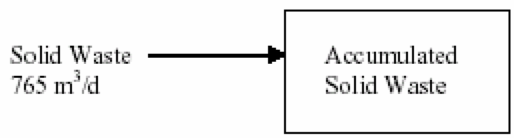
CHAPTER 2
SOLUTIONS

2-1 Expected life of landfill

Given: 16.2 ha at depth of 10 m, 765 m^3 dumped 5 days per week, compacted to twice delivered density

Solution:

a. Mass balance diagram



b. Total volume of landfill

$$(16.2\ \text{ha})(10^4\ \text{m}^2/\text{ha})(10\ \text{m}) = 1.620 \times 10^6\ \text{m}^3$$

c. Volume of solid waste is ½ delivered volume after it is compacted to 2 times its delivered density

$$(765\ \text{m}^3)(0.5) = 382.5\ \text{m}^3$$

d. Annual volume of solid waste placed in landfill

$$(382.5\ \text{m}^3)(5\ \text{d/wk})(52\ \text{wk/y}) = 9.945 \times 10^4\ \text{m}^3/\text{y}$$

e. Estimated expected life

$$\frac{1.620\times10^6\ \text{m}^3}{9.945\times10^4\ \text{m}^3/\text{y}} = 16.29 \text{ or } 16 \text{ years}$$

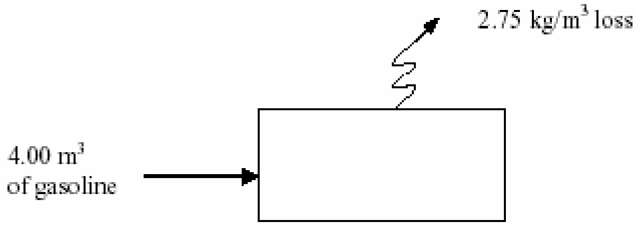
NOTE: the actual life will be somewhat less due to the need to cover the waste with soil each day.

2-4 Annual loss of gasoline

Given: Uncontrolled loss = 2.75 kg/m^3 of gasoline
Controlled loss = 0.095 kg/m^3 of gasoline
Refill tank once a week
Tank volume = 4.00 m^3
Specific gravity of gasoline is 0.80
Condensed vapor density = 0.80 g/mL
Cost of gasoline = $0.80/L

Solution:

a. Mass balance diagram



b. Annual loss with splash fill method

$$\text{Loss} = (4.00 \text{ m}^3/\text{wk})(2.75 \text{ kg/m}^3)(52 \text{ wk/y}) = 572 \text{ kg/y}$$

c. Value of fuel captured with vapor control

$$\text{Mass captured} = (4.00 \text{ m}^3/\text{wk})(2.75 \text{ kg/m}^3 - 0.095 \text{ kg/m}^3)(52 \text{ wk/y}) = 552.24 \text{ kg/y}$$

Value (note: 1.0 g/mL = 1000 kg/m^3)

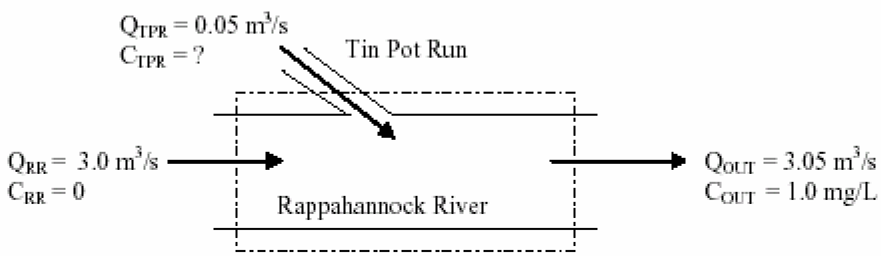
$$\frac{(552.24\,kg/y)(1000\,L/m^3)}{800\,kg/m^3}(\$1.06/L) = \$731.72 \text{ or } \$732/y$$

2-5 Mass rate of tracer addition

Given: Q_{RR} = 3.00 m^3/s, Q_{TPR} = 0.05 m^3/s, detection limit = 1.0 mg/L

Solution:

a. Mass balance diagram (NOTE: $Q_{out} = Q_{RR} + Q_{TPR}$ = 3.05 m^3/s)



b. Mass balance equation

$$C_{RR}Q_{RR} + C_{TRP}Q_{TPR} = C_{out}Q_{out}$$

Because C_{RR} in = 0 this equation reduces to:

$$C_{TPR}Q_{TPR} = C_{out}Q_{out}$$

c. Note that the quantity $C_{TPR}Q_{TPR}$ is the mass flow rate of the tracer into TPR and substitute values

$$C_{TPR}Q_{TPR} = \frac{1.0\text{mg}}{\text{L}} \times \frac{3.05\text{m}^3}{\text{s}} \times \frac{1000\text{L}}{\text{m}^3} \times \frac{1\text{kg}}{10^6\text{mg}} \times \frac{86400\text{s}}{\text{d}} = 264\,\text{kg/d}$$

d. Concentration in Tin Pot Run

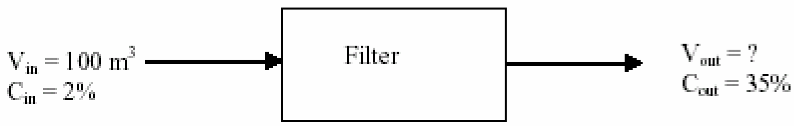
$$C_{TPR} = \frac{C_{TPR}Q_{TPR}}{Q_{TPR}} = \frac{(264\,kg/d)(10^6\,mg/kg)}{(0.05\,m^3/s)(86400\,s/d)(1000\,L/m^3)} = 61 \text{ or } 60\text{ mg/L}$$

2-8 Volume of sludge after filtration

Given: Sludge concentration of 2%, sludge volume = 100 m^3, sludge concentration after filtration = 35%

Solution:

a. Mass balance diagram



b. Mass balance equation

$$C_{in}\forall_{in} = C_{out}\forall_{out}$$

c. Solve for $\forall_{out}$

$$V_{out} = \frac{C_{in}V_{in}}{C_{out}}$$

d. Substituting values

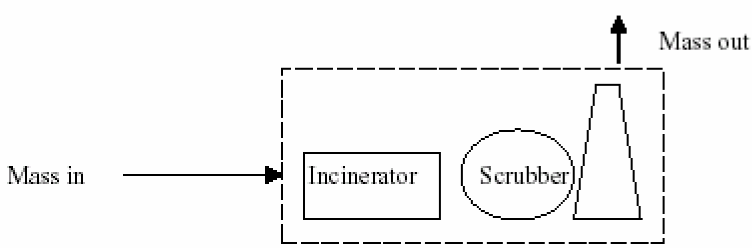
$$V_{out} = \frac{(0.02)(100m^3)}{0.35} = 5.71m^3$$

2-9 Hazardous waste incinerator emission

Given: Four nines DRE
Mass flow rate in = 1.0000 g/s
Incinerator is 90% efficient

Solution:

a. Mass balance diagram



b. Allowable quantity in exit stream

Mass out = (1 - DRE)(Mass in)

= (1 – 0.9999)(1.0000 g/s) = 0.00010 g/s

c. Scrubber efficiency

Mass out of incinerator = (1 – 0.90)(1.000 g/s) = 0.10000 g/s

Mass out of scrubber must be 0.00010 g/s from "b", therefore

$$\eta = \frac{0.1000\,\text{g/s} - 0.00010\,\text{g/s}}{0.1000\,\text{g/s}} = 0.999 \text{ or } 99.9\%$$

2-10 Sampling filter efficiency

Given: First filter captures 1941 particles
Second filter captures 63 particles
Figure P-2-10
Each filter has same efficiency

Solution:

a. Note that

$$\eta = \frac{C_2}{C_1} \text{ and } \eta = \frac{C_3}{C_2}$$

b. The concentration C_2 is

$$C_2 = C_1 - 1{,}941$$

c. Substitute efficiency for C_1 and C_2

$$\frac{63}{\eta} = \frac{1941}{\eta} - 1941$$

d. Solve for η

$$63 = 1{,}941 - 1941\eta$$

$$-1{,}941\eta = 63 - 1941 = -1{,}878$$

$$\eta = \frac{1878}{1941} = 0.9675$$

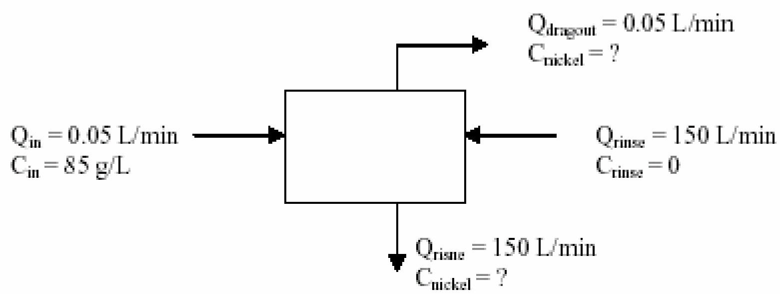
e. The efficiency of the sampling filters is 96.75%

2-11 Concentration of nickel in wastewater stream

Given: Figure P – 2-11, concentration of plating solution = 85 g/L, drag-out rate = 0.05 L/min, flow into rinse tank = 150 L/min, assume no accumulation in tank.

Solution:

a. Mass balance diagram



b. Mass balance equation

$$Q_{in}C_{in} + Q_{rinse}C_{rinse} - Q_{dragout}C_{nickel} - Q_{rinse}C_{nickel} = 0$$

c. Because $C_{rinse} = 0$ this reduces to

$$Q_{in}C_{in} = Q_{dragout}C_{nickel} + Q_{rinse}C_{nickel}$$

d. Solving for C_{nickel}

$$C_{nickel} = \frac{Q_{in}C_{in}}{Q_{dragout} + Q_{rinse}}$$

e. Substituting values

$$C_{nickel} = \frac{(0.05\,L/min)(85\,g/L)}{0.05\,L/min + 150\,L/min} = 28\,mg/L$$

2-14 Oxygen concentration in bottle

Given: Starting O_2 concentration = 8 mg/L, rate constant of 0.35 d^{-1}

Solution:

a. General mass balance equation for the bottle is Eqn 2-28

$$C_t = C_o e^{-kt}$$

b. With C_o = 8.0 mg/L and k = 0.35, the plotting points for oxygen remaining are:

Day	Oxygen Remaining, mg/L
1	5.64
2	3.97
3	2.79
4	1.97
5	1.39

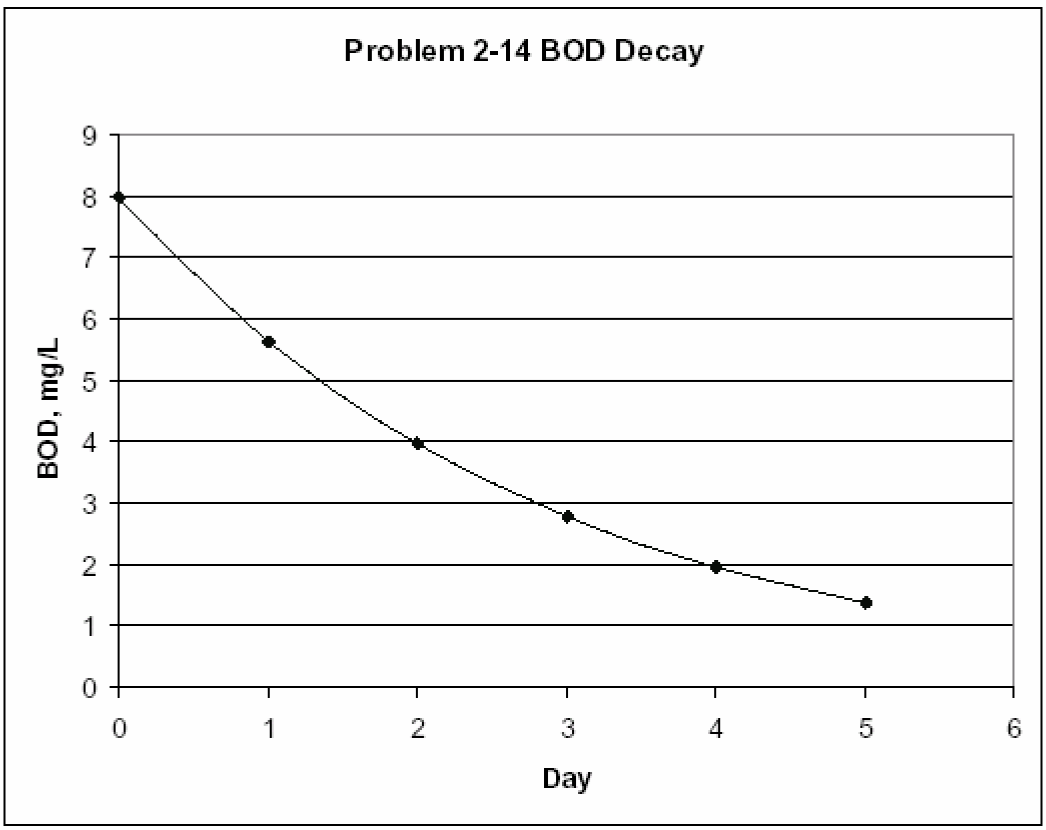


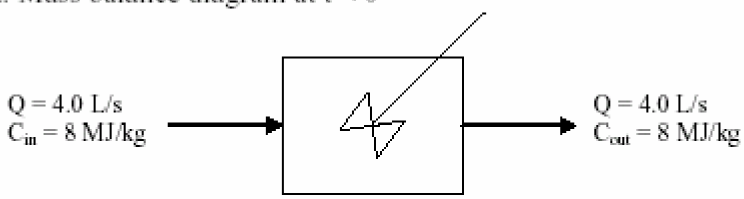
Figure S-2-14: BOD decay

2-19 Mixing time to achieve desired energy content

Given: CMFR, current waste energy content = 8.0 MJ/kg, new waste energy content = 10.0 MJ/kg, volume of CMFR = 0.20 m^3, flow rate into and out of CMFR = 4.0 L/s, effluent energy content = 9 MJ/kg.

Solution:

a. Mass balance diagram at t < 0



b. Step change in influent concentration at $t \geq 0$

C_{in} = 8 MJ/kg increases to C_{in} = 10 MJ/kg

c. Assuming this is non-reactive then the behavior is as shown in Figure 2-8 and Eqn 2-30 applies. Using the given values:

$$9\frac{MJ}{kg} = 8\frac{MJ}{kg}e^{-t/\theta} + 10\frac{MJ}{kg}\left(1 - e^{-t/\theta}\right)$$

Compute theoretical detention time:

$$\theta = \frac{0.20m^3}{(4.0\,L/s)(10^{-3}\,m^3/L)} = 50s$$

Solving for the exponential term:

$$9 = 8e^{-t/50} + 10 - 10e^{-t/50}$$

$$-1 = (8 - 10)e^{-t/50}$$

$$0.50 = e^{-t/50}$$

Taking the natural log of both sides

$$-0.693 = \frac{-t}{50}$$

t = 34.66 or 35 s

2-22 Brine pond dilution

Given: Pond volume = 20,000 m^3, salt concentration = 25,000 mg/L, Atlantic ocean salt concentration = 30,000 mg/L, final salt concentration = 500 mg/L, time to achieve final concentration = 1 year.

Solution:

a. Assuming the pond is completely mixed, treat as a step decrease in CMFR and use Eqn 2-33 and solve for θ.

$$500 = 25000 \exp\left(-\frac{1\text{year}}{\theta}\right)$$

$$0.020 = \exp\left(\frac{-1\text{y}}{\theta}\right)$$

Take the natural log of both sides

$$-3.912 = \left(\frac{-1\text{y}}{\theta}\right)$$

$$\theta = \frac{1}{3.912} = 0.2556\text{y}$$

b. Recognize that

$$\theta = \frac{\forall}{Q}$$

and solve for Q

$$0.2556\text{y} = \frac{20000\text{m}^3}{Q}$$

$$Q = \frac{20000\text{m}^3}{0.2556\text{y}} = 78{,}240\,\text{m}^3/\text{y}$$

c. Convert to units of m^3/s

$$78{,}240\,\text{m}^3/\text{y} \times \frac{1}{365\,\text{d/y}} \times \frac{1}{86400\,\text{s/d}} = 0.0025\,\text{m}^3/\text{s}$$

2-23 Venting water tower after disinfection

Given: Volume = 1,900 m^3, chlorine concentration = 15 mg/m^3, allowable concentration = 0.0015 mg/L, air flow = 2.35 m^3/s.

Solution:

a. Assume the water tower behaves as CMFR and apply Eqn 2-33

$$\theta = \frac{1900 m^3}{2.35 m^3/s} = 808.51 s$$

Convert concentration to similar units

(0.0015 mg/L)(1,000 L/m^3) = 1.5 mg/m^3

Now solve Eqn 2-33

$$1.5 mg/m^3 = 15 mg/m^3 \exp\left(-\frac{t}{808.51 s}\right)$$

$$0.10 = \exp\left(\frac{-t}{808.51 s}\right)$$

Take the natural log of both sides

$$-2.303 = \left(\frac{-t}{808.51 s}\right)$$

t = 1,861.66 s or 31 min or 30 min

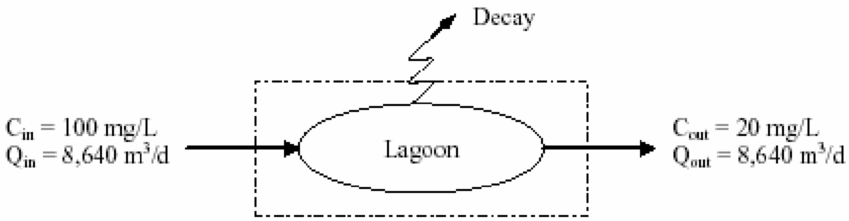
2-26 Rate constant for sewage lagoon

Given: Area = 10 ha, depth = 1 m, flow into lagoon = 8,640 m^3/d, biodegradable material = 100 mg/L, effluent must meet = 20 mg/L, assume 1st order reaction.

Solution:

a. There are two methods to solve this problem: (1) by using mass balance, (2) using equation from Table 2-2

b. First by mass balance



The mass balance equation is

$$\frac{dM}{dt} = C_{in}Q_{in} - C_{out}Q_{out} - kC_{lagoon}\forall$$

Assuming steady state, CMFR then

$$\frac{dM}{dt} = 0 \text{ and } C_{lagoon} = C_{out}$$

So,

$$C_{in}Q_{in} - C_{out}Q_{out} - kC_{out}\forall = 0$$

Solving for k

$$C_{in}Q_{in} - C_{out}Q_{out} = kC_{out}\forall$$

$$k = \frac{C_{in} Q_{in} - C_{out} Q_{out}}{C_{out} \forall}$$

Note that 1 mg/L = 1 g/m^3

$$k = \frac{(100\,g/m^3)(8640\,m^3/d) - (20\,g/m^3)(8640\,m^3/d)}{(20\,g/m^3)(10ha)(10000\,m^2/ha)(1m)}$$

$k = 0.3456\ d^{-1}$

c. Repeat using Table 2-2 equation for CMFR and 1st order reaction

$$C_t = \frac{C_o}{1 + k\theta}$$

$$\theta = \frac{\forall}{Q} = \frac{(10ha)(10000\,m^2/ha)(1m)}{8640\,m^3/d} = 11.574d$$

$$20\,mg/L = \frac{100\,mg/L}{1 + k(11.574d)}$$

Solve for k

$$0.20 = \frac{1}{1 + k(11.574d)}$$

$5.00 = 1 + k(11.574\ d)$

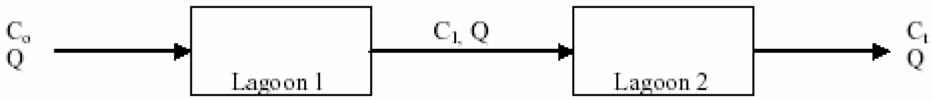
$$k = \frac{4.00}{11.574d} = 0.3456d^{-1}$$

2-27 Rate constant for two lagoons in series

Given: Data from Problem 2-26, two lagoons in series, area of each lagoon = 5 ha, depth = 1 m

Solution:

a. Mass balance diagram



Thus, the output from the 1st lagoon is the input to the 2nd lagoon. Solve the problem sequentially.

b. Calculate volume and hydraulic retention time

$$\forall = (5 \text{ ha})(10{,}000 \text{ m}^2/\text{ha})(1 \text{ m}) = 5.0 \text{ x } 10^4 \text{ m}^3$$

$$\theta = \frac{\forall}{Q} = \frac{5.0 \times 10^4 \text{ m}^3}{8640 \text{ m}^3/\text{d}} = 5.787 \text{d}$$

c. Using Table 2-2

$$C_1 = \frac{C_o}{1 + k\theta}$$

d. Because $C_1 = C_o$ for the second lagoon and the second lagoon has the same relationship

$$C_t = \frac{C_1}{1 + k\theta}$$

Substituting for C_1

$$C_t = \left(\frac{1}{1 + k\theta}\right)\left(\frac{C_o}{1 + k\theta}\right)$$

$$\frac{C_t}{C_o} = \left(\frac{1}{1 + k\theta}\right)^2$$

$$\left(\frac{C_t}{C_o}\right)^{1/2} = \frac{1}{1 + k\theta}$$

$$1 + k\theta = \left(\frac{C_o}{C_t}\right)^{1/2}$$

$$k = 0.2136 \text{ or } 0.21 \text{ d}^{-1}$$

2-31 Compare efficiency of CMFR and PRF

Given: $\forall = 280\ m^3$, $Q = 14\ m^3/d$, $k = 0.05\ d^{-1}$

Solution:

a. CMFR

From Table 2-2

$$C_t = \frac{C_o}{1 + k\theta}$$

$$\theta = \frac{\forall}{Q} = \frac{280 m^3}{14\, m^3/d} = 20d$$

$$\frac{C_t}{C_o} = \left(\frac{1}{1 + (0.05)(20)}\right) = 0.50$$

Using Eqn 2-8

$$\eta = \frac{C_o - 0.50 C_o}{C_o} \times 100\% = 50\%$$

b. PFR

From Table 2-2

$C_t = C_o \exp(-k\theta)$

$$\frac{C_{out}}{C_o} = \exp(-k\theta)$$

$$\frac{C_{out}}{C_o} = \exp(-(0.05)(20))$$

$$\frac{C_{out}}{C_o} = 0.37$$

Using Eqn 2-8

$$\eta = \frac{C_o - 0.37C_o}{C_o} \times 100\% = 63\%$$

2-32 Volume required to achieve 95% efficiency

Given: $Q = 14\ m^3/d$, $k = 0.05$

Solution:

a. Solve Eqn 2-8 for fraction of C_o

$$\eta = 0.95 = \frac{C_o - (X)C_o}{C_o}$$

$1 - X = 0.95$

$X = 0.05$

Therefore

$$\frac{C_t}{C_o} = 0.05$$

b. CMFR

From Table 2-2

$$C_t = \frac{C_o}{1 + k\theta}$$

Solve for θ

$$\frac{1}{1+k\theta} = \frac{C_t}{C_o}$$

$$\frac{C_o}{C_t} = 1 + k\theta$$

$$k\theta = \frac{C_o}{C_t} - 1$$

$$\theta = \frac{\frac{C_o}{C_t} - 1}{k}$$

Substituting values,

$$\theta = \frac{20-1}{0.05} = 380\text{d}$$

Solve for the volume

$$\theta = \frac{\forall}{Q}$$

$\forall = (\theta)(Q) = (380 \text{ d})(14 \text{ m}^3/\text{d}) = 5{,}320 \text{ m}^3$

c. PFR

From Table 2-2

$$\frac{C_t}{C_o} = \exp[-k\theta]$$

As in (a.) above

$0.05 = \exp(- 0.05\theta)$

Take the natural log of both sides

$-2.9957 = -0.05\theta$

2-36 Temperature of river after cooling water discharge

Given: River flow rate = 40 m^3/s, river temperature = 18° C, power plant discharge = 2 m^3/s, cooling water temperature = 80° C

Solution:

This is a simple energy balance as in Example 2-12. Assume the density of water is 1000 kg/m^3. The balance equation would be:

$$Q_{river}(\rho)(C_p)(\Delta T) = Q_{cooling\ water}(\rho)(C_p)(\Delta T)$$

Because the density is assumed constant and the specific heat is the same the equivalence reduces to:

$$Q_{river}(T - (273.15 + 18)) = Q_{cooling\ water}((273.15 + 80) - T)$$

Or,

$$40(T - 291.15) = 2(353.15 - T)$$

$$40T - 11{,}646 = 706.30 - 2T$$

$$42T = 12{,}352.30$$

$$T = 294.10 \text{ K or } 20.95°\text{C} \quad \text{or } 21° \text{ C}$$