

# 1. Water Quality in Grant City

## (a) Concentrations of major ions

$$\text{Ca}^{2+} : 76 \frac{\text{mg}}{\text{L}} * \frac{1 \text{ mmol}}{40.08 \text{ mg}} = \underline{1.9 \frac{\text{mmol}}{\text{L}}} * \frac{2 \text{ meq}}{1 \text{ mmol}} = \underline{3.8 \text{ meq/L}}$$

$$\text{Mg}^{2+} : 34 \frac{\text{mg}}{\text{L}} * \frac{1 \text{ mmol}}{24.31 \text{ mg}} = \underline{1.4 \frac{\text{mmol}}{\text{L}}} * \frac{2 \text{ meq}}{1 \text{ mmol}} = \underline{2.8 \text{ meq/L}}$$

$$\text{Na}^+ : 6.9 \frac{\text{mg}}{\text{L}} * \frac{1 \text{ mmol}}{22.99 \text{ mg}} = \underline{0.30 \frac{\text{mmol}}{\text{L}}} * \frac{1 \text{ meq}}{1 \text{ mmol}} = \underline{0.3 \text{ meq/L}}$$

$$\text{HCO}_3^- : 366 \frac{\text{mg}}{\text{L}} * \frac{1 \text{ mmol}}{61 \text{ mg}} = \underline{6.0 \frac{\text{mmol}}{\text{L}}} * \frac{1 \text{ meq}}{1 \text{ mmol}} = \underline{6.0 \text{ meq/L}}$$

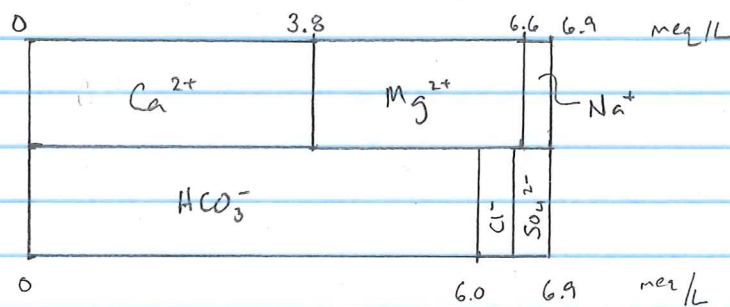
$$\text{Cl}^- : 14 \frac{\text{mg}}{\text{L}} * \frac{1 \text{ mmol}}{35.45 \text{ mg}} = \underline{0.40 \frac{\text{mmol}}{\text{L}}} * \frac{1 \text{ meq}}{1 \text{ mmol}} = \underline{0.4 \text{ meq/L}}$$

$$\text{SO}_4^{2-} : 24 \frac{\text{mg}}{\text{L}} * \frac{1 \text{ mmol}}{96.06 \text{ mg}} = \underline{0.25 \frac{\text{mmol}}{\text{L}}} * \frac{2 \text{ meq}}{1 \text{ mmol}} = \underline{0.5 \text{ meq/L}}$$

Charge balance : Cations  $3.8 \text{ meq/L} + 2.8 \text{ meq/L} + 0.3 \text{ meq/L} = 6.9 \text{ meq/L}$

Anions  $6.0 \text{ meq/L} + 0.4 \text{ meq/L} + 0.5 \text{ meq/L} = 6.9 \text{ meq/L}$

The balance is good. ✓



## (b) Hardness

$$[\text{Ca}^{2+}] + [\text{Mg}^{2+}] = 6.6 \text{ meq/L}$$

$$6.6 \frac{\text{meq}}{\text{L}} * \frac{100 \text{ mg CaCO}_3}{2 \text{ meq}} = \underline{330 \text{ mg/L as CaCO}_3}$$

## (c) Osmotic pressure

$$\pi = \phi CRT$$

C = sum of all ion concentrations

$$= 1.9 \frac{\text{mol}}{\text{m}^3} + 1.4 \frac{\text{mol}}{\text{m}^3} + 0.3 \frac{\text{mol}}{\text{m}^3} + 6.0 \frac{\text{mol}}{\text{m}^3} + 0.4 \frac{\text{mol}}{\text{m}^3} + 0.25 \frac{\text{mol}}{\text{m}^3} = 10.25 \frac{\text{mol}}{\text{m}^3}$$

$$\pi = (0.95)(10.25 \text{ mol/m}^3)(8.314 \text{ Pa}\cdot\text{m}^3/\text{mol}\cdot\text{K})(273+15 \text{ K}) = \underline{23,300 \text{ Pa}}$$

$$= \underline{0.23 \text{ bar}}$$

## 2. Disinfection with chlorine

What concentration of chlorine residual is required?

### Short method

When  $Ct = (4.0 \frac{mg}{L})(5 \text{ min}) = 20$ , we get two nines removal

When  $Ct = (3.0 \frac{mg}{L})(10 \text{ min}) = 30$ , we get three nines removal

So for four nines removal, we need  $Ct = 40$

$$(C)(15 \text{ min}) = 40 \frac{mg}{L} \cdot \text{min} \Rightarrow \underline{\underline{C = 2.7 \frac{mg}{L}}}$$

### Long method

Batch reactor  $N(t) = N_0 e^{-kt} \Rightarrow \frac{N}{N_0} = e^{-kt}$

Chick-Watson rule  $k = \lambda C$  where  $C = \text{conc. of disinfectant}$

$$\therefore \frac{N}{N_0} = e^{-\lambda Ct}$$

Given 99% inactivation when  $C = 4.0 \frac{mg}{L}$  and  $t = 5 \text{ min}$

99% inactivation  $\Rightarrow N/N_0 = 0.01$

$$0.01 = \exp(-\lambda Ct)$$

$$0.01 = \exp\left[-\lambda \left(4.0 \frac{mg}{L}\right)(5 \text{ min})\right]$$

$$\ln(0.01) = -\lambda \left(4.0 \frac{mg}{L}\right)(5 \text{ min})$$

$$\lambda = \frac{\ln(0.01)}{-(4.0 \frac{mg}{L})(5 \text{ min})} = 0.23 \frac{L}{mg \cdot \text{min}}$$

Check the other data point given ...  $C = 3.0 \frac{mg}{L}$   $t = 10 \text{ min}$

$$\frac{N}{N_0} = \exp\left[-\left(0.23 \frac{L}{mg \cdot \text{min}}\right)\left(3.0 \frac{mg}{L}\right)(10 \text{ min})\right] = 0.001$$

$N/N_0 = 0.001$  so 99.9% inactivation ✓ It is correct.

So now in our PFR:

$$N_E = N_I e^{-k\theta} \Rightarrow \frac{N_E}{N_I} = \exp(-k\theta) = \exp[-\lambda C \theta]$$

99.99% inactivation  $\Rightarrow N_E/N_I = 0.0001$

$$0.0001 = \exp\left[-\left(0.23 \frac{L}{mg \cdot \text{min}}\right) C (15 \text{ min})\right]$$

$$C = \frac{\ln(0.0001)}{-\left(0.23 \frac{L}{mg \cdot \text{min}}\right)(15 \text{ min})} = \underline{\underline{2.7 \frac{mg}{L}}}$$

Both methods work, but if you see the short cut, it is a lot quicker!

### 3. Lime softening for Grant City

(a) Is soda ash necessary?

Currently the hardness is  $330 \text{ mg/L}$  as  $\text{CaCO}_3$

That is equivalent to  $6.6 \text{ meq/L}$

We must soften to  $50 \text{ mg/L}$ , which is  $1.0 \text{ meq/L}$

So we must remove  $280 \text{ mg/L}$  of hardness, or  $5.6 \text{ meq/L}$  hardness.

But from problem 1, we have  $6.0 \text{ meq/L}$  of  $\text{HCO}_3^-$

Therefore we have sufficient  $\text{HCO}_3^-$  in the water  $\dots 6.0 > 5.6$

We do not need soda ash

(b) Rate of  $\text{CaO}$  addition

To remove  $3.8 \text{ meq/L}$  of  $\text{Ca}^{2+}$  which is  $1.9 \text{ mmol/L}$   $\text{Ca}^{2+}$ :



So we need  $1.9 \text{ mmol/L}$  of lime to remove  $1.9 \text{ mmol/L}$   $\text{Ca}^{2+}$

To remove  $1.8 \text{ meq/L}$  of  $\text{Mg}^{2+}$  which is  $0.9 \text{ mmol/L}$   $\text{Mg}^{2+}$ :



So we need  $1.8 \text{ mmol/L}$  of lime to remove  $0.9 \text{ mmol/L}$   $\text{Mg}^{2+}$

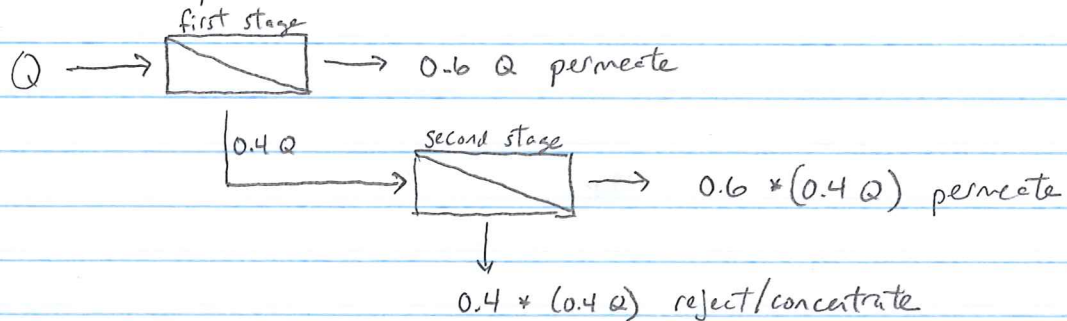
Thus overall we need  $1.9 \frac{\text{mmol}}{\text{L}} + 1.8 \frac{\text{mmol}}{\text{L}} = 3.7 \frac{\text{mmol}}{\text{L}}$  lime

$$\begin{aligned} & \left(950 \frac{\text{m}^3}{\text{hr}}\right) \left(\frac{24 \text{ hr}}{1 \text{ d}}\right) \left(\frac{1000 \text{ L}}{1 \text{ m}^3}\right) \left(3.7 \times 10^{-3} \frac{\text{mol CaO}}{\text{L}}\right) \left(\frac{56 \text{ g CaO}}{1 \text{ mol CaO}}\right) \left(\frac{1 \text{ kg}}{1000 \text{ g}}\right) \\ & = \underline{4700 \text{ kg/d CaO}} \\ & = 4.7 \text{ tons/d} \end{aligned}$$

That is a lot of lime for Grant City!

#### 4. Reverse osmosis for Grant City

(a) Overall recovery?



$$\text{Overall recovery} = 0.6 + 0.6 * 0.4 = \underline{\underline{0.84}} = \underline{\underline{84\%}}$$

(b) How much groundwater needed?

$$950 \text{ m}^3/\text{hr} = (0.84) (Q_{\text{total}}) \Rightarrow Q_{\text{total}} = \frac{950 \text{ m}^3/\text{hr}}{0.84} = \underline{\underline{1130 \text{ m}^3/\text{hr}}}$$

$$\text{So split among 30 pressure vessels, } \frac{1130 \text{ m}^3/\text{hr}}{30} = \underline{\underline{38 \text{ m}^3/\text{hr}}} \text{ to each pressure vessel}$$

(c) What mass transfer coefficient is needed?

$$\text{Feed to the pressure vessel} = 37.7 \text{ m}^3/\text{hr}$$

$$12\% \text{ recovery} = (0.12)(37.7 \text{ m}^3/\text{hr}) = 4.52 \text{ m}^3/\text{hr} \text{ from the first element}$$

$$= 4520 \text{ L/hr}$$

$$\left(4520 \frac{\text{L}}{\text{hr}}\right) = k_w (35 \text{ m}^2) (\Delta P - \Delta \pi)$$

$$\text{Given } \Delta P = 40 \text{ bar, know } \Delta \pi \approx 0.23 \text{ bar from 1c}$$

$$4520 \frac{\text{L}}{\text{hr}} = k_w (35 \text{ m}^2) (40 \text{ bar} - 0.23 \text{ bar})$$

$$k_w = \frac{4520 \text{ L/hr}}{(35 \text{ m}^2)(39.77 \text{ bar})} = \underline{\underline{3.25 \frac{\text{L}}{\text{m}^2 \cdot \text{hr}}}} * \frac{1 \text{ hr}}{3600 \text{ s}} = \underline{\underline{9.0 \times 10^{-4} \frac{\text{L}}{\text{m}^2 \cdot \text{bar} \cdot \text{s}}}}$$

NOTE: I did this calculation for the first membrane element in the vessel.

The second element is required to produce less water ... 12% of 88%. So this  $k_w$  should be fine for elements #2 through #7.

## 5. Nitrogen removal in new Sprawlville wastewater plant

(a) How much  $\text{NH}_4^+$  removal in anaerobic, anoxic reactors?

We would not expect any  $\text{NH}_4^+$  removal in these two reactors.

$\text{NH}_4^+$  is "removed" when it is transformed to nitrate,  $\text{NO}_3^-$ , via nitrification. That happens in the oxic/aerobic reactor. So in the first two reactors,  $\text{NH}_4^+$  should be unreactive. no oxygen  $\Rightarrow$  no nitrification!

(Subtle note: there is a process called "anaerobic ammonium oxidation" or ANAMMOX, which could lead to  $\text{NH}_4^+$  removal in these reactors. But that process usually does not occur to an appreciable extent so we will ignore it here.)

(b) Loading of N to oxic/aerobic reactor

$$\left(900 \frac{\text{m}^3}{\text{hr}}\right) \left(28 \frac{\text{mg N}}{\text{L}}\right) \left(\frac{1000 \text{ L}}{\text{m}^3}\right) \left(\frac{1 \text{ kg}}{10^6 \text{ mg}}\right) \left(\frac{24 \text{ hr}}{\text{d}}\right) = \underline{\underline{600 \frac{\text{kg N}}{\text{d}}}}$$

(c) Size the aerobic reactor

$$\begin{aligned} \text{Allowable loading} &= 256 \frac{\text{mg}}{\text{L} \cdot \text{d}} * 0.8 \text{ pH correction} = 205 \frac{\text{mg N}}{\text{L} \cdot \text{d}} \\ &= 205 \frac{\text{g N}}{\text{m}^3 \cdot \text{d}} = 0.205 \text{ kg N} / \text{m}^3 \cdot \text{d} \end{aligned}$$

$$\text{Volume} = \frac{(600 \text{ kg N/d})(1.5 \text{ peaking factor})}{0.205 \text{ kg N} / \text{m}^3 \cdot \text{d}} = \underline{\underline{4400 \text{ m}^3}}$$

$$\text{Residence time} = \frac{(28 \text{ mg/L})(1.5 \text{ peaking})}{(256 \frac{\text{mg}}{\text{L} \cdot \text{d}})(0.8 \text{ correction})} = 0.205 \text{ d} = \underline{\underline{4.9 \text{ hr}}}$$

$$\text{Check volume} = Q\theta = (900 \text{ m}^3/\text{hr})(4.9 \text{ hr}) = 4400 \text{ m}^3 \checkmark. \text{ They agree.}$$

6. BOD removal in the A<sup>2</sup>O process

(a) Why is BOD<sub>5</sub> entering the aerobic reactor so low?

Reason #1: Some of the carbon is used for denitrification in the anoxic reactor. When the carbon is oxidized by NO<sub>3</sub><sup>-</sup>, the BOD<sub>5</sub> decreases as the carbon is removed.

Reason #2: The stream is diluted after it leaves the flow equalization tank. The RAS comes from the settling tank, and the NO<sub>3</sub><sup>-</sup> return stream enters the anoxic tank. Both of these streams are low in BOD<sub>5</sub>. Since the original stream (80 mg/L) is being mixed with new streams at a lower conc., the overall conc. of BOD<sub>5</sub> decreases.

(b) Find the solids retention time.

$$\frac{1}{\theta_c} = \mu - k_d = \mu_{\max} \frac{S}{S + K_s} - k_d = (2.0 \text{ d}^{-1}) \left( \frac{9 \text{ mg/L}}{9 \frac{\text{mg}}{\text{L}} + 60 \frac{\text{mg}}{\text{L}}} \right) - 0.14 \text{ d}^{-1}$$

$$\frac{1}{\theta_c} = 0.26 \text{ d}^{-1} - 0.14 \text{ d}^{-1} = 0.12 \text{ d}^{-1} \Rightarrow \underline{\underline{\theta_c = 8.3 \text{ d}}}$$

(c) Find the required volume and aeration time

$$\theta = \frac{\theta_c Y (S_0 - S)}{X [1 + k_d \theta_c]} = \frac{(8.3 \text{ d})(0.6 \text{ mg/mg})(20 \text{ mg/L} - 9 \text{ mg/L})}{(2000 \text{ mg/L}) [1 + (0.14 \text{ d}^{-1})(8.3 \text{ d})]}$$

$$\theta = 0.0127 \text{ d} = \underline{\underline{0.30 \text{ hr}}} = 18 \text{ min} \dots \text{very short!!}$$

$$V = \theta Q = (0.30 \text{ hr})(900 \text{ m}^3/\text{hr}) = \underline{\underline{274 \text{ m}^3}}$$

Since we only need very little BOD removal ... 20  $\frac{\text{mg}}{\text{L}}$  to 9  $\frac{\text{mg}}{\text{L}}$  ... the reactor can be small and  $\theta$  can be short.

(d) What controls reactor size?

Need the bigger reactor so both processes can occur ... 4400 m<sup>3</sup> ... denitrification controls reactor size

## 7. Sludge handling

② What is solids conc. of WAS in % by mass?

Consider 1 L of WAS.

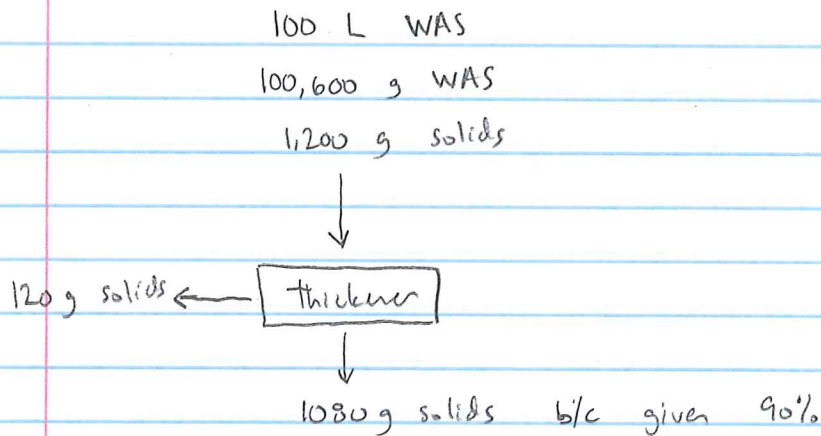
We know it has 12,000 mg of solids (given), or 12 g solids.

We know it has a total mass of 1006 g (given).

$$\frac{12 \text{ g solids}}{1006 \text{ g sludge}} = 0.01193 = 1.19\% = \underline{\underline{1.2\% \text{ by mass}}}$$

This is good, because we know  $10,000 \frac{\text{mg}}{\text{L}} \approx 1\%$ , so  $12,000 \frac{\text{mg}}{\text{L}} \approx 1.2\% \checkmark$

③ For 100 L WAS, how much to digestion, how much returned?



Mass of thickened sludge:  $\frac{1080 \text{ g solids}}{0.03} = 36,000 \text{ g thickened sludge}$

Volume of thickened sludge:  $\frac{36,000 \text{ g sludge}}{1017 \text{ g/L}} = \underline{\underline{35.4 \text{ L thickened sludge to digester}}}$

Mass of liquid return:  $100,600 \text{ g WAS} - 36,000 \text{ g thickened sludge} = 64,600 \text{ g of liquid return}$

Volume of liquid return:  $\frac{64,600 \text{ g}}{1000 \text{ g/L}} = \underline{\underline{64.6 \text{ L liquid return}}}$

So the gravity thickener does a good job, reduces the sludge volume by approximately 65%.