1. Solid waste management

Some risks from improper management of solid waste:

ⓐ Direct risk of disease from items like dirty diapers, which might harbor pathogens. If people contact these items, there is risk of illness.

ⓑ Risk of vector-borne disease. Open dumps attract rats, flies, birds, mosquitoes. These animals are "vectors" that can transmit diseases.

ⓒ Risk of fire if flammable materials are not disposed properly.

ⓓ Risk of toxicity if hazardous solid wastes are not separated from non-hazardous municipal solid waste.

Probably you listed two of these. Maybe you thought of a couple others that didn't occur to me!

Proper solid waste management will separate hazardous waste and dispose of it separately, thus mitigating risk ⓓ. Municipal solid waste will be either incinerated or stored in a sanitary landfill, thus minimizing direct human contact, and reducing risk ⓐ. When stored in a landfill, waste is covered at the end of every day with dirt, tire chips, or other safe material, thus mitigating risks ⓑ and ⓒ.

(A couple obscure ones ...

ⓔ Open dumps attract birds which are hazardous to airplanes.

ⓕ Open dumps attract bears in parts of the country where bears are endemic. Bears are hazardous to people!

These are both true, but relatively minor compared to ⓐ - ⓓ.)

Oh, a few people mentioned contamination of nearby water bodies via runoff or leachate ... that's a good one too!

2. Risk of cancer from dioxin

Risk = CDI * slope factor

Allowable risk = Allowable CDI * slope factor   ...   look up SF in table

1×10^{-6} = Allowable CDI * $(1.16 \times 10^5 \; kg \cdot d/mg)$

Allowable CDI = $8.6207 \times 10^{-12} \; \frac{mg}{kg \cdot d}$

$$CDI = \frac{(conc. \; in \; air)(20 \; m^3/d)}{68 \; kg} \cdot \frac{350 \; d}{365 \; d} \cdot \frac{15 \; yr}{70 \; yr}$$

This assumes that I spend all day at my house, thus breathing $20 \; m^3/d$ of contaminated air ... if you assumed something other than $20 \; m^3/d$, that is fine, as long as you explained your assumptions.

I also assumed that I spend 15 days each year out of town, hence the factor $350/365$.

Allowable concentration in air = $\left(8.6207 \times 10^{-12} \; \frac{mg}{kg \cdot d} \right) \left(\frac{68 \; kg}{20 \; m^3/d} \right) \left(\frac{365}{350} \right) \left(\frac{70}{15} \right)$

= $1.43 \times 10^{-10} \; \frac{mg}{m^3}$ * $1000 \, \mu g / 1 \, mg$

Allowable Conc = $1.4 \times 10^{-7} \; \mu g/m^3$

ALTERNATE VERSION:

living in house for 25 years rather than 15 years.

Allowable conc = $(8.6207 \times 10^{-12}) \left(\frac{68}{20} \right) \left(\frac{365}{350} \right) \left(\frac{70}{25} \right)$ = $8.6 \times 10^{-11} \; mg/m^3$

= $8.6 \times 10^{-8} \; \mu g/m^3$

3. Emissions from the incinerator

(a) Emission rate of dioxin from the incinerator

$$\left(180,000 \text{ people}\right)\left(\frac{2.0 \text{ kg MSW}}{\text{person} \cdot d}\right)\left(\frac{25 \text{ μg dioxin produced}}{\text{ton MSW burned}}\right)\left(\frac{1 \text{ ton MSW}}{1000 \text{ kg MSW}}\right) = \underline{9000 \frac{\text{μg}}{d}}$$

{ Alternate version: 150,000 people ⇒ 7500 μg/d }

(b) Estimate/calculate required stack height

$$C(x,y,z) = \frac{E}{2\pi u \, \sigma_y \, \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right)\left\{ \exp\left[-\frac{(z-H)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(z+H)^2}{2\sigma_z^2}\right]\right\}$$

We know E from part (a)

Given $u = 4.0$ m/s

Worst-case scenario: $y = 0$ (directly downwind)

Assume house is at ground level ⇒ $z = 0$ ⇒ can use simplified formula

How about $\sigma_y \; \sigma_z$?

It's a mostly-cloudy day so "slight" insolation ⇒ stability class C

$x = 4000$ m ⇒ from graphs, $\sigma_y = 390$ m $\sigma_z = 220$ m

from equations, $\sigma_y = 372$ m $\sigma_z = 239$ m

I'll use values from the equations

Given that the acceptable concentration is 5.0×10^{-8} μg/m³

$$5.0 \times 10^{-8} \frac{\text{μg}}{\text{m}^3} = \frac{\left(9000 \text{ μg/d}\right)\left(1 \, d/86400 \, s\right)}{(\pi)(4.0 \text{ m/s})(372 \text{ m})(239 \text{ m})} \exp\left(-\frac{H^2}{2\sigma_z^2}\right)$$

$$0.5363 = \exp\left(-\frac{H^2}{2\sigma_z^2}\right) \Rightarrow -0.623 = \frac{-H^2}{2\sigma_z^2}$$

$$H^2 = (0.623)(2)(239 \text{ m})^2 \Rightarrow \underline{\underline{H = 267 \text{ m}}}$$

{ Alternate version:
E = 7500 μg/d,
U = 2.5 m/s ⇒
$0.4022 = \exp\left(-H^2/2\sigma_z^2\right)$
H = 322 m }

(c) To protect my health, the stack at the incinerator would have to be 267 m high. This is probably not structurally feasible. I don't think they can build the incinerator if they care about my health.

4.   Wastewater treatment

ⓐ SRT required

$$\frac{1}{SRT} = \mu_{max}\left(\frac{S}{S+K_s}\right) - k_d$$

$$\frac{1}{SRT} = (3.0\ d^{-1})\left(\frac{5\ mg/L}{5\ mg/L + 60\ mg/L}\right) - 0.10\ d^{-1}$$

$$\frac{1}{SRT} = 0.1308\ d^{-1}$$

$$\boxed{SRT = 7.6\ d}$$

Alternate test versions:

$\mu = 3.5\ d^{-1} \Rightarrow SRT = 5.9\ d$

$\mu = 4.0\ d^{-1} \Rightarrow SRT = 4.8\ d$

ⓑ Mass balance for soluble substrate
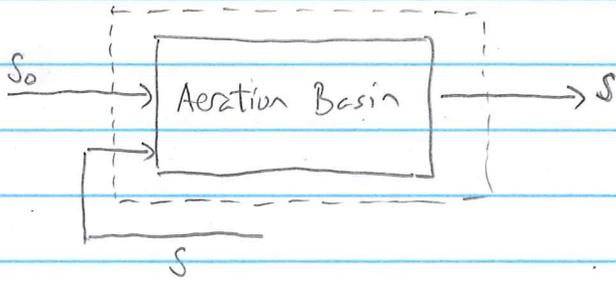
- balancing the mass of soluble substrate
- two streams in, one out

Accumulation = Flow in - Flow out + Sources - Sinks

$$0 = Q_0 S_0 + Q_R S - (Q_0 + Q_R) S + 0 - V R_{su}$$

$$0 = Q_0 S_0 + Q_R S - Q_0 S - Q_R S + 0 - V \frac{1}{Y} R_g$$

$$0 = Q_0 (S_0 - S) - V\left(\frac{1}{Y}\right) \mu_{max}\left(\frac{S}{S+K_s}\right) X$$

Divide by Q_0

$$0 = (S_0 - S) - \theta\left(\frac{1}{Y}\right)(\mu_{max})\left(\frac{S}{S+K_s}\right) X$$

$$X = \frac{Y(S_0 - S)}{\theta(\mu_{max})\left(\frac{S}{S+K_s}\right)} = \frac{(0.65)(90\ mg/L - 5\ mg/L)}{(2.0\ hr)\left(\frac{1\ d}{24\ hr}\right)(3.0\ d^{-1})\left(\frac{5\ mg/L}{65\ mg/L}\right)}$$

$$X = 2873\ mg/L \approx \boxed{2900\ mg/L}$$

This is quite reasonable... we usually expect $1500 < X < 4500\ \frac{mg}{L}$ in an aeration basin

Alternate test versions:

$\mu = 3.5\ d^{-1} \Rightarrow X = 2463\ mg/L \approx 2500\ mg/L$

$\mu = 4.0\ d^{-1} \Rightarrow X = 2155\ mg/L \approx 2200\ mg/L$

(c) Sludge wasting rate

$$SRT = \frac{VX}{Q_E X_E + Q_W X_W} = \frac{Q_o \, \theta \, X}{Q_E X_E + Q_W X_W}$$

$$7.65 \, d = \frac{(15 \, ^{m^3}/_{min})(60 \, ^{min}/_{hr})(2.0 \, hr)(2873 \, ^{mg}/_L)(1 \, ^{kg}/_{10^6 \, mg})(1000 \, ^{L}/_{m^3})}{(15 \, ^{m^3}/_{min})(1440 \, ^{min}/_d)(5.0 \, ^{mg}/_L)(1 \, ^{kg}/_{10^6 \, mg})(1000 \, ^{L}/_{m^3}) + Q_W X_W}$$

$$7.65 \, d = \frac{5171.4 \, kg}{108 \, ^{kg}/_d + Q_W X_W}$$

$$108 \, ^{kg}/_d + Q_W X_W = 5171.4 \, kg/7.65 \, d = 676 \, ^{kg}/_d$$

$$Q_W X_W = 676 \, ^{kg}/_d - 108 \, ^{kg}/_d = \boxed{568 \, ^{kg}/_d} \quad \text{sludge wasting rate}$$

Alternate versions:
$\mu = 3.5 \, d^{-1} \Rightarrow Q_W X_W = 642 \, kg/d$
$\mu = 4.0 \, d^{-1} \Rightarrow Q_W X_W = 698 \, kg/d$

Extra credit

(d) Recycle ratio Q_R/Q_o
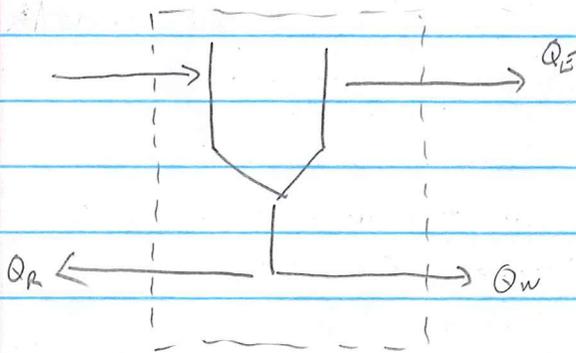
· balancing the bacterial biomass
· one stream in, three streams out

Accumulation = Flow in - Flow out + Sources - Sinks

$$0 = (Q_o + Q_R) X - [Q_E X_E + Q_W X_W + Q_R X_R] + 0 - 0$$

$$Q_R X_R = (Q_o + Q_R) X - [Q_E X_E + Q_W X_W]$$

$$Q_R X_R = Q_o X + Q_R X - 676 \, kg/d \quad \text{— this is from part c}$$

$$Q_R (X_R - X) = Q_o X - 676 \, kg/d$$

$$Q_R (11,000 \, ^{mg}/_L - 2873 \, ^{mg}/_L)\left(\frac{1000 \, L}{1 \, m^3}\right)\left(\frac{1 \, kg}{10^6 \, mg}\right)$$
$$= (15 \, ^{m^3}/_{min})(1440 \, ^{min}/_d)(2873 \, ^{mg}/_L)\left(\frac{1000 \, L}{1 \, m^3}\right)\left(\frac{1 \, kg}{10^6 \, mg}\right)$$
$$- 676 \, kg/d$$

$$Q_R \left(8.127 \, \frac{kg}{m^3}\right) = 61381 \, ^{kg}/_d \Rightarrow Q_R = 7553 \, ^{m^3}/_d = \boxed{5.2 \, ^{m^3}/_{min}}$$

$$Q_R/Q_o = 35\% \quad \cdots \quad \text{seems fine!}$$

Alternate versions:
$\mu = 3.5 \, d^{-1} \Rightarrow 4.3 \, m^3/min = 28\%$
$\mu = 4.0 \, d^{-1} \Rightarrow 3.6 \, m^3/min = 24\%$

5. Environmental chemistry and water treatment

(a) Concentration of PO_4^{3-}

$$AlPO_4 (s) \rightleftharpoons Al^{3+} + PO_4^{3-}$$

$$\frac{\{Al^{3+}\}\{PO_4^{3-}\}}{\{AlPO_4 (s)\}} = K_{sp} \Rightarrow \frac{[Al^{3+}][PO_4^{3-}]}{1} = 6.3 \times 10^{-19}$$
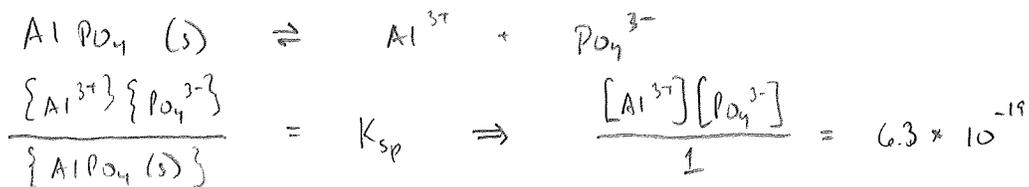
$$[Al^{3+}] = 0.2 \frac{mg}{L} \times \frac{1\ g}{1000\ mg} \times \frac{1\ mole}{27\ g} = 7.41 \times 10^{-6} \frac{mol}{L}$$

$$\left(7.41 \times 10^{-6} \frac{mol}{L}\right)[PO_4^{3-}] = 6.3 \times 10^{-19} \Rightarrow [PO_4^{3-}] = 8.5 \times 10^{-14} \frac{mol}{L}$$

$$8.5 \times 10^{-14} \frac{mol\ PO_4^{3-}}{L} \times \frac{1\ mol\ P\ atoms}{1\ mol\ PO_4^{3-}\ molecules} \times \frac{31\ g\ P}{1\ mol\ P} \times \frac{1000\ mg}{1\ L}$$

$$= \underline{\underline{2.6 \times 10^{-9}\ mg/L}}\quad as\ P$$

Alternate version: $[Al^{3+}] = 0.05\ mg/L$
$[PO_4^{3-}] = 1.1 \times 10^{-8} \frac{mg}{L}$ as P

(b) Concentrations of H_3PO_4 $H_2PO_4^-$ HPO_4^{2-}

$$HPO_4^{2-} \rightleftharpoons H^+ + PO_4^{3-}\qquad pK_a = 12.3\quad from\ text\ p.\ 85$$
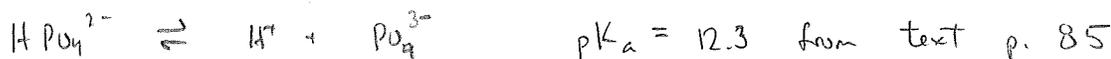
$$\frac{\{H^+\}\{PO_4^{3-}\}}{\{HPO_4^{2-}\}} = 10^{-12.3} \Rightarrow \frac{[H^+][8.5 \times 10^{-14}]}{[HPO_4^{2-}]} = 5.0 \times 10^{-13}$$

$$pH = 5.3 \Rightarrow [H^+] = 10^{-5.3} = 5.0 \times 10^{-6} \frac{mol}{L}$$

$$[HPO_4^{2-}] = \frac{[H^+][PO_4^{3-}]}{K_A} = \frac{(5.0 \times 10^{-6})(8.5 \times 10^{-14})}{(5.0 \times 10^{-13})} = \underline{\underline{8.5 \times 10^{-7} \frac{mol}{L}}}$$

HPO_4^{2-} :

$$8.5 \times 10^{-7} \frac{mol\ HPO_4^{2-}}{L} \times \frac{1\ mol\ P\ atoms}{1\ mol\ HPO_4^{2-}\ molecules} \times \frac{31,000\ mg\ P}{1\ mol\ P} = \underline{\underline{0.026 \frac{mg}{L}}}$$

$$H_2PO_4^- \rightleftharpoons H^+ + HPO_4^{2-}\qquad pK_A = 7.2\quad from\ text\ p.\ 85$$
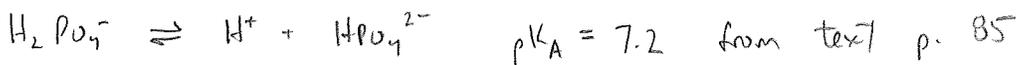
$$[H_2PO_4^-] = \frac{[H^+][HPO_4^{2-}]}{K_A} = \frac{(5.0 \times 10^{-6})(8.5 \times 10^{-7})}{10^{-7.2}} = 6.74 \times 10^{-5} \frac{mol}{L}$$

$H_2PO_4^-$:

$$6.74 \times 10^{-4} \frac{mol\ H_2PO_4^-}{L} \times \frac{1\ mol\ P\ atoms}{1\ mol\ H_2PO_4^-\ molecules} \times \frac{31,000\ mg\ P}{1\ mol\ P} = \underline{\underline{2.1 \frac{mg}{L}}}\ as\ P$$

(b) continued

$$H_3PO_4 \rightleftharpoons H^+ + H_2PO_4^- \qquad pK_A = 2.1 \quad \text{from text } p. \ 85$$
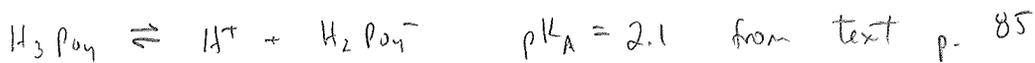
$$[H_3PO_4] = \frac{[H^+][H_2PO_4^-]}{K_A} = \frac{(5.0 \times 10^{-6})(6.74 \times 10^{-5})}{10^{-2.1}} = 4.24 \times 10^{-8} \ mol/L$$

H_3PO_4:

$$4.24 \times 10^{-8} \ \frac{mol}{L} \times \frac{1 \ mol \ P \ atoms}{1 \ mol \ H_3PO_4 \ molecules} \times \frac{31,000 \ mg \ P}{1 \ mol \ P} = \underline{0.0013 \ mg/L \ as \ P}$$

(c) Conc. of TP

$$[TP] = [PO_4^{3-}] + [HPO_4^{2-}] + [H_2PO_4^-] + [H_3PO_4]$$

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Alternate version:
pH = 5.5
[H₂PO₄⁻] = 3.3 mg/L as P
[TP] = 3.4 mg/L as P
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$$= negligible + 0.026 \ \frac{mg}{L} + 2.1 \ \frac{mg}{L} + 0.0013 \ \frac{mg}{L}$$

$$[TP] \approx \underline{2.1 \ mg/L \ as \ P}$$

We didn't meet the treatment objective. Still a bit too much phosphorus.

(d) What size $AlPO_4$ particles can be 100% removed?

For particles to be removed 100%, we require $V_s > OR$.

Given $OR = 36 \ \frac{m^3/d}{m^2} \times \frac{1 \ d}{86400 \ s} = 4.167 \times 10^{-4} \ \frac{m}{s}$

Assume for now that $Re < 1 \implies V_s = \frac{g(\rho_s - \rho_w) d_p^2}{18 \ \mu}$

$$\frac{(4.167 \times 10^{-4} \ \frac{m}{s})(18)(1.06 \times 10^{-3} \ \frac{kg}{m \cdot s})}{(9.81 \ m/s^2)(2570 \ kg/m^3 - 999 \ kg/m^3)} \leq d_p^2$$

$$5.158 \times 10^{-10} \ m^2 \leq d_p^2 \implies d_p \geq 2.27 \times 10^{-5} \ m = \underline{23 \ \mu m}$$

Now check if $Re < 1$ to be sure it's ok

$$Re = \frac{\rho v d}{\mu} = \frac{(999 \ kg/m^3)(4.2 \times 10^{-4} \ \frac{m}{s})(2.27 \times 10^{-5} \ m)}{1.06 \times 10^{-3} \ kg/m \cdot s} = 0.009 \ll 1 \ \checkmark$$

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Alternate version:
OR = 48 m/d
dp ≥ 27 μm
Re = 0.015
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6. Reactor theory + Mass balances

(a) Mass balance for Chemical A, using entire system
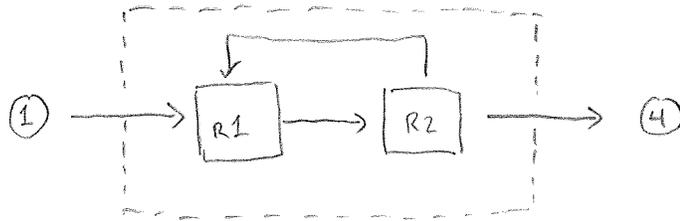
One stream in,
one stream out

Accumulation = Flow in - Flow out + Sources - Sinks

$$0 = Q_1 [A]_1 - Q_4 [A]_4 + 0 - V_2 R$$

↑ because chemical A is converted to chemical B in Reactor 2!

$R = k[A]_4$ because CMFR

(conc. in the reactor equals conc. leaving the reactor)

$$0 = Q_1 [A]_1 - Q_4 [A]_4 - V_2 k [A]_4$$

$$[A]_4 = \left(\frac{Q_1}{Q_4 + V_2 k} \right) [A]_1 \implies [A]_4 = (3.0 \ \tfrac{mmol}{L}) \frac{0.3 \ L/hr}{0.3 \ \tfrac{L}{hr} + (4.0 \ L) \, k}$$

Test version 1: $k = 4.0 \ hr^{-1} \implies [A]_4 = 0.055 \ mmol/L$

version 2: $k = 3.0 \ hr^{-1} \implies [A]_4 = 0.073 \ mmol/L$

(b) Mass balance for Chemical B, using Reactor 2
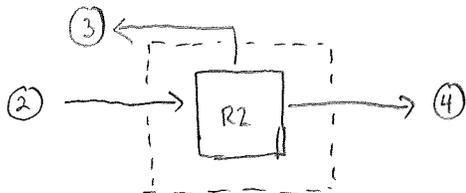
• one stream in, two streams out
• source term in the reactor

Accumulation = Flow in - Flow out + Sources - Sinks

$$0 = Q_2 [B]_2 - \{ Q_3 [B]_3 + Q_4 [B]_4 \} + V_2 R - 0$$

$R = k [A]_4$ because $A \to B$

$$0 = Q_2 [B]_2 - \{ Q_3 [B]_3 + Q_4 [B]_4 \} + V_2 k [A]_4$$

                    3 UNKNOWNS   KNOWN

where
$k = 4.0 \ hr^{-1}$
or $3.0 \ hr^{-1}$

© Mass balance for Chemical B, using Reactor 1
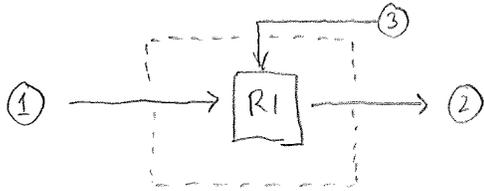
- one stream in, two streams out
- Chemical B removed by reaction

Accumulation = Flow in − Flow out + Sources − Sinks

$$0 = \{Q_1 [B]_1 + Q_3 [B]_3\} - Q_2 [B]_2 + 0 - V_1 R$$

Notice $[B]_1 = 0$ ... given

$$R = k [B]_2$$

$$0 = Q_3 [B]_3 - Q_2 [B]_2 - V_1 k [B_2]$$

$$0 = Q_3 [B]_3 - (Q_2 + V_1 k)[B]_2 \qquad \text{where } k = 0.33 \ hr^{-1} \text{ or } 0.40 \ hr^{-1}$$

TWO UNKNOWNS, $[B]_3$ and $[B]_2$

ⓓ Solve for $[B]_4$

Let's notice that $[B]_3 = [B]_4$ because Reactor 2 is a CMFR.

Thus our mass balance from part ⓑ becomes:

$$0 = (1.8 \ ^L/hr) [B]_2 - (1.8 \ ^L/hr) [B]_3 + (4.0 \ L) k_2 [A]_4$$

And our mass balance from part © is:

$$0 = (1.5 \ ^L/hr) [B]_3 - \{1.8 \ ^L/hr + (2.0 L)(k_1)\} [B]_2$$

multiply the second of these by $\frac{1.8}{1.5}$

$$0 = (1.8 \ \tfrac{L}{hr}) [B]_3 - \left(\frac{1.8}{1.5}\right) \{1.8 \ \tfrac{L}{hr} + (2.0 L)(k_1)\} [B]_2$$

Now add the two equations, and $[B]_3$ drops out

$$0 = (1.8 \ \tfrac{L}{hr}) [B]_2 + (4.0 L) k_2 [A]_4 - \left(\frac{1.8}{1.5}\right) \{1.8 \ \tfrac{L}{hr} + (2.0 L)(k_1)\} [B]_2$$

$$(4.0 L) k_2 [A]_4 = \left\{ \left(\frac{1.8}{1.5}\right) \{1.8 \ \tfrac{L}{hr} + (2.0 L)(k_1)\} - 1.8 \ \tfrac{L}{hr} \right\} [B]_2$$

(d) continued

$$[B]_2 = \frac{V_2\, k_2\, [A_4]}{\left(\frac{Q_2}{Q_3}\right)\left[Q_2 + V_1\, k_1\right] - Q_2} = \frac{0.77\ \frac{mmol}{L}}{0.67\ \frac{mmol}{L}}\quad \text{or}$$

Now we can find $[B]_3$ which is the same as $[B]_4$.

$$[B]_4 = [B]_3 = \left(\frac{Q_2 + V_1\, k_1}{Q_3}\right)[B]_2 = \boxed{\begin{array}{l} 1.26\ \frac{mmol}{L}\ \text{(version 1)}\quad \text{or} \\[2ex] 1.15\ \frac{mmol}{L}\ \text{(version 2)} \end{array}}$$

(e) What is overall removal?

Version 1: $[A]_4 + [B]_4 = 0.055\ \frac{mmol}{L} + 1.26\ \frac{mmol}{L} = 1.3\ \frac{mmol}{L}$

$$\text{Removal} = 1 - \frac{1.3\ mmol/L}{3.0\ mmol/L} = \boxed{56\%\ \text{removal}}$$

Version 2: $[A]_4 + [B]_4 = 0.073\ \frac{mmol}{L} + 1.15\ \frac{mmol}{L} = 1.23\ \frac{mmol}{L}$

$$\text{Removal} = 1 - \frac{1.23\ mmol/L}{3.0\ mmol/L} = \boxed{59\%\ \text{removal}}$$

My student and I want to increase the reaction rate coefficient in Reactor 1 so that the overall removal will get up to about 75%.