

PROBLEM: Removal of viruses and bacteria

(a) Show that sedimentation won't work.

Pretty sure that  $Re \ll 1$  for both of these.

$$\text{Thus } v_s = \frac{g \Delta \rho d^2}{18 \mu}$$

$$\text{Viruses: } v_s = \frac{(9.81 \text{ m/s}^2)(1350 \text{ kg/m}^3 - 997 \text{ kg/m}^3)(1.0 \times 10^{-7} \text{ m})^2}{(18)(0.89 \times 10^{-3} \text{ kg/m}\cdot\text{s})}$$

$$v_s = 2.2 \times 10^{-9} \text{ m/s} = 7.8 \times 10^{-6} \text{ m/hr}$$

$$\text{Check } Re = \frac{(997 \text{ kg/m}^3)(2.2 \times 10^{-9} \text{ m/s})(1.0 \times 10^{-7} \text{ m})}{(0.89 \times 10^{-3} \frac{\text{kg}}{\text{m}\cdot\text{s}})} \ll 1 \checkmark$$

$$\text{Bacteria: } v_s = \frac{(9.81 \text{ m/s}^2)(1100 \text{ kg/m}^3 - 997 \text{ kg/m}^3)(1.0 \times 10^{-6} \text{ m})^2}{(18)(0.89 \times 10^{-3} \text{ kg/m}\cdot\text{s})}$$

$$v_s = 6.3 \times 10^{-8} \text{ m/s} = 2.3 \times 10^{-4} \text{ m/hr}$$

$$\text{Check } Re = \frac{(997 \text{ kg/m}^3)(6.3 \times 10^{-8} \text{ m/s})(1.0 \times 10^{-6} \text{ m})}{(0.89 \times 10^{-3} \frac{\text{kg}}{\text{m}\cdot\text{s}})} \ll 1 \checkmark$$

Viruses settle at  $7.8 \times 10^{-6} \text{ m/hr}$ , bacteria settle at  $2.3 \times 10^{-4} \text{ m/hr}$

For both,  $v_s \ll 1.5 \text{ m/hr}$ , the overflow rate

Thus fractional removal is negligible for both pathogen types  $\checkmark$

(b) Estimate fractional removal during flocculation

The key is that we need  $\beta$  for both pathogen types.

$$\beta = \beta_M + \beta_{\mu} + \beta_{DS}$$

$$\text{Viruses: } \beta_{\mu} = \left(\frac{2kT}{3\mu}\right) \left(\frac{1}{d_i} + \frac{1}{d_j}\right) (d_i + d_j)$$

$$\beta_{\mu} = \frac{(2)(1.381 \times 10^{-23} \frac{\text{J}}{\text{K}})(298 \text{ K})}{(3)(0.89 \times 10^{-3} \frac{\text{kg}}{\text{m}\cdot\text{s}})} \left(\frac{1}{10^{-7} \text{ m}} + \frac{1}{30 \times 10^{-6} \text{ m}}\right) (10^{-7} \text{ m} + 30 \times 10^{-6} \text{ m})$$

$$\beta_{\mu} = 9.31 \times 10^{-16} \frac{\text{m}^3}{\text{s}}$$

$$\beta_M = \frac{1}{6} G (d_i + d_j)^3 = \left(\frac{1}{6}\right)(60 \text{ s}^{-1})(10^{-7} \text{ m} + 30 \times 10^{-6} \text{ m})^3$$

$$\beta_M = 2.73 \times 10^{-13} \text{ m}^3/\text{s} \dots \text{surprised that } \beta_M \gg \beta_{\mu}$$

$$\beta_{DS} = \frac{\pi \Delta \rho g}{12 \mu} [(d_i + d_j)^3 (d_i - d_j)] \dots \text{continued next pg.}$$

(b) continued

Viruses, continued

$$\beta_{Ds} = \frac{\pi (1350 \frac{\text{kg}}{\text{m}^3} - 997 \frac{\text{kg}}{\text{m}^3}) (9.81 \frac{\text{m}}{\text{s}^2})}{(72) (0.89 \times 10^{-3} \frac{\text{kg}}{\text{m} \cdot \text{s}})} \left[ (10^{-7} \text{ m} + 3 \times 10^{-5} \text{ m})^3 (3 \times 10^{-5} \text{ m} - 10^{-7} \text{ m}) \right]$$

$$\beta_{Ds} = 1.38 \times 10^{-13} \text{ m}^3/\text{s}$$

$$\beta = (9.31 \times 10^{-16} + 2.73 \times 10^{-13} + 1.38 \times 10^{-13}) \text{ m}^3/\text{s} = 4.1 \times 10^{-13} \frac{\text{m}^3}{\text{s}}$$

$$\frac{N_1}{N_0} = \frac{1}{1 + (1) (4.1 \times 10^{-13} \text{ m}^3/\text{s}) (30 \text{ min}) (\frac{60 \text{ s}}{\text{min}}) (1.0 \times 10^{10} \frac{\#}{\text{m}^3})}$$

$$\boxed{N_1/N_0 = 0.12} \quad \text{for viruses}$$

Bacteria: OK to ignore  $\beta_p$  because bacteria are even bigger than viruses, and  $\beta_p$  was unimportant for viruses.

$$\beta_m = \frac{1}{6} G (d_i + d_j)^3 = (\frac{1}{6}) (60 \text{ s}^{-1}) (10^{-6} \text{ m} + 30 \times 10^{-6} \text{ m})^3$$

$$\beta_m = 2.98 \times 10^{-13} \text{ m}^3/\text{s}$$

$\beta_{Ds}$  is tricky... technically the formula only applies to particles of the same density, which is not the case here. But we will use it anyway, because

deriving a new equation would be pretty complicated.

$$\beta_{Ds} = \frac{\pi (1100 \frac{\text{kg}}{\text{m}^3} - 997 \frac{\text{kg}}{\text{m}^3}) (9.81 \frac{\text{m}}{\text{s}^2})}{(72) (0.89 \times 10^{-3} \frac{\text{kg}}{\text{m} \cdot \text{s}})} \left[ (10^{-6} \text{ m} + 30 \times 10^{-6} \text{ m})^3 (3 \times 10^{-5} \text{ m} - 10^{-6} \text{ m}) \right]$$

$$\beta_{Ds} = 4.28 \times 10^{-14} \dots \text{best we can do without a lot of work}$$

$$\beta = (\text{negligible} + 2.98 \times 10^{-13} + 4.28 \times 10^{-14}) \text{ m}^3/\text{s} = 3.4 \times 10^{-13} \text{ m}^3/\text{s}$$

$$\frac{N_1}{N_0} = \frac{1}{1 + (1) (3.4 \times 10^{-13} \text{ m}^3/\text{s}) (30 \text{ min}) (\frac{60 \text{ s}}{\text{min}}) (1.0 \times 10^{10} \frac{\#}{\text{m}^3})}$$

$$\boxed{N_1/N_0 = 0.14} \quad \text{for bacteria}$$

c) Estimate fractional removal in filter

$$N_2/N_1 = \exp\left[-\frac{3}{2}(1-\epsilon)\alpha\eta\frac{L}{d_p}\right], \quad \text{text eqn 11-36}$$

Given  $\alpha=1$ ,  $L=1.5\text{ m}$ ,  $d_p=0.5\text{ mm} = 5.0 \times 10^{-4}\text{ m}$

So we need  $\eta$  for viruses and bacteria

$$\eta = \eta_I + \eta_G + \eta_D$$

Use model of Yao, Habibian, O'Melia because it's simplest

Viruses:  $\eta_I = \frac{3}{2}\left(d_p/d_g\right)^2 \dots \text{text eqn 11-37}$

$$\eta_I = \frac{3}{2}\left(1.0 \times 10^{-7}\text{ m} / 7.0 \times 10^{-4}\text{ m}\right)^2 = 3.06 \times 10^{-8}$$

there's a short-cut for this calculation... use part a

$$\eta_G = \frac{(9.81\text{ m/s}^2)(1350-997\text{ kg/m}^3)(1.0 \times 10^{-7}\text{ m})^2}{(18)(0.89 \times 10^{-3}\text{ kg/m}\cdot\text{s})(5.0\text{ m/hr})\left(\frac{1\text{ hr}}{3600\text{ s}}\right)} = 1.56 \times 10^{-6}$$

$$\eta_D = 4\text{ Pe}^{-2/3} \dots \text{text eqn 11-39}$$

$$\text{Pe} = \frac{(3)(\pi)(0.89 \times 10^{-3}\text{ kg/m}\cdot\text{s})(1.0 \times 10^{-7}\text{ m})(7.0 \times 10^{-4}\text{ m})(5.0\text{ m/hr})\left(\frac{1\text{ hr}}{3600\text{ s}}\right)}{(1.381 \times 10^{-23}\text{ J/K})(298\text{ K})}$$

$$\text{Pe} = 1.98 \times 10^5 \Rightarrow \eta_D = 4\text{ Pe}^{-2/3} = 1.18 \times 10^{-3}$$

$$\eta = (3.06 \times 10^{-8} + 1.56 \times 10^{-6} + 1.18 \times 10^{-3}) = 1.18 \times 10^{-3}$$

$$\frac{N_2}{N_1} = \exp\left[-\frac{3}{2}(0.6)(1)(1.18 \times 10^{-3})\left(\frac{1.5\text{ m}}{7.0 \times 10^{-4}\text{ m}}\right)\right] = \boxed{0.10}$$

Bacteria:  $\eta_I = \frac{3}{2}\left(1.0 \times 10^{-6}\text{ m} / 7.0 \times 10^{-4}\text{ m}\right)^2 = 3.06 \times 10^{-6}$

$$\eta_G = v_s/v_f = (2.3 \times 10^{-4}\text{ m/hr}) / (5\text{ m/hr}) = 4.6 \times 10^{-5}$$

$$\text{Pe} = \frac{(3\pi)(0.89 \times 10^{-3}\text{ kg/m}\cdot\text{s})(1.0 \times 10^{-6}\text{ m})(7.0 \times 10^{-4}\text{ m})(5.0\text{ m/hr})\left(\frac{1\text{ hr}}{3600\text{ s}}\right)}{kT}$$

... clearly it's 10 times higher than before ...  $1.98 \times 10^6$

$$\eta_D = 2.54 \times 10^{-4}$$

$$\eta = (3.06 \times 10^{-6} + 4.55 \times 10^{-5} + 2.54 \times 10^{-4}) = 3.02 \times 10^{-4}$$

$$\frac{N_2}{N_1} = \exp\left[-\frac{3}{2}(0.6)(1)(3.02 \times 10^{-4})\left(\frac{1.5\text{ m}}{7.0 \times 10^{-4}\text{ m}}\right)\right] = \boxed{0.56}$$

## Estimating virus and bacterial removal with model of Tufenkji and Elimelech

### Properties of the pathogens

Virus diameter	0.1 $\mu\text{m}$ =	0.0000001 m
Bacteria diameter	1.0 $\mu\text{m}$ =	0.000001 m
Virus density	1350 kg/m <sup>3</sup>	
Bacteria density	1100 kg/m <sup>3</sup>	

### Properties of the water

T	298 K	
density	997 kg/m <sup>3</sup>	
viscosity	8.9E-04 kg/(m-s)	

### Properties of the filter

d_g	0.7 mm =	0.0007 m
epsilon	0.4	
bed depth	1.5 m	
filter velocity	5.0 m/hr =	1.4E-03 m/s
sticking efficiency alpha	1	
gamma	0.843	
A_S	38.0	

### Physical constants

g	9.81 m/s <sup>2</sup>	
Boltzmann's constant	1.381E-23 J/K	
Hamaker constant	1.0E-20 J	

	<u>Virus removal</u>	<u>Bacterial removal</u>
N_A	8.6E-02	8.6E-04
N_R	1.4E-04	1.4E-03
eta_I	5.6E-06	1.5E-04
N_vdW	2.43	2.43
N_G	1.6E-06	4.5E-05
eta_G	6.9E-07	1.7E-05
Pe	2.0E+05	2.0E+06
eta_D	2.8E-03	4.5E-04
eta	2.8E-03	6.2E-04
<b>N2/N1</b>	<b>0.0043</b>	<b>0.30</b>



d) Overall removal of bacteria and viruses

$$\text{Viruses: } \frac{N_2}{N_0} = \frac{N_2}{N_1} \times \frac{N_1}{N_0} = 0.10 \times 0.12 = 0.012$$

$$\text{Fraction persisting} = 0.012$$

$$\text{Fraction removed} = 0.988 = \boxed{99\% \text{ removal}}$$

$$\text{Bacteria: } \frac{N_2}{N_0} = \frac{N_2}{N_1} \times \frac{N_1}{N_0} = 0.50 \times 0.14 = 0.070$$

$$\text{Fraction persisting} = 0.070$$

$$\text{Fraction removed} = 0.930 = \boxed{93\% \text{ removal}}$$

e) Discuss briefly

Flocculation works about equally well on viruses and bacteria, removing somewhere around 85-90% of both. But filtration works better on viruses, so therefore the overall removal is higher for viruses. Filtration doesn't work great on bacteria because bacteria are about 1 micron in size, and that is the size at which none of the three filtration mechanisms are very effective. This is why it is necessary to include a disinfection step as part of the process -- flocculation and sedimentation and filtration might remove 90-95% of bacteria, but that isn't good enough -- disinfection will hopefully get the rest. (...and the rest of the viruses, too!)

PROBLEM: Disinfection

(a) Estimate  $k_1$  for the reactors

Batch reactor, first-order:  $N = N_0 e^{-k_1 t}$

$$N/N_0 = e^{-k_1 t}$$

$$\ln(N/N_0) = -k_1 t \quad \Rightarrow \quad \ln(N_0/N) = +k_1 t$$

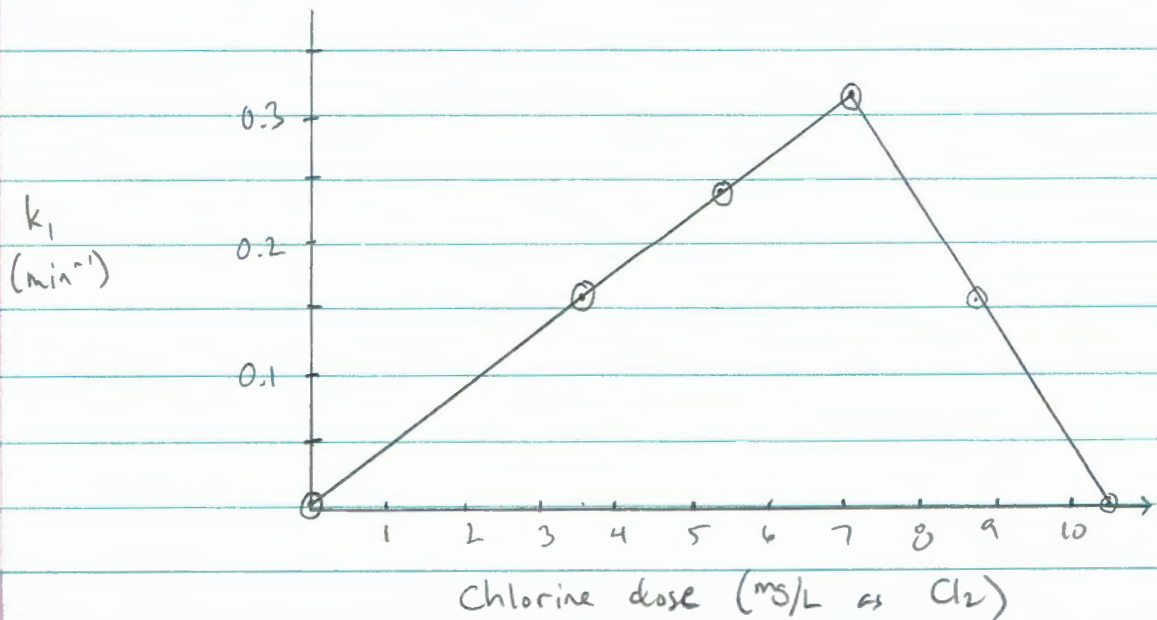
$$k_1 = \frac{\ln(N_0/N)}{t}$$

... given  $t = 10$  min for all reactors

given  $N_0 = 235$  CFU/L for all reactors

Reactor #	Apparent $k_1$ ( $\text{min}^{-1}$ )
1	0.0004
2	0.16
3	0.24
4	0.32
5	0.16
6	0.0009

(b) Graph  $k_1$  vs. chlorine dose for these six reactors.



© Why does Doerville have a problem?

The shape of the graph looks like the "breakpoint chlorination" graph. It must be that the water contains some ammonia ( $\text{NH}_3$ ), and the ammonia is doing two things. First, the ammonia converts free chlorine to combined chlorine, which is less effective. Second, the chloramines can actually react to remove disinfectant from the system, which is why the performance got worse when the  $\text{Cl}_2$  dose went up. To fix this, we need to "break" the chlorine.

© Estimate conc. of  $\text{NH}_3$  in the water

This could be estimated either from the peak or from the break point. We know the peak is reached when the  $\text{Cl}_2$  dose (molar conc.) equals the  $\text{NH}_3$  molar conc.

$$7.1 \frac{\text{mg Cl}_2}{\text{L}} * \frac{1 \text{ g}}{1000 \text{ mg}} * \frac{1 \text{ mole Cl}_2}{2 * 35.453 \text{ g}} = 1.0 * 10^{-4} \text{ mol/L}$$

$$\Rightarrow \text{NH}_3 \text{ conc. must be } 1.0 * 10^{-4} \text{ mol/L}$$

Or from the break point

$$10.6 \frac{\text{mg Cl}_2}{\text{L}} * \frac{1 \text{ g}}{1000 \text{ mg}} * \frac{1 \text{ mole Cl}_2}{2 * 35.453 \text{ g}} = 1.5 * 10^{-4} \text{ mol/L}$$

$$\Rightarrow \text{NH}_3 \text{ conc. must be } \frac{1.5 * 10^{-4} \text{ mol/L}}{1.5} = 1.0 * 10^{-4} \frac{\text{mol}}{\text{L}}$$

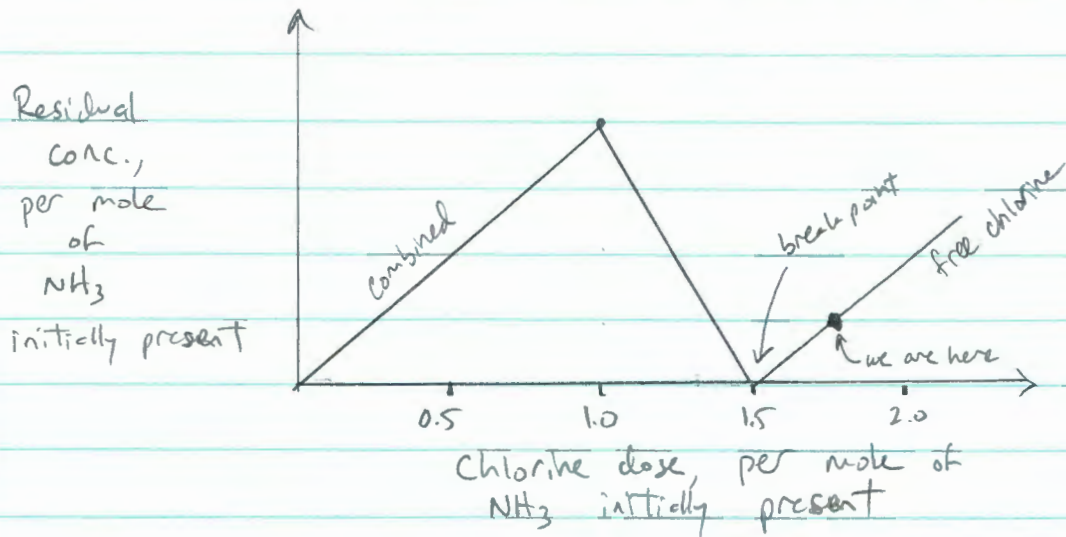
Same answer either way

$$\text{Conc. of NH}_3 \text{ in water} = \boxed{1.0 * 10^{-4} \frac{\text{mol}}{\text{L}}}$$

$$1.0 * 10^{-4} \frac{\text{mol}}{\text{L}} * \frac{14 \text{ g N}}{1 \text{ mol}} * \frac{1000 \text{ mg}}{1 \text{ g}} = \boxed{1.4 \text{ mg/L as N}}$$



② What residual conc if they dose at 12.4 mg/L Cl<sub>2</sub>?



$$12.4 \frac{\text{mg Cl}_2}{\text{L}} * \frac{1 \text{ g Cl}_2}{1000 \text{ mg}} * \frac{1 \text{ mol Cl}_2}{2 * 35.453 \text{ g}} = 1.75 * 10^{-4} \frac{\text{mol}}{\text{L}}$$

Ratio of Cl<sub>2</sub> dose / NH<sub>3</sub> initially present = 1.75

Break point occurs at 1.5

Therefore the remaining residual will be 1.75 - 1.5 = 0.25

$$(0.25)(1.0 * 10^{-4} \frac{\text{mol}}{\text{L}}) = 2.5 * 10^{-5} \frac{\text{mol}}{\text{L}} \text{ as Cl}_2$$

$$(2.5 * 10^{-5} \frac{\text{mol}}{\text{L}}) \left( \frac{2 * 35.453 \text{ g}}{\text{mole}} \right) \left( \frac{1000 \text{ mg}}{1 \text{ g}} \right) = 1.8 \text{ mg/L as Cl}_2 \text{ free chlorine}$$

③ Estimate k<sub>1</sub> if dosing at 12.4 mg/L Cl<sub>2</sub>

C = 1.8 mg/L as Cl<sub>2</sub>, free chlorine

From graph, 99% removal if Ct = 1.0  $\frac{\text{min} \cdot \text{mg}}{\text{L}}$

Chick-Watson  $\ln(N/N_0) = -\lambda Ct$

$$\ln(0.01) = -\lambda (1.0 \frac{\text{min} \cdot \text{mg}}{\text{L}}) \Rightarrow \lambda = 4.605 \frac{\text{L}}{\text{min} \cdot \text{mg}}$$

$$k_1 = \lambda C = (4.605 \frac{\text{L}}{\text{min} \cdot \text{mg}})(1.8 \text{ mg/L})$$

$$k_1 = 8.3 \text{ min}^{-1} \dots \text{that is quite high! Very effective.}$$



⑨ Estimate removal of E Coli at dose of 12.4 mg/L

5 CTRs in series

$$\frac{N_E}{N_I} = \left[ \frac{1}{1 + k_1 \tau} \right]^5$$

When dosing at 5.3 mg/L,  $k_1 = 0.24 \text{ min}^{-1}$

$$\frac{N_E}{N_I} = \left[ \frac{1}{1 + (0.24 \text{ min}^{-1})(10 \text{ min})} \right]^5 = 0.0022$$

99.8% removal when dosing at 5.3 mg/L

When dosing at 12.4 mg/L,  $k_1 = 8.3 \text{ min}^{-1}$

$$\frac{N_E}{N_I} = \left[ \frac{1}{1 + (8.3 \text{ min}^{-1})(10 \text{ min})} \right]^5 = 2 \times 10^{-10} \text{ or so}$$

Essentially 100% removal when dosing at 12.4 mg/L

The problem has been solved! "Breaking" the ammonia to provide free chlorine will solve the problem.

PROBLEM: Reverse osmosis

4 (a) Osmotic pressure of feed

$$\text{NaCl} : 22.990 \text{ g/mol} + 35.453 \text{ g/mol} = 58.443 \text{ g/mol}$$

$$C = 11,700 \frac{\text{mg}}{\text{L}} * \frac{1 \text{ g}}{1000 \text{ mg}} * \frac{1 \text{ mol}}{58.443 \text{ g}} = 0.200 \text{ mol/L}$$

But we need  $C$  for  $\text{Na}^+$  and  $\text{Cl}^-$  separately, so  $0.400 \text{ mol/L}$

$$\Pi = \phi CRT$$

$$\Pi = (0.95)(0.400 \text{ mol/L})(1000 \text{ L/m}^3)(0.314 \frac{\text{Pa} \cdot \text{m}^3}{\text{mol} \cdot \text{K}})(299 \text{ K})$$

$$\Pi = 942396 \text{ Pa} * \frac{1 \text{ bar}}{10^5 \text{ Pa}}$$

$$\boxed{\Pi = 9.4 \text{ bar}}$$

3 (b) Water flux through membranes

$$J = k_w (\Delta P - \Delta \Pi)$$

$$\Delta P = \text{trans-membrane pressure} = 40 \text{ bar, given}$$

$$\Delta \Pi = \Pi_{\text{feed}} - \Pi_{\text{perm}} = 9.4 \text{ bar} - 0 \text{ bar} = 9.4 \text{ bar}$$

$$J_w = (1.3 \frac{\text{L}}{\text{m}^2 \cdot \text{hr} \cdot \text{bar}})(40 \text{ bar} - 9.42 \text{ bar})$$

$$\boxed{J_w = 40 \text{ L/m}^2 \cdot \text{hr}}$$

2 (c) Salt flux through the membrane

$$J_s = k_s \Delta C$$

$$\Delta C = 11,700 \frac{\text{mg}}{\text{L}} - 0 \frac{\text{mg}}{\text{L}} = 11,700 \frac{\text{mg}}{\text{L}}$$

$$J_s = (0.5 \frac{\text{L}}{\text{m}^2 \cdot \text{hr}})(11,700 \frac{\text{mg}}{\text{L}})$$

$$\boxed{J_s = 5850 \text{ mg/m}^2 \cdot \text{hr}}$$

(d) Salt concentration in permeate

$$C_s = J_s / J_w = (5850 \text{ mg/m}^2 \cdot \text{hr}) / (39.74 \text{ L/m}^2 \cdot \text{hr})$$

$$\boxed{C_s = 147 \text{ mg/L}}$$

3 e) Recovery and rejection

$$Q^{perm} = J_w \times A = (39.74 \text{ L/m}^2 \cdot \text{hr})(260 \text{ m}^2) = 10,332 \text{ L/hr}$$

$$\text{Recovery} = (10,332 \text{ L/hr}) / (16,400 \text{ L/hr})$$

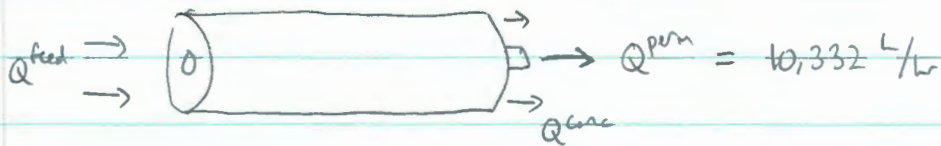
$$\boxed{\text{Recovery} = 63\%} \quad \dots \text{ pretty good for first stage!}$$

$$\text{Rejection} = 1 - c^{perm}/c^{feed}$$

$$\text{Rejection} = 1 - (147 \text{ mg/L}) / (11,700 \text{ mg/L})$$

$$\boxed{\text{Rejection} = 98.7\%} \quad \dots \text{ OK if you said } 99\%$$

3 f) Volumetric flow rate of concentrate



If we assume that the density of all the streams is about equal, then  $Q^{feed} = Q^{perm} + Q^{conc}$

$$\therefore Q^{conc} = Q^{feed} - Q^{perm} = 16,400 \text{ L/hr} - 10,332 \text{ L/hr} =$$

$$\boxed{Q^{conc} = 6070 \text{ L/hr}}$$

4 g) Concentration of salt in the concentrate stream



Accumulation = Flow in - Flow out + Sources - Sinks

$$Q = (Q^{feed} c^{feed}) - (Q^{perm} c^{perm} + Q^{conc} c^{conc}) + 0 - 0$$

$$c^{conc} = \frac{Q^{feed} c^{feed} - Q^{perm} c^{perm}}{Q^{conc}} = \frac{(16400 \frac{\text{L}}{\text{hr}})(11700 \frac{\text{mg}}{\text{L}}) - (10332 \frac{\text{L}}{\text{hr}})(147 \frac{\text{mg}}{\text{L}})}{6068 \text{ L/hr}}$$



③ continued

$$C^{\text{conc}} = 31,370 \text{ mg/L}$$

... probably too many significant digits -- let's say

$$31,000 \text{ mg/L}$$

4 (h) Osmotic pressure in feed-concentrate channel

$$\text{Average conc} = (11,700 \text{ mg/L} + 31,370 \text{ mg/L}) / 2 = 21,536 \text{ mg/L}$$

$$C = (21,536 \text{ mg/L}) \left( \frac{1 \text{ g}}{1000 \text{ mg}} \right) \left( \frac{1 \text{ mol}}{58.443 \text{ g}} \right) = 0.3685 \text{ mol/L}$$

but we need to double it for  $\text{Na}^+$  and  $\text{Cl}^-$  so  $0.737 \frac{\text{mol}}{\text{L}}$

$$\pi = (0.95) (0.737 \frac{\text{mol}}{\text{L}}) \left( \frac{1000 \text{ L}}{\text{m}^3} \right) \left( 8.314 \frac{\text{Pa} \cdot \text{m}^3}{\text{mol} \cdot \text{K}} \right) (298 \text{ K})$$

$$\pi = 1,734,672 \text{ Pa} \times \frac{1 \text{ bar}}{10^5 \text{ Pa}}$$

$$\pi = 17 \text{ bar}$$

2 (i) Osmotic pressure of the permeate

$$C = (147 \text{ mg/L}) \left( \frac{1 \text{ g}}{1000 \text{ mg}} \right) \left( \frac{1 \text{ mol}}{58.443 \text{ g}} \right) = 0.0025 \text{ mol/L}$$

Double it to get  $\text{Na}^+$  and  $\text{Cl}^-$  so  $0.005 \text{ mol/L}$

$$\pi = (1.0) (0.005 \text{ mol/L}) \left( \frac{1000 \text{ L}}{\text{m}^3} \right) \left( 8.314 \frac{\text{Pa} \cdot \text{m}^3}{\text{mol} \cdot \text{K}} \right) (298 \text{ K})$$

$$\pi = 12,463 \text{ Pa}$$

$$\pi = 0.12 \text{ bar}$$

4 (j) Re-calculate the water flux and the recovery

$$J_w = k_w (\Delta P - \Delta \pi)$$

$$J_w = (1.3 \text{ L/m}^2 \cdot \text{hr} \cdot \text{bar}) [40 \text{ bar} - (17.35 \text{ bar} - 0.12 \text{ bar})]$$

$$J_w = 29.6 \text{ L/m}^2 \cdot \text{hr} \approx 30 \text{ L/m}^2 \cdot \text{hr}$$

$$Q^{\text{perm}} = (260 \text{ m}^2) (29.6 \text{ L/m}^2 \cdot \text{hr}) = 7696 \text{ L/hr}$$

$$\text{Recovery} = (7696 \text{ L/hr}) / (16,400 \text{ L/hr}) = 47\% \text{ recovery}$$

The estimate changed a lot! 47% recovery instead of 63%!

... fine but not superb

(k) Re-calculate salt flux and rejection

$$J_s = k_f \Delta C$$
$$J_s = \left(0.5 \frac{\text{L}}{\text{m}^2 \cdot \text{hr}}\right) \overbrace{\left(21536 \frac{\text{mg}}{\text{L}} - 147 \frac{\text{mg}}{\text{L}}\right)}^{\text{UPDATED VALUES}} = \boxed{10,700 \frac{\text{mg}}{\text{m}^2 \cdot \text{hr}}} \quad \text{a big change}$$

$$C_s = \left(10,700 \frac{\text{mg}}{\text{m}^2 \cdot \text{hr}}\right) / \left(29.6 \frac{\text{L}}{\text{m}^2 \cdot \text{hr}}\right)$$

$$C_s = 361 \text{ mg/L} \quad \dots \text{ up from } 147 \text{ mg/L}$$

$$\text{Rejection} = 1 - \underbrace{\left(361 \text{ mg/L}\right) / \left(11700 \text{ mg/L}\right)}_{\text{STILL USE FEED CONC}} = \boxed{96.9\%} \approx 97\%$$

Things look worse. Only 97% rejection instead of 99% rejection.

Still acceptable, but no longer great.

(l) So, what do you think?

This exercise has shown that using feed-water characteristics to represent the feed-concentrate channel is too optimistic. The salt concentration in the feed is low compared to the rest of the feed-concentrate channel. We need to consider the changing quality of the water in the feed-concentrate channel.

By the way, we could continue to do more iterations. So far we have done two iterations ... we could keep going. It turns out that the second iteration is too pessimistic. Eventually the solution converges to something in between the first and second iterations. The recovery is about 52% and the rejection is almost 98%. These sound about right for RO!