

ENV 504
Remediation of soils and groundwater

Final exam 2024 – solution

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Problem 1: Bioremediation and air stripping

$$C_{aq,TCE,0} = 1,000 \mu g/L$$

$$C_{aq,toluene,0} = 10 \frac{mg}{L}$$

$$Y = 0.007 \frac{g_{cells}}{mg}$$

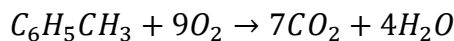
$$b = 10^{-4} d^{-1}$$

$$k = -0.05 \frac{mg_{toluene}}{d \cdot g_{cells}}$$

$$K_s = 0.1 mg_{toluene}/L$$

$$B_0 = 1,000 \frac{mg_{cells}}{L}$$

2. Concentration of oxygen needed for complete oxidation of toluene to CO₂



$$C_{aq,O_2} = 9 * \frac{C_{aq,toluene,i}}{M_{toluene}} * M_{O_2} = 9 * 10 \frac{mg}{L} * \frac{\left(32 \frac{g}{mol}\right)}{\left(7 * 12 + 8 \frac{g}{mol}\right)} = 31.3 mg/L$$

3. Concentration of toluene after 200 days (O₂ not limiting)

$$\frac{dC}{dt} = k \frac{B_0 + Y(C_0 - C)}{K_s + C}$$

$$C_0 \gg K_s \text{ and } B_0 \gg YC_0 \rightarrow \text{zeroth order no growth: } C = C_0 + kB_0t$$

After 200 days:

$$C_{aq,toluene,200} = 10 \frac{mg}{L} - \frac{0.05 mg_{toluene}}{d \cdot g_{cells}} * 1,000 \frac{mg_{cells}}{L} * \frac{1 g}{1000 mg} * 200 \text{ days}$$

$$= 0 mg/L$$

4. Total mass of TCE in 1m³ of aquifer

$$m_{TCE,0} = C_{aq,TCE,0}(\epsilon + \rho_b K_D) = 1,000 \frac{\mu g}{L} \left(0.3 + 1.75 \frac{g}{mL} * 0.1 \frac{mL}{g} \right)$$

$$= 475 mg_{TCE}/m_{aquifer}^3$$

5. Concentration of TCE after 200 days in 1 m³ of groundwater

Second-order batch reactor: $C_t = C_0/(1 + ktC_0)$

$$C_{aq,TCE,200} = \frac{1,000 \frac{\mu g}{L}}{1 + 0.07 \frac{L}{mg \cdot d} * 200 d * 1,000 \frac{\mu g}{L} * \frac{1 mg}{1,000 \mu g}} = 67 \mu g/L$$

6. TCE left after 200 days:

$$\frac{m_{TCE,200}}{m_{TCE,0}} = \frac{C_{aq,TCE,200}}{C_{aq,TCE,0}} = \frac{67}{1000} = 6.7\%$$

7. Effluent concentration of TCE from air stripping tower (20°C)

$$R = \frac{K_H Q_A}{Q_w} = 0.415 * 160 = 66.4$$

$$L = \frac{Q_w \rho_L}{S} = 60 \frac{L}{s} * 0.997 \frac{kg}{L} * \frac{1}{\pi 0.3^2 m^2} = 212 \frac{kg}{m^2 s}$$

$$L_M = \frac{L}{MW} = 212 \frac{kg}{m^2 s} * \frac{1}{18 \frac{g}{mol}} = 11,778 \frac{mol}{m^2 s}$$

$$HTU = \frac{11,778 \frac{mol}{m^2 s}}{55.6 \frac{mol}{m^3} * 77 \frac{m^2}{s}} = 2.75 m$$

$$K_L a = \alpha D_L \left(\frac{L}{\mu_L} \right)^{1-n} \left(\frac{\mu_L}{\rho_L D_L} \right)^{0.5}$$

$$= 490 * 5.3 * 10^{-4} \left(\frac{212}{1.002 * 10^{-3}} \right)^{1-0.28} \left(\frac{1.002 * 10^{-3}}{997 * 5.3 * 10^{-4}} \right)^{0.5} = 77 \frac{m^2}{s}$$

$$NTU = \frac{5.5}{2.75} = 2$$

Finally extracting the outlet concentration:

$$\ln \left(\frac{\left(\frac{C_{in}}{C_{out}} \right) (R - 1) + 1}{R} \right) = \frac{NTU(R - 1)}{R} = 1.97$$

$$\frac{C_{in}}{C_{out}} = \frac{Re^{1.97} - 1}{R - 1} = 7.27$$

$$C_{out} = 137.5 \mu g/L$$

8. Compare the two approaches

Cometabolism: in-situ, lower concentration reach, but additional oxygen and toluene needed (O_2 concentration in question 2. is higher than saturation, and toluene concentration after 200 is 0 mg/l which is not possible, degradation will stop before)

Air-stripping: we can't extract information on cost or duration because we don't have the total volume to treat

Problem 2: Adsorption

$$C_{PAC} = 2.7 \text{ mg/L}$$

$$\log(C_s) = 0.008 + 0.85 * \log(C_{aq})$$

$$C_{in} = 6 \text{ } \mu\text{g/L}$$

1. Is absorption a feasible strategy?

Mass balance when equilibrium aqueous concentration reaches legal limit $C_t = 0.05 \text{ } \mu\text{g/L}$, with N the number of batches (1,000 needed prior to regeneration for the strategy to be economically feasible). We consider $C_{out} = 0 \text{ } \mu\text{g/L}$ for all batches, because $0.05 \text{ } \mu\text{g/L} \ll 6 \text{ } \mu\text{g/L}$.

$$N * V_{batch} * (C_{in} - C_{out}) = C_{PAC} V_{batch} C_s$$

$$N C_{in} = C_{PAC} C_s$$

Sorbed concentration when C_{out} reaches $0.05 \text{ } \mu\text{g/L}$:

$$C_s = 10^{0.008+0.85*\log(0.05)} = 1.02 * 0.05^{0.85} = 0.08 \frac{\text{mg}}{\text{mg}}$$

$$N = 2.7 \frac{\text{mg}}{\text{L}} * \frac{0.08 \frac{\text{mg}}{\text{mg}}}{6 \frac{\mu\text{g}}{\text{L}} * \left(\frac{1 \text{ mg}}{1000 \mu\text{g}} \right)} = 36$$

The carbon will be exhausted after 36 cycles so the strategy is not economically viable.

2. Concentration of PAC to use to achieve desired removal

$$C'_{PAC} = C_{PAC} * \frac{1,000}{N} = 75 \frac{\text{mg}}{\text{L}}$$

Problem 3: Biopiles

1. Volume of water to add to each biopile

$$V'_L = V_T \theta' = 500 * 0.8 * 0.2 = 80 \text{ m}^3$$

$$V_L = V_T \theta = 500 * 0.1 = 50 \text{ m}^3$$

$$V_{added} = V'_L - V_L = 30 \text{ m}^3/\text{biopile}$$

2. Mass of ammonium sulfate and trisodium phosphate to be added to each biopile

Number of biopiles:

$$N = \frac{10,000 \text{ m}^3}{500 \text{ m}^3} = 20$$

Moles of C from benzene per biopile:

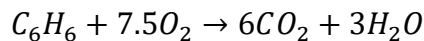
$$n_{benzene} = \frac{m_{benzene}}{M_{benzene}} = \frac{\frac{2,000}{20} \text{ kg}}{78 * 10^{-3} \frac{\text{kg}}{\text{mol}}} = 1,282 \text{ mol}$$

$$n_C = 6 * n_{benzene} = 7,692 \text{ mol}$$

$$n_N = 641 \text{ mol}; m_N = 641 \text{ mol} * \frac{132}{2} \frac{\text{g}}{\text{mol}} = 42 \text{ kg}$$

$$n_P = 64 \text{ mol}; m_P = 64 \text{ mol} * 380 \frac{\text{g}}{\text{mol}} = 24 \text{ kg}$$

3. Amount of O_2 present in each biopile sufficient for the degradation of benzene?



Quantity of O_2 needed per biopile:

$$n_{O_2,needed} = 7.5 * 1,282 \text{ mol} = 9,615 \text{ mol}$$

Quantity of O_2 available (gas phase and dissolved):

$$V_G = V_T - V_S - V'_L = V_T - \frac{M_S}{\rho_s} - V'_L$$

$$M_S = \rho_{wb} * V_T - \theta V_T = 500 \text{ m}^3 \left(1,875 \frac{\text{kg}}{\text{m}^3} - 997 \frac{\text{kg}}{\text{m}^3} * 0.1 \right) = 887.5 * 10^3 \text{ kg}$$

$$V_G = 500 \text{ m}^3 - \frac{887.5 * 10^3 \text{ kg}}{2,500 \frac{\text{kg}}{\text{m}^3}} - 80 \text{ m}^3 = 65 \text{ m}^3$$

$$V_{O_2} = 21\% * V_G = 13,650 \text{ L}$$

$$n_{O_2,g} = \frac{13,650}{22.4 \text{ L/mol}} = 610 \text{ mol}$$

$$n_{O_2,aq} = V'_L C_{O_2,sat} = 80,000 \text{ L} * 9.2 \frac{\text{mg}}{\text{L}} * \frac{1}{32 \frac{\text{g}}{\text{mol}}} = 23 \text{ mol}$$

$$n_{O_2,tot,available} = 633 \text{ mol} \ll n_{O_2,needed}$$

4. Number of air volumes needed:

$$N = \frac{n_{O_2,needed} - n_{O_2,available}}{n_{O_2,g}} = \frac{9,615 - 633}{610} = 15$$

5. How long to treat the entire amount of soil assuming sufficient oxygen and nutrient applied?

$$k = 1 \frac{\text{mg}}{\text{kg}_{dry \text{ soil}} \text{d}}$$

$$C_t = 30 \text{ mg/kg}_{dry \text{ soil}}$$

$$\begin{aligned} C_0 = C_{aq} K_D &= \frac{\frac{m_{benzene}}{N}}{K_D M_S + K_H V_G + V'_L} K_D \\ &= \frac{\frac{2,000}{20} \text{ kg}}{(0.03 * 887.5 * 10^3 + 2.08 * 65 + 80) \text{ m}^3} * 0.03 \frac{\text{m}^3}{\text{kg}} = 111 \frac{\text{mg}}{\text{kg}} \end{aligned}$$

Treatment duration:

$$t = \frac{C_0 - C_t}{k} = \frac{111 \frac{\text{mg}}{\text{kg}} - 30 \frac{\text{mg}}{\text{kg}}}{1 \frac{\text{mg}}{\text{kg} \cdot \text{d}}} = 80 \text{ days}$$