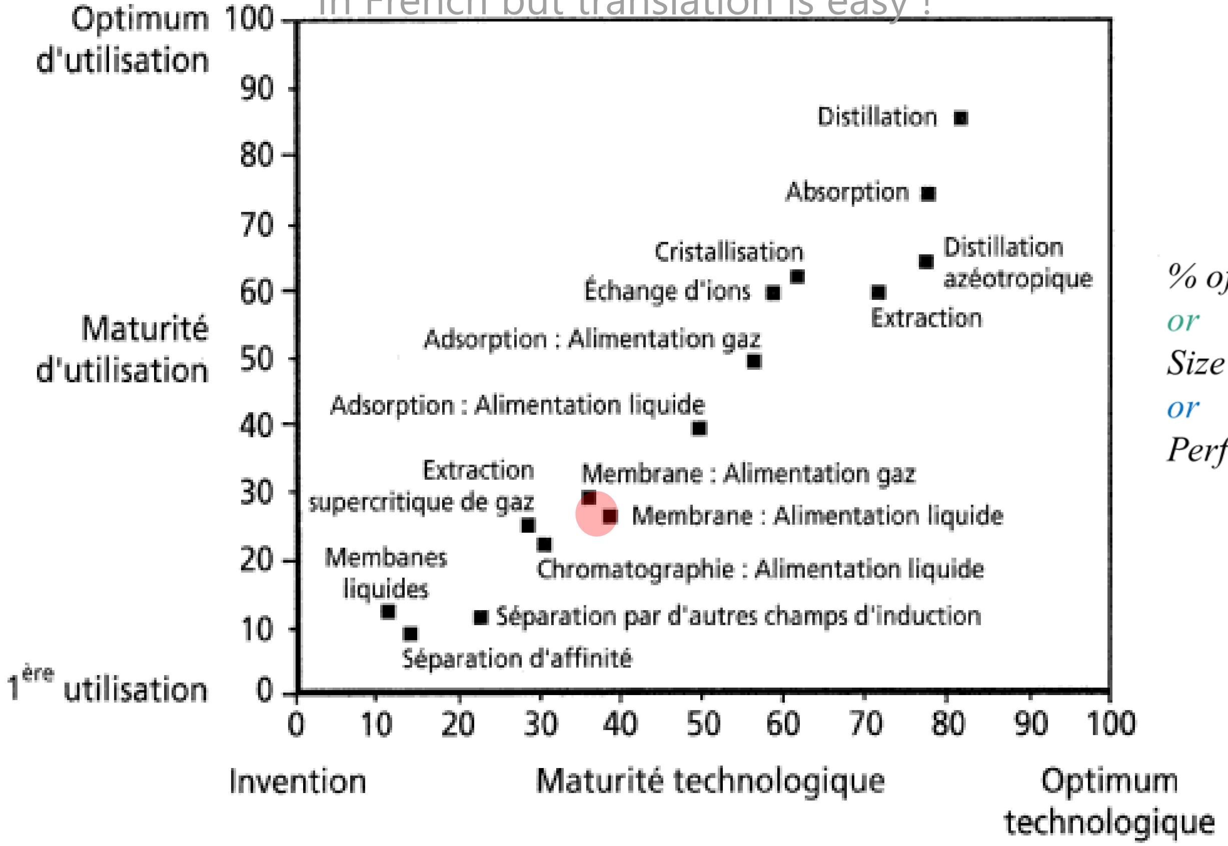
Prevention and cleaning strategies

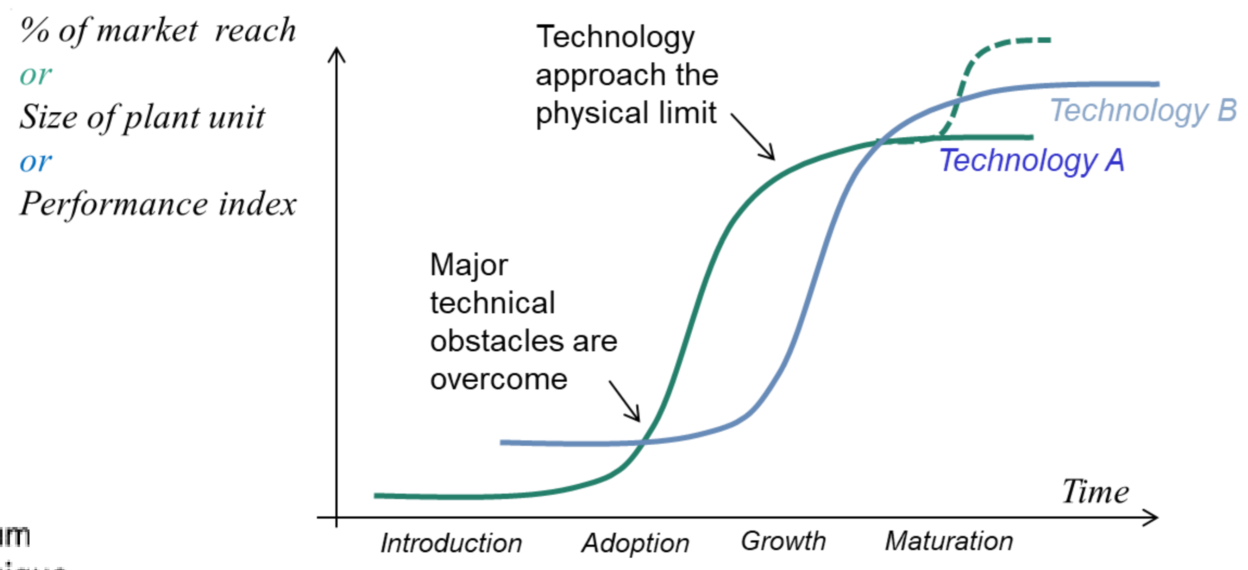
Membrane filtration: a mature process in full industrial development

In French but translation is easy !



J.L. HUMPHREY et G.E. KELLER, 2001

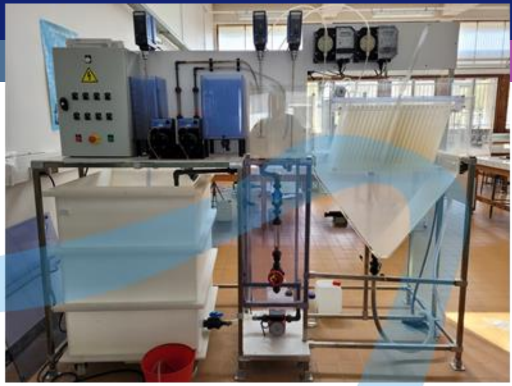
The industrial growth follows the universal S-shaped curve



Stages of industrial developement of ultrafiltration for drinking water

Amoncourt	1989	240 m^3/d (world first)
Fillière	1994	2 000 m^3/d
Rouen	2000	24 000 m^3/d
Moscou	2005	275 000 m^3/d

INDUSTRIAL EXAMPLE :DRINKING WATER PRODUCTION



Drinking water station (24,000 m3/day) in ROUEN with 4*24 modules of 125 m2 surface area. Commissioned in 2000

CLARIFICATION (PARTICLES REMOVAL)

- Coagulation + (settling or sand filtration)
  - And/or
- Ultrafiltration

SMALL MOLECULES REMOVAL (pesticides …)

- Adsorption on active carbon

DISINFECTION (PATHOGENES REMOVAL)

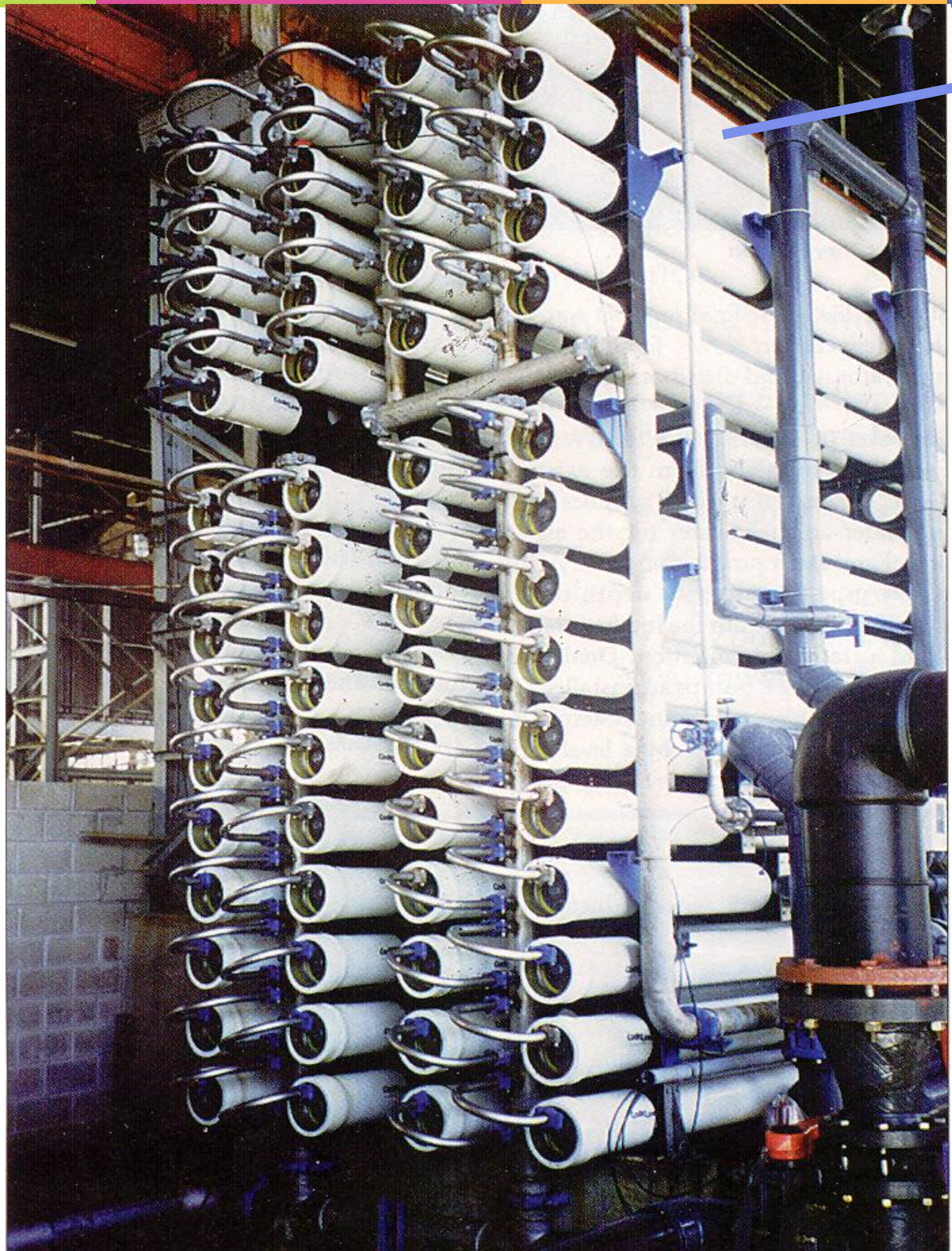
- Ozonation and/or UV

CHLORINATION (remanent disinfection)

INDUSTRIAL EXEMPLE : DESALINATION

Desalting plant of CURAÇAO (Antilles Néerlandaises)

- Capacity : 3.000 m^3/day
- Started in 1997
- DOW FILMTEC Membranes
- Salinity of the producted water : 20 mg/l



C. Fritzmann et al. / Desalination 216 (2007) 1–76

111 m^2

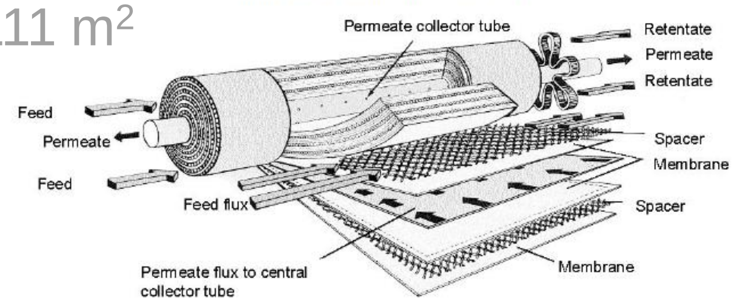


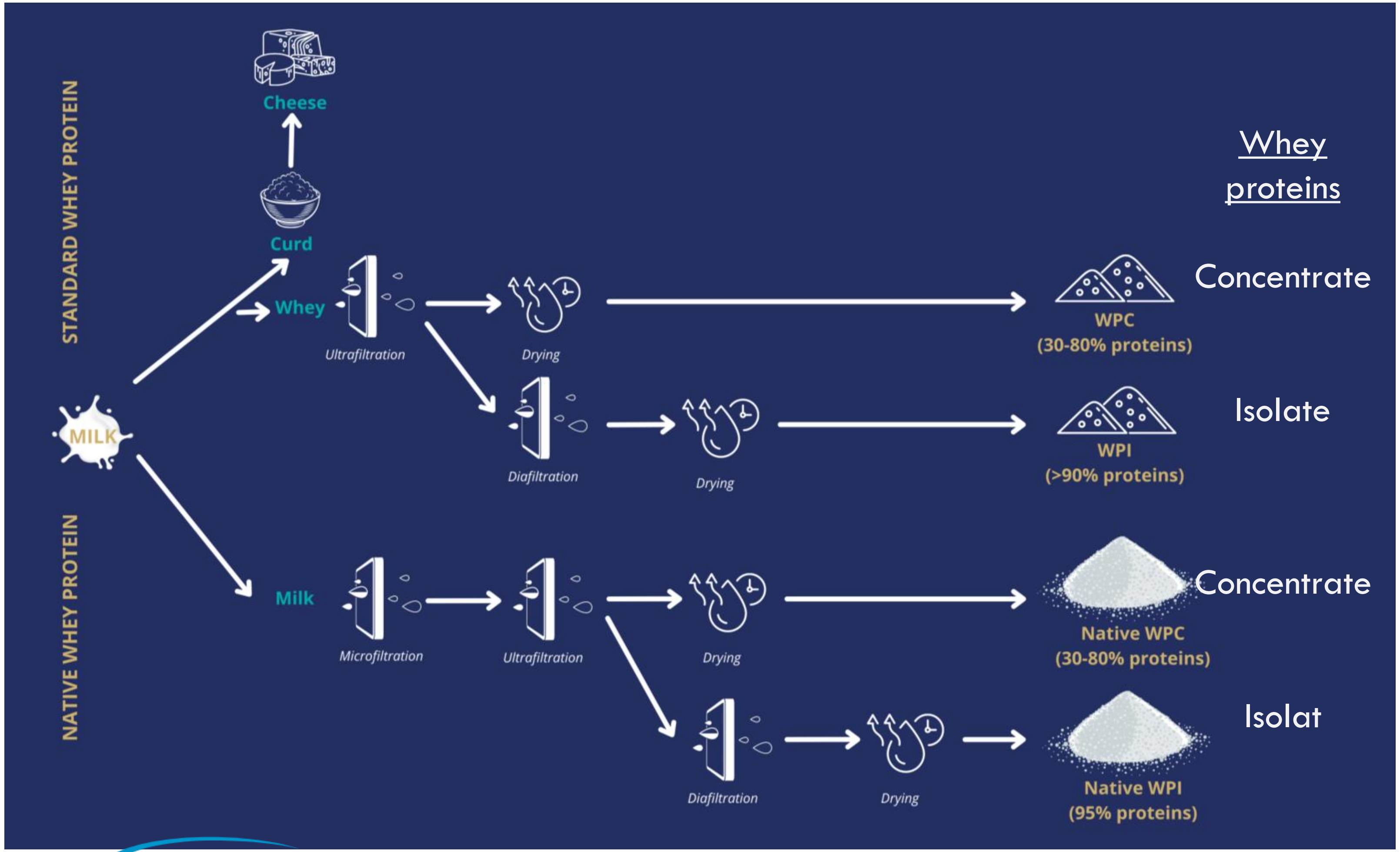
Table 4
Comparison of key operational data of thermal and membrane based desalination technologies [2,16]

	MSF	RO	Electro-dialysis
Thermal energy consumption [kWh/m ³]	12	—	—
Electrical energy [kWh/m³]	35	0.4–7	1
Typical salt content of raw water	30,000–100,000	1,000–45,000	100–3,000
Product water quality (ppm TDS)	<10	<500	<500

C. Fritzmann et al. / Desalination 216 (2007) 1–76

INDUSTRIAL EXAMPLE : PRODUCTION OF MILK PROTEINS

Microfiltration unit
for whey treatment

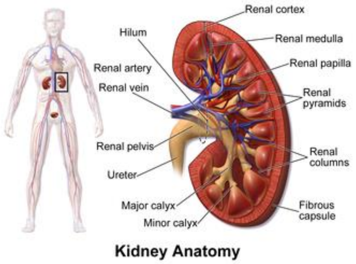


Whey proteins	Nutrition
Concentrate	Infantile
Isolate	Sportive
Concentrate	
Isolat	

LACTALIS ingredients https://www.lactalisingredients.com/fr/news/blog/concentre-vs-isolat-quelle-proteine-serique-pour-quelle-utilisation/

BIOMEDICAL EXAMPLE: KIDNEY DIALYSIS

Kydney → Diagnostic of kidney failure → Technical solution → Patient caring → Regulation Reactovigilance



Bioinspiration

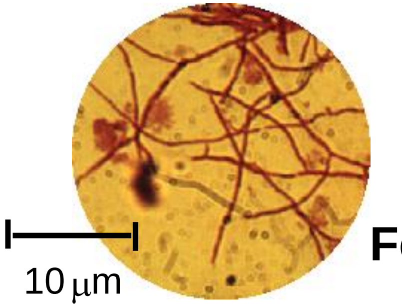
Risks management

Urea and toxins removal

by diffusion from the blood to the dialysate

(dialysis session 4h / osmosed water consumption 150 L)

INDUSTRIAL EXAMPLE: DOWNSTREAM PROCESS IN BIOTECHNOLOGY



Product with high added value

Fermentation broth
biomass
+ active product

Fermentation (production)
100 m^3

Clarification (separation)
biomass

Active product

Extraction (purification)
Purified active product
2 kg

ULTRAFILTRATION
or
CONVENTIONAL FILTRATION OR
ROTARY DRUM
or
CENTRIFUGATION

LIQUID/LIQUID EXTRACTION
and
PREPARATIVE CHROMATOGRAPHY
and
CRISTALLISATION / FILTRATION / DRYING

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A LAST INDUSTRIAL EXAMPLE

Inevitable in Bordeaux ?!

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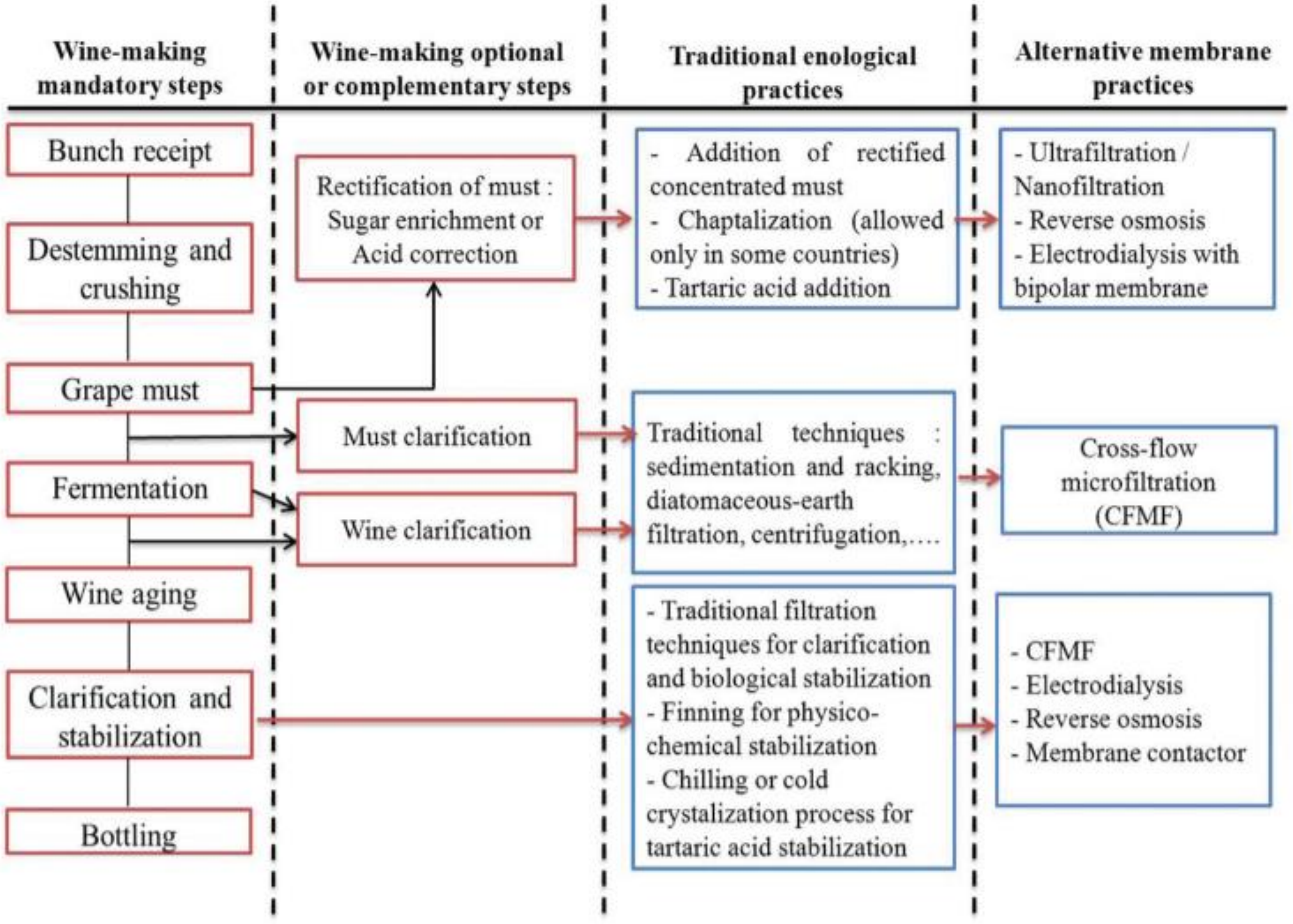
INDUSTRIAL EXAMPLE: MEMBRANE IN WINE INDUSTRY



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El Rayess, Youssef and Mietton-Peuchot, Martine Membrane Technologies in WineIndustry: An Overview. (2016) Critical Reviews in Food Science and Nutrition, 56(12). 2005-2020. ISSN 1040-8398

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Membrane : definitions, classifications, applications

Questions ?

Interactions

Membrane characterisation

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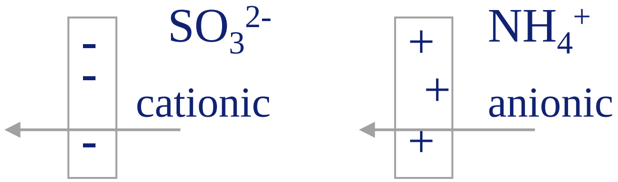
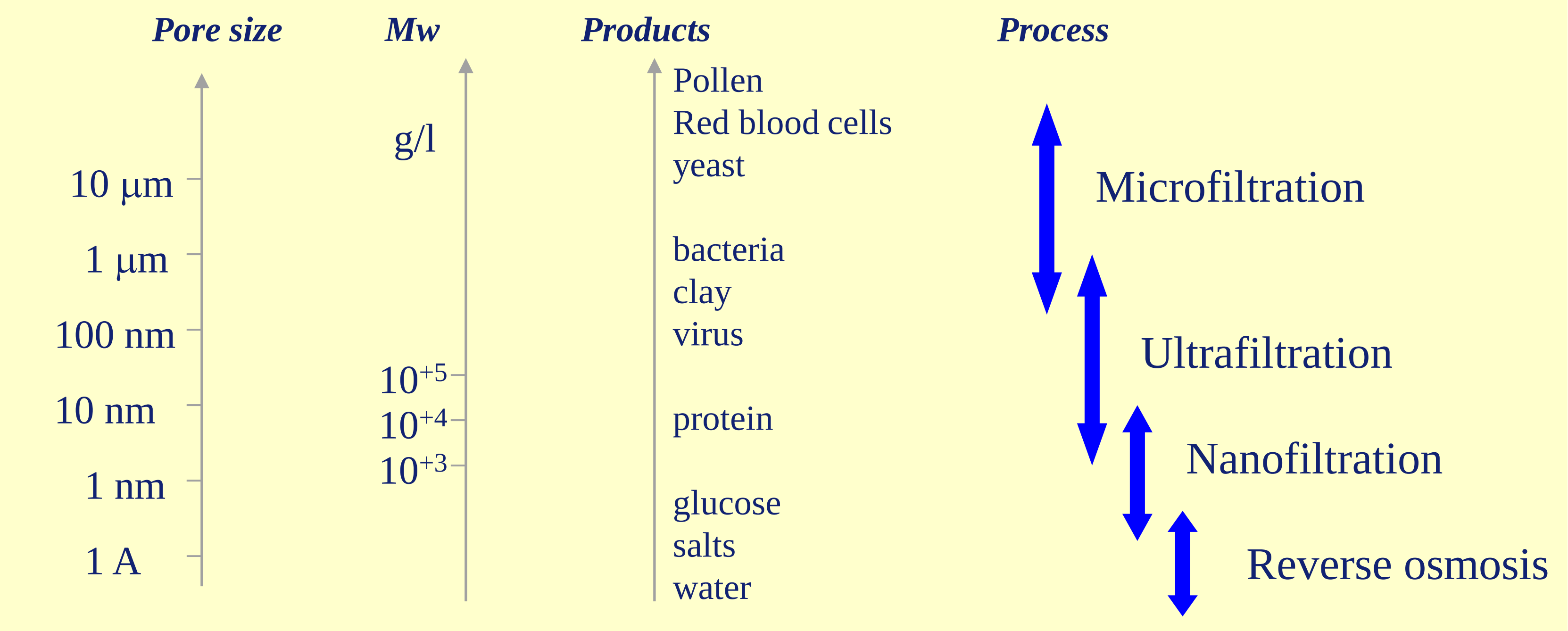
Membranes ... from structure to function

Structure

Charged



Porous



Dense

Hydrophilic or hydrophobic material

Functions

Selective transport of charged molecules (ions, …)

Electrostatic interaction

Selective transport according to the size

Steric effect

Selective transport of the solvent

Hydration interaction

Possibility to combine transport phenomena

How the membrane selectiviy occurs in porous media ?

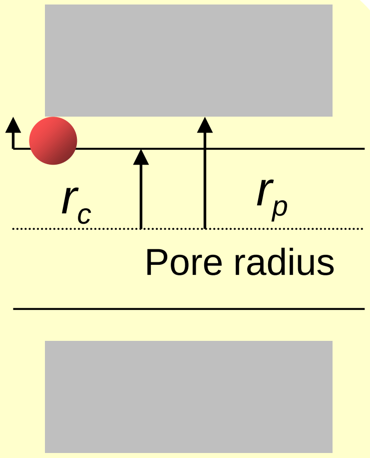
Effect of the size (steric effect)

$$R = 1 - \frac{c_p}{c_m} = (1-(1-\lambda)^2)^2$$

(Ferry law)

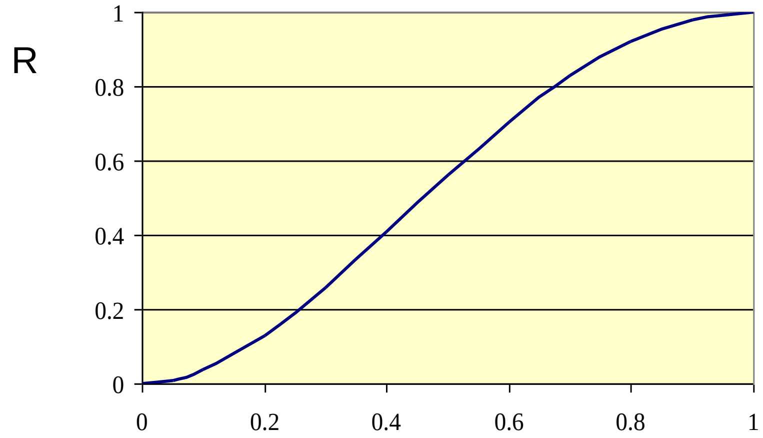
Solute radius r_s

Carrier radius $r_c = r_p - r_s$



$$\lambda = \frac{r_s}{r_p}$$

$$u = u_0 (1 - (\frac{r}{r_p})^2)$$



Effect of the charge (electrostatic effect)

The **Debye lenght** can allow to estimate the range of electrostatic interaction : an additional exclusion layer that reduces the carrier raidus of the pore and increases the solte size

$$\lambda = \frac{r_s + \lambda_D}{r_p - \lambda_D}$$

With : $\lambda_D = \sqrt{\frac{\varepsilon RT}{2F^2 \sum z_i^2 c_i}} = \frac{3.07 \ 10^{-10}}{\sqrt{I}}$

λ_D → m; I → mol/l

$$I = \frac{1}{2} \sum_i z_i^2 c_i$$

What are the parameters when operating membranes ?

Trans-Membrane Pressure

$$\Delta P = \frac{P_E + P_S}{2} - P_P$$ ➤ Driving force

Or TMP

Tangential flow

Q_R ➤ Hydrodynamic

Pressure drop

$P_S - P_E$ ➤ Sweeping energy

energy

Separation efficiency

Permeate flux

$$J = \frac{Q_P}{S}$$ ➤ « Productivity »

Retention

$$R = 1 - \frac{C_P}{C_0}$$ ➤ « Efficacy »

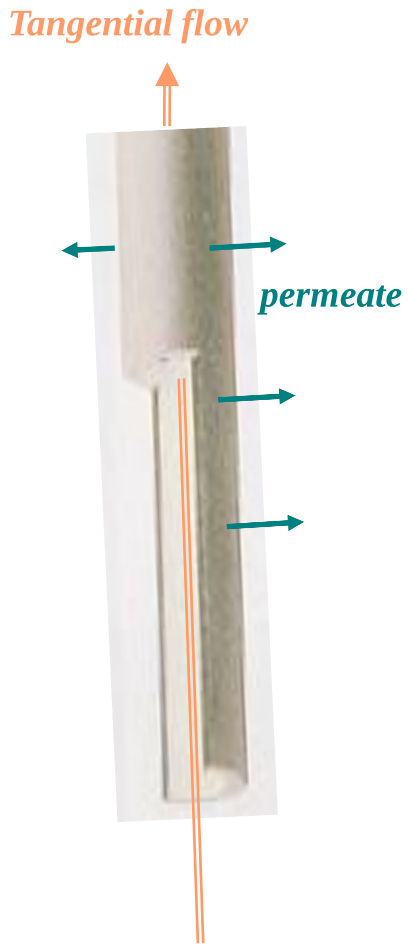
Conversion rate

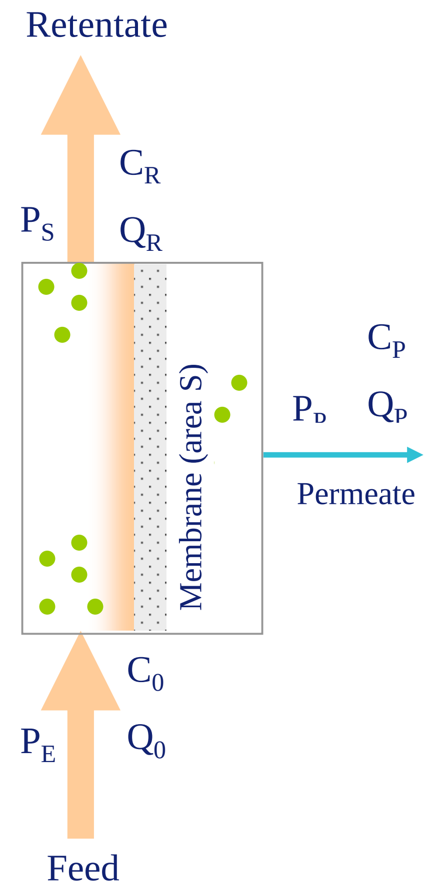
$$Y = \frac{Q_P}{Q_0}$$ ➤ « Yield »

Dead end Mode : Q_R=0 or cross flow : Q_R>0

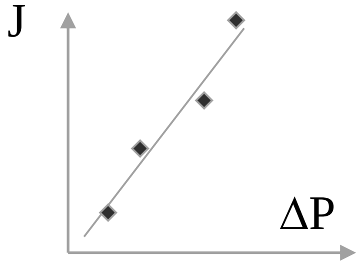
(more energy required but less fouling)

Cross flow





Solvent permeation



Porosity
Pore size

$$J = \frac{\Delta P}{\mu R_m} = \frac{A}{\mu}\Delta P = A^*\Delta P$$

A : permeability (m) –intrinsic property-

A^* : permeability ($L.h^{-1}.m^{-2}.bar^{-1}$)
but the solvent and temperature (which determines viscosity) must be indicated

In French but translation is easy !

Tableau 2 – Ordre de grandeur des perméabilités

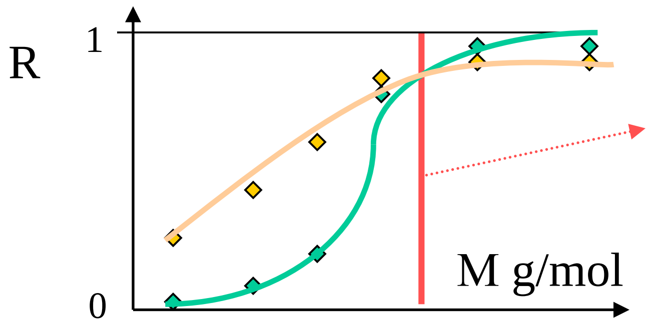
Catégorie	Perméabilité à l'eau à 20 °C, A^* ($m \cdot s^{-1} \cdot Pa^{-1}$)	Perméabilité à l'eau à 20 °C, A^* ($L \cdot h^{-1} \cdot m^{-2} \cdot bar^{-1}$)	Perméabilité A (m)
Micro-filtration	$1,4 \times 10^{-9}$ à $2,8 \times 10^{-8}$	500 à 10 000 (voire plus)	$1,4 \times 10^{-12}$ à $2,8 \times 10^{-11}$
Ultra-filtration	$1,4 \times 10^{-10}$ à $1,4 \times 10^{-9}$	50 à 500	$1,4 \times 10^{-13}$ à $1,4 \times 10^{-12}$
Nano-filtration	$2,8 \times 10^{-11}$ à $2,8 \times 10^{-10}$	10 à 100	$2,8 \times 10^{-14}$ à $2,8 \times 10^{-13}$
Osmose inverse	$8,3 \times 10^{-12}$ à $5,5 \times 10^{-11}$	3 à 20	$8,3 \times 10^{-15}$ à $5,5 \times 10^{-14}$

Filtration membranaire, Aimar P., Bacchin P., Maurel A. Techniques de l'ingénieur, J2790

Membrane characterization : selectivity

“Solute” (molecule, macromolecule or colloids) permeation

R Retention rate $R = 1 - \frac{c_p}{c_r}$

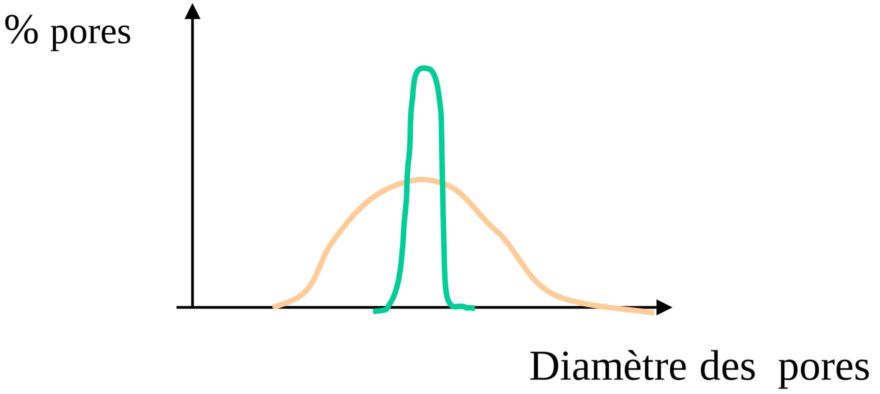


CutOff
in g/mol (ou Da)

minimum molar mass of a 90% retained solute

Membrane cutoff

Pore size distribution



Dewetting (drainage)

$$r_p = \frac{2\gamma \cos\theta}{P}$$

Maximum pore size

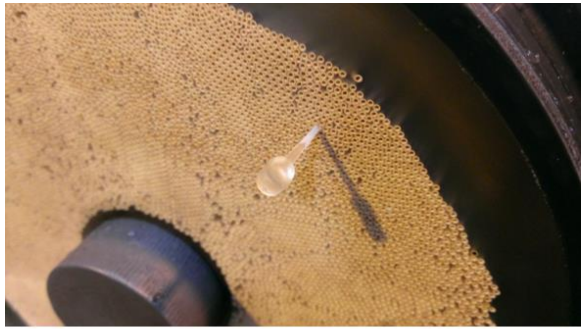
Distribution of pores

Integrity test also called Bubble point method

Detection of broken or damaged fibers

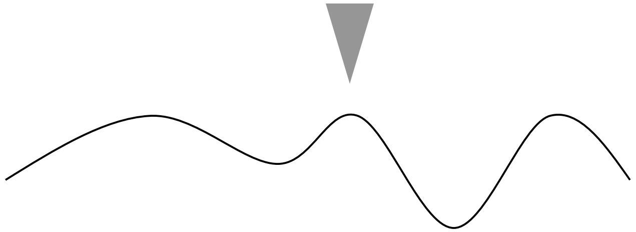
https://www.youtube.com/watch?v=eYb4onYIBwo
At 2:20

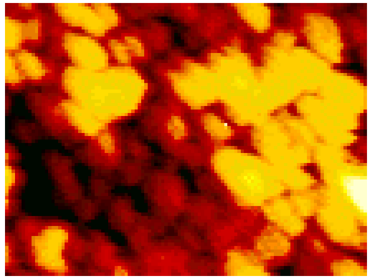
Repair



Membrane characterization : surface properties

AFM (atomic force microscopy)

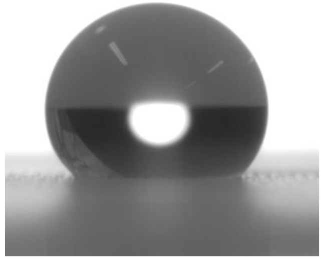




© LGC -CEMES

Rugosity
Pore size
membrane/soluté interactions

Wettability

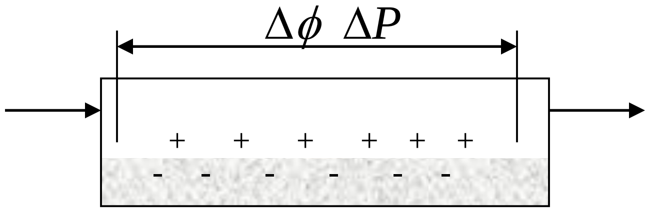


Adhesion force

Surface energy

Hydrophilic/phobic effects

Surface charge (by streaming potential)



$$\frac{\Delta\phi}{\Delta P} = \frac{\varepsilon\zeta}{\eta k}$$

Surface charge

Electrostatic effects

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Membrane characterisation

Membrane fouling

Questions ?

Interactions

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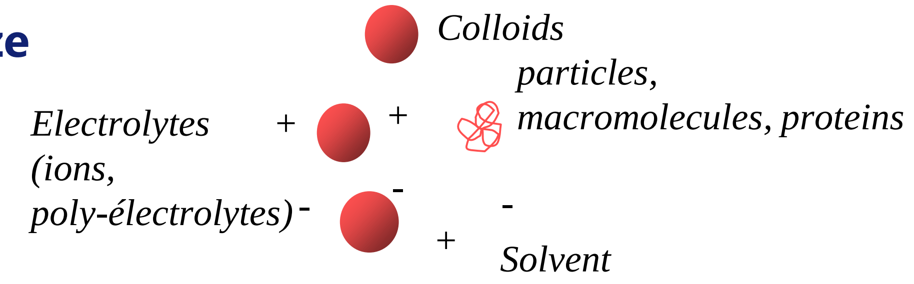
Problem number 1: Vairous fouling mechanisms

A fluid with different scales of size and interaction …



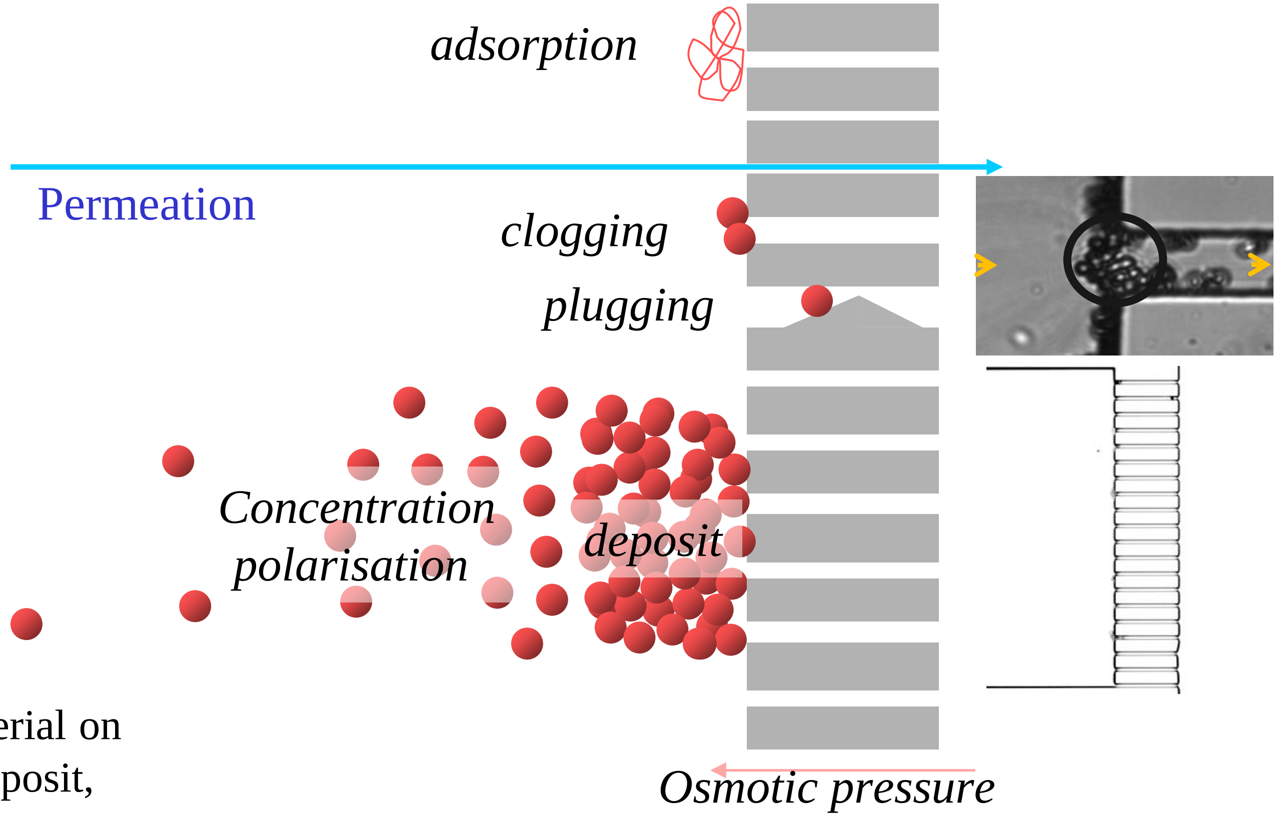
… causes multiple fouling phenomena …

Adsorption of molecules or macromolecules with a chemical affinity for the membrane material

Clogging or mechanical plugging by particles in the membrane

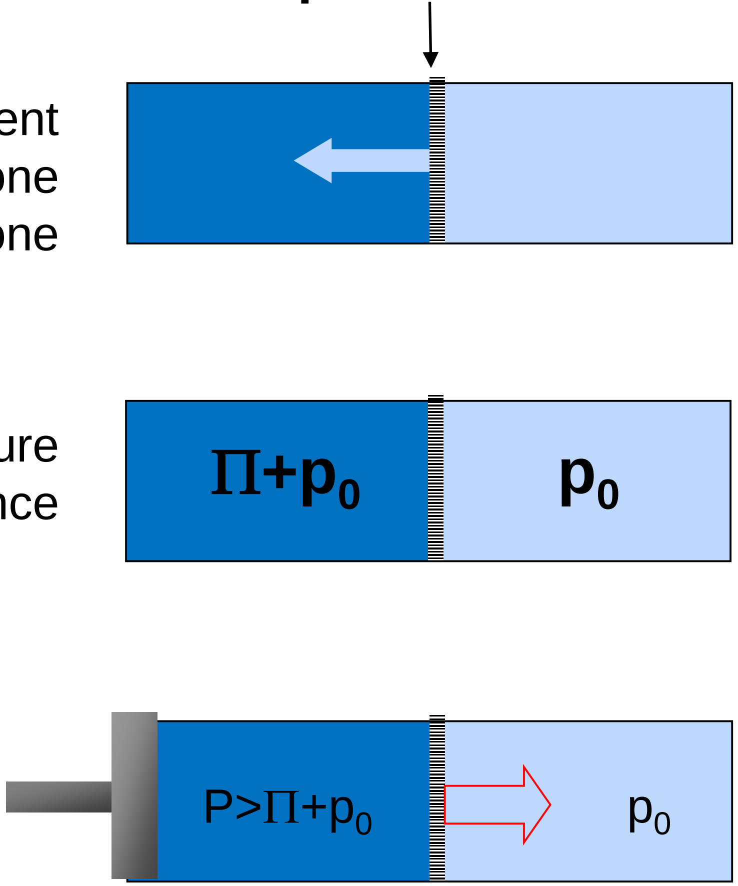
Concentration polarisation : reversible accumulation of at the surface, resulting in osmotic counter-pressure

Deposition (irreversible) deposition of material on the membrane surface (particulate matter: deposit, molecular matter: gel)



Osmotic pressure and reverse osmosis

Semi-permeable membrane
solvent permeable
But non permeable to solute



Transfert of the solvent
from **dilute** zone
Toward concentrated zone

Osmosis

At **equilibrium** : an osmotic pressure compensante the concentration difference

Equilibrium

If a pressure > $\Pi + p_0$ is applied

Reverse osmosis

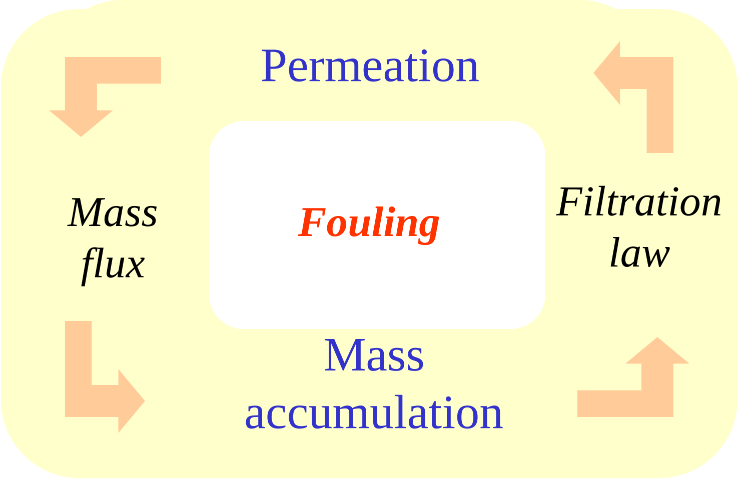
The solvent (water) is extracted from the concentrated feed

1748

Fouling : description and consequences

Fouling depends on a number of operating parameters ….

Hydrodynamics
Diffusion
Interaction



Applied pressure
Membrane permeability

… and control the process efficiency

Reduction of the permeation
(process productivity)

Modification of solute transfer
(Separation efficiency)

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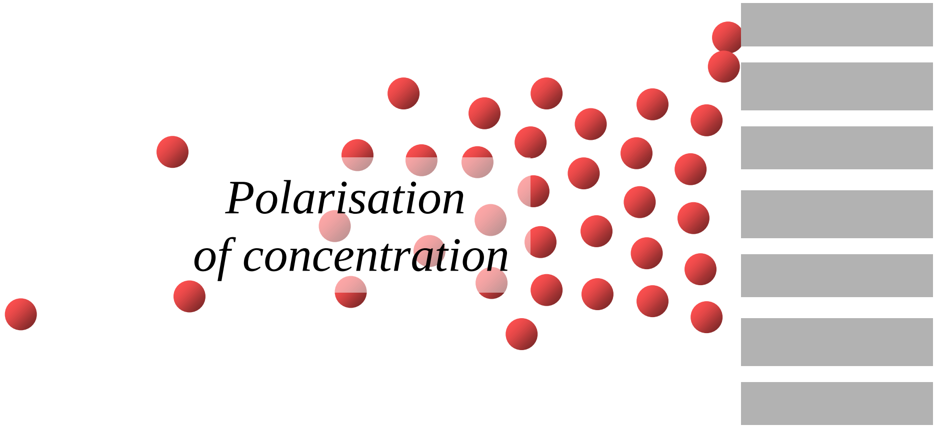
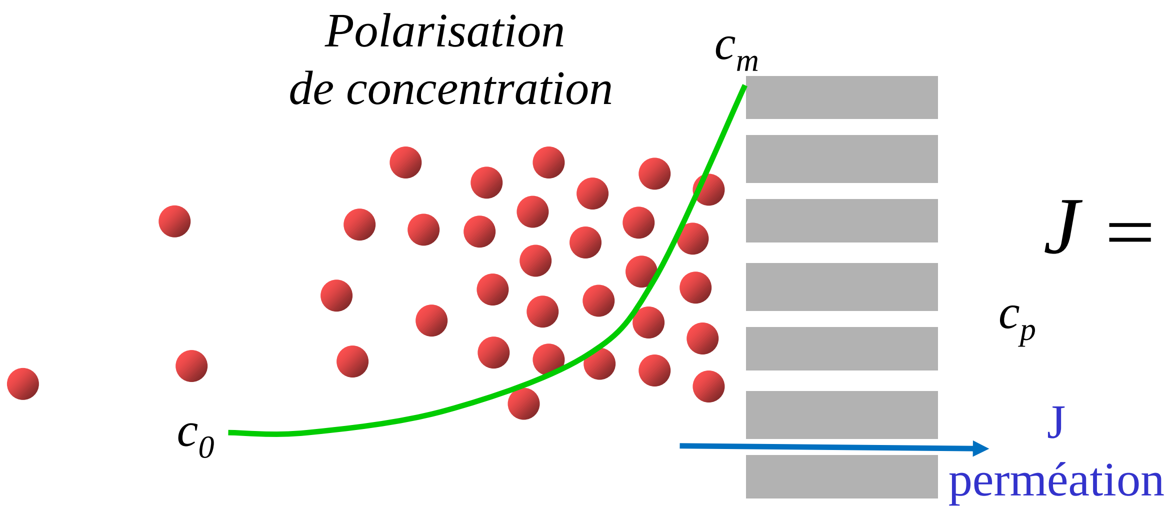
Level 1 : How do you model concentration polarisattion ?



Filtration law



$$J = \frac{\Delta P - \Delta\pi}{\mu R_m}$$

$$\Delta\pi = \pi(c_m) - \pi(c_p)$$

Counter osmotic pressure

Osmotic pressure : estimation with Van’t Hoff law

Osmotic pressure, Π, in Pa

$$\Pi = cRT$$

c number of dissociated moles in the solution
R Perfect gas law constant
T temperature in Kelvins

Van 't Hoff law 1886 (Nobel prize in 1901)

Exemple : solution of NaCl at 35 g/l ≈ sea water

$$c_{NaCl} = \frac{35}{58{,}5} = 0{,}60 \ \textbf{mol/L} = c_{Na^+} = c_{Cl^-}$$

$$\pi = 2 \text{ x } 0{,}6\ 10^3 \text{ x } 8{,}134 \text{ x } 298 = 29{,}1.10^5\ Pa$$

$$29{,}1\ bar$$

Reverse osmosis and production rate

Calculation of the flow rate passing through the RO membrane

$$Q = S * A * (P - p_0 - \Pi)$$

S : membrane surface m^2

A : perméability constant

A= 3.10^{-12} m/(s.Pa)

Surface for 3 000 m^3 of water per day with an applied pressure of 50 atm

Data: NaCl 30 g/l

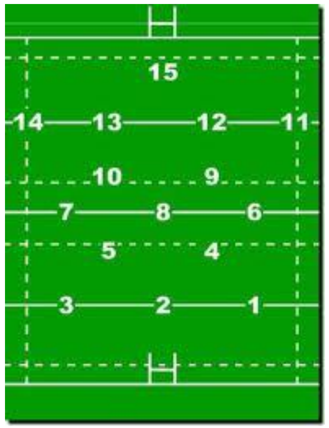
p_0=1 atm

(no concentration polarisation)

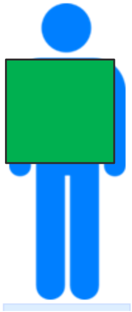
S = 4 780 m^2

Excel

Is it possible ?



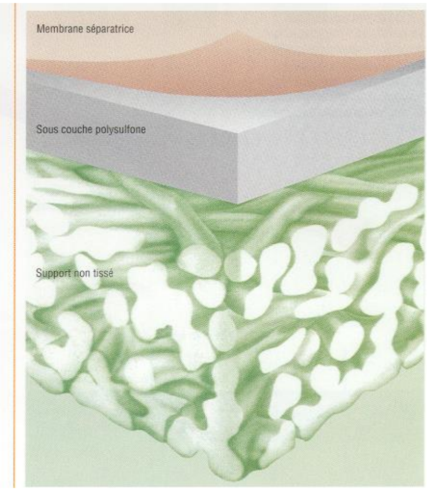
m^2 for 10 000



m^2 for 1

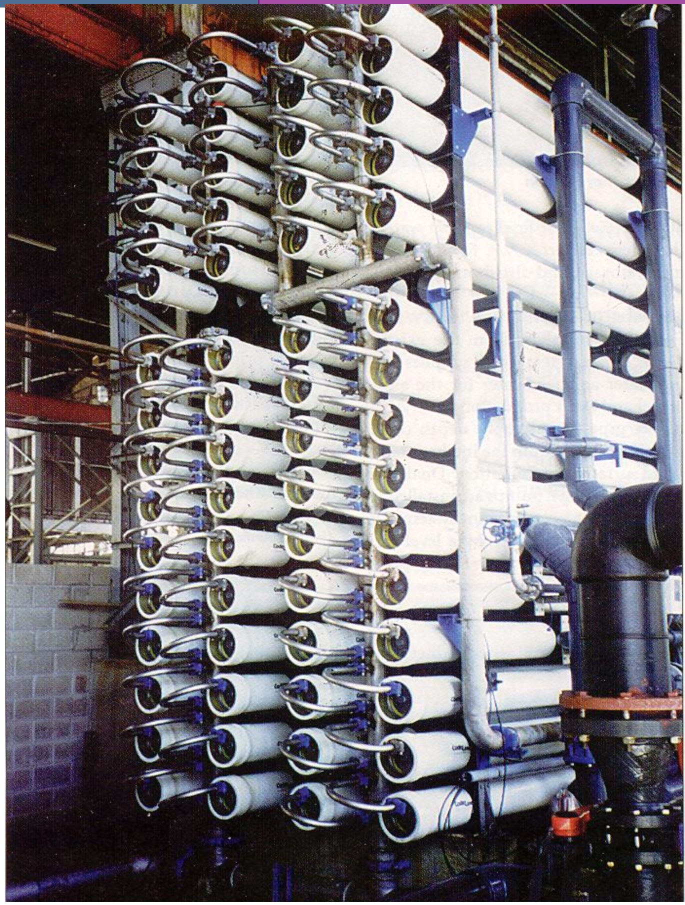
Yes, we can

Thanks to ultrathin membranes -> high permeability



← polyamide membrane 0,2 µm
← polysulfone sub-layer 40,0 µm

← polyester layer 120,0 µm

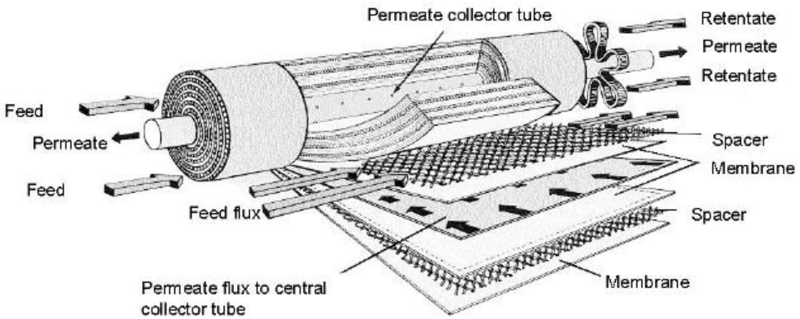


•Capacity : 3.000 m^3/day

•Membrane surface 6660 m2

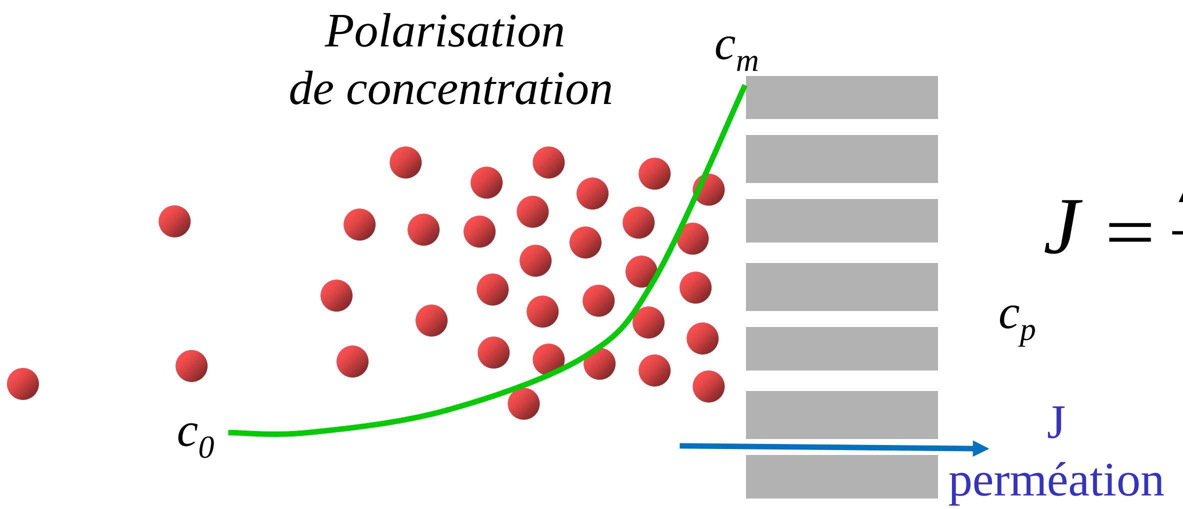
Thanks to technologies allowing to have important surface in a small volume

C. Fritzmann et al. / Desalination 216 (2007) 1–76



How do you model fouling?

Filtration law



$$J = \frac{\Delta P - \Delta\pi}{\mu R_m}$$

$$\Delta\pi = \pi(c_m) - \pi(c_p)$$

Counter osmotic pressure

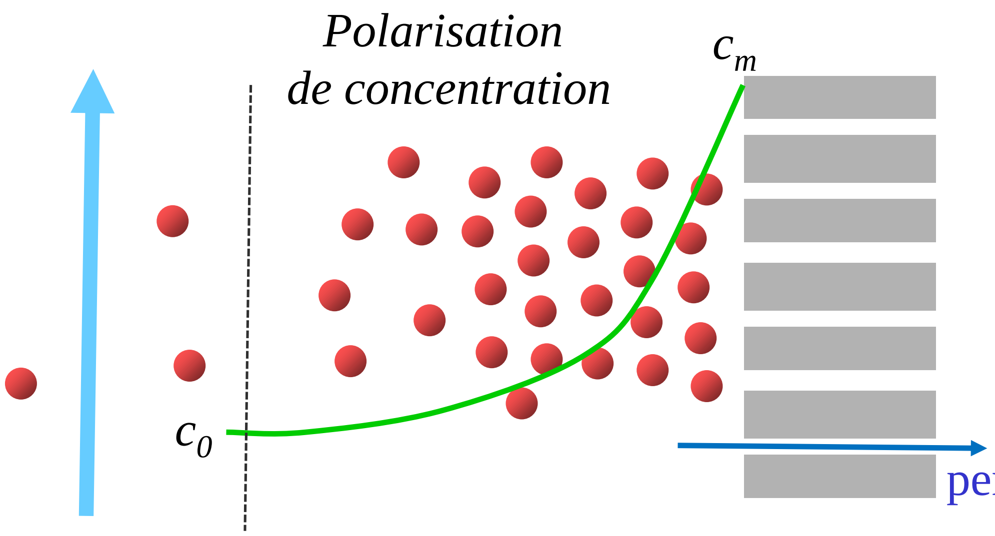
How to model the effect of concentration polarisation ?

How do you model fouling?

Solute transfer

$$\frac{c_m - c_p}{c_0 - c_p} = e^{Pe}$$

$$Pe = \frac{J}{D/\delta} = \frac{perméation}{diffusion}$$



Mass boundary layer
Thickness induced
by the tangential flow

Filtration law

$$J = \frac{\Delta P - \Delta \pi}{\mu R_m}$$

$$\Delta \pi = \pi(c_m) - \pi(c_p)$$

Counter osmotic pressure

Level 1 achieved !You have two equations, two unknows c_m and J

An example of modeling

Mass transfer

$$\frac{c_m - c_p}{c_0 - c_p} = e^{\frac{J\delta}{D}}$$

Filtration law

$$J = \frac{\Delta P - \Delta\pi}{\mu R_m}$$

$$\Delta\pi = \pi(c_m) - \pi(c_p)$$

If the membrane is fully retentive (c_p=0)

$$\frac{c_m - c_p}{c_0 - c_p} - e^{\frac{\frac{\Delta P - \pi(c_m)}{\mu R_m}\delta}{D}} = 0 \rightarrow \begin{cases} c_m \\ J \end{cases}$$

Fruit juice filtration

Membrane : 
diameter 6 mm Lenght 1,2 m
velocity 0,05-0,1 m/s

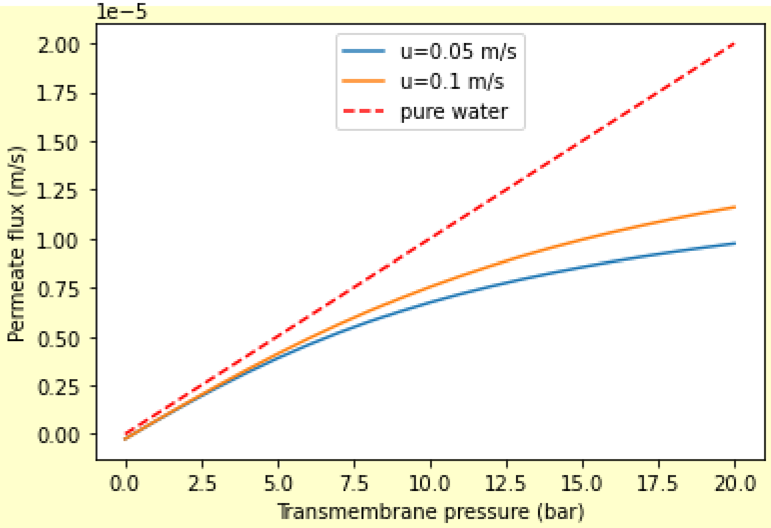
Fruit juice:

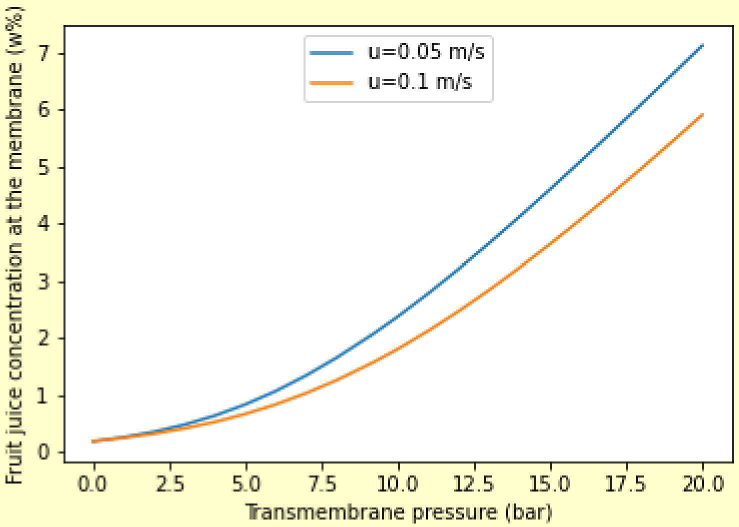
c (% mass)= 1

$$\pi(bar) = \frac{133{,}75c}{100 - c} \quad *$$

ρ = 1200 kg/m^3
μ = 0,002 Po
D= 7.10^{-10} m^2.s^{-1}

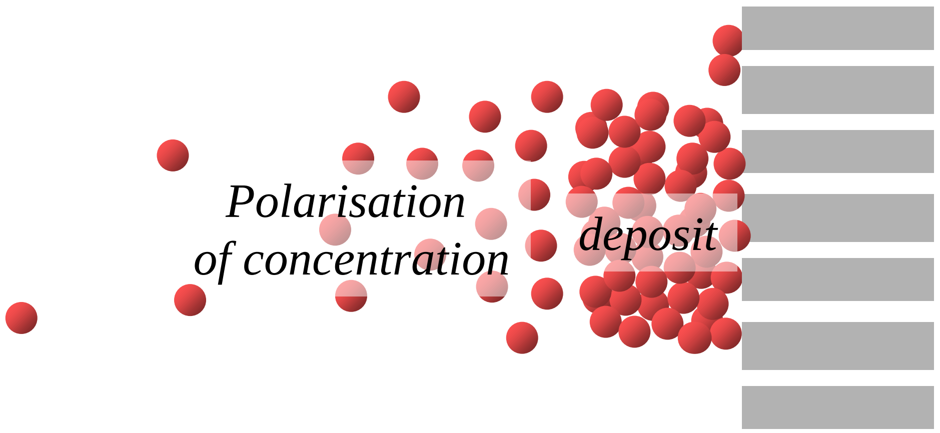
Python code





*Techniques de l'ingénieur J2786 eq.31

Level 2 : How do you model deposit formation ?



$$J = \frac{\Delta P - \Delta\pi}{\mu(R_m + R_d)}$$

Resistance in series

+

model to describe the transition from concentration polarisation to deposit

⇨ Level 2 !

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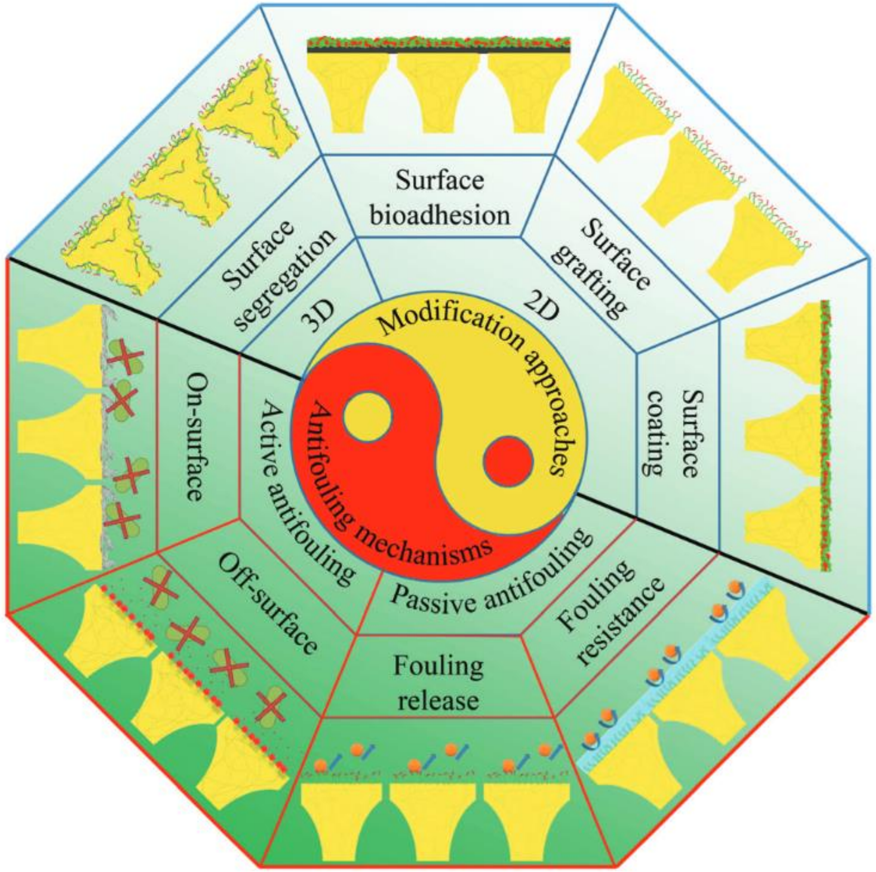
Prevention of fouling : Surface modification



Surface modification

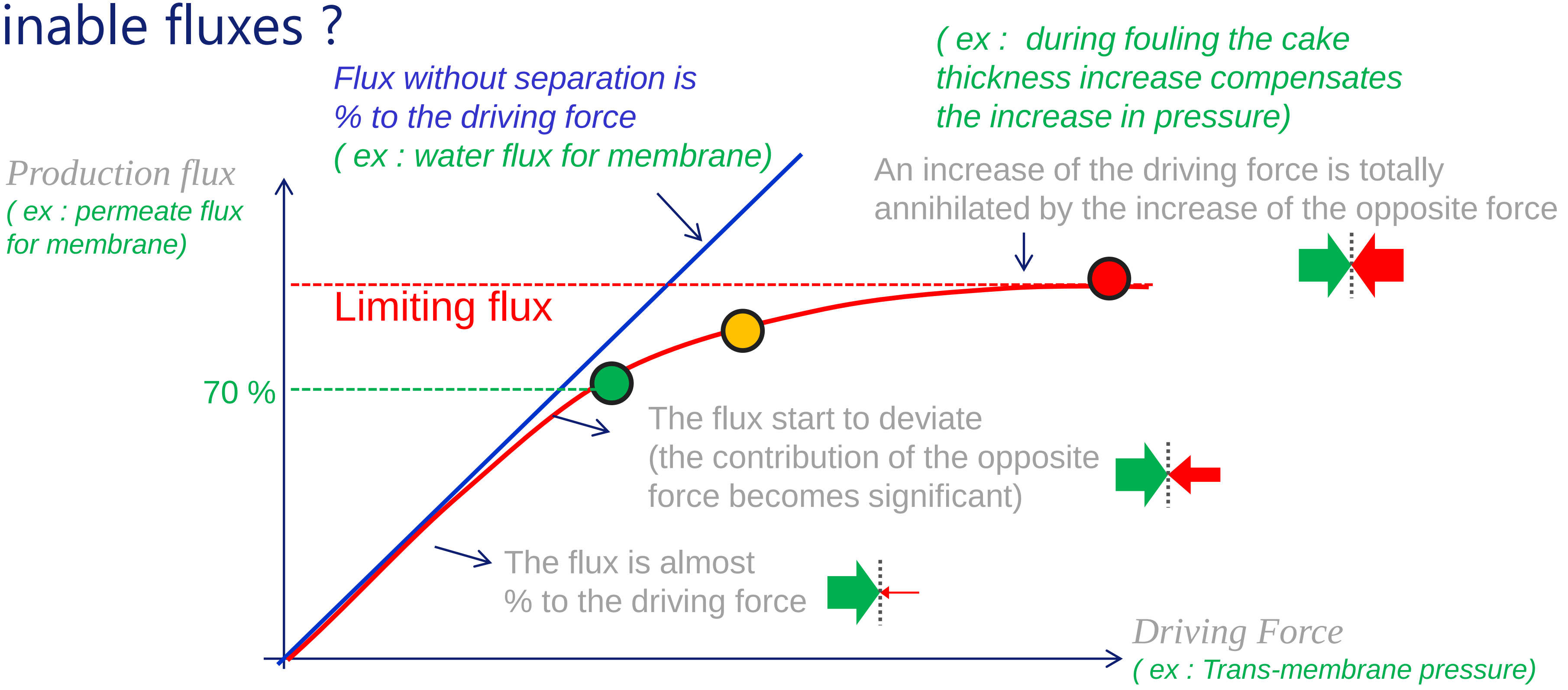
Grafting
Coating
Segregation (during phase inversion)

Bioinspired from cell membranes (Quorum quenching, zwitterionic properties, hydrophobic patches …)

Zhang, R., Liu, Y., He, M., Su, Y., Zhao, X., Elimelech, M., & Jiang, Z. (2016). Antifouling membranes for sustainable water purification: strategies and mechanisms. *Chemical Society Reviews*, *45*(21), 5888-5924..

Prevention of fouling : Adapting operating conditions

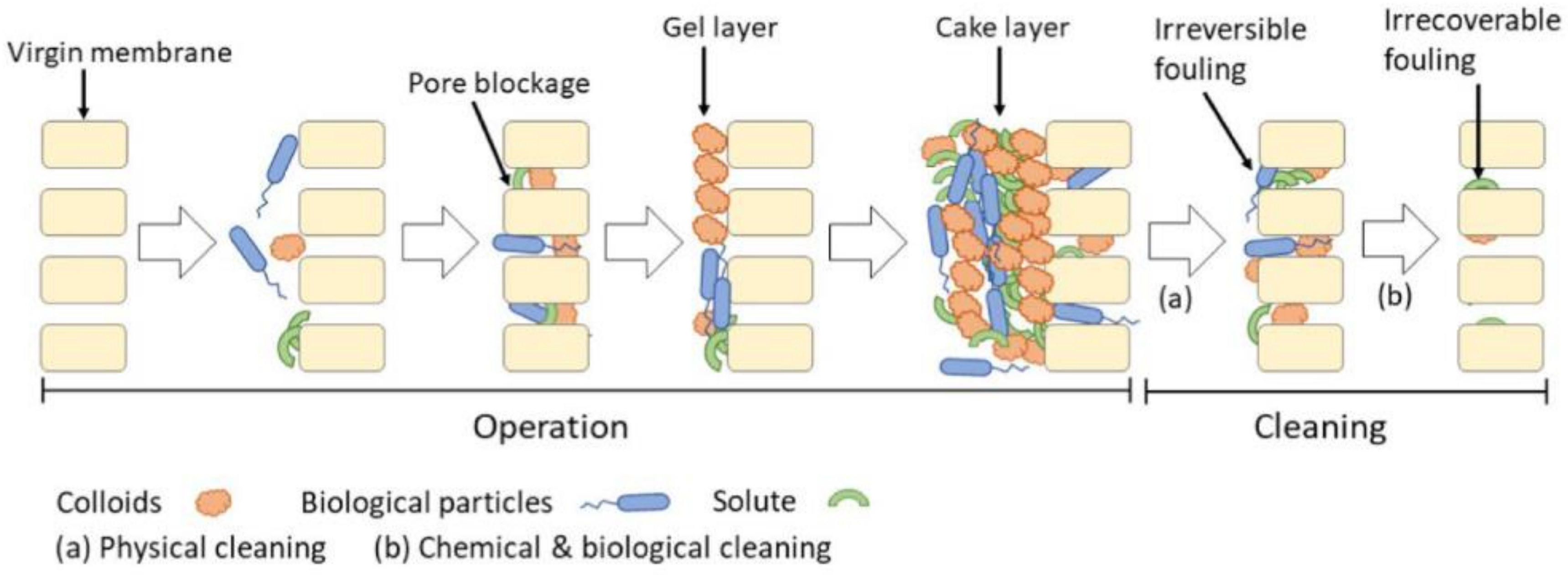
How to find subtainable fluxes ?



A **sustainable way to operate** is to work at 70 % of the limiting flux
(above a significant part of the energy is used to fight against the opposite force)

Bacchin, P., Aimar, P., & Field, R. W. (2006). Critical and sustainable fluxes: Theory, experiments and applications. Journal of membrane science, 281(1-2), 42-69.

Cleaning strategies



Physical cleaning
- Hydraulic cleaning cycle
- Air scouring
- Ultrasonic cleaning
- CO_2 bubble formation

Chemical cleaning
- Acid or alkaline cleaning
- Fenton cleaning (strong oxidant)

Biological cleaning
- Quorum quenching

Xiao, T., Zhu, Z., Li, L., Shi, J., Li, Z., & Zuo, X. (2023). Membrane fouling and cleaning strategies in microfiltration/ultrafiltration and dynamic membrane. Separation and Purification Technology, 318, 123977.

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Let’s practice

Membrane Serious Game

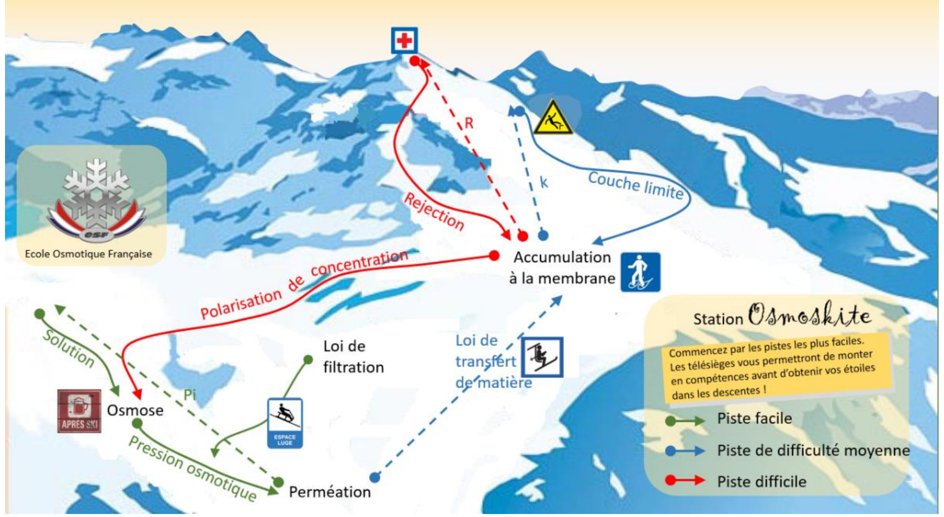
A serious game to progress in membrane science

www.patricebacchin.fr/cours/membrane_eng/

Acquire “high altitude” knowledge with chair lifts

and

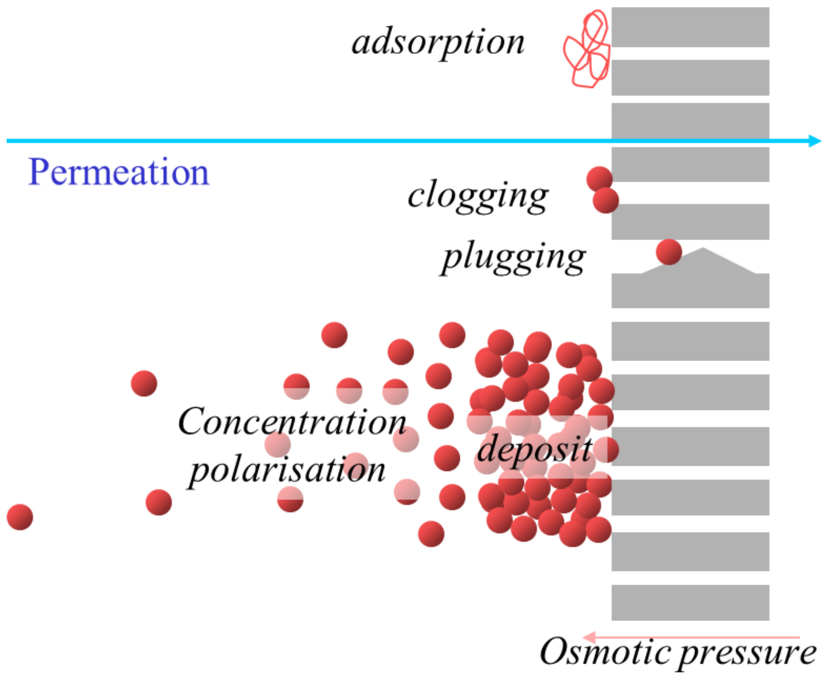
Test your “slipping” knowledge on the ski slopes



Conclusions

Membrane : A mature process applied in various applications

As with all processes, opposing forces limit separation : membrane fouling.



But fouling is now well understood and prevention and cleaning strategies exist.

Fouling is unpredictable for complex fluids and experimental testing of performance (productivity and selectivity) remains necessary.

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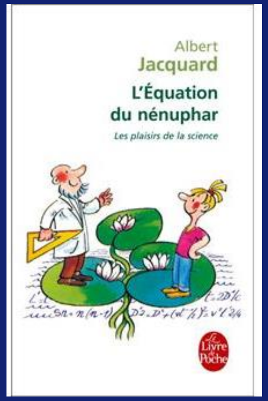
Thanks for your attention

Questions ? Interactions

Interactions lead to an increase of complexity
that is the source of the emergence of unexpected performances

Les interactions (…) entraînent un accroissement de complexité
source de l'émergence de performances inattendues

Albert Jacquard (geneticist), L'équation du nénuphar



BACKUP SLIDES

Example of scaling-up principles

Problematic of Brakwish water during desalination

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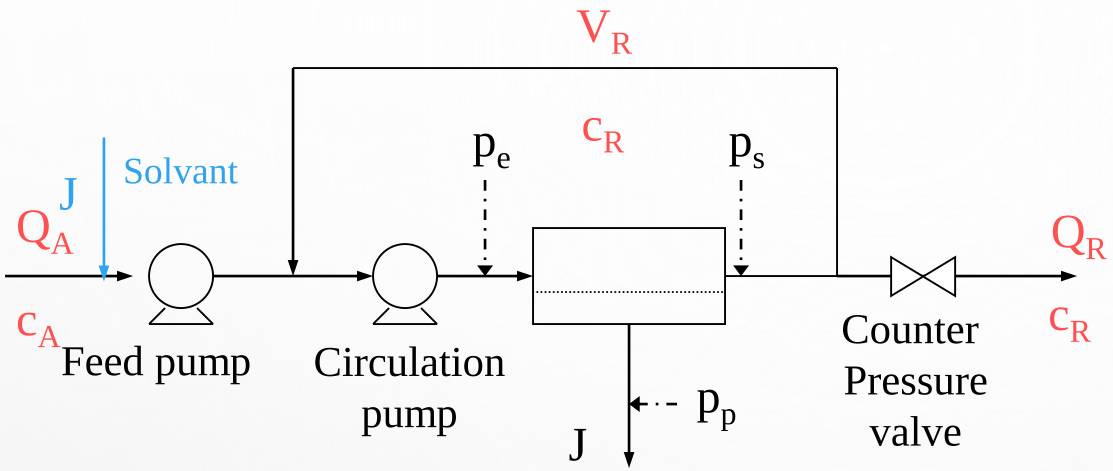
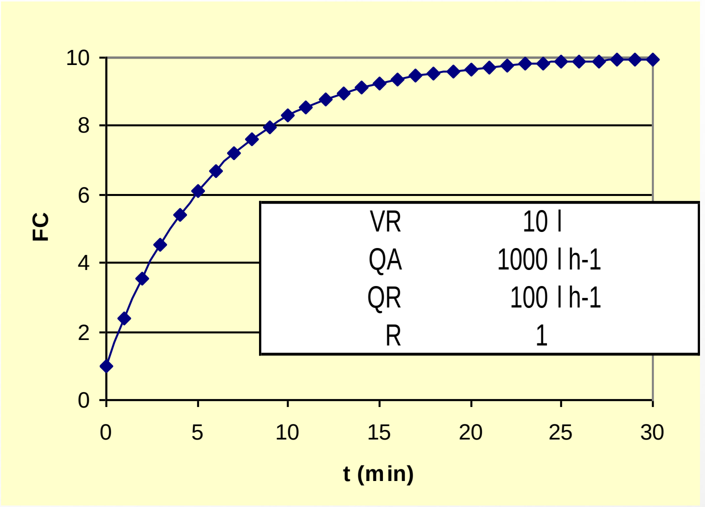
Example of scaling-up principles

Continuous concentration mode





Mass balance

With $t_S = \frac{V_R}{Q_A}$

$$Q_A c_A - Q_R c_R - Q_p c_p = V_R \frac{dc_R}{dt}$$

$$Q_A = Q_R + Q_p$$

$$\frac{dFC}{dt} = \frac{Q_A - (Q_A - Q_p R)FC}{V_R}$$

$$\frac{dFC}{dt} = \frac{1 - \alpha.FC}{t_s}$$

Limit $Q_A >= Q_P$

$$FC < \frac{1}{1-R}$$

$$FC = \frac{1}{\alpha} + \left(1 - \frac{1}{\alpha}\right) e^{-\alpha \frac{t}{t_S}}$$

with

$$\alpha = 1 - \frac{FRV - 1}{FRV} R$$

$$FRV = \frac{Q_A}{Q_R}$$

- If $t \to \infty$ then $FC = \frac{1}{\alpha}$
- If R=0 then FC=1
- If R=1 then FC=FRV

Operating conditions : —— Concentration

—— Diafiltration

Continuous concentration mode

Scaling up (in steady state)

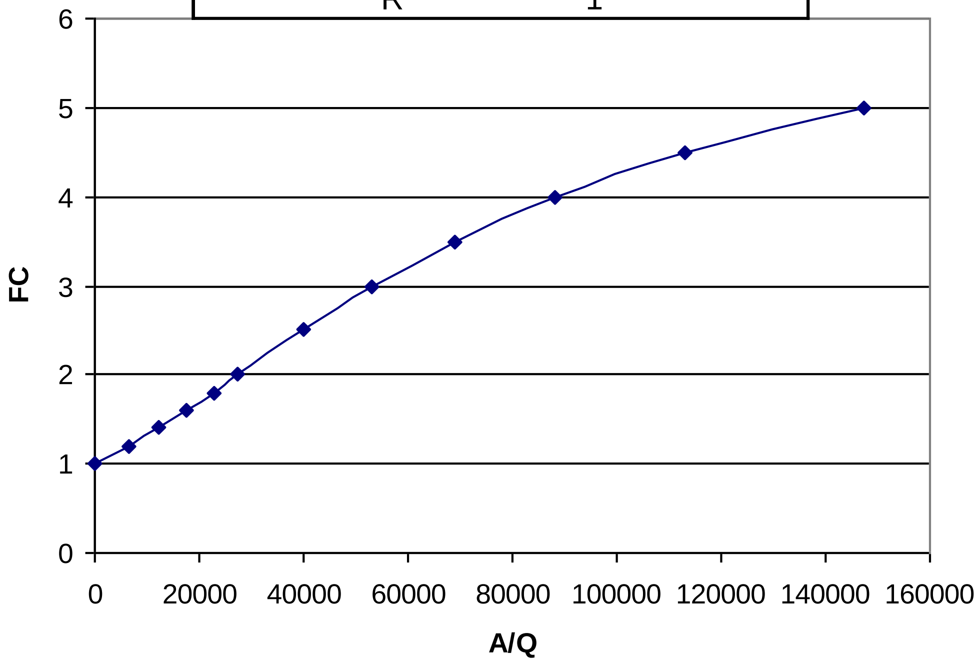
$$\frac{A}{Q_A} = \frac{FC - 1}{J.R.FC}$$

Surface to concentrate 5 time
a flow rate of 1000 l/h ?

Relationship for the dependence of permetate flux to concentration

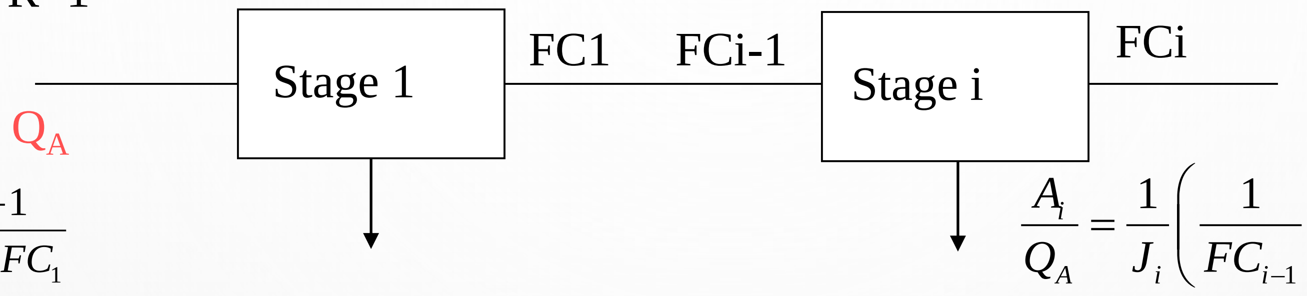
$$J = a - b\ln(FC)$$

a	100 l.h-1.m-2
b	50 l.h-1.m-2
R	1



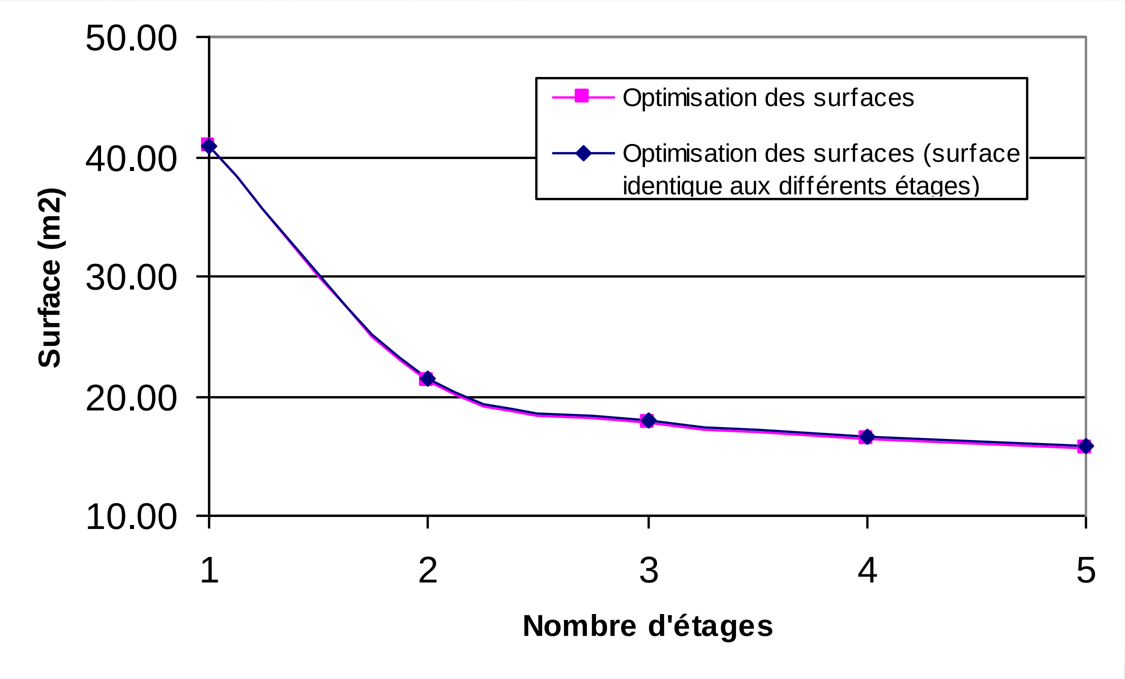
Multistage continuous mode

If R=1



$$\frac{A_1}{Q_A} = \frac{FC_1 - 1}{J(FC_1).FC_1}$$

$$\frac{A_i}{Q_A} = \frac{1}{J_i}\left(\frac{1}{FC_{i-1}} - \frac{1}{FC_i}\right)$$



Surface reduction with multistage process

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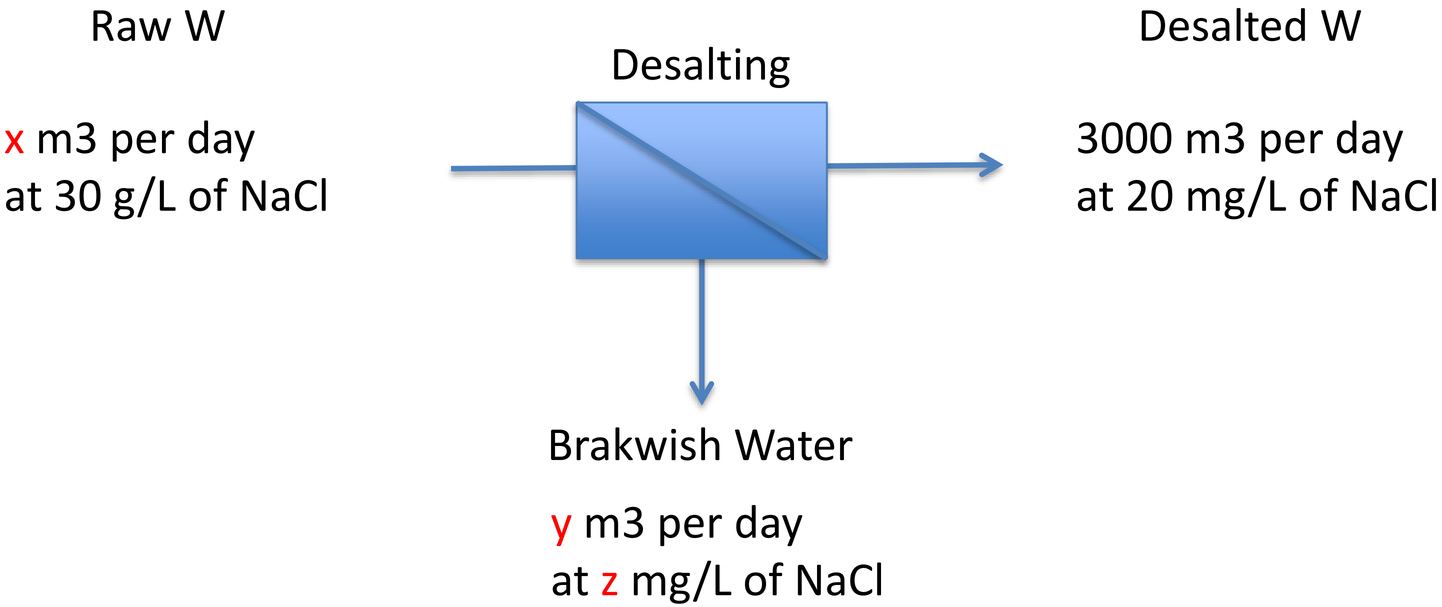
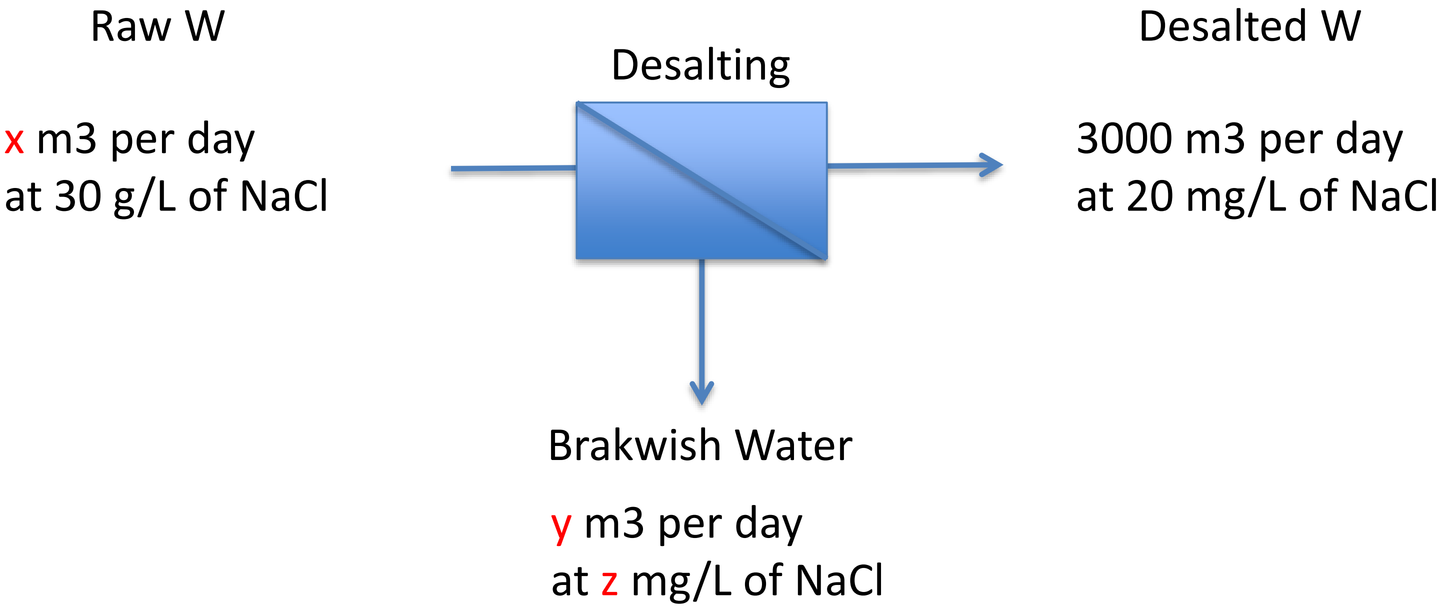
Problematic of Brakwish water during desalination

Brakwish water ?



x ? y? z ?



$$x = y + 3000$$

$$x*30 = y*z + 3000*0.02$$

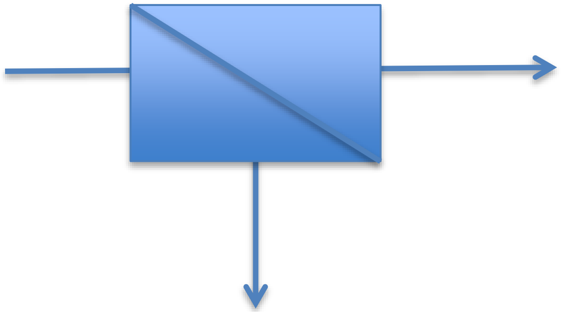
x and y in m^3

z in kg/m^3

Raw W

x m3 per day
at 30 g/L of NaCl

Desalting



Desalted W

3000 m3 per day
at 20 mg/L of NaCl

Brakwish Water

y m3 per day
at z mg/L of NaCl

NaCl in retentate should not exceed 80% of 357 kg/m^3 to avoid precipitation of salt in the membrane z=285

The solubility of NaCl in water is 357 kg/m^3 at 20°C

Raw W

3352 m3 per day
at 30 g/L of NaCl

Desalting

Desalted W

3000 m3 per day
at 20 mg/L of NaCl

Brakwish Water

352 m3 per day
at 285 g/L of NaCl

100 tons of salt per day

per

More often the yield is $Y=Qp/Q=0.4$

Raw W

7500 m3 per day
at 30 g/L of NaCl

Desalting

Desalted W

3000 m3 per day
at 20 mg/L of NaCl

Brakwish Water

4500 m3 per day
at 50 g/L of NaCl

100 tons of salt per day

per