

HOMEWORK #1 (Air Pollution, Water Pollution)

1. The National Ambient Air Quality Standard (NAAQS) for sulfur dioxide (SO₂) is 0.144 ppm_v (24-hr average). What is the concentration in ug/m³ assuming an air temperature of 25 degrees C?

0.053 ppm_v

Temperature of 25 °C + 273.15 = 298.15 K

Pressure of 1 atm

Molar mass (MM) of NO₂ = 46,0055 g/mol

Using the formula :

$$[\text{m}_3\text{mg}] = 22.4 \text{ ppm}_v \times \text{mol} \times \text{molar mass} \times \frac{T(\text{K})}{273.15 \text{ K}} \times \frac{1 \text{ atm}}{P(\text{atm})}$$

$$[\text{m}_3\text{mg}] = 22.4 \times 0.053 \times 1 \text{ mol} \times 46.0055 \text{ g/mol} \times \frac{298.15}{273.15} \times \frac{1 \text{ atm}}{1 \text{ atm}} = 0.0997 \approx 0.1 \text{ m}_3\text{mg}$$

Hence, the NO₂ concentration in mg/m³ at a temperature of 25 °C and a pressure of 1 atm is 0.1 mg/m³.

2. A water sample contains $10 \text{ mg NO}_3^-/\text{L}$. What is the concentration in

a) ppm?

SOLUTION:

$$\frac{10 \text{ mg NO}_3^-}{\text{L}} \cdot \frac{10^{-3} \text{ g}}{\text{mg}} \cdot \frac{1 \text{ L}}{10^3 \text{ g}} \cdot \frac{10^6 \text{ ppm}}{\text{wt. fraction}} = 10 \text{ ppm}$$

b) moles/L

SOLUTION

$$\frac{10 \text{ mg NO}_3^-}{\text{L}} \cdot \frac{10^{-3} \text{ g}}{\text{mg}} \cdot \frac{\text{mole}}{62 \text{ g}} = 0.00016 \frac{\text{moles}}{\text{L}}$$

c) $\text{mg NO}_3^- \text{ N/L}$

SOLUTION:

$$\frac{10 \text{ mg NO}_3^-}{\text{L}} \cdot \frac{14 \text{ mg N}}{62 \text{ mg NO}_3^-} = 2.26 \frac{\text{mg NO}_3^- \text{ N}}{\text{L}}$$

d) ppb

SOLUTION:

Start with the answer to part a

$$10 \text{ ppm} \cdot \frac{10^3 \text{ ppb}}{\text{ppm}} = 10^4 \text{ ppb}$$

3. Formaldehyde (CH_2O) is commonly found in the indoor air of improperly designed and constructed buildings. If the concentration of formaldehyde in a home is 0.7 ppm , and the inside volume is 800 cubic meters , what mass (in grams) of formaldehyde vapor is inside the home? Assume $T=298\text{K}$, $P=1 \text{ atm}$.

$$\begin{aligned}\frac{g}{m^3} &= ppm_v \times \frac{P}{RT} \times MW \left(\frac{g}{mole} \right) \times 10^{-6} = \\ \frac{g}{m^3} &= \frac{0.7 ppm_v \times \left(30 \frac{g}{mole} \right) \times 1 atm}{\left(8.205 \times 10^{-5} \frac{m^3 \cdot atm}{mole \cdot K} \right) \times 298 K} \times 10^{-6} = \\ &= 858.9 \times 10^{-6} \frac{g}{m^3} \times \frac{10^6 \mu g}{g} = 858.9 \frac{\mu g}{m^3}\end{aligned}$$

The mass of formaldehyde equals

$$\frac{858.9 \mu g}{m^3} \times 800 m^3 \times \frac{g}{10^6 \mu g} = \boxed{0.7 g}$$

4. A water quality analysis of a well water used for drinking water in a rural home found an arsenic concentration of 0.5 micromolar. This value seems very small to you. But you need to see if it still exceeds the drinking water standard of 10 ppb_m. Is the well water violating the standard (and therefore the water would require treatment)?

Conc of PPB by mass = 10 ppb

Mass of the solution = 100g

$$= wb/w \times 10^6$$

$$= wb/100 \times 10^6$$

$$Wb = 15 \times 100 / 10^6 = 1.5 \times 10^{-3}$$

Percent mass of solution = $wb/w \times 100$

$$= 1.5 \times 10^{-3} \times 100 / 100$$

$$= 1.5 \times 10^{-3} \%$$

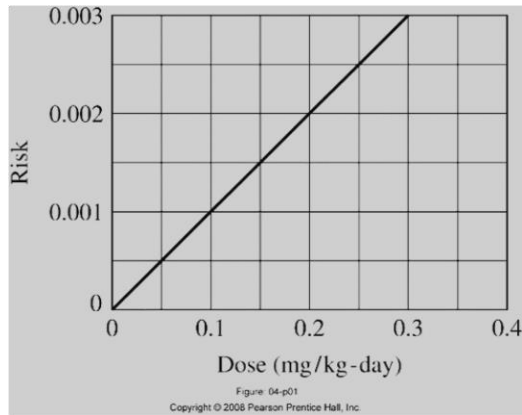
5. Find out what air or water pollutants are being released in your hometown. Go to the EPA's Toxics Release Inventory website, <https://www.epa.gov/toxics-release-inventory-tri-program>

a. Go to the search engine at the bottom of the webpage, "Learn More About TRI in Your Community: Get Location-Based Factsheets and Information on Specific Facilities". Search the zip code of your hometown (or current residence if there are no hits for your hometown). Browse the site—lots of interesting facts on who is releasing what chemicals to the environment. If there are not companies listed at this zip code, either try another zip code or instead search by metropolitan area and enter in the name of any city.

- b. Go to the section “Top five facilities by total disposal or other releases”. Click on one of the company names.
- c. Review this TRI Facility Report for this company.
- d. Report, in a list or table, the company name, what toxic chemicals are used/treated/released there, and what lbs of what chemical(s) was released in the most recent year for data, if these chemicals were air or water releases. Much of this information can be found under the “chemicals” or “releases” tabs.

HOMEWORK (Risk Assessment)

1. Consider a carcinogenic VOC with the dose-response curve shown in Figure P4.1 in the Masters & Ela textbook.



If 70-kg people breathe 20 m³/day of air containing 10⁻³ mg/m³ of this VOC throughout their entire 70-year lifetime, find the cancer risk (you first need to find the potency). You may assume typical exposure values for air inhalation.

From the slope of Figure P4.1, potency = 0.001/0.1 (mg/kg-day) = 0.01 (mg/kg-day)⁻¹

$$CDI = \frac{\text{Concentration (mg/m}^3\text{)} \times \text{Intake rate (m}^3\text{/day)} \times \text{Exposure (days/life)}}{\text{Body weight (kg)} \times 70 \text{ (yr/life)} \times 365 \text{ (days/yr)}}$$

$$= \frac{10^{-3} \text{ mg/m}^3 \times 20 \text{ m}^3/\text{d} \times 200 \text{ days/yr} \times 50 \text{ yr/life}}{70 \text{ kg} \times 70 \text{ yr/life} \times 365 \text{ days/yr}} = 1.1182 \times 10^{-4} \text{ mg/kg-day}$$

$$\text{Risk} = CDI \times \text{potency} = 1.1182 \times 10^{-4} (\text{mg/kg-day}) \times 0.01 (\text{mg/kg-day})^{-1} = 1.1182 \times 10^{-6}$$

2. Suppose a city's water supply has 0.2 ppb (1ppb=10⁻³ mg/L) of polychlorinated biphenyls (PCBs) in it. Using the PCB oral slope factor (7.7 (mg/kg-d)⁻¹) and the EPA recommended exposure factors given in Table 6.14 below,

- What would be the individual lifetime cancer risk for an adult male residential consumer?
- In a city of 1 million people, use this risk assessment to estimate the number of extra cancers per year caused by the PCBs in the water supply. "Extra" cancers refers to cancers caused by PCBs (as opposed to other causes such as smoking, etc.)
- Assume the average cancer death rate in the United States is 193 per 100,000 per year. How many cancer deaths would be expected in a city of 1 million? Do you think the incremental cancers caused by PCBs in the drinking water would be detectable?

$$a) \text{ CDI} = \frac{0.2 \times 10^{-3} \text{ mg/L} \times 2 \text{ L/d} \times 350 \text{ d/yr} \times 30 \text{ yr}}{70 \text{ kg} \times 365 \text{ d/yr} \times 70 \text{ yr}} = 2.35 \times 10^{-6} \text{ mg/kg-d}$$

$$b) \text{ Potency for PCB} = 7.7 \text{ (mg/kg-d)}^{-1} \text{ (Table 4.9 – page 150 of textbook).}$$

$$\text{Risk} = \text{CDI} \times \text{Potency} = 2.35 \times 10^{-6} \text{ mg/kg-d} \times 7.7 \text{ (mg/kg-d)}^{-1} = 18.1 \times 10^{-6}$$

$$c) \text{ Extra cancers/yr} = \frac{18.1 \times 10^{-6} \text{ cancers/life} \times 10^6 \text{ people}}{70 \text{ yr/life}} = 0.26 \text{ cancers/yr}$$

$$d) \text{ Expected cancer rate: } \frac{193 \text{ deaths/yr}}{100000 \text{ people}} \times 10^6 \text{ people} = 1930 \text{ deaths/yr}$$

0.26 is much smaller than 1930, so adding 0.26 cancers per year would not be detectable.

3. It has been estimated that about 75 million people in the Ukraine and Byelorussia were exposed to an average of 0.4 rem of radiation as a result of the Chernobyl nuclear accident. Human exposure to radiation is often measured in rems (roentgen-equivalent man) or millirems (mrem). The cancer risk caused by exposure to radiation is thought to be approximately 1 fatal cancer per 8,000 person-rems of exposure (for example, this is like saying when 8000 people are exposed to 1 rem each, one person will die of cancer caused by this exposure).

- (a) How many extra cancer deaths might eventually be expected from this exposure?
- (b) If the normal probability of dying of cancer from all causes is 0.22 (that is, 22% of any population of people will die of cancer), how many cancer deaths would you normally expect among those 75 million people?

a. The overall number of extra cancer deaths caused by this amount of radiation is

$$N_{\text{cancer}}^{\text{extra}} = \frac{1(\text{cancer_death})}{8000(\text{person_rem})} \times 0.4(\text{rem}) \times 75 \cdot 10^6 (\text{person}) = 3750(\text{cancer_death})$$

b. The number of deaths caused by all cancers in these people is

$$N_{\text{cancer}}^{\text{overall}} = 0.22 \times 75 \cdot 10^6 (\text{person}) = 16.5 \cdot 10^6 (\text{cancer_death})$$

4. A man works in an aluminum smelter for 10 years. The drinking water in the smelter contains 0.070 mg/L arsenic and 0.560 mg/L methylene chloride. His only exposure to these chemicals in water is at work. Recall the total HI (i.e. the total overall risk) is the sum of individual HI values.

- (a) What is the hazard index (HI) associated with this exposure?
- (b) Does the HI indicate this is a safe level of exposure?
- (c) What is the incremental lifetime cancer risk for the man due solely to the water he drinks at work *and* does it seem to be an acceptable risk according to the EPA's standard of acceptable risk?

Answer: Risk = CDI \times potency = 2.85×10^{-4} (mg/kg-day) $\times 0.01$ (mg/kg-day) $^{-1}$ = 2.9×10^{-6}

5. Calculate a risk-based groundwater standard (in ppb) for the chemical 1,2-dichloroethane for a residential homeowner where the person's well used for drinking water is contaminated with 1,2-dichloroethane. Assume the risk is for an average adult who weighs 70 kg. The state where you work has determined that an acceptable risk is one cancer occurrence per 10^6 people. Use the values for route of intake, exposure frequency, exposure duration, and averaging time provided for residential use in the following table 6.14. Assume an oral slope factor for 1,2-dichloroethane of 9.2×10^{-2} per (mg/kg)/day.

- a) IRIS states that this chemical's oral slope factor is 7.3 per (mg/kg)/day.

$$Conc = \frac{(50 \text{ kg})(10^{-5})(70 \text{ yr})\left(\frac{365 \text{ days}}{\text{yr}}\right)\left(\frac{1,000 \mu\text{g}}{\text{mg}}\right)}{\left(\frac{7.3}{\text{mg/kg-day}}\right)\left(\frac{350 \text{ days}}{\text{yr}}\right)(30 \text{ yr})\left(2 \frac{\text{L}}{\text{day}}\right)}$$

$$= 0.083 \frac{\mu\text{g}}{\text{L}} \quad (0.083 \text{ ppb})$$

- b) As stated in IRIS, the weight-of-evidence judgment of the likelihood that benzo(a)pyrene is a probable human carcinogen.

- c) The "target soil leachate concentration" is the concentration in the pore water of the contaminated soil. It is defined as the applicable groundwater criteria multiplied by a dilution-attenuation factor. We assumed the DAF was 16 in an example problem.

$$\text{Thus, } 0.083 \frac{\mu\text{g}}{\text{L}} \times 16 = 1.3 \frac{\mu\text{g}}{\text{L}}$$

Table / 6.14

Land Uses and Examples of Exposure Assessment Associated with Each Use The EPA publishes an *Exposure Factors Handbook* (EPA, 2011b) that provides more detail on specific values used in exposure assessment (EPA/600/R-09/052F, 2011).

Land Use	Examples of This Land Use	Example IR for Drinking Water; Air Inhalation, and Soil Ingestion	Example Exposure Frequency (EF) (days per year) and Exposure Duration (ED) (years)
Residential (primary activity is residential)	Single-family dwellings, condominiums, apartment buildings	Children drink 1 L/day Adults drink 2 L/day Adults inhale 20 m ³ /day Children age 1–6 consume 200 mg soil/day Adults consume 100 mg soil/day	For drinking water EF: 350 days/year ED: 30 years For air inhalation EF: 350 days/year ED: 30 years For soil ingestion ED: 6 years for children 1–6 ED: 24 years for adults EF: 350 days for children and adults
Industrial (primary activity is industrial, or zoning is industrial)	Manufacturing, utilities, industrial research, and development, petroleum bulk storage	Adults drink 1 L/day Adults inhale 10 m ³ /day	For drinking water EF: 245 days/year ED: 21 year For air inhalation EF: 245 days/year ED: 21 years For soil ingestion ED: 21 years for adults EF: 245 days for children and adults
Commercial (use is a business or is intended to house, educate, or provide care for children, the elderly, the infirm, or other sensitive subpopulations)	Day-care centers, educational facilities, hospitals, elder-care facilities and nursing homes, retail stores, professional offices, warehouses, gas stations, auto services, financial institutions, government buildings	Adults drink 1 L/day Adults inhale 10 m ³ /day	For drinking water EF: 245 days/year ED: 21 years For air inhalation EF: 245 days/year ED: 21 years For soil ingestion ED: 21 years for adults EF: 245 days for children and adults

*Recall that the average weight for a male, female, and child are 70 kg, 50 kg, and 10 kg, respectively.

HOMEWORK (Environmental Chemistry)

1. Consider the following reaction representing the combustion of propane:



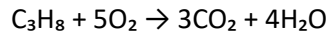
- Balance the equation.
- How many moles of oxygen are required to burn 1 mol of propane?
- How many grams of oxygen are required to burn 100 g of propane?
- At standard temperature (0 degrees C) and pressure, what volume of oxygen (in cubic meters) would be required to burn 100 g of propane? If air is 21 percent oxygen, what volume of air at STP would be required?

(e) At STP, what volume of CO_2 (in cubic meters) would be produced when 100 g of propane are burned?

5.6 L of oxygen at STP are required to burn completely 2.2g of propane.

Explanation:-

The balanced chemical equation for the reaction is :-



- Molar mass of Carbon (C) = 12 g/mol
- Molar mass of Hydrogen (H) = 1 g/mol

Hence, molar mass of Propane [C_3H_8] :-

$$= 12 \times 3 + 1 \times 8$$

$$= 36 + 8$$

$$= 44 \text{ g/mol}$$

Now, from the balanced equation :-

\Rightarrow 44g of C_3H_8 requires 5 moles of O_2

We know that, one mole of any gas at STP occupies a volume of 22.4 L.

\therefore 5 mole of O_2 will occupy a volume of :-

$$= 5 \times 22.4$$

$$= 112 \text{ L}$$

\therefore 44g C_3H_8 requires 112 L O_2

\therefore 2.2g of propane will require :-

$$= 2.2 \times 112 / 44$$

$$= 0.05 \times 112$$

$$= 5.6 \text{ L } \text{O}_2$$

2. Suppose totally world energy consumption of fossil fuels, equal to 3×10^{17} kJ/yr, were to be obtained entirely by combustion of petroleum with the approximate chemical formula C_2H_3 . Combustion of petroleum (with O_2) releases an amount of energy about 43×10^3 kJ/kg (seems like a lot of moles of

C₂H₃). Estimate the emissions of CO₂ per year in units of kg CO₂, assuming complete conversion of all C in petroleum to CO₂.

Calorific value is the amount of energy released or produced when 1 kg of fuel burns.

Given that on complete combustion of 2.4 kg of fuel 3,60,000 kJ of heat energy is produced

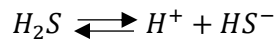
That is, 360000 kJ of heat for 2.4 kg

It's calorific value will be = 360000/2.4 = 150000 kJ/kg

3. Hydrochloric acid, HCl, completely ionizes to H⁺ and Cl⁻ when dissolved in water. Calculate the pH of a solution after 25 mg/L of HCl is added to water.

Answer - $\text{HCl} + \text{H}_2\text{O} \rightarrow \text{Cl}^- + \text{H}_3\text{O}^+$

4. Hydrogen sulfide (H₂S) is an odorous gas that can be stripped from solution by bubbling air through the solution. H₂S when dissolved in water is also a weak acid that can deprotonate to bisulfide ions which are not removed by air stripping. That reaction is



With equilibrium constant $K_a = 0.86 \times 10^{-7}$.

Find the fraction of hydrogen sulfide in the H₂S form at pH 6 and pH 8. At which pH would you expect to have an easier time to strip away H₂S gas?

$$\frac{[\text{H}_2\text{S}]}{[\text{H}_2\text{S}] + [\text{HS}^-]} = \frac{\frac{[\text{H}_2\text{S}]}{[\text{H}_2\text{S}] + [\text{HS}^-]}}{\frac{[\text{H}_2\text{S}]}{[\text{H}_2\text{S}]}}$$

$$\frac{[\text{H}_2\text{S}]}{[\text{H}_2\text{S}] + [\text{HS}^-]} = \frac{1}{1 + \frac{[\text{HS}^-]}{[\text{H}_2\text{S}]}}$$

$$\text{The fraction of H}_2\text{S} = \frac{1}{1 + \frac{0.86 \times 10^{-7}}{10^{-\text{pH}}}}$$

5. Determine the equilibrium pH of aqueous solutions of the following strong acids or bases. Remember, strong acids and bases completely dissociate. (a) 15 mg/L of HSO₄⁻, (b) 10 mM NaOH, (c) 2,500 µg/L of HNO₃.

$$2500 \text{ ug} = 2500 \times 10^{-6} = 2.5 \times 10^{-3} \text{ gm}$$

$$M = 2.5 \times 10^{-3} / 63 = 2.9 \times 10^{-5}$$

$$PH = -\log [8.9 \times 10^{-5}] = 4.3$$

6. The chemical 1,4-dichlorobenzene (1,4-DCB) is sometimes used as a disinfectant in public lavatories. Its odor could be particularly annoying. At 20°C (68°F) the vapor pressure is 5.3×10^{-4} atm. What would be the concentration in the air in units of g/m³? The molecular weight of 1,4-DCB is 147 g/mole. $R=0.08205 \text{ Latm/moleK}$

The chemical 1,4-dichlorobenzene (1,4-DCB) is used in an enclosed area. At 20°C the saturated vapor pressure of DCB is 5.3×10^{-4} atm. What would be the concentration of DCB in the air of the enclosed area (in units g/m³) at 20°C. Molecular weight of DCB is 147 g/mole $R=0.08205 \text{ Latm/moleK}$

$$\begin{aligned} \frac{n}{V} &= \frac{P}{RT} = \frac{5.3 \times 10^{-4} \text{ atm}}{0.08205 \frac{\text{Latm}}{\text{molK}} \times 293 \text{ K}} = \\ &= 2.2 \times 10^{-5} \frac{\text{moles}}{\text{L}} \times \frac{1000 \text{ L}}{\text{m}^3} \times \frac{147 \text{ g}}{\text{mole}} = 3.2 \frac{\text{g}}{\text{m}^3} \end{aligned}$$

7. Pure toluene comes into contact with groundwater. (a) What is the concentration of toluene in the water at equilibrium? (b) This groundwater flows slowly through the soil that has a K_{oc} value of 9%. Estimate the concentration (in mg/kg) of toluene in the soil at equilibrium.

A/q to dalton's law

Partial pressure = mole fraction x Total press

$$X_a P_a = X_r P_r$$

For total pressure

$$P_s = X_a P_a + X_b$$

$$P_s = 0.5 \times 37 + 0.5 \times 119$$

$$P_s = 78 \text{ torr}$$

$$\text{Now, } X_a P_a = Y_a P_r$$

$$Y_a = X_a P_a / P_t = 0.5 \times 37 / 78 = 0.23$$

HOMEWORK (Mass Balances, Reactors)

1. Five million gallons per day (MGD) of wastewater, with a concentration of 10.0 mg/L of a conservative pollutant, is released into a stream having an upstream flow of 10 MGD and pollutant concentration of 3.0 mg/L.

(a) What is the concentration in ppm just downstream?

(b) How many pounds of substance per day pass a given spot downstream?

Answer: a) 5.3 mg/L

b) 66.5.74 lb/day

2. A lake with constant volume $10 \times 10^6 \text{ m}^3$ is fed by a pollution-free stream with flow rate $50 \text{ m}^3/\text{s}$. A factory dumps $5 \text{ m}^3/\text{s}$ of a nonconservative waste with concentration 100 mg/L into the lake. There is one outflow from the lake. The pollutant decays and has a first order reaction rate coefficient k of 0.25/day. Assuming the pollutant is well mixed in the lake, find the steady-state concentration of pollutant in the lake.

$$V_{\text{lake}} = 10^6 \text{ m}^3$$

$$\text{Pollution free stream: Mass of pollutant input} = Q_{\text{stream}} \cdot \text{conc.} = (50.0 \text{ m}^3/\text{s}) \cdot 0 = 0$$

$$\text{Industrial effluent: Mass of pollutant input} = Q_{\text{eff}} \cdot \text{conc.}$$

$$= (4.5 \text{ m}^3/\text{s}) \cdot 90 \text{ mg/L} = (4.5 \cdot 1000 \text{ L/s}) \cdot 90 \text{ mg/L}$$

$$= 405 \text{ g/s} = 405 \cdot (24 \cdot 3.600) \text{ kg/day} = 34,992 \text{ kg/day}$$

3. A lagoon is to be designed to accommodate an input flow of $0.10 \text{ m}^3/\text{s}$ of nonconservative pollutant with concentration 30.0 mg/L and reaction rate constant 0.20/day. The effluent from the lagoon must have pollutant concentration of less than 10.0 mg/L. Assuming complete mixing, how large must the lagoon be?

$$\text{Answer: } 86,400 \text{ m}^3$$

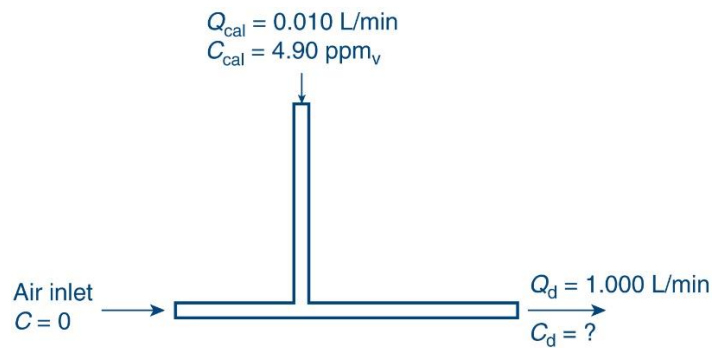
4. A lagoon with volume $1,200 \text{ m}^3$ has been receiving a steady flow of conservative waste at a rate of $100 \text{ m}^3/\text{day}$ for a long enough time to assume that steady-state conditions apply. The waste entering the lagoon has a concentration of 10 mg/L. Assuming completely mixed conditions, what would be the concentration of pollutant in the effluent leaving the lagoon?

$$\text{Answer: } 3,430 \text{ mg/L}$$

5. Repeat problem 4 for a nonconservative pollutant with rate constant $k=0.20/\text{d}$.

$$\text{Answer: } 2,760 \text{ mg/L}$$

6. A mixture of two gas flows is used to calibrate an air pollution measurement instrument. The calibration system is shown below. If the calibration gas concentration C_{cal} is 4.9 ppm_v, the calibration gas flow rate Q_{cal} is 0.010 L/min, and the total gas flow rate Q_{total} is 1.000 L/min, what is the concentration of calibration gas after mixing (C_d)? Assume that the concentration upstream of the mixing point is zero.



$$Q_{cal} \times C_{cal} = Q_{total} \times C_d$$

$$\left(1.000 \frac{L}{min} - 0.010 \frac{L}{min}\right)(0) + \left(0.010 \frac{L}{min}\right)(4.90 ppm_v) = \left(1.000 \frac{L}{min}\right)(C_d)$$

$$C_d = 0.049 ppm_v = \boxed{49.0 ppbv}$$

7. Poorly treated municipal wastewater is discharged to a stream. The river flow rate upstream of the discharge point is $Q_{us} = 8.7$ cubic meters per second. The discharge occurs at a flow of $Q_d = 0.9$ cubic meters per second and has a BOD concentration of 50 mg/L. Assuming that the upstream BOD concentration is negligible. (a) What is the BOD concentration just downstream of the discharge point, after mixing? (b) If the stream has a cross-sectional area of 10 square meters, what would the BOD concentration be 50 km downstream? BOD is removed with a first-order decay rate constant equal to 0.20/day.

$$Q_{u/s} (0) + Q_d (C_d) = Q_{total} C_{down}$$

$$0.9 \frac{m^3}{s} \times 50 \frac{mg}{L} = \left(8.7 \frac{m^3}{s} + 0.9 \frac{m^3}{s}\right) \times C_{down}$$

$$\boxed{C_{down} = 4.7 \frac{mg}{L}}$$

8. You are designing a reactor that uses chlorine in a plug flow reactor or a completely stirred tank reactor to destroy pathogens in water. A minimum contact time of 30 min is required to reduce the pathogen concentration from 100 pathogens/L to below 1 pathogen/L through a first-order decay process. You plan on treating water at a rate of 1,000 gal/min. (a) What is the first-order decay rate constant? (b) What is the minimum size (in gallons) of the reactor required for a plug flow reactor? (c) What size (in gallons) of CSTR would be required to reach the same outlet concentration?

- a. Convert the formaldehyde threshold for eye irritation (0.05 ppmv) to units of mg/m^3 .

Ans: $0.0613 \frac{\text{mg}}{\text{m}^3}$

- b. How many people can be at the party without causing the formaldehyde concentration to exceed the eye irritation threshold at steady state?

Ans: 18 people

- c. Unfortunately, several people crash the party. This causes the steady state formaldehyde concentration in the apartment to reach $0.16 \text{ mg}/\text{m}^3$, which is above the formaldehyde eye irritation threshold, by the end of the party. After the party ends, how long would it take for the formaldehyde concentration in the apartment to reach the formaldehyde eye irritation level? Assume that all smoking stops when the party ends.

HOMEWORK (Energy balances, Watershed balances)

1. Two-thirds of the energy content of fuel entering a 1,000-MW_e nuclear power plant is removed by condenser cooling water that is withdrawn from a local river (there are no stack losses, as it the case for a fossil fuel-fired plant). Note, the 1,000-MW_e refers to the actual electricity generated and sent to the power lines, after waste heat is taken away from cooling water. The river has an upstream flow of 100 m³/s and a temperature of 20° C.

(a) If the cooling water is only allowed to rise in temperature by 10°C, what flow rate from the river would be required?

(b) How much would the river temperature rise as it receives the heated cooling water?

Step 1 of 4

(a)

Determine input power with which energy enters the power plant.

$$\text{input power} = \frac{\text{output power}}{\text{efficiency}}$$

Substitute 1000 MW_e for output power and $\left(\frac{1}{3}\right)$ for efficiency.

$$\begin{aligned}\text{input power} &= \frac{1000 \text{ MW}_e}{\left(\frac{1}{3}\right)} \\ &= 3000 \text{ MW}_e\end{aligned}$$

Since, two-third of input power is removed by the condenser cooling water.

$$\begin{aligned}\text{loss of heat} &= \frac{2}{3}(3000 \text{ MW}_e) \\ &= 2000 \text{ MW}\end{aligned}$$

Calculate the actual input power as follows:

$$\begin{aligned}\text{actual input power} &= \text{input power} - \text{loss of heat} \\ &= 3000 - 2000 \\ &= 1000 \text{ MW}\end{aligned}$$

Therefore, the input power with which energy enters the power plant is 1000 MW .

Step 2 of 4

Determine the rate of heat added to cooling water.

Here, m is mass flow rate across the system, c is specific heat of water, and ΔT is change in temperature.

Substitute $2000 \times 10^6 \text{ W}$ for heat, 10 degrees for ΔT , and $4.184 \text{ kJ/kg} \cdot ^\circ\text{C}$ for c .

$$(2000 \times 10^6 \text{ W}) = m(4.184 \text{ kJ/kg} \cdot ^\circ\text{C})(10^\circ)$$

$$m = \frac{(2000 \times 10^6 \text{ W}) \times \left| \frac{1 \text{ J/s}}{1 \text{ W}} \right|}{\left(4.184 \frac{\text{kJ}}{\text{kg} \cdot ^\circ\text{C}} \right) \times \left| \frac{1000 \text{ J}}{1 \text{ kJ}} \right| \times (10^\circ\text{C})}$$

$$m = 47.8 \times 10^3 \text{ kg/s}$$

Determine the percentile change in the flow rate as follows:

$$\text{change in flow rate} = \left(\frac{\text{calculated flow rate} - \text{given}}{\text{given flow rate}} \right)$$

Substitute $47.8 \text{ m}^3/\text{s}$ for calculated flow rate and $40.6 \text{ m}^3/\text{s}$ for given flow rate (from example 1.12 of the text book).

$$\begin{aligned} \text{change in flow rate} &= \left(\frac{47.8 \text{ m}^3/\text{s} - 40.6 \text{ m}^3/\text{s}}{40.6 \text{ m}^3/\text{s}} \right) \times 10 \\ &= 17.73\% \\ &\approx 18\% \end{aligned}$$

Therefore, the increase in flow is 18% .

(b)

Determine the change in temperature.

$$\Delta T = \frac{\Delta E}{mc}$$

Here, m is mass flow rate across the system, c is specific heat of water, and ΔT is change in temperature.

Substitute $100 \text{ m}^3/\text{s}$ for m , 2000 MW for ΔE , and $4.184 \text{ kJ/kg}^\circ\text{C}$ for c .

$$\begin{aligned} \Delta T &= \frac{2000 \text{ MW} \times \left| \frac{10^6 \text{ W}}{1 \text{ MW}} \right| \times \left| \frac{1 \text{ J/s}}{\text{W}} \right|}{(100 \text{ m}^3/\text{s}) (10^3 \text{ kg/m}^3) \left(4.184 \frac{\text{kJ}}{\text{kg} \cdot ^\circ\text{C}} \right) \times \left| \frac{10^3 \text{ J}}{1 \text{ kJ}} \right|} \\ &= 4.78^\circ \text{C} \end{aligned}$$

The river temperature rises by 4.78°C .

Therefore, the temperature of river before receiving heated cooling water is 20°C and therefore, the temperature after receiving heated cooling water is 24.78°C .

Step 3 of 4

Calculate the flow rate in m^3/s as follows:

$$\rho = \frac{m}{V}$$

Here, ρ is the density of water, m is the mass, and V is the volume of water.

Substitute 1000 kg/m^3 for ρ and $47.8 \times 10^3 \text{ kg/s}$ for m .

$$1000 \text{ kg/m}^3 = \frac{47.8 \times 10^3 \text{ kg/s}}{V}$$

$$V = 47.8 \text{ m}^3/\text{s}$$

Therefore, the flow rate of heat required from the river is

$$47.8 \text{ m}^3/\text{s}.$$

2. A 600-MW_e power plant has an efficiency of 36 percent with 15 percent of the waste heat being released to the atmosphere as stack heat and the other 85 percent taken away in the cooling water. Instead of drawing water from a river, heating it, and returning it to the river, this plant uses an evaporative cooling tower wherein heat is released to the atmosphere as cooling water is evaporated to vapor at 100 °C. At what rate must 15°C makeup water be provided from the river to offset the water lost in the cooling tower?

Answer: 401.3 kg/s

Explanation: The power plant has an efficiency of 36%. This means 64% of the heat from the source (q_1) will become waste heat. Of the waste heat, 85% will be taken away by water (q_w).

$$q_w = 0.85 * q_2$$

$$q_2 = 0.64 * q_1$$

$$p = 0.36 * q_1$$

$$q_1 = p / 0.36$$

$$q_2 = 0.64 / 0.36 * p$$

$$q_w = 0.85 * 0.64 / 0.36 * p$$

$$q_w = 0.85 * 0.64 / 0.36 * 600 = 907 \text{ MW}$$

In evaporation water becomes vapor absorbing heat without going to the boiling point (similar to how sweating takes heat from the human body) The latent heat for the vaporization of water is:

$$\text{SLH} = 2.26 \text{ MJ/kg}$$

So, to dissipate 907 MW

$$G = q_w \cdot \text{SLH} = 907 / 2.26 = 401.3 \text{ kg/s}$$

3. Your house has an electric water heater. Several friends are visiting you over the weekend and they are taking consecutive showers. Assume that at the maximum heating level, the heater uses 50 kW of electricity. The water use rate is a continuous 4 gallons per minute with the new water saving showerhead you recently installed. Your very old showerhead had used 7 gallons per minute. You replaced the showerhead because you learned that heating water was the second highest energy use in your home. By slowing the flow of water through the heater, the water temperature should increase to a higher temperature. (a) What is the change in temperature (ΔT) for the old showerhead? (b) What is the change in temperature (ΔT) for the new showerhead? Assume the system is at steady state, and all of the 50 kW energy used is heating the water.

Number	Equation ^a
Nusselt (Nu) – natural convection	$2 + \frac{\left\{ 0.589 (Gr \text{ Pr})^{\frac{1}{4}} \right\}}{\left\{ 1 + \left(\frac{0.469}{Pr} \right)^{\frac{9}{16}} \right\}^{\frac{4}{9}}}$
Nusselt (Nu) – forced convection	$2 + \left\{ 0.4 \left(Re^{\frac{1}{2}} \right) + \left(0.06 Re^{\frac{2}{3}} \right) \right\} (Pr^{0.4})^{\frac{1}{4}}$
Grashof (Gr)	$\frac{g d_b^3 (T_s - T_A)}{\nu^2 T_A}$
Reynolds (Re)	$\nu d_b V^{-1}$
Prandtl (Pr)	$\rho c_p \nu k^{-1}$

4. Water is taken from a river to cool a power plant. The water accepts waste heat and is returned water back to the river. The return water has a flow rate of 200 gal/min, and the receiving river has a flow rate of 3,000 gal/min and a temperature of 18 degrees C in the summer at the point of mixing. If the maximum allowable temperature of the river after mixing is 22 degrees C before the fish die, what is the maximum allowable temperature of the return water?

Answer: 45-degrees

5. The average annual rainfall in an area is 60 cm. The average annual evapotranspiration is 35 cm. Thirty percent of the rainfall infiltrates and percolates into the underlying aquifer, the remainder is runoff that moves along or near the ground surface. The underlying aquifer is connected to a stream. Assuming there are no other inputs or outputs of water to the underlying aquifer and the aquifer is at steady state (neither gains nor loses water), what is the amount of baseflow contributed to the stream from the groundwater?

In this system the infiltration (I) into the aquifer is equal to 30 percent of the rainfall.

$$I = 0.3 \times 60 \text{ cm} = 18 \text{ cm}$$

Under steady-state conditions baseflow (B) to streams and lakes is defined based on groundwater inputs. Thus, we can equate the infiltration to the baseflow.

$$B = I = 18 \text{ cm}$$

6. A small public well is used to supply drinking water to a small residential community located in a 26 square kilometer watershed. For the month of June, the measured rainfall was 12 cm, the estimated evapotranspiration was 7.5 cm and the surface water runoff entered a small stream with an average flow of $0.32 \text{ m}^3/\text{sec}$ that leaves the watershed. Estimate the average flow (m^3/day) from the public well without depleting the underlying aquifer (neither gains nor loses water). Assume that all water that infiltrates will percolate to the aquifer. There is no baseflow.

Answer: 1,76,44,432 (m^3/day)

7. Estimate the daily water demand and wastewater generation for a new 8-storey building. The first six floors are occupied by a department store. On each floor are two sets of men's and women's lavatories. The seventh floor is an office with 40 employees. The eighth floor is a restaurant that typically serves 220 customers per day. Use table 7.12 in the notes.

Serial Number	1F	2F	1P	2P	3P
A-18	2	-	3.00 (0.48)	18.00 (2.86)	-
B-16	2	-	4.00 (0.63)	16.00 (2.54)	-
C-21	2.5	-	4.00 (0.63)	21.00 (3.33)	-
A-25	2	3	3.00 (0.48)	14.00 (2.22)	25.00 (3.97)
B-23	2	3	4.00 (0.63)	12.00 (1.90)	23.00 (3.65)
C-32	2.5	3.5	4.00 (0.63)	17.00 (2.70)	32.00 (5.08)

Notes: 1F and 2F indicate the sizes of the initial and second blocks (per capita m^3/month). 1P, 2P, and 3P indicate the rates of the initial, second, and third blocks [RMB/m^3 ($\text{US}\$/\text{m}^3$)].

HOMEWORK (Water Treatment)

1. You are evaluating the performance of a settling basin within a drinking water treatment plant.

(a) What is the terminal settling velocity of a particle with a specific gravity of 1.4 and a diameter of 0.010 mm in 20°C water?

(b) Would particles of the size in part a be completely removed in a settling basin with a width of 10.0 m, a depth of 3.00 m, a length of 30.0 m, and a flow rate of 7,500 m³/d? Answer yes or no, and prove with calculations.

(c) What is the smallest diameter particle (in micrometers) of specific gravity 1.4 that would be removed in the sedimentation basin described in part b?

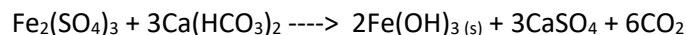
$$\begin{aligned}\text{Retention time} &= \frac{\text{volume}}{\text{flow rate}} \\ &= \frac{\text{depth}}{\text{minimum settling velocity}} \\ &= \frac{4}{0.4 \times 10^{-3}} = 10\,000 \text{ s (2.8 hours)}\end{aligned}$$

$$\begin{aligned}\text{Flow rate} &= \frac{\text{volume}}{\text{retention time}} \\ &= \frac{\text{area} \times \text{depth}}{\text{retention time}} \\ &= \frac{700 \times 4}{10\,000} = 0.28 \text{ m}^3 \text{ s}^{-1}\end{aligned}$$

2. You are trying to remove 10.0 µm diameter particles in a water treatment plant, so you design a settling basin. The water is at 20°C (giving a water density of 998.2 kg/m³, but really you can assume 1000 kg/m³ here), and the particle density is 1.2 g/mL. The plant treats 0.100 m³/s of water. It is proposed to use a 3.5 m deep, rectangular sedimentation tank with a length to width ratio of 5:1. What is the minimum required width of the basin?

Answer - 3.64 x 10⁻⁵ m

3. You are being consulted for the design of a coagulation-flocculation basin for a water treatment plant. Ferric sulfate is available as a commercial coagulant and is popular at removing turbidity and color. The chemical reaction for its addition to water is:



Results of a jar test to determine the optimal coagulant dose are provided below. The initial water sample has a pH=6.5 and turbidity of 30 NTU.

Ferric sulfate dose, mg/L:	5	10	15	20	25
Turbidity, NTU:	15	5	1	0.9	2

What is the optimal mass of ferric sulfate you would need to purchase every day to treat 10⁶ gallons/day to a turbidity below 1 NTU (assume 100% purity of the coagulant).

SOURCE WATER TOC (mg/L)	SOURCE WATER ALKALINITY (mg/L as CaCO ₃)		
	0 to 60	>60 to 120	>120
>2.0 - 4.0	35.0%	25.0%	15.0%
>4.0 - 8.0	45.0%	35.0%	25.0%
>8.0	50.0%	40.0%	30.0%

4. A water treatment plant processes 21,000 cubic meters of water per day. Assume two types of flocculated particles enter the basin. You are asked to evaluate the performance of a rectangular sedimentation basin that has dimensions of depth=4 m, width= 6 m, and length= 40 m. The first type of particles has a settling velocity of 0.5 m/hr and the other type has a settling velocity of 1.8 m/hr. What percent of particles are removed for each of the two types of particles?

Answer: 34.3%

5. Chlorine is used for primary disinfection at a water treatment plant that treats 0.20 m³/s of reservoir water. *Giardia* (a protozoan) is the primary pathogen of concern, and the *Giardia* inactivation rate constant for free chlorine disinfection is 0.53 min⁻¹. Note that the inactivation rate constant is k^* in the simplified Chick-Watson equation where the rate of inactivation $r(N)$:

$$r(N) = -k^*N \text{ and } k^* = kC^n$$

The plant achieves 3-log removal of *Giardia* at pH 6.0-9.0 in a plug flow contact chamber using free chlorine concentration of 2.0 mg/L.

- What is the volume of contact chamber?
- If a CSTR, rather than PFR, contact chamber were used, what would the required volume need to be?
- What volume of contact chamber would be needed if it were constructed as five separate CSTR chambers in series? The volume asked for is the combined volume of all five separate chambers.
- Assuming a coefficient of dilution of 1.0, what is the coefficient of specific lethality for *Giardia* under these conditions?

Answer: 156.40 m³

6. Given the following data, graph the data for the *Poliomyelitis* virus, using hypobromite as a disinfectant. Determine the inactivation constant and the time required for 99.99 percent (4 log removals) inactivation of this virus. The concentration of hypobromite is 0.1 mg/L.

Time (s)	N (# organisms/L)
0.0	1,000
2.0	350
4.0	78
6.0	20
8.0	6
10.0	2
12.0	1

Area of watershed is 220 km²

Annual precipitation in the watershed area is 4.2*10⁹

Equivalent depth is

$$4.2 \times 10^9 / 220 \times 10^6 = 19.1 \text{ m}$$

7. What is the difference between 'coagulation' and 'flocculation'.

The concentrations and flocculation of undesirable compounds are two of the most often utilized water treatment procedures. However, any suspension procedure can typically be approved. Coagulation includes the application of a coagulant that can remove charged particles pre-charged from the suspension. In contrast, stability in the slope is caused by physical approaches, such mixing solution, and the inclusion of polymers in some cases. The distinction between coagulation and flocculation is crucial.

8. Explain the meaning of the term "Ct" in disinfection processes design.

The current disinfection standard in Alberta is CT Disinfection. It is used to show your water's degree of disinfection. During the interaction with your water chlorine is merely an injection of chlorine in your fluids. In order to neutralize the usage of free-chlorine bacteria, at least 6 milligrams (6 mg-min/L) should be necessary for the treatment before initial client. This is frequently called "CT." This number. A minimum of 6 mg-min/L (6 mg-min/L) should be essential before initial customer in order to neutralize the use of free-chlorine bacteria. It's often referred to as "CT."

EXTRA CREDIT: Find the schematic of unit operations for the drinking water treatment plant that serves your hometown. Provide this schematic, and label all the unit operations. Below the schematic, write the purpose of each unit operation (that is, what analyte is removed, or how is water quality improved). Write the name of the water treatment plant and/or the name of the town/city.

EXTRA EXTRA CREDIT: You are interested in camping out in the wilderness for several weeks. Your supply of water will be a forest stream. You need a personalized water treatment unit. Find three such water treatment devices online and provide a picture of the device, a schematic of how it works (e.g. cutaway drawing), and a detailed description of how it transforms raw water to potable water.

HOMEWORK (BOD)

1. The following data have been obtained in a BOD test that is made to determine how well a wastewater treatment plant is operating. You need to process the data.

	Initial DO (mg/L)	Final DO (mg/L)	Volume of wastewater (mL)	Volume of dilution water (mL)
Untreated sewage	6.0	2.0	5	295
Treated sewage	9.0	4.0	15	285

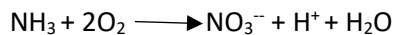
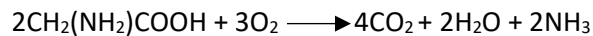
What percentage of the BOD is being removed by this treatment plant? If this is a secondary treatment plant that is supposed to remove 85% of the BOD₅, would you say it is operating properly?

Answer: 23.67%

2. Some waste has a five-day BOD at 20°C equal to 210 mg/L and an ultimate BOD of 350 mg/L. Find the five-day BOD at 25°C. Note, reaction rate coefficients can be adjusted for temperature using the Arrhenius equation, which is $k_{T2} = k_{T1}\Theta^{(T2-T1)}$, where Θ is 1.047 typically.

Answer: 0.36

3. For a solution containing 200 mg/L of glycine [CH₂(NH₂)COOH] whose oxidation can be represented as



- Find the theoretical CBOD.
- Find the nitrogenous portion of BOD (BOD only due to oxidation of N compounds).
- Find the total theoretical BOD.

$$3\text{O}_2 = (3)(16)(2)$$

$$3\text{O}_2 = 96\text{g}$$

So three moles of the oxygen oxidizes the two moles of the Glycine(150g / mol)

Amino acid glycine (NH₂ – CH₂ – COOH) exists as a zwitter ion in aq. Solution. The K_a and K_b values of glycine are 1.6×10^{-10} (pK_a = 9.8) and 2.5×10^{-12} (pK_b = 11.6) respectively. The K_a and K_b values are for zwitter ion of Amino acid with following structures [NH₃⁺ – CH₂ – COO[–]]

An aqueous solution of glycine has pH:

4. A waste has an ultimate BOD of 1,000 mg/L and a k_L of 0.1/day. What is its 5-day BOD?

$$y_5 = L_0 \times (1 - e^{-k_L \times t})$$

$$y_5 = 1000 \frac{\text{mg}}{\text{L}} \times (1 - e^{-0.1/\text{day} \times 5 \text{ day}}) = \boxed{393 \frac{\text{mg}}{\text{L}}}$$

5. (a) Calculate the ultimate BOD of a waste that has a measured 5-day BOD of 20 mg/L, assuming a BOD rate coefficient of 0.15/day measured at 20 degrees C. (b) Estimate the rate coefficient if the temperature of the waste is raised to 30 degrees C. (c) What would be the BOD5 at 30 deg. C? You can use the Arrhenius equation and theta value in question 2.

$$y_5 = L_0 \times (1 - e^{-k_L \times t})$$

$$20 \frac{\text{mg}}{\text{L}} = L_0 \times (1 - e^{-0.15/\text{day} \times 5 \text{ day}})$$

$$\boxed{L_0 = 38 \frac{\text{mg}}{\text{L}}}$$

$$DO_{\text{sat}} = \frac{1.125 \times 10^{-3} \text{ moles}}{\text{L} \cdot \text{atm}} \times 0.21 \text{ atm} = \frac{2.36 \times 10^{-4} \text{ moles } O_2}{\text{L}}$$

and converting to mg O_2 /L:

$$DO_{\text{sat}} = \frac{2.36 \times 10^{-4} \text{ moles } O_2}{\text{L}} \times \frac{32 \text{ g } O_2}{\text{mole } O_2} \times \frac{1,000 \text{ mg } O_2}{\text{g } O_2} = \frac{7.6 \text{ mg } O_2}{\text{L}}$$

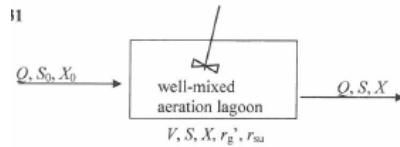
Now calculate the oxygen deficit:

$$D = DO_{\text{sat}} - DO_{\text{act}}$$

$$D = 7.6 \frac{\text{mg}}{\text{L}} - 3 \frac{\text{mg}}{\text{L}} = \boxed{4.6 \frac{\text{mg}}{\text{L}}}$$

HOMEWORK (Wastewater Treatment)

Questions 1 and 2 refer to a well-mixed aeration pond or aeration lagoon that can be modeled according to the diagram below. The pond is simply a body of water that holds the wastewater for some detention time before the waste degrades or leaves in the effluent stream. There is no recycle line. You should derive a mass balance on X to solve these problems, make sure to include all terms in the mass balance. You may assume no X flows in with the influent.



1. The perfectly mixed aeration pond with no recycle (return line) above serves as the biological reactor for a small community. The pond receives $30 \text{ m}^3/\text{d}$ of influent with a BOD_5 of 350 mg/L that must be reduced to 20 mg/L before discharge. It has been found that the kinetic constants for the system are $K_s = 100 \text{ mg/L BOD}_5$, $k_d = 0.10 \text{ d}^{-1}$, $\mu_m = 1.6 \text{ d}^{-1}$, and Y is $0.60 \text{ mg VSS/mg BOD}_5$. Note: In this system each day, the bacteria have to grow at the same rate as they leave in the effluent, in order for the bacteria population to stay at a steady state concentration. What must the hydraulic detention time be in the aeration pond? You should perform a mass balance on microbe mass to solve this question.

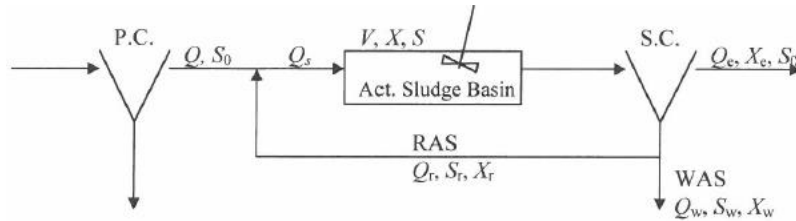
Answer: 10.9 mg / liter

2. A rectangular, well-mixed aeration lagoon that has the same conceptual model above is 60 m long, 5 m wide, and 2 m deep. It receives $400 \text{ m}^3/\text{d}$ of wastewater with a BOD_5 of $336 \text{ mg BOD}_5/\text{L}$ for treatment. The biodegradation rate constants for the wastewater are yield coefficient $= 0.8 \text{ mg VSS/mg BOD}_5$, endogenous decay constant $= 0.08 \text{ d}^{-1}$, maximum specific microbial growth rate $= 1.10 \text{ d}^{-1}$, and the half velocity constant $= 76.0 \text{ mg BOD}_5/\text{L}$. Note: BOD refers to substrate concentration and it also refers to how much O_2 is required to consume the substrate.

(a) What is the efficiency of BOD_5 removal of the lagoon?

(b) The pond's efficiency of BOD_5 removal depends on oxygen being always available for the microbes to use in degrading the wastewater organic carbon. How much oxygen gas (in kg/d) must be supplied daily to the pond?

3. A wastewater treatment uses an activated sludge process for secondary treatment of $0.3 \text{ m}^3/\text{s}$ of primary effluent. The activated sludge has a biomass concentration of $2,100 \text{ mg VSS/L}$, and the return activated sludge line (also known as RAS) concentration is $10,000 \text{ mg VSS/L}$. The substrate concentration in the primary effluent is $220 \text{ mg BOD}_5/\text{L}$. The F/M ratio for the activated sludge tank is $0.52 \text{ mg BOD}_5 \times \text{mg VSS}^{-1} \times \text{d}^{-1}$, and the cell residence time is 9.0 d .



- (a) What is the volume of the activated sludge tank?
- (b) What is the waste line (also known as WAS) flow rate?
- (c) What is the flow rate of the effluent from the entire system?
- (d) What is the hydraulic residence time for the activated sludge tank? Hint: You will need to also write a mass balance for biomass X around the secondary clarifier, and a flow balance around the secondary clarifier, as part of the solution.

4. You are provided with the following information about a municipal wastewater treatment plant. This plant uses the traditional activated sludge process. Assume the microorganisms are 60 percent efficient at converting food to biomass (this refers to the yield coefficient), the organisms have a first order death rate constant of 0.1/day, and the microbes reach half of the maximum growth rate when the BOD_5 concentration is 22 mg/L. There are 220,000 people in the community (their wastewater production is 225 L/day-capita, 0.1 kg BOD_5 /capita-day). The effluent standard is $BOD_5 = 20$ mg/L and TSS = 20 mg/L. Suspended solids were measured as 4,000 mg/L in a wastewater sample obtained from the activated sludge basin (so this is volatile suspended solids), 16,500 mg/L in the secondary sludge, 230 mg/L in the plant influent, and 110 mg/L in the primary clarifier effluent. SRT is equal to 4.5 days.

- (a) what is the design volume of the aeration basin (the activated sludge basin) (m^3)?
- (b) what is the plant's aeration period (the hydraulic retention time) (days)?
- (c) How many kg of secondary dry solids (solids removed from the secondary clarifier to waste) need to be processed daily from the treatment plants?
- (d) if the sludge wastage rate (Q_w) is increased in the plant, will the solids retention time go up, go down, or remain the same?
- (e) Determine the F/M ratio in units of mg BOD_5 /mg VSS-day.
- (f) What is the mean cell residence time?

5. The community of San Antonio is located in the Caranavi Province, Bolivia. According to the 2005 year survey, there are 420 habitants of the community. The population is estimated to increase to 940 by the year 2035. The average peak flow is currently 1.2 L/sec and is expected to increase to 2.14 L/sec by 2035. The organic load is estimated to be 45 gram BOD_5 /capita-day. The community is considering a free surface wetland to treat their wastewater.

- (a) What is the BOD_5 loading generated in the year 2035 (kg/day)?

(b) Use the BOD loading to estimate the maximum surface area (ha) required for a free surface wetland that would serve the community in 2035 and remove BOD to 30 mg/L.

(c) Assuming you are now considering sizing a facultative lagoon instead of a free surface wetland. Quickly estimate the required surface area (m²) for a facultative lagoon to handle a peak flow in 2035, assuming a design water depth of 4 m and a hydraulic detention time of 20 days.

6. A city of 200,000 people deposits 37 cubic feet per second (cfs) of sewage having a BOD of 28.0 mg/L and 1.8 mg/L of DO into a river that has a flow rate of 250 cfs and a flow speed of 1.2 ft/s. Just upstream of the release point, the river has a BOD of 3.6 mg/L and a DO of 7.6 mg/L. The saturation value of DO is 8.5 mg/L. The deoxygenation coefficient k_d is 0.61/day, and the reaeration coefficient k_r is 0.76/day. Assume complete and instantaneous mixing of the sewage and river.

(a) Find the initial oxygen deficit and ultimate BOD just downstream of the outfall.- 6.75 mg / L

(b) Find the time and distance to reach the minimum DO. 20.6 miles

(c) Find the minimum DO. – 5.65 mg / L

(d) Find the DO that could be expected 10 miles downstream. – 5.9 mg/L

a. initial conditions:

$$DO = \frac{37 \text{ cfs} \times 1.8 \text{ mg/L} + 250 \text{ cfs} \times 7.6 \text{ mg/L}}{37 + 250 \text{ cfs}} = 6.85 \text{ mg/L}$$

$$\text{Initial deficit} = D_0 = 8.5 \text{ mg/L} - 6.85 \text{ mg/L} = 1.65 \text{ mg/L}$$

$$\text{Initial BOD} = L_0 = \frac{37 \text{ cfs} \times 28 \text{ mg/L} + 250 \text{ cfs} \times 3.6 \text{ mg/L}}{37 + 250 \text{ cfs}} = 6.75 \text{ mg/L}$$

b. critical point:

$$t_c = \frac{1}{k_r - k_d} \ln \left(\frac{k_r}{k_d} \left[1 - \frac{D_0(k_r - k_d)}{k_d L_0} \right] \right)$$

$$= \frac{1}{0.76 - 0.61/\text{d}} \ln \left(\frac{0.76}{0.61} \left[1 - \frac{1.65(0.76 - 0.61)}{0.61 \times 6.75} \right] \right) = 1.05 \text{ days}$$

$$\text{critical distance} = x_c = 1.2 \frac{\text{ft}}{\text{s}} \times 3600 \frac{\text{s}}{\text{hr}} \times 24 \frac{\text{hr}}{\text{d}} \times 5280 \frac{\text{ft}}{\text{mi}} \times 1.05 \text{ day} = 20.7 \text{ miles}$$

c. minimum DO:

$$D_{\max} = \frac{k_d L_0}{k_r - k_d} (e^{-k_d t} - e^{-k_r t}) + D_0 e^{-k_d t}$$

$$= \frac{0.61/\text{d} \times 6.75 \text{ mg/L}}{(0.76 - 0.61)/\text{d}} (e^{-0.61 \times 1.05} - e^{-0.76 \times 1.05}) + 1.65 e^{-0.61 \times 1.05} = 2.85 \text{ mg/L}$$

$$DO_{\min} = DO_{\text{sat}} - D_{\max} = 8.5 - 2.85 = 5.6 \text{ mg/L}$$

d. 10 miles downstream:

$$t = \frac{10 \text{ mi} \times 5280 \text{ ft/mi}}{1.2 \text{ ft/s} \times 3600 \text{ s/hr} \times 24 \text{ hr/d}} = 0.51 \text{ days}$$

$$D = \frac{k_d L_0}{k_r - k_d} (e^{-k_d t} - e^{-k_r t}) + D_0 e^{-k_d t}$$

$$= \frac{0.61 \times 6.75}{0.76 - 0.61} (e^{-0.61 \times 0.51} - e^{-0.76 \times 0.51}) + 1.65 e^{-0.61 \times 0.51} = 2.6 \text{ mg/L}$$

$$DO = 8.5 - 2.6 = 5.9 \text{ mg/L}$$

7. For the following waste and river characteristic just upstream from the outfall, find the minimum downstream DO that could be expected:

Parameter	Wastewater	River
Flow (m ³ /s)	0.3	0.9
Ultimate BOD (mg/L)	6.4	7.0
DO (mg/L)	1.0	6.0
K _d (day ⁻¹)	--	0.2
K _r (day ⁻¹)	--	0.37
Speed (m/s)	--	0.65
DO _{sat} (mg/L)	8.0	8.0

(a) What is the DO concentration as mg/L at Martin's Creek?

$$\text{speed} = \frac{\text{distance}}{\text{time}} \rightarrow t = \frac{d}{s}$$

$$t = 15.5 \text{ km} \times \frac{1000 \text{ m}}{1 \text{ km}} \times \frac{1 \text{ s}}{0.390 \text{ m}} \times \frac{1 \text{ hour}}{3600 \text{ s}} \times \frac{1 \text{ day}}{24 \text{ hours}} = 0.461 \text{ days} \quad (\text{time to travel})$$

$$\text{Temp. downstream: } \frac{Q_w T_w + Q_r T_r}{Q_w + Q_r} = \frac{(0.1507 \text{ m}^3/\text{s})(16^\circ\text{C}) + (1.08 \text{ m}^3/\text{s})(28^\circ\text{C})}{(0.1507 \text{ m}^3/\text{s}) + (1.08 \text{ m}^3/\text{s})} = 26.5$$

Use ratio to solve for DO_{sat} @ 26.5°C: * using Table 5.11 values *

$$\frac{30^\circ\text{C} - 25^\circ\text{C}}{7.56 - 8.26 \text{ mg/L}} = \frac{26.5^\circ\text{C} - 25^\circ\text{C}}{x - 8.26 \text{ mg/L}} \rightarrow x - 8.26 = \frac{(1.50)(-0.7)}{5}$$

$$x = 8.05 \text{ mg/L}$$

$$D_a = D_{O_s} - \left[\frac{Q_w D_{O_w} + Q_r D_{O_r}}{Q_w + Q_r} \right]$$

$$D_a = 8.05 \text{ mg/L} - \left[\frac{(0.1507 \text{ m}^3/\text{s})(1.0 \text{ mg/L}) + (1.08 \text{ m}^3/\text{s})(7.95 \text{ mg/L})}{(0.1507 \text{ m}^3/\text{s}) + (1.08 \text{ m}^3/\text{s})} \right] = 0.95 \text{ mg/L}$$

$$L_o @ 28^\circ\text{C} = L_o @ 20^\circ\text{C} = 11.40 \text{ mg/L}$$

k @ 16°C:

$$k_T = k_{20} \theta^{(T-20)} \rightarrow k_{16} = (0.4375/\text{day})(1.135)^{(16-20)} = 0.264/\text{day}$$

now solve for L_o @ 16°C:

$$BOD_5 = L_o (1 - e^{-kt}) \rightarrow L_o = \frac{BOD_5}{(1 - e^{-kt})} = \frac{12.8 \text{ mg/L}}{(1 - e^{-(0.264/\text{day})(5 \text{ days})})} = 174.66 \text{ mg/L}$$

$$L_a = \frac{Q_w L_w + Q_r L_r}{Q_w + Q_r} = \frac{(0.1507 \text{ m}^3/\text{s})(174.66 \text{ mg/L}) + (1.08 \text{ m}^3/\text{s})(11.40 \text{ mg/L})}{(0.1507 \text{ m}^3/\text{s}) + (1.08 \text{ m}^3/\text{s})}$$

$$= 31.39 \text{ mg/L}$$

Solve for k_d and k_r :

$$k_r(20^\circ\text{C}) = k_r = \frac{3.9 \text{ h}^{-1/2}}{h^{3/2}} = \frac{3.9 (0.390 \text{ m/s})^{1/2}}{(2.8 \text{ m})^{3/2}} = 0.5198/\text{day}$$

$$k_{a,26.5} = 0.5198 (1.024)^{(26.5-20)} = 0.6064/\text{day}$$

$$k_d(20^\circ\text{C}): k_d = k + \frac{\mu}{h} = 0.4375/\text{day} + \left(\frac{0.390 \text{ m/s}}{2.8 \text{ m}} \right) (0.2) = 0.4654/\text{day}$$

$$k_d(26.5^\circ\text{C}): k_{d,26.5} = 0.4654/\text{day} (1.056)^{(26.5-20)} = 0.6632/\text{day}$$

$$D_t = \frac{k_d L_0}{k_r - k_d} (e^{-k_d t} - e^{-k_r t}) + D_0 e^{-k_r t}$$

$$= \frac{(0.6632/\text{day})(31.39 \text{ mg/L})}{(0.6064/\text{day}) - (0.6632/\text{day})} (e^{-(0.6632/\text{day})(0.461)} - e^{-(0.6064/\text{day})(0.461)}) + 0.95 \text{ mg/L} (e^{-(0.6064/\text{day})(0.461 \text{ day})})$$

$$= 7.88 \text{ mg/L} \rightarrow DO = DO_s - DO_t = 8.05 \text{ mg/L} - 7.88 \text{ mg/L} = \underline{\underline{0.17 \text{ mg/L}}}$$

(b) does your answer make sense based on the complaint?

Yes. DO close to zero = odor.

8. A river traveling at a velocity of 10 km/day has a dissolved oxygen content of 5 mg/L and an ultimate cBOD of 25 mg/L at distance $x=0$ km, that is, immediately downstream of a waste discharge. The waste has a cBOD decay coefficient k_1 of 0.2/day. The stream has a reaeration rate coefficient k_2 of 0.4/day and a saturation dissolved oxygen concentration of 9 mg/L.

- What is the initial dissolved oxygen deficit?
- What is the location of the critical point, in time and distance?
- What is the dissolved oxygen deficit at the critical point?
- What is the dissolved oxygen concentration at the critical point?

EXTRA CREDIT: Find the schematic of unit operations for the wastewater treatment plant that serves your hometown. Provide this schematic, and label all the unit operations. Below the schematic, write the purpose of each unit operation.

HOMEWORK (Air Pollution Control)

1. Consider a new 38% efficient 600-MW power plant burning 9,000 Btu/lb coal containing 1% sulfur. If a 70% efficient scrubber is used, what would be the emission rate of sulfur (lb/hr)?

Coal required per hour = Work done/(power efficiency x burning rate)

$$= \{ (2.04728498 \times 10^9 \text{ Btu/hour}) / (0.38 \times 9,000 \text{ Btu/lb}) \}$$

$$= 598,621.34 \text{ lb/hour.}$$

Rate of sulfur = 1% x coal requirement per hour

$$= (1/100) \times 598,621.34 \text{ lb/hour.}$$

$$= 5,986.21 \text{ lb/hour}$$

Emission rate of sulfur per hour

= rate of sulfur x Scrubber efficiency

$$= (5,986.21 \text{ lb/hour}) \times 70/100$$

$$= 4,190.35 \text{ lb/hr}$$

Therefore, the emission rate of sulfur is 4,190.35 lb/hr

Step-by-step explanation

Work done = 600 MW

This work is equivalent to $2.04728498 \times 10^9 \text{ Btu/hour}$.

power efficiency = 38% = $(38/100) = 0.38$

Scrubber efficiency = 70% = $(70/100) = 0.70$

Burning rate = 9,000 Btu/lb

Since it contains 1% sulfur then for every 1 lb Coal the sulfur content is 0.01 lb.

Coal required per every hour will be ;

Coal required per hour = Work done/(power efficiency x burning rate)

$$= \{ (2.04728498 \times 10^9 \text{ Btu/hour}) / (0.38 \times 9,000 \text{ Btu/lb}) \}$$

$$= 598,621.34 \text{ lb/hour.}$$

Rate of sulfur = 1% x coal requirement per hour

$$= (1/100) \times 598,621.34 \text{ lb/hour.}$$

$$= 5,986.21 \text{ lb/hour}$$

Emission rate of sulfur per hour

= rate of sulfur x Scrubber efficiency

$$= (5,986.21 \text{ lb/hour}) \times 70/100$$

$$= 4,190.35 \text{ lb/hr}$$

2. A new coal-fired power plant has been built using a sulfur emission control system that is 70 percent efficient. If all of the sulfur oxidizes to SO₂ and if the emission of SO₂ are limited to 0.6 lb SO₂ per million Btu of heat into the power plant, what maximum percent sulfur content can the fuel have if 15,000 Btu/lb coal is burned?

Answer - 27.34 %

3. A point source Gaussian plume model for a power plant uses 50 m as the effective stack height. You are concerned about pollutant levels at night, and the night is typically fully overcast with a wind speed

of 5 m/s. Your concern is with ground-level pollution at two house locations, A and B, which are 1.2 and 1.4 km directly downwind from the stack. Figure 7.52 in the Masters & Elia text would be helpful.

(a) At what distance will the maximum concentration of pollution occur under these conditions? Which location (A or B) would have the higher level of pollution?

(b) Suppose during the day the sky clears up, and the atmosphere becomes moderately unstable, and the wind speed stays around 5 m/s. Will the location downwind at which the maximum concentration occurs move? If so, will it move closer to the stack or further away from the stack? (H remains 50 m).

(c) Under the new conditions in part b, which house would experience the most pollution?

Answer: According to Table 7.52, class D stability should be assumed for overcast conditions, day or night, regardless of wind speed.

From Figure under class A conditions and an effective stack height of 50 m, the peak downwind concentration occurs at 1.1 km. Therefore, location A will have a higher level of pollution than location B. For a clear sky and wind speed of less than 5 m/s at night,

E stability. From Figure the peak downwind concentration now occurs at about 1.4 km, further away from the stack. This makes sense since it takes plumes longer to reach the ground under more stable conditions. Location B will now experience higher pollution than location A

4. A stack emitting 80 g/s of NO has an effective stack height of 100 m. The windspeed is 4 m/s at 10 m, and it is a clear summer day with the sun nearly overhead. Use a P value appropriate for the stability class. Estimate the ground-level NO concentration

(a) Directly downwind at a distance of 2 km. – 45%

(b) at the point downwind where NO is a maximum. – 200 meters

(c) at a point located 2 km downwind and 0.1 km off the downwind axis. - zero

5. A baghouse that employs a shaker collection method is being designed to remove sawdust particles originating from a sawmill plant. What fabric area is required for the baghouse if it treats 15,000 ft³/min of polluted air? How many bags are required if the bags are cylindrical and are 6 inches in diameter and 15 ft long? Assume the filter manufacturer has specified a woven fabric.

Answer: 237 bags are required

6. A thermal oxidizer incinerator operates as a plug flow reactor at a temperature of 250 deg C. The first order rate constant for vinyl chloride removal is 45/sec at 250 degrees C and the inside diameter of the incinerator (which is shaped like a cylinder) is 1 m.

(a) If the pollutant (Vinyl chloride) enters the incinerator at a flow rate of 3,000 m³/min and it is desired to remove 99.99% of the pollutant, what should the length of the incinerator be? 48 meters

(b) What is the length of the incinerator if the desired removal is increased to 99.99995%? 12 meters

7. What is the expected efficiency of an electrostatic precipitator that has a total collector plate area of 5000 square meters, a flow rate of 150 cubic meters per second, and a drift velocity of 0.1 m/s? What is the efficiency if the plate area is increased to 7500 square meters or to 10,000 square meters?

The efficiency of an electrostatic precipitator is given by the formula

$$\eta = 1 - e^{(-WA/Q)}$$

Where W is the drift velocity, A is the total collection area, and Q is the airflow rate.

Step-by-step explanation

Here, the total plate area is 5,000 m², the flow rate is 150 m³/s, and drift velocity is 0.15 m/s.

Thus,

$$\begin{aligned}\eta &= 1 - e^{(-WA/Q)} \\ &= 1 - e^{(-0.15 \cdot 5,000 / 150)} \\ &= 0.9932 \\ \Rightarrow \eta &= 0.9932\end{aligned}$$

if the area is increased to 7500, that is, A = 7500

$$\begin{aligned}\eta &= 1 - e^{(-0.15 \cdot 7500 / 150)} \\ \eta &= 0.9994\end{aligned}$$

If the area is increased to 10000, that is, A = 10000,

$$\begin{aligned}\eta &= 1 - e^{(-0.15 \cdot 10000 / 150)} \\ \eta &= 0.9999\end{aligned}$$

8. A flue gas contains mainly 15 micron sized particles (density 2000 kg/m³) to be removed by a cyclone collector. The body diameter is assumed to be 0.8 m. A high efficiency mode is desired. The inlet velocity is 15 m/s with a density of 1.225 kg/m³. What is the efficiency of removal of the 15 micron sized particles?

Answer: 76%

EXTRA CREDIT: Find a plume from a smokestack, take some photos, and submit those photos via email by the last day of class. Paste the photos within a powerpoint file and indicate with a text box the location (city and state) and time the photo was taken as well as your characterization of the plume shape. The plume must be an actual plume from a smokestack and not just some vapor leaving a steam vent.

HOMEWORK (Waste Management)

1. One way to estimate the energy content of wastes is based on an empirical equation described in Rhyner et al. (1995), which utilizes an elemental analysis (also called an ultimate analysis) of the material in question:

$$\text{HHV (kJ/kg)} = 339(\text{C}) + 1,440(\text{H}) - 139(\text{O}) + 105(\text{S})$$

where (C), (H), and (S) are the mass percentages of carbon, hydrogen, oxygen, and sulfur in dry material (for example, cardboard is 43.73 percent carbon, so $\text{C}=43.73$). For the following materials, find the higher heating values (HHV) of the dry waste and the HHV of “as received” waste accounting for the moisture content. Excel may be helpful.

Material	Moisture (% as received)	Dry Weight Percentages			
		C	H	O	S
(a) Corrugated boxes	5.20	43.73	5.70	44.93	0.21
(b) Junk mail	4.56	37.87	5.41	42.74	0.09
(c) Mixed garbage	72.0	44.99	6.43	28.76	0.52
(d) Lawn grass	75.24	46.18	5.96	36.43	0.42
(e) Demolition softwood	7.7	51.0	6.2	41.8	0.1
(f) Tires	1.02	79.1	6.8	5.9	1.5
(g) Polystyrene	0.20	87.10	8.45	3.96	0.02

Now, assume a city's waste is 10% corrugated boxes, 10% junk mail, 40% mixed garbage, 10% lawn grass, 10% demolition softwood, 10% tires, and 10% polystyrene. What is the average “as-received” HHV (kJ/kg) of this waste?

Finally, how much waste needs to be burned per day to power a 4 MW power plant for the city? Assume the efficiency is 50% (that is, 50% of energy created goes to electricity generation).

Answer: 4.02 Tons

2. Suppose a city of 50,000 people generates 40,000 tons of MSW per year. At current recovery and recycling rates, 22 percent of that is recovered or recycled and the rest goes to a landfill. Suppose also that the landfill density is 1,000 lb/yd³, cell depth is 10 ft, and 80 percent of the cell is MSW.

(a) What lift area would be required per year?

(b) If the current landfill site covers 50 acres, including 10 acres needed for access roads and auxiliary facilities, and two more lifts are envisioned, how long would it take to complete this landfill?

$$\text{Volume of MSW generated by town per year} = (0.05 \times 1000) \times 500000 / 500 = 50000 \text{ m}^3$$

$$\text{Land fill lift per year} = [50000 / (0.85)] / (0.8 \times 150 \times 100) = 4.902 \text{ m}$$

No. of years for which the land fill can be used = $25/4.902 = 5.1$ years

3. If the city described in problem 2 increases its recovery and recycling rate to 40 percent, how many years would it take to complete the landfill?

Answer – 3.2 years

4. A new solid waste landfill site is being designed. The landfill will serve a population of 250,000 residents that generates 1 kg solid waste/day-person. Assume that yard waste makes up 15% of the total waste (by weight), paper makes up 40% of the total waste (by weight), and metals make up 10% of the waste (by weight). The municipality bans the placement of yardwaste in landfills and has a recycling program that collects one half of all discarded metals (the other half of metals goes to the landfill). What is the volume of waste that is discarded by the community every day? Assume a waste density at the curb of 140 kg/m^3 .

Answer: $1.21 \times 10^6 \text{ m}^3$

5. Daily cells for a landfill are operated so that the following conditions are maintained: thickness of daily cover = 0.2 m; slope (horizontal:vertical) = 3:1, working face for refuse = 30 m; height of refuse = 3 m; and volume of daily refuse = $1,800 \text{ m}^3/\text{day}$. The landfill is interested in reducing requirements for daily cover soil over its 20 year life and is considering three options (that is, have a lower V_s/V_r). Which option should be the best? Why?

Option 1: Increase height of refuse to 4 m.

Option 2: Increase daily refuse volume to $2000 \text{ m}^3/\text{day}$.

Option 3: Decrease working face to 20 m.

The initial daily length is given by:

$$V_r = H \times L \times W$$

$$1,800 \text{ m}^3/\text{day} = 3 \text{ m} \times L \times 30 \text{ m}$$

$$L = 20 \text{ m}$$

$$V_s/V_r = [(1 + 0.2/3)(1 + (3 \times 0.2)/20)(1 + (3 \times 0.2)/30)] - 1 = 0.121$$

The other options will need to have a lower V_s/V_r to be better.

Option 1:

$$V_r = 1,800 \text{ m}^3/\text{day} = 4 \text{ m} \times L \times 30 \text{ m}$$

$$L = 15 \text{ m}$$

$$V_s/V_r = 0.114 \text{ (better than current situation)}$$

Option 2:

$$V_r = 2,000 \text{ m}^3 / \text{day} = 3 \text{ m} \times L \times 30 \text{ m}$$

$$L = 22.2 \text{ m}$$

$$V_s/V_r = 0.117 \text{ (better, but not as good as option 1)}$$

Option 3:

$$V_r = 1,800 \text{ m}^3 / \text{day} = 3 \text{ m} \times L \times 20 \text{ m}$$

$$L = 30 \text{ m}$$

$$V_s/V_r = 0.121 \text{ (same as current situation)}$$

Option 1, because the same 0.2 layer will be used to cover 4 m instead of 3 m and that gives 25% more refuse to cover ratio.