SOLUTIONS MANUAL

Wastewater Engineering:

Treatment and Resource Recovery
Fifth Edition

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CONTENTS

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INTRODUCTION TO WASTEWATER TREATMENT

PROBLEM 1-1

Instructors Note: The first six problems are designed to illustrate the application of the mass balance principle using examples from hydraulics with which the students should be familiar.

Problem Statement - See text, page 53

Solution

1. Write a materials balance on the water in the tank

   Accumulation = inflow – outflow + generation

$$\frac{dV}{dt} = \frac{dh}{dt}A = Q_{in} - Q_{out} + 0$$

2. Substitute given values for variable items and solve for h

$$\frac{dh}{dt}A = 0.2\ m^3/s - 0.2\left(1 - \cos\frac{\pi t}{43{,}200}\right) m^3/s$$

   $A = 1000\ m^2$

3. $$dh = 2x10^{-4}\left(\cos\frac{\pi t}{43{,}200}\right)dt$$

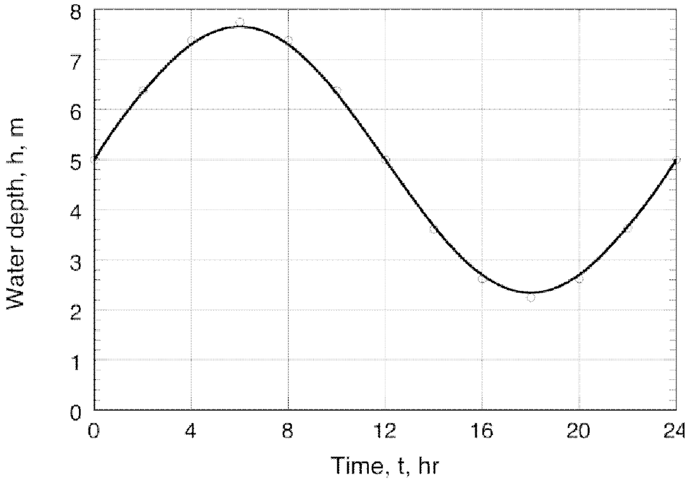
   Integrating the above expression yields:

$$h - h_o = \left[\frac{(43{,}200)\,(2x10^{-4})}{\pi}\right]\left(\sin\frac{\pi t}{43{,}200}\right)$$

4. Determine h as a function of time for a 24 hour cycle

t, hr	t, s	h, m	t, hr	t, s	h, m
0	0	5.00	14	50,400	3.62
2	7200	6.38	16	57,600	2.62
4	14,400	7.38	18	64,800	2.25
6	21,600	7.75	20	72,000	2.62
8	28,800	7.38	22	79,200	3.62
10	36,000	6.38	24	84,400	5.00
12	43,200	5.00			

5. Plot the water depth versus time



PROBLEM 1-2

Instructors Note: The first six problems are designed to illustrate the application of the mass balance principle using examples from hydraulics with which the students should be familiar.

Problem Statement - See text, page 53

Solution

1. Write a materials balance on the water in the tank

   Accumulation = inflow – outflow + generation

$$\frac{dV}{dt} = \frac{dh}{dt}A = Q_{in} - Q_{out} + 0$$

2. Substitute given values for variable items and solve for h

$$\frac{dh}{dt}A = 0.33\ m^3/s - 0.2\left(1 - \cos\frac{\pi t}{43{,}200}\right) m^3/s$$

$$\frac{dh}{dt}A = 0.13\ m^3/s + 0.2\left(\cos\frac{\pi t}{43{,}200}\right) m^3/s$$

$A = 1600\ m^2$

$$\frac{dh}{dt}(1600) = 0.13\ m^3/s + 0.2\left(\cos\frac{\pi t}{43{,}200}\right) m^3/s$$

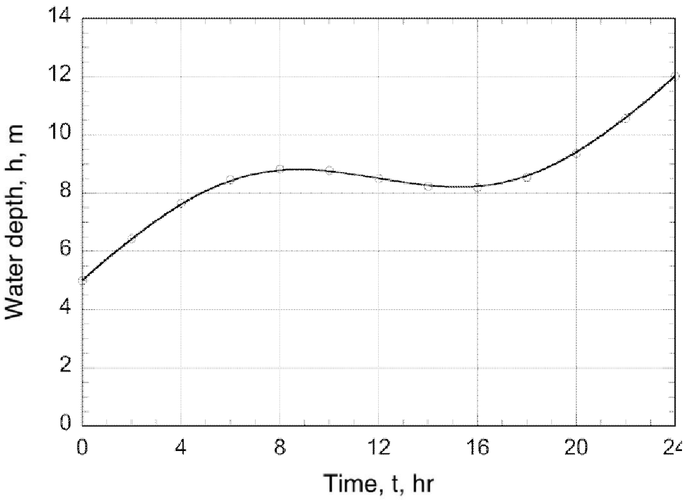
3. Integrating the above expression yields:

$$h - h_o = \frac{(0.13\ m^3/s)t}{1600} + \frac{(0.2)(43{,}200)}{\pi 1600}\left(\sin\frac{\pi t}{43{,}200}\right) m^3/s$$

Determine h as a function of time for a 24 hour cycle

t, hr	t, s	h, m	t, hr	t, s	h, m
0	0	5.00	14	50,400	8.24
2	7200	6.44	16	57,600	8.19
4	14,400	7.66	18	64,800	8.55
6	21,600	8.47	20	72,000	9.36
8	28,800	8.83	22	79,200	10.58
10	36,000	8.78	24	84,400	12.02
12	43,200	8.51			

4. Plot the water depth versus time



PROBLEM 1-3

Instructors Note: The first six problems are designed to illustrate the application of the mass balance principle using examples from hydraulics with which the students should be familiar.

Problem Statement - See text, page 53

Solution

1. Write a materials balance on the water in the tank

   Accumulation = inflow – outflow + generation

$$\frac{dV}{dt} = \frac{dh}{dt}A = Q_{in} - Q_{out} + 0$$

2. Substitute given values for variable items and solve for h

$$\frac{dh}{dt}A = 0.3\left(1 + \cos\frac{\pi t}{43{,}200}\right) m^3/s \ - 0.3\ m^3/s$$

$A = 1000\ m^2$

$$dh = 3 x 10^{-4}\left(\cos\frac{\pi t}{43{,}200}\right) dt$$

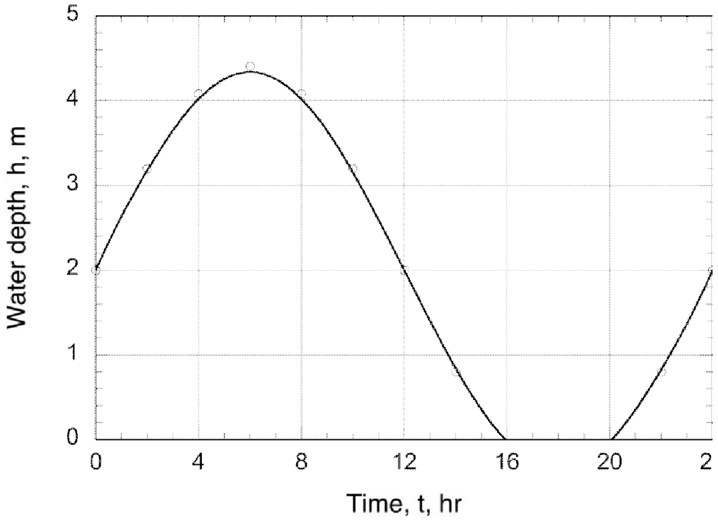
3. Integrating the above expression yields:

$$h - h_o = \left[\frac{(43{,}200)\ (3 \times 10^{-4})}{\pi}\right]\left(\sin\frac{\pi t}{43{,}200}\right)$$

1. Determine h as a function of time for a 24 hour cycle

t, hr	t, s	h, m	t, hr	t, s	h, m
0	0	5.00	14	50,400	2.94
2	7200	7.06	16	57,600	1.43
4	14,400	8.57	18	64,800	0.87
6	21,600	9.13	20	72,000	1.43
8	28,800	8.57	22	79,200	2.94
10	36,000	7.06	24	84,400	5.00
12	43,200	5.00			

5. Plot the water depth versus time



PROBLEM 1-4

Instructors Note: The first six problems are designed to illustrate the application of the mass balance principle using examples from hydraulics with which the students should be familiar.

Problem Statement - See text, page 53

Solution

1. Write a materials balance on the water in the tank

   Accumulation = inflow – outflow + generation

   $$\frac{dV}{dt} = \frac{dh}{dt}A = Q_{in} - Q_{out} + 0$$

2. Substitute given values for variable items and solve for h

   $$\frac{dh}{dt}A = 0.35\left(1 + \cos\frac{\pi t}{43{,}200}\right) m^3/s - 0.35\ m^3/s$$

   $A = 2000\ m^2$

   $$dh = 1.75 \times 10^{-4}\left(\cos\frac{\pi t}{43{,}200}\right)dt$$

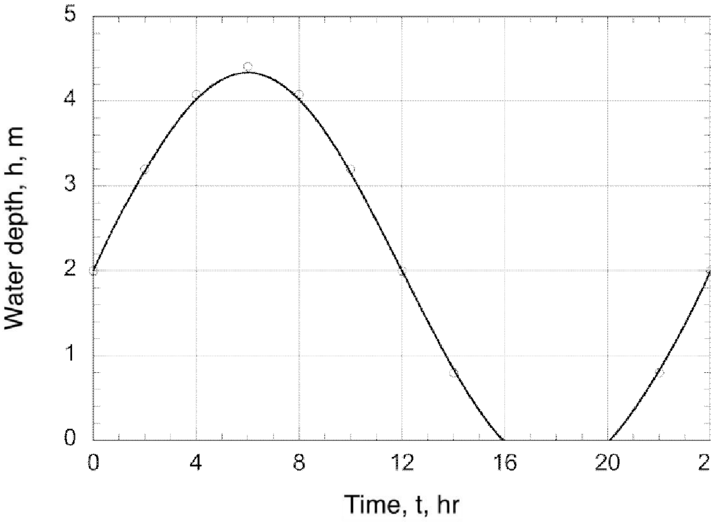
3. Integrating the above expression yields:

$$h - h_o = \left[\frac{\left(0.35\ \mathrm{m^3/s}\right)\left(43{,}200\right)}{\pi 2000\ \mathrm{m^2}}\right]\left(\sin\frac{\pi t}{43{,}200}\right)$$

4. Determine h as a function of time for a 24 hour cycle

t, hr	t, s	h, m	t, hr	t, s	h, m
0	0	2.00	14	50,400	0.80
2	7200	3.20	16	57,600	-0.08
4	14,400	4.08	18	64,800	-0.41
6	21,600	4.41	20	72,000	-0.08
8	28,800	4.08	22	79,200	0.80
10	36,000	3.20	24	84,400	2.00
12	43,200	2.00			

5. Plot the water depth versus time



PROBLEM 1-5

Instructors Note: The first six problems are designed to illustrate the application of the mass balance principle using examples from hydraulics with which the students should be familiar.

Problem Statement - See text, page 53

Solution

1. Write a materials balance on the water in the tank

Accumulation = inflow – outflow + generation

$$\frac{dV}{dt} = \frac{dh}{dt}A = Q_{in} - Q_{out} + 0$$

2. Substitute given values for variable items and solve for h

$$\frac{dh}{dt}A = 0.5\ m^3/min - [(2.1\,m^2/min)(h,m)]$$

Integrating the above expression yields

$$\int_0^h \frac{dh}{0.5 - 2.1\,h} = \frac{1}{A}\,dt$$

$$-\frac{1}{2.1}\left(\ln\frac{0.5 - 2.1\,h}{0.5}\right) = \frac{t}{A}$$

Solving for h yields

$$h = \frac{1}{2.1}(0.5)(1 - e^{-2.1\,t/A})$$

$$h = 0.24(1 - e^{-2.1\,t/A})$$

Area = $(\pi/4)\ (4.2)^2 = 13.85\ m^2$

$$h = 0.24(1 - e^{-2.1\,t/13.85}) = 0.24(1 - e^{-0.152\,t})$$

3. Determine the steady-state value of h

As $t \rightarrow \infty$
$h \rightarrow 0.24$ m

PROBLEM 1-6

Instructors Note: The first six problems are designed to illustrate the application of the mass balance principle using examples from hydraulics with which the students should be familiar.

Problem Statement - See text, page 53

Solution

1. Write a materials balance on the water in the tank

Accumulation = inflow – outflow + generation

$$\frac{dV}{dt} = \frac{dh}{dt}A = Q_{in} - Q_{out} + 0$$

2. Substitute given values for variable items and solve for h

$$\frac{dh}{dt}A = 0.75\ m^3/min - [(2.7\ m^2/min) \times h(m)]$$

Integrating the above expression yields

$$\int_0^h \frac{dh}{0.75 - 2.7\ h} = \frac{1}{A}\,dt$$

$$-\frac{1}{2.7}\left(\ln \frac{0.75 - 2.7\ h}{0.75}\right) = \frac{t}{A}$$

Solving for h yields

$$h = \frac{1}{2.7}(0.75)(1 - e^{-2.7\ t/A})$$

$$h = 0.28(1 - e^{-2.7\ t/A})$$

Area = $(\pi/4)\ (4.2)^2 = 13.85\ m^2$

$$h = 0.28(1 - e^{-2.7\ t/13.85}) = 0.28(1 - e^{-0.195\,t})$$

3. Determine the steady-state value of h

As $t \rightarrow \infty$
$h \rightarrow 0.28$ m

PROBLEM 1-7

Problem Statement - See text, page 53

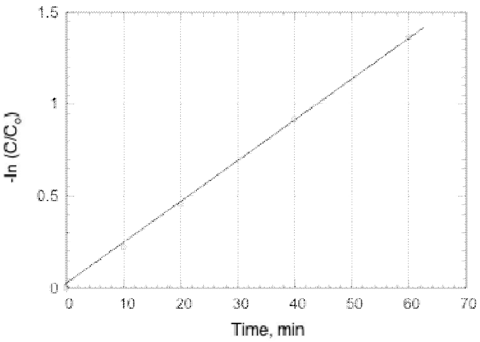
Solution: Graphical Approach

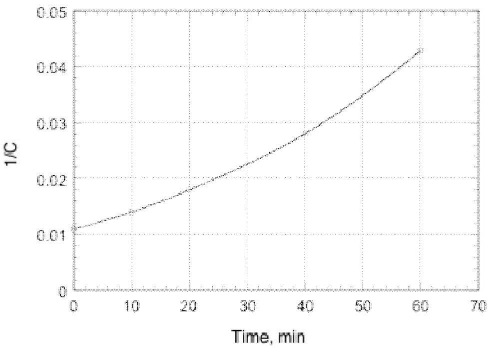
1. Determine the reaction order and the reaction rate constant using the integration method. Develop the data needed to plot the experimental data functionally for reactant 1, assuming the reaction is either first or second order.

Time, min	C, mg/L	$-\ln (C/C_o)$	1/C
0	90	0.000	0.011
10	72	0.223	0.014

20	57	0.457	0.018
40	36	0.916	0.028
60	23	1.364	0.043

2. To determine whether the reaction is first- or second-order, plot – ln(C/C_o) and 1/C versus t as shown below. Because the plot of – ln(C/Co) versus t is a straight line, the reaction is first order with respect to the concentration C.





3. Determine the reaction rate coefficient.

   Slope = k

   The slope from the plot = $\dfrac{1.364 - 0.223}{60\text{ min} - 10\text{ min}}$ = 0.023/min

   k = 0.023/min

   Summary of results for Problem 1-7

Reactant	Order	k, min^{-1}	k, $\text{m}^3/\text{g•min}$
1	First	0.023	
2	Second		0.0121
3	Second		0.0003
4	First	0.035	

Solution: Mathematical Approach

1. The following analysis is based on **reactant 1**
2. For zero order kinetics the substrate utilization rate would remain constant. Because the utilization rate is not constant for reactant 1, the reaction rate is not zero order.

3. Assume first order kinetics are applicable and compute the value of the rate constant at various times.

Time, min	C/C_o	$\ln C/C_o$	k, min^{-1}
0	1.00	0.000	
10	0.80	-0.223	0.022
20	0.63	-0.457	0.023
40	0.40	-0.916	0.023
60	0.26	-1.364	0.023

3. Because the reaction rate constant is essentially constant, it can be concluded that the reaction is first order with respect to the utilization of reactant 1.

PROBLEM 1-8

Problem Statement - See text, page 53

Solution

1. Write a materials balance for the batch reactor

Accumulation = inflow – outflow + generation

$$\frac{d[A]}{dt} = 0 - 0 + (-k[A][B])$$

However, because [A] = [B]

$$\frac{d[A]}{dt} = -k[A]^2$$

2. Integrate the above expression

$$\int_{A_o}^{A} \frac{d[A]}{[A]^2} = -k\int_0^t dt$$

$$-(\frac{1}{A} - \frac{1}{A_o}) = -kt$$

3. Determine the reaction rate constant k

$$-\left[\frac{1}{0.9(1)}-\frac{1}{1}\right]=-k(10)$$

k = 0.011 L/mole•min

4. Determine the time at which the reaction will be 90 percent complete

$$-\left[\frac{1}{0.1(1)}-\frac{1}{1}\right]=-0.011(t)$$

t = 818 min

PROBLEM 1-9

Problem Statement - See text, page 53

Solution

1. Write a materials balance for the batch reactor

Accumulation = inflow – outflow + generation

$$\frac{d[A]}{dt}=0-0+(-k[A][B])$$

However, because [A] = [B]

$$\frac{d[A]}{dt}=-k[A]^2$$

2. Integrate the above expression

$$\int_{A_o}^{A}\frac{d[A]}{[A]^2}=-k\int_0^t dt$$

$$-(\frac{1}{A}-\frac{1}{A_o})=-kt$$

3. Determine the reaction rate constant k

$$-\left[\frac{1}{0.92(1.33)}-\frac{1}{1.33}\right]=-k(12)$$

k = 0.00545 L/mole•min

4. Determine the time at which the reaction will be 96 percent complete

$$-\left[\frac{1}{0.04(1.33)}-\frac{1}{1.33}\right]=-0.00545\ (t)$$

t = 3313 min

PROBLEM 1-10

Problem Statement - See text, page 53

Solution

1. Solve Eq. (1-41) for activation energy. The required equation is:

$$E=\frac{RT_1T_2}{(T_2-T_1)}\left(\ln\frac{k_2}{k_1}\right)=\frac{R\ \ln\left(k_2\,/\,k_1\right)}{\left(1/\,T_1-1/\,T_2\right)}$$

where k_2/k_1 = 2.75

T_1 = 10°C = 283.15 K

T_2 = 25°C = 298.15 K

R = 8.314 J/mole•K

2. Solve for E given the above values:

$$E=\frac{(8.314)[\ln\left(2.75\right)]}{(1/\,298.15-1/\,283.15)}=47{,}335\ \mathrm{J/mole}$$

PROBLEM 1-11

Problem Statement - See text, page 53

Solution

1. Determine the activation energy using Eq. (1-41):

$$\ln\frac{k_2}{k_1}=\frac{E(T_2-T_1)}{RT_1T_2}=\frac{E}{RT_1T_2}(T_2-T_1)$$

where k_2/k_1 = 2.4

E = 58,000 J/mole

R = 8.314 J/mole•K

2. Given $k_2 > k_1$, the lowest reaction rate is observed at k_1. Therefore, T_1 = 15°C. Insert know values into Eq. (1-41) and solve for T_2 to determine the temperature difference between T_1 and T_2:

$$\ln\frac{k_2}{k_1} = 0.8755 = \frac{E(T_2 - T_1)}{RT_1T_2} = \frac{(58{,}000\ \mathrm{J/mole})(T_2 - 288.15\ \mathrm{K})}{(8.314\ \mathrm{J/mole}\cdot\mathrm{K})(288.15\ \mathrm{K})T_2}$$

$$= \frac{58{,}000T_2}{2395.68T_2} - \frac{16{,}712{,}700}{2395.68T_2}$$

$$= 24.21 - 6976.18/T_2$$

$$\frac{1}{T_2} = \frac{24.21 - 0.8755}{6976.18} = 0.003345$$

$$T_2 = 298.96\ \mathrm{K} = 26^\circ\mathrm{C}$$

3. The temperature difference is therefore 11 °C.

PROBLEM 1-12

Problem Statement - See text, page 53

Solution

1. Use Eq. (1-41) to determine $\ln(k_2/k_1)$:

$$\ln\frac{k_2}{k_1} = \frac{E(T_2 - T_1)}{RT_1T_2} = \frac{E}{RT_1T_2}(T_2 - T_1)$$

where T_1 = 27 °C – 15 °C = 12 °C = 285.15 K

T_2 = 27 °C = 300.15 K

E = 52,000 J/mole

R = 8.314 J/mole•K

2. Solve for $\ln(k_2/k_1)$ given the above values:

$$\ln\frac{k_2}{k_1} = \frac{(52{,}000\ \mathrm{J/mole})}{(8.314\,\mathrm{J/mole}\bullet\mathrm{K})(285.15\ \mathrm{K})(300.15\ \mathrm{K})}(285.15\ \mathrm{K} - 300.15\ \mathrm{K})$$

$$= 1.0962$$

3. The difference in the reaction rates is:

$$\ln\frac{k_2}{k_1} = \ln(k_2) - \ln(k_1) = 1.0962$$

PROBLEM 1-13

Problem Statement - See text, page 54

Solution

1. Determine the activation energy using Eq. (1-41)

$$\ln\frac{k_2}{k_1} = \frac{E(T_2 - T_1)}{RT_1T_2} = \frac{E}{RT_1T_2}(T_2 - T_1)$$

where $k_{25°C}$ = 1.5 x 10^{-2} L/mole•min

$k_{45°C}$ = 4.5 x 10^{-2} L/mole•min

T_1 = 25°C = 298.15 K

T_2 = 45°C = 318.15 K

R = 8.314 J/mole•K

2. Solve the above expression for E

$$E = \frac{RT_1T_2}{(T_2 - T_1)}\left(\ln\frac{k_2}{k_1}\right)$$

$$E = \frac{(8.314)(298.15)(318.15)}{(318.15 - 298.15)}\left(\ln\frac{4.5\,\text{x}\,10^{-2}}{1.5\,\text{x}\,10^{-2}}\right) = 43{,}320 \text{ J/mole}$$

3. Determine the rate constant at 15°C

$$\ln\frac{k_2}{k_1} = \frac{E}{RT_1T_2}(T_2 - T_1)$$

where $k_{15°C}$ = ? L/mole•min

$k_{25°C}$ = 1.5 x 10^{-2} L/mole•min

T_1 = 25°C = 298.15 K

T_2 = 15°C = 288.15 K

R = 8.314 J/mole•K

$$\ln\frac{k_{15°C}}{1.5\,x10^{-2}} = \frac{43{,}320}{(8.314)(298.15)(288.15)}(288.15-298.15)$$

$$\ln\frac{k_{15°C}}{1.5\,x10^{-2}} = -0.6065$$

$k_{15°C}$ = (1.5 x 10^{-2})(0.5453) = 0.818 x 10^{-2}

PROBLEM 1-14

Problem Statement - See text, page 54

Solution

1. Determine the activation energy using Eq. (1-41)

$$\ln\frac{k_2}{k_1} = \frac{E(T_2-T_1)}{RT_1T_2} = \frac{E}{RT_1T_2}(T_2-T_1)$$

where $k_{20°C}$ = 1.25 x 10^{-2} L/mole•min

$k_{35°C}$ = 3.55 x 10^{-2} L/mole•min

T_1 = 20°C = 293.15 K

T_2 = 35°C = 308.15 K

R = 8.314 J/mole•K

2. Solve the above expression for E

$$E = \frac{RT_1T_2}{(T_2-T_1)}\left(\ln\frac{k_2}{k_1}\right)$$

$$E = \frac{(8.314)(293.15)(308.15)}{(308.15-293.15)}\left(\ln\frac{3.55\,x10^{-2}}{1.25\,x10^{-2}}\right) = 52{,}262\ \mathrm{J/mole}$$

3. Determine the rate constant at 15°C

$$\ln\frac{k_2}{k_1} = \frac{E}{RT_1T_2}(T_2-T_1)$$

where $k_{15°C}$ = ? L/mole•min

$$k_{20°C} = 1.25 \times 10^{-2} \text{ L/mole}\bullet\text{min}$$

$$T_1 = 20°C = 293.15 \text{ K}$$

$$T_2 = 15°C = 288.15 \text{ K}$$

$$R = 8.314 \text{ J/mole}\bullet\text{K}$$

$$\ln\frac{k_{15°C}}{1.25 \times 10^{-2}} = \frac{52{,}262}{(8.314)(293.15)(288.15)}(288.15 - 293.15)$$

$$\ln\frac{k_{15°C}}{1.25 \times 10^{-2}} = -0.372$$

$$k_{15°C} = (1.25 \times 10^{-2})(0.689) = 0.862 \times 10^{-2}$$

PROBLEM 1-15

Problem Statement - See text, page 53

Solution

1. Write a materials balance for a complete-mix reactor. Use the generic rate expression for chemical reactions given in Table 1-11.

   Accumulation = inflow – outflow + generation

   $$\frac{dC}{dt}V = QC_o - QC + (-kC^n)V$$

2. Solve the mass balance at steady-state for kC^n

   From stoichiometry, $C = C_o - 1/2C_R$

   Substituting for C yields:

   $$0 = QC_o - Q(C_o - \frac{1}{2}C_R) + (-kC^n)V$$

   $$0 = \frac{1}{2}QC_R - kC^n V$$

   $$kC^n = \frac{QC_R}{2V}$$

3. Determine the reaction order and the reaction rate constant at 13°C

   a. Consider Run 1

$$k_{13^\circ C}[1 - 1/2(1.8)]^n = \frac{(2\ \text{cm/s})(1.8\ \text{mole/L})}{2(5\ \text{L})(10^3\ \text{cm}^3/\text{L})} = 3.6 \times 10^{-4}\ \text{mole/L} \bullet \text{s}$$

b. Consider Run 2

$$k_{13^\circ C}[1 - 1/2(1.5)]^n = \frac{(15\ \text{cm/s})(1.5\ \text{mole/L})}{2(5\ \text{L})(10^3\ \text{cm}^3/\text{L})} = 2.25 \times 10^{-3}\ \text{mole/L} \bullet \text{s}$$

c. Divide a by b

$$\frac{k_{13^\circ C}(0.1)^n}{k_{13^\circ C}(0.25)^n} = \frac{3.6 \times 10^{-4}}{2.25 \times 10^{-3}}$$

$$\left(\frac{0.1}{0.25}\right)^n = 0.16$$

n = 2

4. Determine the reaction rate constant at 84°C

$$k_{84^\circ C} = \frac{QC_R}{2VC^2} = \frac{(15\ \text{cm/s})(1.8\ \text{mole/L})}{2(5\ \text{L})(10^3\ \text{cm}^3/\text{L})(0.1)^2} = 2.7 \times 10^{-1}\ \text{L/mole} \bullet \text{s}$$

5. Determine the temperature coefficient θ using Eq. (1-44)

$$\frac{k_{84^\circ C}}{k_{13^\circ C}} = \theta^{(T_2 - T_1)}$$

where $k_{13^\circ C} = (k_{13^\circ C}C^2)/C^2 = 3.6 \times 10^{-2}$

$$\frac{2.7 \times 10^{-1}}{3.6 \times 10^{-2}} = \theta^{(357.15 - 286.15)}$$

ln (7.5) = 71 ln θ

ln θ = 2.015/71 = 0.0284

θ = 1.029

PROBLEM 1-16

Problem Statement - See text, page 53

Solution

1. Write a materials balance for the batch reactor

Accumulation = inflow – outflow + generation

$$\frac{dC}{dt}V = 0 - 0 + (-\frac{kC}{K + C})V$$

2. Solve the mass balance for t

$$\left(\frac{K + C}{C}\right)dC = -k\,dt$$

$$\int_{C_o}^{C}\left[\left(\frac{K}{C}\right) + 1\right]dC = -k\int_{0}^{t}dt$$

$K \ln(C_o/C) + (C_o - C) = kt$

$$t = \frac{K \ln(C_o/C) + C_o - C}{k}$$

3. Compute t for the given data:

$C_o = 1000\ mg/m^3$

$C = 100\ mg/m^3$

$k = 40\ mg/m^3 \cdot min$

$K = 100\ mg/m^3$

$$t = \frac{100 \ln(1000/100) + (1000-100)}{40} = 28.3\ min$$

Comment

An explicit expression for the concentration C cannot be obtained as a function of time. The concentration C at any time t must be obtained by successive trials.

PROBLEM 1-17

Problem Statement - See text, page 54

Solution

1. Write a materials balance for the batch reactor

Accumulation = inflow – outflow + generation

$$\frac{dC}{dt}V = 0 - 0 + (-\frac{kC}{K + C})V$$

2. Solve the mass balance for t

$$\left(\frac{K + C}{C}\right) dC = -k\ dt$$

$$\int_{C_o}^{C}\left[\left(\frac{K}{C}\right) + 1\right] dC = -k\int_0^t dt$$

$$K \ln(C_o/C) + C_o - C = kt$$

$$t = \frac{K \ln(C_o/C) + C_o - C}{k}$$

3. Compute t for the given data:

$C_o = 1000\ g/m^3$

$C = 100\ g/m^3$

$k = 28\ g/m^3 \bullet min$

$K = 116\ g/m^3$

$$t = \frac{116 \ln(1000/100) + (1000\text{-}100)}{28} = 41.7\ min$$

Comment

An explicit expression for the concentration C cannot be obtained as a function of time. The concentration C at any time t must be obtained by successive trials.

PROBLEM 1-18

Problem Statement - See text, page 54

Solution

1. Write a materials balance on the water in the complete-mix reactor

Accumulation = inflow – outflow + generation

$$\frac{dC}{dt} = QC_o - QC + (-kC)V$$

2. Determine the flowrate at steady state

$$0 = QC_o - QC + (-kC)V$$

solve for C/C_o

$$\frac{C}{C_o} = \frac{Q}{Q + kV}$$

Substitute known values and solve for Q at 98 percent conversion ($C/C_o = 0.02$)

$$0.02 = \frac{Q}{Q + (0.15/d)(20\ m^3)}$$

$Q = 0.02Q + 0.06$

$Q = 0.0612\ m^3/d$

3. Determine the corresponding reactor volume required for 92 percent conversion at a flowrate of $0.0612\ m^3/d$

$$0.08 = \frac{(0.0612\ m^3/d)}{(0.0612\ m^3/d) + (0.15/d)V}$$

$V = 4.7\ m^3$

PROBLEM 1-19

Problem Statement - See text, page 54

Solution

1. The general expression for reactors in series for first order kinetics is:
   a. For reactors of the same size the expression [Eq. (1-75)] is:

   $$C_n = \frac{C_o}{[1 + (kV/nQ)]^n} = \frac{C_o}{[1 + (k\tau)]^n}$$

   where τ = hydraulic detention time of individual reactors

   b. For reactors of unequal size the expression is:

$$C_n = \left[\frac{C_o}{1+(k\tau_1)}\right]\left[\frac{C_o}{1+(k\tau_2)}\right]\cdots\left[\frac{C_o}{1+(k\tau_n)}\right]$$

where $\tau_1, \tau_2, \ldots \tau_n$ = hydraulic detention of individual reactors

2. Demonstrate that the maximum treatment efficiency in a series of complete-mix reactors occurs when all the reactors are the same size.

   a. Determine efficiency for three reactors in series when the reactors are of the same size.

      Assume $C_o = 1$, $V_T = 3$, $\tau = 1$, $k = 1$, and $n = 3$

      $$\frac{C_3}{C_o} = \frac{1}{[1+(k\tau)]^n} = \frac{1}{[1+(1 \text{ x } 1)]^3} = 0.125$$

   b. Determine efficiency for three reactors in series when the reactors are not of the same size.

      Assume $C_o = 1$, $V_T = 3$, $\tau_1 = 2$, $\tau_2 = 0.5$, $\tau_3 = 0.5$, and $k = 1$

      $$\frac{C_3}{C_o} = \left[\frac{1}{1+(1 \text{ x } 2)}\right]\left[\frac{1}{1+(1 \text{ x } 0.5)}\right]\left[\frac{1}{1+(1 \text{ x } 0.5)}\right] = 0.148$$

   c. Determine efficiency for three reactors in series when the reactors are not of the same size and are of a different configuration from b

      Assume $C_o = 1$, $V_T = 3$, $\tau_1 = 1$, $\tau_2 = 1.5$, $\tau_3 = 0.5$, $k = 1$, and $n = 3$

      $$\frac{C_3}{C_o} = \left[\frac{1}{1+(1 \text{ x } 1)}\right]\left[\frac{1}{1+(1 \text{ x } 1.5)}\right]\left[\frac{1}{1+(1 \text{ x } 0.5)}\right] = 0.133$$

3. Demonstrate mathematically that the maximum treatment efficiency in a series of complete-mix reactors occurs when all the reactors are the same size.

   a. For two reactors in series

      $$\frac{C_o}{C_2} = (1+k\tau_1)(1+(k\tau_2)$$

   b. Determine τ_1 and τ_2 such that C_o/C_2 will be maximized

      $$\nabla(C_o / C_2) = (1+k^2\tau_1)\,\hat{i} + (1+k^2\tau_2)\,\hat{j}$$

   c. To maximize the above expression let $\nabla(C_o/C_2) = 0$

$$0 = (1 + k^2\tau_1)\,\hat{i} + (1 + k^2\tau_2)\,\hat{j}$$

$1 + k^2\tau_1 = 0$

$1 + k^2\tau_2 = 0$

thus, $\tau_1 = \tau_2$ for $k \neq 0$

d. Check to identify maximum or minimum

Let $\tau_1 + \tau_2 = 2$ and $k = 1$

If $\tau_1 = \tau_2 = 1$

Then $\dfrac{C_o}{C_2} = (1 + k\tau_1)(1 + (k\tau_2) = [1 + (1 \text{ x } 1)][1 + (1 \text{ x } 1)] = 4$

e. For any other combination of $\tau_1 + \tau_2$, C_o/C_2 will be less than 4. Thus, C_o/C_2 will be maximized when $\tau_1 = \tau_2$.

f. By extension it can be shown that the maximum treatment efficiency in a series of complete-mix reactors occurs when all of the reactors are of the same size.

PROBLEM 1-20

Problem Statement - See text, page 54

Solution

1. For n complete-mix reactors in series the corresponding expression is given by Eq. (1-75)

$$\frac{C_n}{C_o} = \frac{1}{[1 + (kV/nQ)]^n} = \frac{1}{[1 + (k/\tau)]^n}$$

where τ = hydraulic detention time for individual reactors

2. Determine the number of reactors in series

$$[1 + (k/\tau)]^n = \frac{C_o}{C_n}$$

Substitute the given values and solve for n, the number of reactors in series

$$[1 + (6.1/\text{h})/(0.5\text{ h})]^n = \frac{10^6}{14.5}$$

$$n \log [1 + (6.1/\text{h})/(0.5\ \text{h})] = \log\left(\frac{10^6}{14.5}\right)$$

$n \approx 10.2$,   Use 10 reactors

PROBLEM 1-21

Problem Statement - See text, page 54

Solution

1. The expression for an ideal plug flow reator is given in Eq. (1-21)

$$\frac{\partial C}{\partial t} = -v\frac{\partial C}{\partial \text{x}}$$

The influent concentration must be equal to the effluent concentration and the change with respect to distance is equal to zero by definition.

2. The rate of reaction is defined as retarded first order given in Eq. (1-53),

$$\frac{\text{d}C}{\text{d}t} = -\frac{k\text{C}}{(1 + r_t t)^n}$$

Bringing like terms together, integrate between the limits $C = C_o$ and $C = C$ and $t = 0$ and $t = t$,

$$\int_{C=C_o}^{C=C}\frac{\text{d}C}{\text{C}} = -\int_{\text{t}=0}^{t=t}\frac{k}{(1 + r_t t)^n}\text{d}t$$

3. For n = 1,

$$\ln\left(\frac{\text{C}}{\text{C}_\text{o}}\right) = -\frac{\text{k}}{\text{r}_\text{t}}\ln(1 + \text{r}_\text{t}\text{t})$$

$$\text{C} = \text{C}_\text{o}\exp\left[-\frac{\text{k}}{\text{r}_\text{t}}\ln(1 + \text{r}_\text{t}\text{t})\right]$$

4. For n ≠ 1,

$$\ln\left(\frac{\text{C}}{\text{C}_\text{o}}\right) = -\frac{\text{k}}{\text{r}_\text{t}(\text{n}-1)}\left[1 - \frac{1}{(1 - \text{r}_\text{t}\text{t})^{\text{n}-1}}\right]$$

$$\text{C} = \text{C}_\text{o}\exp\left\{-\frac{\text{k}}{\text{r}_\text{t}(\text{n}-1)}\left[1 - \frac{1}{(1 - \text{r}_\text{t}\text{t})^{\text{n}-1}}\right]\right\}$$

PROBLEM 1-22

Problem Statement - See text, page 54

Solution

1. Develop basic materials balance formulations for a complete-mix reactor (CMR) and a plug-flow reactor (PFR).

   a. CMR

   Accumulation = inflow – outflow + generation

   $$\frac{dC}{dt}V = QC_o - QC + r_c V \qquad \text{Eq. (1-57)}$$

   At steady state

   $$0 = QC_o - QC + r_c V$$

   b. PFR

   Accumulation = inflow – outflow + generation

   $$\frac{\partial C}{\partial t}\Delta V = QC\big|_x - QC\big|_{x+\Delta x} + r_c\, dV \qquad \text{Eq. (1-79)}$$

   Taking the limit as Δx goes to zero and considering steady-state yields

   $$0 = -\frac{Q}{A}\frac{dC}{dx} + r_C$$

   For a rate of reaction defined as $r_c = -kC^n$ the above expression can be written as follows. See.

   $$\int_{C_o}^{C}\frac{dC}{C^n} = -k\frac{A}{Q}\int_0^L dx = -k\frac{AL}{Q} = -k\frac{V}{Q} = -k\tau \qquad \text{Eq. (1-83)}$$

2. Solve the complete-mix and plug-flow expressions for r = -k and determine ratio of volumes

   a. Complete-mix reactor

   $$0 = QC_o - QC - kV$$

   $$V_{CMR} = \frac{Q(C_o - C)}{k}$$

   b. Plug-flow reactor

   $$\int_{C_o}^{C} dC = -k\frac{V}{Q} = C - C_o$$

$$V_{PFR} = \frac{Q(C_o - C)}{k}$$

c. Ratio of volumes

$$\frac{V_{PFR}}{V_{CMR}} = \frac{\left[\frac{Q(C_o - C)}{k}\right]}{\left[\frac{Q(C_o - C)}{k}\right]} = 1$$

3. Solve the complete-mix and plug-flow expressions for r = -k$C^{0.5}$ and determine ratio of volumes

a. Complete-mix reactor

$$0 = QC_o - QC - kC^{0.5}V$$

$$V_{CMR} = \frac{Q}{k}\left(\frac{C_o}{C^{0.5}} - C^{0.5}\right)$$

b. Plug-flow reactor

$$\int_{C_o}^{C} \frac{dC}{C^{0.5}} = -k\frac{V}{Q}$$

$$V_{PFR} = \frac{2Q}{k}(C_o^{0.5} - C^{0.5})$$

c. Ratio of volumes

$$\frac{V_{PFR}}{V_{CMR}} = \frac{2C^{0.5}(C_o^{0.5} - C^{0.5})}{(C_o - C)}$$

4. Solve the complete-mix and plug-flow expressions for r = -kC and determine ratio of volumes

a. Complete-mix reactor

$$0 = QC_o - QC - kCV$$

$$V_{CMR} = \frac{Q(C_o - C)}{kC}$$

b. Plug-flow reactor

$$\int_{C_o}^{C} \frac{dC}{C} = -k\frac{V}{Q}$$

$$V_{PFR} = \frac{Q}{k}\ln(C_o / C)$$

c. ratio of volumes

$$\frac{V_{PFR}}{V_{CMR}} = \frac{C\,[\ln(C_o / C)]}{(C_o - C)}$$

5. Solve the complete-mix and plug-flow expressions for $r = -kC^2$ and determine ratio of volumes

a. Complete-mix reactor

$$0 = QC_o - QC - kC^2V$$

$$V_{CMR} = \frac{Q(C_o - C)}{kC^2}$$

b. Plug-flow reactor

$$\int_{C_o}^{C} \frac{dC}{C^2} = -k\frac{V}{Q}$$

$$V_{PFR} = \frac{Q}{k}\left(\frac{1}{C} - \frac{1}{C_o}\right)$$

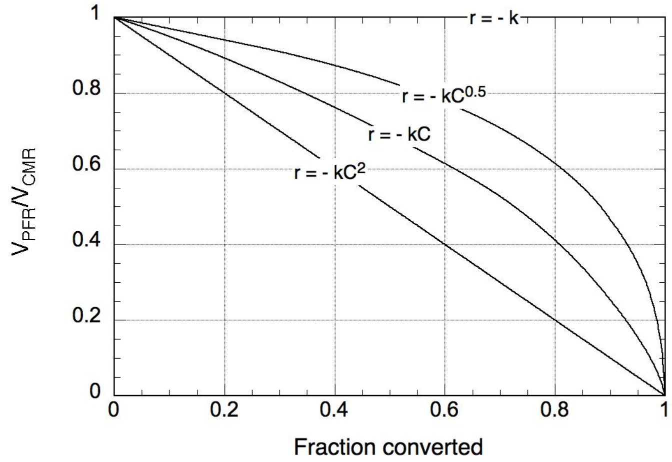
c. Ratio of volumes

$$\frac{V_{PFR}}{V_{CMR}} = \frac{C}{C_o}$$

6. Set up computation table to determine the ratio of volumes (V_{PFR}/V_{CMR}) versus the fraction of the original substrate that is converted

Fraction converted	V_{PFR}/V_{CMR}			
	$r = -k$	$r = -kC^{0.5}$	$r = -kC$	$r = -kC^2$
0.1	1	0.97	0.95	0.90
0.3	1	0.91	0.83	0.70
0.5	1	0.83	0.69	0.50
0.7	1	0.71	0.52	0.30
0.9	1	0.48	0.26	0.10
0.95	1	0.37	0.16	0.05
0.99	1	0.18	0.05	0.01

7. Plot the ratio of volumes versus the fraction of the original substrate that is converted.



8. Determine the ratio of volumes for each rate when C = 0.25 g/m^3 and C_o = 1.0 g/m^3 (fraction converted = 0.75). From the plot in Step 7 the required values are:

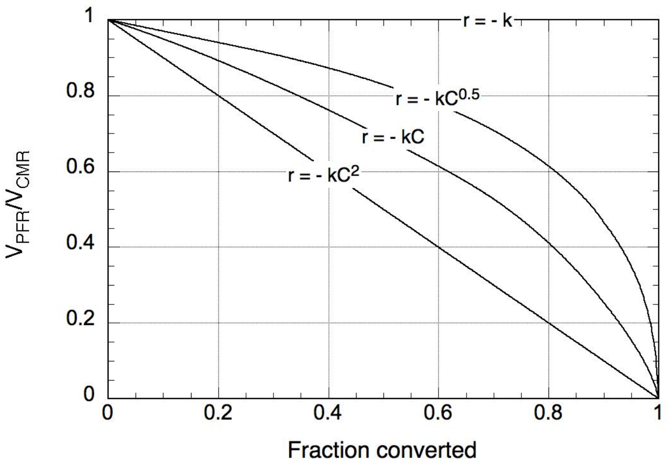
Rate	V_{PFR}/V_{CMR}
r = – k	1.00
r = – $kC^{0.5}$	0.67
r = – kC	0.46
r = – kC^2	0.25

PROBLEM 1-23

Problem Statement - See text, page 54

Solution

1. The ratio of volumes (V_{PFR}/V_{CMR}) versus the fraction of the original substrate converted is given in the following plot (see Problem 1-22).



2. Determine the ratio of volumes for each rate when C = 0.17 g/m^3 and C$_o$ = 1.25 g/m^3 (fraction converted = 0.86). From the plot in Step 7 the required values are:

Rate	V_{PFR}/V_{CMR}
r = – k	1.00
r = – kC$^{0.5}$	0.54
r = – kC	0.31
r = – kC^2	0.14

PROBLEM 1-24

Problem Statement - See text, page 54

Solution: Part 1 (r = -kC^2)

1. Solve the complete-mix and plug-flow expressions for C for r = -kC^2

   a. Complete-mix reactor

$$C^2 - \frac{Q}{kV}C - \frac{Q}{kV}C_o = 0$$

$$C_{CMR} = \frac{Q/kV\left[\sqrt{1+4(kV/Q)C_o} - 1\right]}{2}$$

   b. Plug-flow reactor

$$\int_{C_o}^{C} \frac{dC}{C^2} = -k\frac{V}{Q}$$

$$V_{PFR} = \frac{Q}{k}\left(\frac{1}{C} - \frac{1}{C_o}\right)$$

$$C_{PFR} = \left(\frac{kV}{Q} + \frac{1}{C_o}\right)^{-1}$$

2. Determine the effluent concentration from the combined reactor systems

   a. PFR-CMR

$$C_{PFR} = \left(\frac{kQ}{V} + \frac{1}{C_o}\right)^{-1} = \left(\frac{1\,x\,1}{1} + \frac{1}{1}\right)^{-1} = 0.5\ \text{kg}/\text{m}^3$$

$$C_{CMR} = \frac{Q/kV\left[\sqrt{1+4(kV/Q)C_o} - 1\right]}{2} = \frac{(1/1\,x\,1)\left[\sqrt{1+4(1\,x\,1/1)(0.5)} - 1\right]}{2}$$

$$= 0.366\ \text{kg}/\text{m}^3$$

   b. CMR-PFR

$$C_{CMR} = \frac{Q/kV\left[\sqrt{1+4(kV/Q)C_o} - 1\right]}{2} = \frac{(1/1\,x\,1)\left[\sqrt{1+4(1\,x\,1/1)(1)} - 1\right]}{2}$$

$$= 0.618\ \text{kg}/\text{m}^3$$

$$C_{PFR} = \left(\frac{kQ}{V} + \frac{1}{C_o}\right)^{-1} = \left(\frac{1\,x\,1}{1} + \frac{1}{0.618}\right)^{-1} = 0.382\ \text{kg}/\text{m}^3$$

   c. Because the effluent concentration C is not directly proportional to C_o for second order kinetics, the final concentrations are different

Solution: Part 2 (r = - kC)

1. Solve the complete-mix and plug-flow expressions for C for r = -kC

   a. Complete-mix reactor

$$0 = QC_o - QC - kCV$$

$$C = \frac{C_o}{(1 + kV/Q)}$$

   b. Plug-flow reactor

$$\int_{C_o}^{C} \frac{dC}{C} = -k\frac{V}{Q}$$

$$C = C_o\, e^{-kV/Q}$$

2. Determine the effluent concentration from the combined reactor systems

   a. PFR-CMR

$$C_{PFR} = C_o\, e^{-kV/Q} = (1)e^{-(1\,x\,1)/1} = 0.368\ kg/m^3$$

$$C_{CMR} = \frac{C_o}{(1 + kV/Q)} = \frac{0.368}{[1 + (1x1)/1]} = 0.184\ kg/m^3$$

   b. CMR-PFR

$$C_{CMR} = \frac{C_o}{(1 + kV/Q)} = \frac{1}{[1 + (1x1)/1]} = 0.5\ kg/m^3$$

$$C_{PFR} = C_o\, e^{-kV/Q} = (0.5)e^{-(1\,x\,1)/1} = 0.184\ kg/m^3$$

   c. Because the effluent concentration C is directly proportional to C_o for first order kinetics, the final concentrations are the same

Solution: Part 3 (r = -k)

1. Solve the complete-mix and plug-flow expressions for C for r = -k

   a. Complete-mix reactor

$$0 = QC_o - QC - kV$$

$$C = C_o - k(V/Q)$$

   b. Plug-flow reactor

$$\int_{C_o}^{C} dC = -k\frac{V}{Q}$$

$$C = C_o - k(V/Q)$$

2. Determine the effluent concentration from the combined reactor systems

   a. The two expressions derived above are identical.

   b. Because the two expressions are identical, for the given data the concentration in the second reactor is equal to zero.

PROBLEM   1-25

Problem Statement - See text, page 54

Solution

1. Develop basic mass balance formulation for plug-flow reactor with recycle

   Accumulation = inflow – outflow + generation

$$\frac{\partial C}{\partial t}\Delta V = Q'C'_o\Big|_x - Q'C'_o\Big|_{x+\Delta x} + r_c\,dV \qquad (1\text{-}18)$$

where $Q' = Q(1 + \alpha)$

$$C'_o = \frac{\alpha C + C_o}{1+\alpha}$$

α = recycle ratio = Q/Q_R

2. Solve the mass balance equation for C/C_o

$$\int_{C'_o}^{C} \frac{dC}{C} = -k\frac{V}{Q'}$$

$$\ln C / C'_o = -k\frac{V}{Q}$$

$$C = C'_o\, e^{-kV/Q'} = \frac{\alpha C + C_o}{1+\alpha} e^{-k\frac{V}{Q}\left(\frac{1}{1+\alpha}\right)}$$

With some manipulation,

$$C / C_o = \frac{e^{-k\frac{V}{Q}\left(\frac{1}{1+\alpha}\right)}}{1+\alpha\left[1-e^{-k\frac{V}{Q}\left(\frac{1}{1+\alpha}\right)}\right]}$$

Remembering that $e^x = 1 + x + \frac{x^2}{2!} + \ldots$

$$C / C_o = \frac{1+\left(-k\frac{V}{Q}\frac{1}{1+\alpha}\right)}{1+\alpha\left(1-1+k\frac{V}{Q}\frac{1}{1+\alpha}\right)} = \frac{\left(1-k\frac{V}{Q}\frac{1}{1+\alpha}\right)}{\left(1+k\frac{V}{Q}\frac{\alpha}{1+\alpha}\right)}$$

Thus when $\alpha \to \infty$, the above expression is approximately equal to

$$C / C_o \approx \frac{1}{1 + k\frac{V}{Q}}$$

which is the expression for a complete-mix reactor

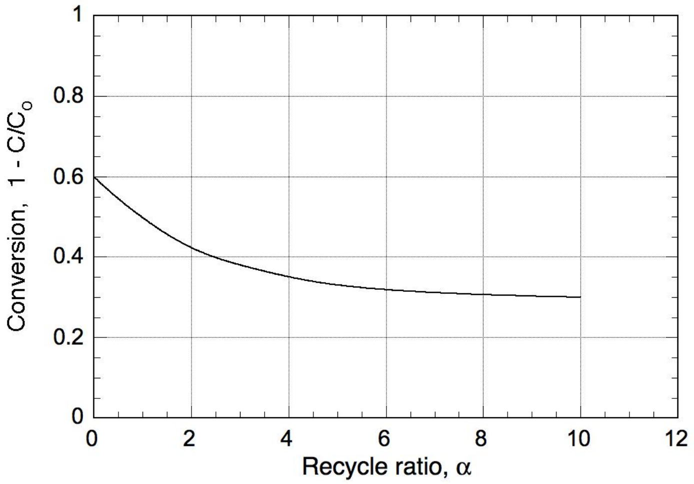
3. Sketch the generalized curve of conversion versus the recycle ratio.

   a. At $\alpha = 0$

   $$1 - C/C_o = 1 - e^{-kV/Q}$$

   b. As $\alpha \to \infty$

   $1 - C/C_o \to$ the conversion of a CMR



4. Sketch a family of curves to illustrate the effect of the recycle rato on the longitudinal concentration gradient.

   a. From Step 2

   $$C / C_o' = e^{-k\frac{V}{Q}\left(\frac{1}{1+\alpha}\right)}$$

   b. The relative conversion is:

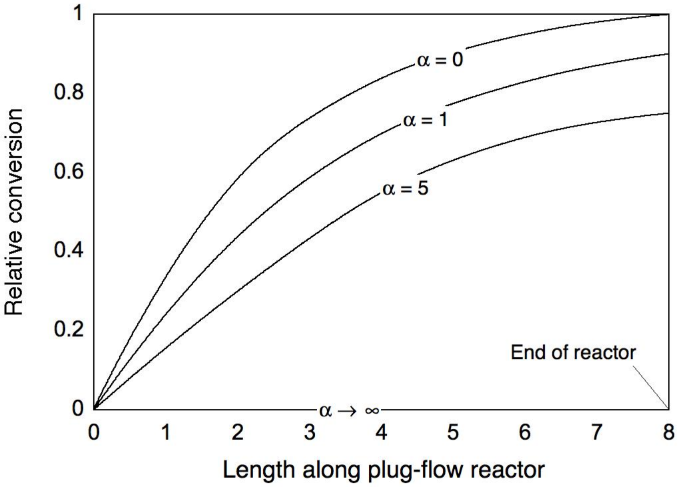
   $$1 - C / C_o' = 1 - e^{-k\frac{V}{Q}\left(\frac{1}{1+\alpha}\right)}$$

   c. When $\alpha = 0$, the longitudinal concentration gradient is given by

   $$1 - C/C_o = 1 - e^{-k\frac{V}{Q}}$$

   d. When $\alpha \to \infty$, the longitudinal concentration gradient is given by

$1 – C/C_o = 1 – 1 = 0$



5. Write a materials balance for a complete mix-reactor with recycle

   Accumulation = inflow – outflow + generation

   $$\frac{dC}{dt} = QC_o + Q_R C - (Q + Q_R)C + (-r_C)V$$

   At steady-state

   $$0 = QC_o + Q_R C - (Q + Q_R)C + (-r_C)V$$

   Because Q_R drops out of the above expression, recycle flow has no effect.

PROBLEM 1-26

Problem Statement - See text, page 54

Solution

1. Write a materials balance for a complete mix-reactor with effluent recycle with first order reaction kinetics

   Accumulation = inflow – outflow + generation

   $$\frac{dC}{dt} = QC_o + Q_R C - (Q + Q_R)C + (-r_C)V$$

2. At steady-state

   $$0 = QC_o + Q_R C - (Q + Q_R)C + (-r_C)V$$

Because Q_R drops out of the above expression, recycle flow has no effect for first or second order reactions.

PROBLEM 1-27

Problem Statement - See text, page 54

Solution

1. Starting with Eq. (1-53), derive an expression that can be used to compute the effluent concentration assuming a retarded second order removal rate coefficient.

$$\int_{C=C_o}^{C=C} \frac{dC}{C^2} = -\int_{t=0}^{t=t} \frac{k}{(1+r_t\,t)}dt$$

   a. Integrating the above expression yields

$$\frac{1}{C}\Bigg|_{C=C_o}^{C=C} = \frac{k}{r_t}\ln\left(1+r_t\,t\right)\Bigg|_{t=0}^{t=t}$$

   b. Carrying out the above substitutions and solving for C yields

$$C = \frac{r_t\,C_o}{r_t + kC_o\ln\left(1+r_t\,t\right)}$$

2. Determine the effect of retardation.

   a. The expression for the effluent concentration for second-order removal kinetics without retardation is (see Problem 1-24, Part 1 for plug-flow reactor):

$$C = \frac{1}{\left(k\,\tau + \dfrac{1}{C_o}\right)}$$

   b. Compare effluent concentrations for the following conditions

$C_o = 1.0$

$k = 0.1$

$r_t = 0.2$

$\tau = 1.0$

$$C_{\text{eff (retarded)}} = \frac{0.2(1.0)}{0.2 + 0.1(1.0)\ln\left[1 + 0.2(1.0)\right]} = 0.92$$

$$C_{\text{eff (unretarded)}} = \frac{1}{\left[0.1(1.0) + \frac{1}{(1.0)}\right]} = 0.91$$

3. From the above computations it can be seen that the effect of retardation is not as significant for a second order reaction. The impact is much greater for first order reactions.

2
CONSTITUENTS IN WASTEWATER

PROBLEM 2-1

Problem Statement - See text, page 171

Solution

1. Set up a computation table to determine the sum of milliequivalents per liter for both cations and anions for **Sample 3**, for example.

		Concentration				Concentration	
Cation	mg/meq	mg/L	meq/L	Anion	mg/meq	mg/L	meq/L
Ca^{2+}	20.04	190.2	9.49	HCO_3^-	61.02	260.0	4.26
Mg^{2+}	12.15	84.1	6.92	SO_4^{2-}	48.03	64.0	1.33
Na^+	23.00	75.2	3.27	Cl^-	35.45	440.4	12.41
K^+	39.10	5.1	0.13	NO_3^-	62.01	35.1	0.58
Fe^{2+}		0.2	0.01	CO_3^{2-}		30.0	1.00
Sum	-	-	19.82	Sum	-	-	19.58

2. Check the accuracy of the cation-anion balance using Eq. (2-5).

$$\text{Percent difference} = 100\ \text{x}\left(\frac{\Sigma\ \text{cations} - \Sigma\ \text{anions}}{\Sigma\ \text{cations} + \Sigma\ \text{anions}}\right)$$

$$\text{Percent difference} = 100\ \text{x}\left(\frac{19.82 - 19.58}{19.82 + 19.58}\right) = -\ 0.6\%\ \text{(ok)}$$

PROBLEM 2-2

Problem Statement - See text, page 171

Solution

1. Determine the mole fraction of each cation and anion in **Sample 1** using Eq. (2-2) written as follows:

$$x_{Ca^{2+}} = \frac{n_{Ca^{2+}}}{n_{Ca^{2+}} + n_{Mg^{2+}} + n_{Na^{+}} + n_{K^{+}} + n_{HCO_3^-} + n_{SO_4^{2-}} + n_{Cl^-} + n_{NO_3^-} + n_w}$$

a. Determine the moles of the solutes.

$$n_{Ca^{2+}} = \frac{(206.6 \text{ mg}/\text{L})}{(40.08 \times 10^3 \text{ mg/mole Ca}^{2+})} = 5.155 \times 10^{-3} \text{ mole/L}$$

$$n_{Mg^{2+}} = \frac{(95.3 \text{ mg/L})}{(24.305 \times 10^3 \text{ mg/mole of Mg}^{2+})} = 3.921 \times 10^{-3} \text{ mole/L}$$

$$n_{Na^{+}} = \frac{(82.3 \text{ mg/L})}{(23.000 \times 10^3 \text{ mg/mole of Na}^{+})} = 3.578 \times 10^{-3} \text{ mole/L}$$

$$n_{K^{+}} = \frac{(5.9 \text{ mg/L})}{(39.098 \times 10^3 \text{ mg/mole of K}^{+})} = 1.509 \times 10^{-4} \text{ mole/L}$$

$$n_{HCO_3^-} = \frac{(525.4 \text{ mg/L})}{(61.017 \times 10^3 \text{ mg/mole of HCO}_3^-)} = 8.611 \times 10^{-3} \text{ mole/L}$$

$$n_{SO_4^{2-}} = \frac{(219.0 \text{ mg/L})}{(96.058 \times 10^3 \text{ mg/mole of SO}_4^{2-})} = 2.280 \times 10^{-3} \text{ mole/L}$$

$$n_{Cl^-} = \frac{(303.8 \text{ mg/L})}{(35.453 \times 10^3 \text{ mg/mole of Cl}^-)} = 8.569 \times 10^{-3} \text{ mole/L}$$

$$n_{NO_3^-} = \frac{(19.2 \text{ mg/L})}{(62.005 \times 10^3 \text{ mg/mole of NO}_3^-)} = 3.097 \times 10^{-4} \text{ mole/L}$$

c. Determine the moles of the water.

$$n_w = \frac{(1000 \text{ g/L})}{(18 \text{ g/mole of water})} = 55.556 \text{ mole/L}$$

d. The mole fraction of calcium in **Sample 1** is:

$$x_{Ca^{2+}} = \frac{5.16\times10^{-3}}{(5.16+3.92+3.58+0.151+8.61+2.28+8.57+3.10)\times10^{-3}+55.56}$$
$$= 9.28\times10^{-5}$$

2. Similarly, the mole fractions of Mg^{2+} and SO_4^{2-} in **Sample 1** are:

$$x_{Mg^{2+}} = \frac{3.92\times10^{-3}}{(5.16+3.92+3.58+0.151+8.61+2.28+8.57+3.10)\times10^{-3}+55.56}$$
$$= 7.05\times10^{-5}$$

$$x_{SO_4^{2-}} = \frac{2.28\times10^{-3}}{(5.16+3.92+3.58+0.151+8.61+2.28+8.57+3.10)\times10^{-3}+55.56}$$
$$= 4.10\times10^{-5}$$

PROBLEM 2-3

Problem Statement - See text, page 171

Solution

1. Determine the ionic strength of the wastewater using Eq. (2-11)

   a. Prepare a computation table to determine the summation term in Eq. (2-11) using the data for **Sample 3** in **Problem 2-1**

Ion	Conc., C, mg/L	C x 10^3, mole/L	Z^2	CZ^2 x 10^3
Ca^{2+}	190.2	4.75	4	19.00
Mg^{2+}	84.1	3.46	4	13.84
Na^+	75.2	3.27	1	3.27
K^+	5.1	0.13	1	0.13
Fe^{2+}	0.2	-	4	-
HCO_3^-	260.0	4.26	1	4.26
SO_4^{2-}	64.0	0.67	4	2.68
Cl^-	440.4	12.42	1	12.42
NO_3^-	35.1	0.57	1	0.57
CO_3^{2-}	30.0	0.50	4	2.00

Sum	58.17

b. Determine the ionic strength for the concentration C using Eq. (2-10)

$$I = \frac{1}{2}\ \Sigma\ C_i\ Z_i^2 = \frac{1}{2}(58.17\ \text{x}\ 10^{-3})\ = 29.09\ \text{x}\ 10^{-3}$$

2. Determine the activity coefficients for monovalent and divalent ions using Eq. (2-12)

a. For monovalent ions

$$\log\gamma = -0.5\,(Z_i)^2\left(\frac{\sqrt{I}}{1+\sqrt{I}} - 0.3\ I\right) = -0.5(1)^2\left[\frac{\sqrt{29.09\ \text{x}\ 10^{-3}}}{1+\sqrt{29.09\ \text{x}\ 10^{-3}}} - 0.3\left(29.09\ \text{x}\ 10^{-3}\right)\right]$$

$$= -0.0685$$

$$\gamma = 0.8541$$

b. For divalent ions

$$\log\gamma = -0.5\,(Z_i)^2\left(\frac{\sqrt{I}}{1+\sqrt{I}} - 0.3\ I\right) = -0.5(2)^2\left[\frac{\sqrt{29.09\ \text{x}\ 10^{-3}}}{1+\sqrt{29.09\ \text{x}\ 10^{-3}}} - 0.3\left(29.09\ \text{x}\ 10^{-3}\right)\right]$$

$$= -0.2739$$

$$\gamma = 0.5322$$

2. Continue the computation table from Part 1 to determine the activity for each ion using Eq. (2-8)

Ion	C x 10^3, mole/L	Activity a_i, mole/L

Ca^{2+}	4.75	2.53
Mg^{2+}	3.46	1.84
Na^{+}	3.27	2.79
K^{+}	0.13	0.11
Fe^{2+}	-	-
HCO_3^-	4.26	3.64
SO_4^{2-}	0.67	0.36
Cl^-	12.42	10.61
NO_3^-	0.57	0.49
CO_3^{2-}	0.50	0.27

PROBLEM 2-4

Problem Statement - See text, page 171

Solution

1. Estimate the TDS for **Sample 3** from **Problem 2-1** using Eq. (2-11)

   $I = 2.5 \times 10^{-5} \times TDS$

   where TDS = total dissolved solids, mg/L or g/m^3

   $$TDS = \frac{I \times 10^5}{2.5} = \frac{(0.02909) \times 10^5}{2.5} = 1163 \text{ mg/L}$$

2. Estimate the TDS for **Sample 3** from by summing the solids concentrations

Ion	Conc., C, mg/L
Ca^{2+}	190.2
Mg^{2+}	84.1
Na^{+}	75.2
K^{+}	5.1
Fe^{2+}	0.2

HCO_3^-	260.0
SO_4^{2-}	64.0
Cl^-	440.4
NO_3^-	35.1
CO_3^{2-}	30.0
Sum	1184.3

The results from the two methods are remarkably close.

PROBLEM 2-5

Problem Statement - See text, page 171

Solution

1. Determine total solids for **Sample 2**.

$$\text{TS} = \frac{\left[\begin{pmatrix}\text{mass of evaporating}\\ \text{dish plus residue, g}\end{pmatrix} - \begin{pmatrix}\text{mass of evaporating}\\ \text{dish, g}\end{pmatrix}\right]\left(\dfrac{10^3\ \text{mg}}{\text{g}}\right)}{\text{sample size, L}}$$

$$\text{TS} = \frac{[(22.6832 - 22.6445)\ \text{g}](10^3\ \text{mg/g})}{0.10\ \text{L}} = 387\ \text{mg/L}$$

2. Determine total volatile solids for **Sample 2**.

$$\text{TVS} = \frac{\left[\begin{pmatrix}\text{mass of evaporating}\\ \text{dish plus residue, g}\end{pmatrix} - \begin{pmatrix}\text{mass of evaporating dish}\\ \text{plus residue after ignition, g}\end{pmatrix}\right]\left(\dfrac{10^3\ \text{mg}}{\text{g}}\right)}{\text{sample size, L}}$$

$$\text{TVS} = \frac{[(22.6832 - 22.6795)\ \text{g}](10^3\ \text{mg/g})}{0.10\ \text{L}} = 37\ \text{mg/L}$$

PROBLEM 2-6

Problem Statement - See text, page 172

Solution

1. Determine total solids for **Sample 2**

$$\mathrm{TS} = \frac{\left[\begin{pmatrix}\text{mass of evaporating}\\ \text{dish plus residue, g}\end{pmatrix} - \begin{pmatrix}\text{mass of evaporating}\\ \text{dish, g}\end{pmatrix}\right]\left(\dfrac{10^3\ \text{mg}}{\text{g}}\right)}{\text{sample size, L}}$$

$$\mathrm{TS} = \frac{\left[(53.5693 - 53.5434)\ \text{g}\right]\left(10^3\ \text{mg/g}\right)}{0.05\ \text{L}} = 518\ \text{mg/L}$$

2. Determine total volatile solids for **Sample 2.**

$$\mathrm{TVS} = \frac{\left[\begin{pmatrix}\text{mass of evaporating}\\ \text{dish plus residue, g}\end{pmatrix} - \begin{pmatrix}\text{mass of evaporating dish}\\ \text{plus residue after ignition, g}\end{pmatrix}\right]\left(\dfrac{10^3\ \text{mg}}{\text{g}}\right)}{\text{sample size, L}}$$

$$\mathrm{TVS} = \frac{\left[(53.5693 - 53.5489)\ \text{g}\right]\left(10^3\ \text{mg/g}\right)}{0.05\ \text{L}} = 408\ \text{mg/L}$$

3. Determine the total suspended solids for **Sample 2.**

$$\mathrm{TSS} = \frac{\left[\begin{pmatrix}\text{mass of filter plus}\\ \text{residue after drying, g}\end{pmatrix} - \begin{pmatrix}\text{tare mass of filter}\\ \text{after drying, g}\end{pmatrix}\right]\left(\dfrac{10^3\ \text{mg}}{\text{g}}\right)}{\text{sample size, L}}$$

$$\mathrm{TSS} = \frac{\left[(1.5521\text{-}1.5435)\ \text{g}\right]\left(10^3\ \text{mg/g}\right)}{0.05\ \text{L}} = 172\ \text{mg/L}$$

4. Determine the volatile suspended solids for **Sample 2.**

$$\mathrm{VSS} = \frac{\left[\begin{pmatrix}\text{residue plus filter}\\ \text{after drying, g}\end{pmatrix} - \begin{pmatrix}\text{residue plus filter}\\ \text{after ignition, g}\end{pmatrix}\right]\left(\dfrac{10^3\ \text{mg}}{\text{g}}\right)}{\text{sample size, L}}$$

$$\mathrm{VSS} = \frac{\left[(1.5455 - 1.5521)\ \text{g}\right]\left(10^3\ \text{mg/g}\right)}{0.05\ \text{L}} = 132\ \text{mg/L}$$

5. Determine the total dissolved solids for **Sample 2.**

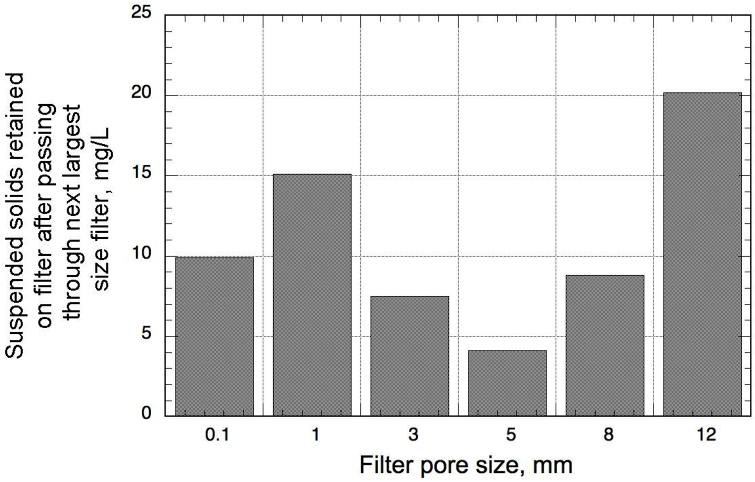
TDS = TS - TSS = (518 – 172) mg/L = 346 mg/L

PROBLEM 2-7

Problem Statement - See text, page 172

Solution

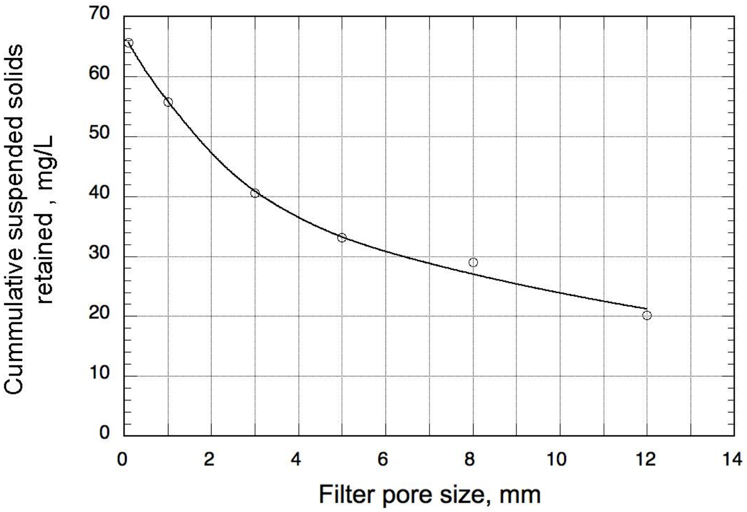
1. Prepare a plot of the suspended solids removed by a filter after passing through the next largest size.



2. Determine the total suspended solids for **Sample 1**, based on a filter with a pore size of 0.1 μm.

Nominal pore size, μm	Suspended solids, mg/L	Cumulative suspended solids, mg/L
12	20.2	20.2
8	8.8	29.0
5	4.1	33.1
3	7.5	40.6
1	15.1	55.7
0.1	9.9	65.6

3. Prepare a cumulative plot of the suspended solids data to estimate the amount of suspended solids that would have been removed using a filter with a nominal pore size of 1.2 μm.



From the above plot, about 54 mg/L would have been measured with a pore size of 1.2 μm. The corresponding error would have been about:

$$\text{Percent error} = \left[\frac{(65.6 - 54)\text{g}}{65.6\,\text{g}}\right] \text{ x } 100 = 17.7\%$$

PROBLEM 2-8

Problem Statement - See text, page 172

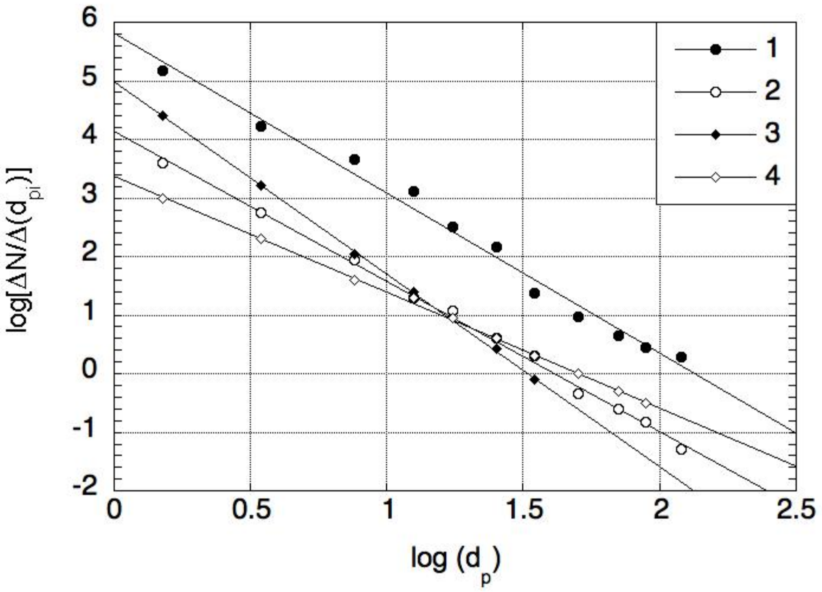
Solution

1. Set up a table to determine the information needed to plot the data for **Sample 3**.

Channel size, μm	Mean diameter d_p, μm	Δ N, number/mL	Channel size interval, $\Delta(d_{pi})$	log (d_p)	log[$\Delta N/\Delta(d_{pi})$]
1 - 2	1.5	20,000	1	0.18	4.30

2 - 5	3.5	6,688	3	0.54	3.35
5 - 10	7.5	3000	5	0.88	2.78
10 - 15	12.5	1050	5	1.1	2.32
15 - 20	17.5	300	5	1.24	1.78
20 - 30	25.0	150	10	1.4	1.18
30 - 40	35.0	27	10	1.54	0.43
40 - 60	50.0	12	20	1.7	-0.22
60 - 80	70	6	20	1.85	-0.52
80 - 100	90	4	20	1.95	-0.70
100 - 140	120	3	40	2.08	-1.12

2. Prepare a plot of the log of the arithmetic mean particle diameter, d_p, versus the normalized number of particles for the corresponding bin size, $\log[\Delta N/\Delta(d_{pi})]$.



3. Determine A and β in Eq. (2-17)

   a. Determine A is defined as the intercept of the $\log[\Delta N/\Delta(d_{pi})]$ axis when $\log(d_p) = 0$, (i.e., $d_p = 1$).

The intercept value for **Sample 3** is 5.0.

Thus log A = 5.0 and A = $10^{5.0}$

b. Determine the value of β which corresponds to the slope of the line.

$$-\beta = \frac{5.0-(-1.0)}{0-2.5} = -2.4$$

$$\beta = 2.4$$

PROBLEM 2-9

Problem Statement - See text, page 173

Solution

1. Use Beers-Lambert Law [Eq. (2-19)] to develop the required equation for average intensity. See definition sketch given in Example 2-5.

$$I_{avg} \times d = \int_0^d I_o e^{-kx} dx = -\frac{I_o}{k} e^{-kx} \Big]_0^d = -\frac{I_o}{k} e^{-kd} + \frac{I_o}{k} = \frac{I_o}{k}\left(1 - e^{-kd}\right)$$

$$I_{avg} = \frac{I_o}{kd}\left(1 - e^{-kd}\right)$$

2. Solve the above equation for measured intensity at the water surface, I_o.

   a. Using an average intensity 5 mW/cm^2 and a water depth of 8 mm and the given absorptivity, k, = 1.25 cm^{-1}:

$$I_o = \frac{I_{avg} \times kd}{1 - e^{-kd}} = \frac{\left(5 \text{ mW / cm}^2\right)\left(1.25 \text{cm}^{-1}\right)\left(0.8 \text{ cm}\right)}{1 - e^{\left(-1.25 \text{ cm}^{-1}\right)\left(0.8 \text{cm}\right)}} = 7.91 \text{ mW / cm}^2$$

PROBLEM 2-10

Problem Statement - See text, page 2-117

Solution

1. The definition of alkalinity in molar quantities is

   Alk, eq/m^3 = meq/L = [HCO_3^-] + 2 [CO_3^{2-}] + [OH^-] - [H^+]

   The corresponding expression in terms of equivalents is:

Alk, eq/m^3 = (HCO_3^-) + (CO_3^{2-}) + (OH^-) - (H^+)

For **Sample 3** from Problem 2-1, the alkalinity in meq/L is

Alk, meq/L = (HCO_3^- = 4.26) + (CO_3^{2-} = 1) = 5.26

Milliequivalent mass of $CaCO_3$ = 50 mg/meq [Eq. (2-34)]

2. The alkalinity, expressed as $CaCO_3$, is:

$$\text{Alkalinity water C} = \left(\frac{5.26\ \text{meq}}{\text{L}}\right)\left(\frac{50\ \text{mg CaCO}_3}{\text{meq CaCO}_3}\right) = 263\ \text{mg/L as CaCO}_3$$

PROBLEM 2-11

Problem Statement - See text, page 173

Solution

1. Determine the molar mass of a gas at 20°C assuming the gas has a density of 0.68 g/L at standard temperature and pressure (STP) using the following relationship from Appendix B-3.

$$\rho_a = \frac{P\,M}{RT}$$

where P = atmospheric pressure = 1.01325 x 10^5 N/m^2

M = mole of air (see Table B-1) = 28.97 kg/kg mole

R = universal gas constant = [8314 N•m/(kg mole air)•K]

T = temperature, K (Kelvin) = (273.15 + °C)

$$\text{Mole of gas} = \frac{[8314\ \text{Nm/(kg-mole air)}\cdot \text{K}]\,[(273.15+20)\text{K}]\,(0.68\ \text{kg/m}^3)}{(1.01325\times 10^5\ \text{N/m}^2)}$$

$$= 16.36\ \text{kg/kg-mole}$$

PROBLEM 2-12

Problem Statement - See text, page 173

2-12. At what pH would 95 percent of NH_3 be present as gas. Apply Eq. 2-40 and give the acid ionization (dissociation) constant at 25°C.

Solution

1 Rearrange Eq. (2-40) to solve for the hydrogen ion concentration

a. Given K_a at 25°C = 5.62×10^{-10}

$$\left[H^+\right] = \left[\left(\frac{100}{NH_3,\%}\right) - 1\right](K_a) = \left[\left(\frac{100}{95}\right) - 1\right]\left(5.62 \times 10^{-10}\right) = 2.96 \times 10^{-11}$$

b. Solve for pH using Eq. (2-27)

$$pH = -\log_{10}\left[H^+\right] = -\log_{10}\left(2.96 \times 10^{-11}\right) = 10.53$$

PROBLEM 2-13

Problem Statement - See text, page 173

Solution

1 Compare the saturation concentrations of O_2, N_2, and CO_2 between San Francisco (sea level) and La Paz Bolivia (elevation 4,270 m) using the following relationship from Appendix B-4 which can be used to compute the change in atmospheric pressure with elevation.

$$\frac{P_b}{P_a} = \exp\left[-\frac{gM(z_b - z_a)}{RT}\right]$$

where P = pressure, 1.01325×10^5 N/m^2

g = 9.81 m/s^2

M = mole of air (see Table B-1) = 28.97 kg/kg mole

z = elevation, m

R = universal gas constant = [8314 N•m/(kg mole air)•K]

T = temperature, K (Kelvin) = (273.15 + °C)

a. For oxygen

$$\frac{P_b}{P_a} = \exp\left[-\frac{(9.81\,\text{m/s}^2)(32\ \text{kg/kg}\pm\text{mole})(4{,}270-0)}{[8314\,\text{Nm/(kg mole air)K}](273.15+20)\text{T}}\right] = 0.58$$

b. For nitrogen

$$\frac{P_b}{P_a} = \exp\left[-\frac{(9.81\,\text{m/s}^2)(28\ \text{kg/kg}\pm\text{mole})(4{,}270-0)}{[8314\,\text{Nm/(kg mole air)K}](273.15+20)\text{T}}\right] = 0.61$$

c. For carbon dioxide

$$\frac{P_b}{P_a} = \exp\left[-\frac{(9.81\,\text{m/s}^2)(44\ \text{kg/kg}\pm\text{mole})(4{,}270-0)}{[8314\,\text{Nm/(kg mole air)K}](273.15+20)\text{T}}\right] = 0.47$$

PROBLEM 2-14

Problem Statement - See text, page 173

Solution

1. Determine the value of Henry’s constant using Eq. (2-48)

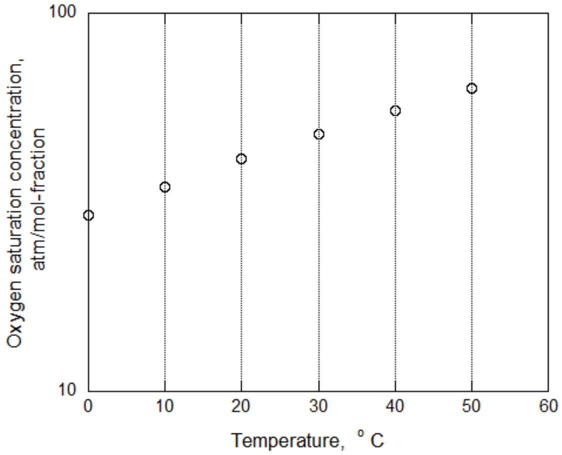
$$\log_{10} H = \frac{-A}{T} + B$$

From Table 2-7, for oxygen A = 595.27 and B = 6.644

Temperature		H, atm/mole fraction
°C	K	
0	273.15	29,155
10	283.15	34,808
20	293.15	41,058

30	303.15	47,905
40	313.15	55,346
50	323.15	63,374

The required plot is given below



PROBLEM 2-15

Problem Statement - See text, page 173

Solution

1. The gas in the head space contains 80 percent oxygen by volume.

   Therefore, p_g = 0.80 mole O_2/mole air

2. Determine the concentration of the gas using Henry's law

   a. From Table 2-7, at 20°C, Henry's constant is:

   $$H = 4.11 \times 10^4 \frac{\text{atm (mole gas / mole air)}}{\text{(mole gas / mole water)}}$$

   b. Using Eq (2-46), the value of X_g is:

   $$X_g = \frac{P_T}{H} p_g$$

   $$= \frac{3.0\text{ atm}}{4.11 \times 10^4 \dfrac{\text{atm (mole gas/mole air)}}{\text{(mole gas/mole water)}}} \text{(0.80 mole gas/mole air)}$$

= 0.584 x 10^{-4} mole gas/mole water

3. One liter of water contains 1000 g/(18 g/mole) = 55.6 mole, thus

$$\frac{n_g}{n_g + n_w} = 0.584 \text{ x} 10^{-4}$$

$$\frac{n_g}{n_g + 55.6} = 0.584 \text{ x} 10^{-4}$$

Because the number of moles of dissolved gas in a liter of water is much less than the number of moles of water,

$$n_g + 55.6 \approx 55.6 \text{ and}$$

$$n_g \approx (55.6)\ 0.584 \text{ x } 10^{-4}$$

$$n_g \approx 32.47 \text{ x } 10^{-4} \text{ mole } O_2 / L$$

4. Determine the saturation concentration of oxygen.

$$C_s \approx \left(\frac{32.47 \text{ x } 10^{-4} \text{ mole } O_2}{L}\right)\left(\frac{32\text{ g}}{\text{mole } O_2}\right)\left(\frac{10^3 \text{ mg}}{1\text{ g}}\right) = 103.9 \text{ mg} / L$$

PROBLEM 2-16

Problem Statement - See text, page 173

Solution

1. The gas in the head space contains 95 percent carbon dioxide by volume.

   Therefore, p_g = 0.95 mole CO_2/mole air

3. Determine the concentration of the gas using Henry's law

a. From Table 2-7, at 25°C, and using Eq. (2-48) Henry's constant is:

$$H = 1.42 \times 10^{3} \ \frac{\text{atm (mole gas / mole air)}}{\text{(mole gas / mole water)}}$$

b. Using Eq (2-46), the value of X_g is:

$$X_g = \frac{P_T}{H} p_g$$

$$= \frac{2.0 \text{ atm}}{1.42 \times 10^{3} \left[\frac{\text{atm (mole gas/mole air)}}{\text{(mole gas/mole water)}} \right]} (0.95 \text{ mole gas/mole air})$$

$$= 0.134 \times 10^{-2} \text{ mole gas/mole water}$$

3. One liter of water contains 1000 g/(18 g/mole) = 55.6 mole, thus

$$\frac{n_g}{n_g + n_w} = 0.134 \times 10^{-2}$$

$$\frac{n_g}{n_g + 55.6} = 0.134 \times 10^{-2}$$

Because the number of moles of dissolved gas in a liter of water is much less than the number of moles of water,

$$n_g + 55.6 \approx 55.6 \quad \text{and}$$

$$n_g \approx (55.6)\, 0.134 \times 10^{-2}$$

$$n_g \approx 74.39 \times 10^{-3} \text{ mole } CO_2 / L$$

Given the above liquid concentration of carbon dioxide, $[CO^2]_{aq}$, we can now use the properties of the carbonate equilibrium to determine pH.

4. Determine the molar concentration of $[H_2CO_3]$ (see Appendix F, Eq. F-2).

$$\frac{[H_2CO_3]}{[CO_2]_{aq}} = K_m$$

$$[H_2CO_3] = K_m [CO_2]_{aq} = (1.58 \times 10^{-3})(74.39 \times 10^{-3})$$

$$= 1.18 \times 10^{-4}$$

5. Determine molar concentration of $[H_2CO_3*]$.

$$[H_2CO_3 *] = [CO_2]_{aq} + [H_2CO_3]$$

$$= (74.39 \times 10^{-3}) + (1.18 \times 10^{-4})$$

$$= 74.51 \times 10^{-3}$$

6. Determine the pH of the soda water.

   a. The equilibrium expression for $[H_2CO_3*]$ is

$$\frac{[H^+][H_2CO_3]}{[H_2CO_3^*]} = K_1$$

   b. Consider electron neutrality, Σcations = Σanions. In this example the hydrogen ion concentration must be balanced by negative ions. In the case of soda water, bicarbonate, carbonate, and hydroxide will be assumed to be the only sources of negative ions. Thus,

$$[H^+] = [OH^-] + 2[CO^{2-}] + [HCO_3^-]$$

Soda water is acidic (pH < 7.0), therefore the values of [OH-] and $[CO^{2-}]$ will be negligible and [H+] ≈ $[HCO_3^-]$. Substituting [H+] for $[HCO_3^-]$ into the equilibrium expression for $[H_2CO_3*]$ yields,

$$\frac{[H^+]^2}{[H_2CO_3^*]} = K_{a1}$$

Substitute for Ka_1 from Appendix F and $[HCO_3^-]$ from step 5 and solve for $[H^+]$.

$$\left[H^+\right]^2 = \left(4.47\times10^{-7}\right)\left(74.51\times10^{-3}\right)$$

$$\left[H^+\right] = 1.83\times10^{-4}$$

$$pH = 3.74$$

PROBLEM 2-17

Problem Statement - See text, page 173

Solution

1. Linearize Eq. 2-54 and log transform the given data

   a. The linearized form of Eq. 2-54 is:

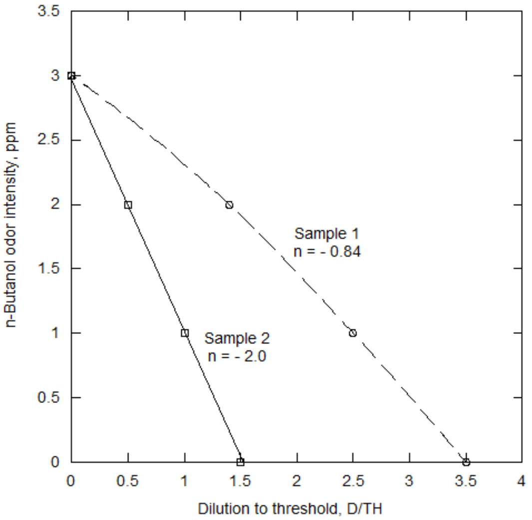
   log I = log k + n log C

   b. The log transformed data are:

	log D/T	
Log I	Sample 1	Sample 2
3	0	0
2	1.4	0.5
1	2.5	1.0
0	3.5	1.5

3. Plot log I versus log C and determine the slope n to determine which sample is more persistent

   a. The required plot is given below



b. The slopes for the two samples are

Sample A = -0.84

Sample B = -2.0

c. Based on the slopes, Sample A is more persistent than Sample B.

PROBLEM 2-18

Problem Statement - See text, page 173

Solution

1. Solve for the threshold odor number, TON, as defined in Eq. 2-53:

$$\text{TON} = \frac{A+B}{A} = \frac{25\text{ mL}+175\text{ mL}}{25\text{ mL}} = 8$$

2. Solve for the dilutions-to-threshold, D/T, as defined in Eq. 2-52:

$$D/T = \frac{\text{volume of odor free air}}{\text{volume of odorous air}} = \frac{\text{volume of dilution water}}{\text{volume of sample}} = \frac{175\text{ mL}}{25\text{ mL}} = 7$$

3. First, find the threshold odor concentration of hydrogen sulfide in Table 2-8:

$$C_{TH,\,H_2S} = 0.0003\text{ ppm}_v$$

Assuming the odor is comprised entirely of H_2S, TON and D/T values can be calculated using either the water volume or the air volume ratio of the sample fluid to dilution fluid because Henry's law is a linear relation. As a proof, Henry's law can again be applied to the undiluted sample (answer to Part 3) to calculate the D/T.

Find the concentration of hydrogen sulfide in the diluted sample using Henry's law (Eq. 2-46). (The unitless form of Henry's Law (Eq. 2-49) can also be applied, see Alternative Solution below.) Henry's constant for hydrogen sulfide at 20°C is given in Table 2-7.

Find the mole fraction, x_g, of H_2S in the sample as defined in Eq. 2-46:

$$x_g = \frac{P_T}{H}p_g = \frac{(1\text{ atm})}{(483\text{ atm})}(0.0003\text{ ppm}_v) = 6.21\times10^{-7}\text{ ppm}_v$$

Using the definition for x_g and given that $n_w >> n_g$ (see Example 2-7):

$$n_g \simeq n_w \cdot x_g = (55.6 \text{ mole/L})(6.21\times10^{-7} \text{ ppm}_v) = 3.45\text{x}10^{-5} \text{ mole/L}$$

Convert to mass concentration:

$$C_{H_2S,\text{ diluted}} = 3.45\text{x}10^{-5} \frac{\text{mole H}_2\text{S}}{\text{L}} \times 34.06 \frac{\text{g}}{\text{mole H}_2\text{S}} \times 10^3 \frac{\text{mg}}{\text{g}} = 1.18 \text{ mg/L}$$

Next, find the initial concentration of hydrogen sulfide in the treated wastewater sample, based on the dilution of 175 mL odor free dilution water for 25 mL odorous sample:

$$C_{H_2S,\text{ sample}} = 1.18 \text{ mg/L} \times \frac{175 \text{ mL}}{25 \text{ mL}} = 8.23 \text{ mg/L}$$

Alternative solution

To use Eq. 2-49, you first must convert the hydrogen sulfide threshold odor concentration from ppm_v to mg/L. Employ the ideal gas law to find the volume of an ideal gas:

$$V = \frac{nRT}{P} = \frac{(1 \text{ mole})(0.082057 \text{ atm}\cdot\text{L/mole}\cdot\text{K})\left[(273.15+20)\text{K}\right]}{1.0 \text{ atm}} = 24.055 \text{ L}$$

The gas volume calculated above and Eq. 2-44 are then used to convert the hydrogen sulfide threshold odor concentration from ppm_v to mg/L:

$$\text{g/m}^3 = \text{mg/L} = \frac{(\text{concentration, ppm}_v)(\text{mw, g/mole of gas})}{(\text{volume, m}^3\text{/mole of gas})}$$

$$= \frac{(4.7\times10^{-3} \text{ ppm}_v)(34.06 \text{ g/mole H}_2\text{S})}{(24.053\times10^{-3} \text{ m}^3\text{/mole of gas})} = 0.67 \text{ mg/L}$$

$$C_s = \frac{C_g}{H_u} = \frac{(0.67 \text{ mg/L})}{(0.36)} = 1.85 \text{ mg/L}$$

Find the initial concentration of hydrogen sulfide as above:

$$C_{\text{H2S, sample}} = 1.85 \text{ mg/L} \times \frac{175 \text{ mL}}{25 \text{ mL}} = 12.9 \text{ mg/L}$$

Note: For the more realistic case where an odor is comprised of a mix of gases, it would not be known how Henry's law applies.

PROBLEM 2-19

Problem Statement - See text, page 173

Solution

1. The plant manager has probably adapted to the plant's odor and is insensitive to low concentrations of the odor. Downwind residents are not adapted and, therefore, more sensitive. Because the Barneyby and Sutcliffe olfactometer does not account for odors to which a person's olfactory system may be adapted to, the readings are erroneous due to subject adaptation.

2. To resolve the differences, a new set of measurements should be taken using non-adapted subjects. The new tests should be free of measurement errors resulting from adaptation and sample modification. The new test results can then be compared with the original values. Based on this analysis, appropriate corrective measures can be taken to reduce or eliminate the odor if it is a real problem.

PROBLEM 2-20

Problem Statement - See text, page 174

Solution

Answers to this problem will tend to be subjective and many answers are possible. The specified answers will depend on the background of each student. Some of the items to be considered are given below.

1. Possible reasons:

   a. Increase in sludge dewatering room odor emissions. These emissions are unlikely to be 100 times the maximum value observed by the odor consultant.

   b. Faulty Direct Reading Olfactometer (DRO). The instrument has been checked and found to be quite reproducible.

c. Faulty sampling techniques. Using glass cylinders, it is found that there is a rapid decay of the odor concentration within the container. Decay within the usual one-hour period between sample collection and sample measurement may be significant.

d. Faulty measurement technique. In the ASTM procedure, lower odor concentration values are specified for high concentration samples. Lower values can occur because of the lack of control over the odor concentrations in the samples placed below the nose when using this method.

e. It can be concluded that reasons c. and d. could provide sufficient margin of error to explain the discrepancy.

2. Resolution:

   a. The odor consultant is not likely to accept the DRO results as his reputation is based on his work with the ASTM method.

   b. The agency, your client, will not like having to add additional odor control equipment and will probably sue the odor consultant or fire you.

   c. The engineering contractor wants to get paid. He will want to use your results to substantiate his claim of poor specifications.

   d. You conclude that the best compromise will involve discussing the differences between the ASTM and DRO techniques and negotiating a contract change order to expand the present odor control system as per your findings.

PROBLEM 2-21

Problem Statement - See text, page 174

Solution

1. First calculate the initial dissolved oxygen concentration of the mixture.

$$(9.1\ \text{g/m}^3) \times \left(294\ \text{mL} / 300\ \text{mL}\right) = 8.92\ \text{g/m}^3$$

2. Now calculate the BOD as defined in Eq. (2-56).

$$\text{BOD} = \frac{D_1 - D_2}{P} = \frac{[(8.92 - 2.8)\ \text{g/m}^3]}{[(6\text{m L})/(300\ \text{mL})]} = 306.0\ \text{g/m}^3$$

3. An alternative approach for calculating the BOD is

$$\text{BOD} = \left\{\left[\left(9.1 - 2.8\right)\ \text{g/m}^3\right] \times \left[\left(300\ \text{mL}\right)/\left(6\ \text{mL}\right)\right]\right\} - \left[\left(9.1 - 0\right)\ \text{g/m}^3\right] = 305.9\ \text{g/m}^3$$

PROBLEM 2-22

Problem Statement - See text, page 174

Solution

1. First calculate, for **Sample 1**, the initial dissolved oxygen concentration of the mixture.

$$(9.0\ \text{g/m}^3) \times \left(292\ \text{mL} / 300\ \text{mL}\right) = 8.76\ \text{g/m}^3$$

2. Now use Eq. (2-56) to calculate the BOD_7

$$\text{BOD}_7 = \frac{D_1 - D_2}{P} = \frac{[(8.76 - 1.8)\ \text{g/m}^3]}{[(8\text{m L})/(300\ \text{mL})]} = 261.0\ \text{g/m}^3$$

3. Determine the 5-day BOD by inputting known values into Eq. (2-60) and solving the two resulting equations simultaneously.

$$\text{BOD}_5 = \text{UBOD}\left[1 - e^{-k_1(5)}\right]$$

$$261 = \text{UBOD}\left[1 - e^{-k_1(7)}\right]$$

Solving the above simultaneous equations for BOD_5:

$$\text{BOD}_5 = 326\ \text{g/m}^3$$

PROBLEM 2-23

Problem Statement - See text, page 174

Solution

1. Write balanced oxidation reactions

    a. For glucose

    $$\underset{180}{C_6H_{12}O_6} + \underset{192}{6\,O_2} \rightarrow 6\,CO_2 + 6\,H_2O$$

    b. For glutamic acid

    $$\underset{146}{C_5H_{10}N_2O_3} + \underset{144}{4.5\,O_2} \rightarrow 5\,CO_2 + 2\,NH_3 + 2\,H_2O$$

2. Determine the UBOD for the mixture

    a. For glucose

    $$\text{UBOD} = \left(\frac{192}{180}\right)(150\ \text{mg/L}) = 160.0\ \text{mg/L}$$

    b. For glutamic acid

    $$\text{UBOD} = \left(\frac{144}{146}\right)(150\ \text{mg/L}) = 147.9\ \text{mg/L}$$

    c. Total UBOD = (147.9 +160) mg/L = 207.9 mg/L

3. Determine the 5-day BOD

    $$\text{BOD} = \text{UBOD}\ [1 - e^{-k_1(t)}]$$

    $$\text{BOD} = 207.9\ [1 - e^{-(0.23\,d^{-1})(5\,d)}] = 142.1\ \text{mg/L}$$

PROBLEM 2-24

Problem Statement - See text, page 174

Solution

1. The 5-day BOD is the amount of oxygen demand that has been exerted at five days. The ultimate BOD (UBOD) is the amount of BOD initially present. To determine UBOD, given the BOD_5, use Eq. (2-60).

   $$BOD_5 = UBOD\left[1 - e^{-k_1(5\ d)}\right]$$

   It is given that $k_1 = 0.23\ d^{-1}$, and for **Sample 1**, $BOD_5 = 185$ mg/L, thus

   $$185 = UBOD\left[1 - e^{-(0.23/d)(5\ d)}\right]$$

   UBOD = 270.7 mg/L

2. Solve for the BOD_{10} using Eq. (2-60).

   $$BOD_{10} = 270.7\left[1 - e^{-(0.23/d)(10\ d)}\right] = 243.6\ mg/L$$

3. Solve for $k_{1,15°C}$ using Eq. (1-44).

   $$k_{1,\ 15°C} = k_{1,\ 20°C}\ \theta^{(15\ -\ 20)}$$

   Assume θ at 15°C is equal to about 1.056 (see Text page 119).

   $$k_{1,\ 15°C} = (0.23\ d^{-1})\ 1.056^{(15\ -\ 20)} = 0.175\ d^{-1}$$

4. The BOD_5 at 15°C is.

   $$BOD_{5,15°C} = 270.7\left[1 - e^{-(0.175/d)(10\ d)}\right] = 223.7\ mg/L$$

PROBLEM 2-25

Problem Statement - See text, page 174

Solution

1. Solve for k_1 by successive trials using Eq. (2-60) for t = 2d and 8d. Other solutions are similar.

   $$BOD_t = UBOD\left[1 - e^{-k_1(t,\ d)}\right]$$

   $125 = UBOD(1 - e^{-2\ k_1})$

   $225 = UBOD(1 - e^{-8\ k_1}$

   $125/225 = (1 - e^{-2\ k_1})/(1 - e^{-8\ k_1})$

   $k_1 = 0.375\ d^{-1}$

2. The UBOD using the 2 d value is:

$$125 = \text{UBOD}\left[1 - e^{-0.375\ \text{d}^{-1}(2\ \text{d})}\right]$$

UBOD = 236.9 mg/L

3. Compute the 5-day BOD.

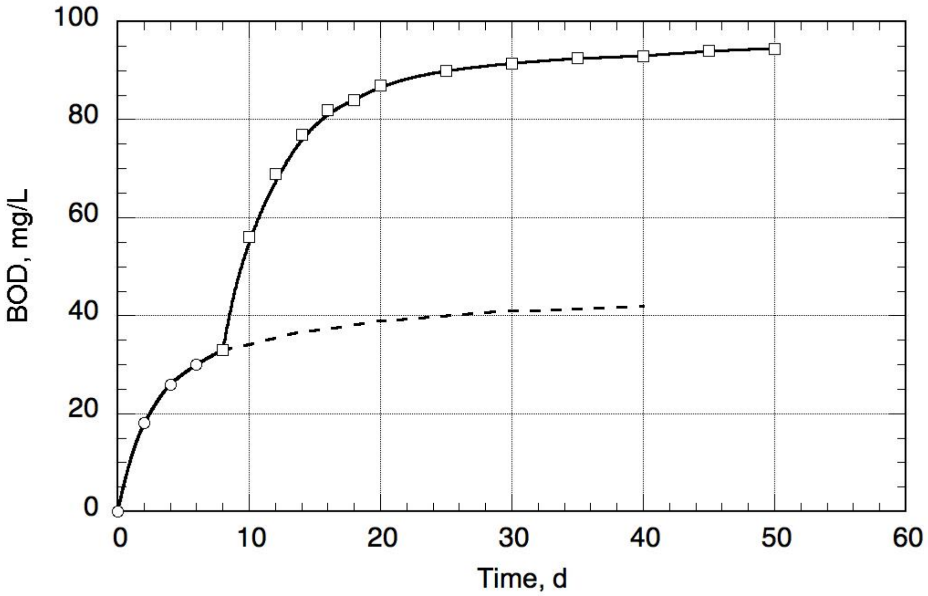
$$\text{BOD} = 236.9\left[1 - e^{-0.375\ \text{d}^{-1}(5\ \text{d})}\right] = 200.6\ \text{mg/L}$$

PROBLEM 2-26

Problem Statement - See text, page 175

Solution

1. Plot the given data (**Sample 1**) to estimate UBOD and NOD, the ultimate carbonaceous and nitrogenous oxygen demand.



a. From the plot,

UBOD ≅ 42 mg/L

NOD ≅ (95 – 42) mg/L = 53 mg/L

b. The nitrogenous demand begins at t = 8d

2. Determine the carbonaceous BOD rate constant using Eq. (2-60)

$$\mathrm{BOD_t = UBOD\,(1 - e^{-k_1 t})}$$

$$28 = 42[1 - e^{-k_1(5)}]$$

$$\ln(1 - \frac{28}{42}) = -k_1(5)$$

$k_1 = 0.22\ \mathrm{d^{-1}}$

3. Determine the nitrogenous rate constant using Eq. (2-60)

$$\mathrm{NOD_t = UNOD\,(1 - e^{-k_n t})}$$

At day 16, the nitrogenous demand is 43 mg/L (82 – 39) mg/L, thus

$$\ln(1 - \frac{43}{53}) = -k_n(8)$$

$k_n = 0.21\ \mathrm{d^{-1}}$

4. Determine the corresponding k values at 25°C using Eq. (1-44).

   a. For k_1

$$k_{25} = k_{20}\theta^{(T_2-20)} = 0.22(1.05)^{25-20} = 0.28\,\mathrm{d^{-1}}$$

   b. For k_n

$$k_{n_{25}} = k_{n_{20}}\theta^{(T_2-20)} = 0.21(1.08)^{25-20} = 0.30\,\mathrm{d^{-1}}$$

Comment

Another solution approach to this problem is to use the method of least squares (or the Thomas method) to solve for UBOD and k_1.

PROBLEM 2-27

Problem Statement - See text, page 176

Solution

1. Solve Eq. (1-41) for activation energy. The required equation is:

$$E = \frac{R\ \ln(k_2 / k_1)}{1/T_2 - 1/T_1}$$

2. Substitute the known values and solve for E. The selected values are k1 = 0.15, k2 = 0.30 d-1, T1 = 10 and T2 = 20°C.

T_1 = (273 + 10°C) = 283 K

T_2 = (273 + 20°C) = 293 K

K_1 = 0.15

k_2 = 0.30

R = 8.314 J/mole•K

$$E = \frac{(8.314\ \text{J/mole}\bullet\text{K})\ [\ln(0.30/0.15)]}{(1/283\text{K} - 1/293\text{K})} = 47{,}785\ \text{J/mole}$$

PROBLEM 2-28

Problem Statement - See text, page 176

Solution

1. Write balanced reaction for the carbonaceous oxygen demand.

$C_9N_2H_6O_2 + 8\ O_2 \rightarrow 2NH_3 + 9CO_2$

2. Write balanced reactions for the nitrogenous oxygen demand.

a. $NH_3 + 3/2\ O_2 \rightarrow HNO_2 + H_2O$

b. $HNO_2 + 1/2\ O_2 \rightarrow HNO_3$

$NH_3 + 2\ O_2 \rightarrow HNO_3 + H_2O$

3. Determine the carbonaceous oxygen demand

$$UBOD = (8)\ \text{mole } O_2/\text{mole } C_9N_2H_6O_2$$

$$= 3\text{-}1/2\ \text{mole } O_2/(\text{mole glycine} \times 32\ \text{g}/\text{mole } O_2)$$

$$= 112\ \text{g } O_2/\text{mole glycine}$$

PROBLEM 2-29

Problem Statement - See text, page 176

Solution

To completely stabilize the water, oxygen must be supplied to meet the ultimate carbonaceous and nitrogenous oxygen demands.

1. Determine the ultimate biochemical oxygen demand, which also corresponds to the COD, utilizing Eq. (2-60),

$$BOD = UBOD(1-e^{-k_1 5})$$

$$400\ \text{mg/L} = UBOD(1-e^{-0.29 \times 5}) = 0.765\ (UBOD)$$

$$UBOD = COD = 523\ \text{mg/L}$$

2. Determine the nitrogenous oxygen demand.

$$NH_3 + 2\ O_2 \rightarrow HNO_3 + H_2O$$

$$\left[\frac{(80\ \text{mg/L}\ NH_3)}{(17\ \text{g/mole}\ NH_3)}\right]\left(\frac{2\ \text{mole}\ O_2}{\text{mole}\ NH_3}\right)\left(\frac{32\ \text{g}}{\text{mole}\ O_2}\right) = 301\ \text{mg/L}$$

3. The total amount of oxygen needed, which also corresponds to the ThOD, is:

$$(523 + 301)\ \text{mg/L} = 824\ \text{mg/L}$$

PROBLEM 2-30

Problem Statement - See text, page 176

Solution

1. Determine the number of moles of nitrogen, carbon and oxygen, that are present in a 100,000 L of the industrial wastewater (note a 100,000 L is used so that the mole numbers are greater than I)

$$\left[\frac{(11\,\text{mg/L})}{(28\text{ g/mole N}_2)}\right]\left(\frac{1\text{ g}}{10^3\text{ mg}}\right)\left(10^5\text{ L}\right)=39.3\text{ mole N}_2$$

$$\left[\frac{(130\text{ mg/L})}{(12\text{ g/mole C})}\right]\left(\frac{1\text{ g}}{10^3\text{ mg}}\right)\left(10^5\text{ L}\right)=1083\text{ mole C}$$

$$\left[\frac{(425\text{ mg/L})}{(32\text{ g/mole O}_2)}\right]\left(\frac{1\text{ g}}{10^3\text{ mg}}\right)\left(10^5\text{ L}\right)=1328\text{ mole O}_2$$

2. Now write the chemical equations. The COD does not include the nitrogenous oxygen demand.

glucose + glycine + stearic acid + oxygen →

water + ammonia + carbon dioxide

a $C_6H_{12}O_6$ + b $C_2H_5O_2N$ + c $C_{18}H_{36}O_2$ + 1328 O_2 →

d H_2O +39.3 NH_3 + 1083 CO_2

Determine the value of b by balancing the nitrogen

b = 39.3 mole/100,000L

Now write and solve a series of simultaneous equations for carbon, hydrogen, and oxygen.

$6(a) + 2(39.3) + 18(c) = 1083$

$12(a) + 5(39.3) + 36(c) = 2(d) + 3(39.3)$

$6(a) + 2(39.3) + 2(c) + 2(1328) = d + 2(1083)$

Solving the above equations yields:

a = 68.16 mole/100,000L

c = 33.08 mole/100,000L

d = 1043.7 mole/100,000L

3. Convert these values to mg/L.

   a. For glucose.

$$\left(\frac{68.16\ \text{mole}}{100{,}000\ \text{L}}\right)\left(\frac{(72+12+96)\ \text{g}}{\text{mole}}\right)\left(\frac{10^3\ \text{mg}}{\text{g}}\right)=79.1\,\text{mg/L}$$

   b. For glycine acid.

$$\left(\frac{39.3\ \text{mole}}{100{,}000\ \text{L}}\right)\left(\frac{(24+5+32+14)\text{g}}{\text{mole}}\right)\left(\frac{10^3\ \text{mg}}{\text{g}}\right)=75.0\ \text{mg/L}$$

   b. For stearic acid.

$$\left(\frac{33.08\ \text{mole}}{100{,}000\ \text{L}}\right)\left(\frac{(216+36.1+32)\text{g}}{\text{mole}}\right)\left(\frac{10^3\ \text{mg}}{\text{g}}\right)=93.9\ \text{mg/L}$$

PROBLEM 2-31

Problem Statement - See text, page 176

Solution

1. Write the chemical equations **for sample of 450 mg/L COD**.

Organic matter + 450 mg/L O_2 = CO_2 + H_2O

Organic matter + $Cr_2O_7^{2-}$ + H+ = Cr^{3+} + CO_2 + H_2O

The amount of organic matter used and the amount of carbon dioxide produced is the same for either condition. The number of moles of oxygen is

450 mg/L O_2 x 1 mole/32g x 1g/1000 mg = 0.0141 mole/L

2. The subtraction of the two equations then gives:

$$0.0141 \text{ mole/L } O_2 - a\ Cr_2O_7^{2-} + b\ H^+ = c\ Cr^{3+} + d\ H_2O$$

3. Balance elements and charges, and solve for the constants.

$2(0.0141) - 7(a) = d$

$2(a) = c$

$b = 2(d)$

$-2(a) + b = +3(c)$

a = 0.00313 mole/L b = 0.0125 mole/L

c = 0.00625 mole/L d = 0.00625 mole/L

4. Convert the answer to mg/L of $Cr_2O_7^{2-}$.

$$\left(\frac{0.00313 \text{ mole}}{\text{L}}\right)\left\{\frac{[(2 \times 52) + (7 \times 16)\text{ g}]}{\text{mole}}\right\}\left(\frac{10^3 \text{ mg}}{\text{g}}\right) = 676 \text{ mg/L}$$

PROBLEM 2-32

Problem Statement - See text, page 176

Solution

1. Determine the energy content of the food waste using Eq. 2-66

   a. Determine the weight fractions of the elements and ash comprising the wastewater using a computation table

Component	Coefficient	Molecular weight	Molecular mass	Weight fraction
Carbon	21.53	12	258.36	0.48
Hydrogen	34.21	1	34.21	0.06

Oxygen	12.66	16	202.56	0.38
Nitrogen	1	14	14	0.03
Sulfur	0.07	32	2.24	0.004
Ash	0	0		0.05
			511.37	1.00

b. The energy content of the organic fraction using Eq. 2-66 is:

HHV (MJ/kg organic fraction) = 34.91 (0.48) + 117.83 (0.06) - 10.34 (0.38)
-1.51 (0.03) + 10.05(0.004) - 2.11 (0.05)

HHV (MJ/kg organic fraction) = 16.76 + 7.49 – 3.89– 0.04 + 0.04 - 0.11 = 20.25

2. Determine the COD of the organic fraction

a. Write a balanced reaction for the chemical oxidation of the food waste neglecting sulfur

$$C_{21.53}H_{34.21}O_{12.66}N_{1.00} + 23.00O_2 \rightarrow 21.53CO_2 + NH_3 + 15.61H_2O$$

511.37 23.00(32)

b. The COD of the organic fraction is:

COD = 23.00(32 g O_2/mole)/(511.37 g organic fraction/ mole)
= 1.44 g O_2/g organic fraction

3. Determine the energy content of the biomass in terms of MJ/kg biosolids COD

$$\text{HHV (MJ/kg organic fraction COD)} = \frac{(20.25 \text{ MJ/kg of organic fraction})}{(1.44 \text{ kg } O_2\text{/kg of organic fraction})}$$
$$= 14.1 \text{ MJ/kg of organic fraction COD}$$

4. Food waste has 1 MJ/kg of organic fraction COD less than wastewater. The greater HHV of wastewater can be explained by the other organic compounds that enter into the wastewater stream including oil and grease.

PROBLEM 2-33

Problem Statement - See text, page

Solution

1. If two bacteria will exist in 30 minutes, and four in 60 minutes, etc., the general formula is:

   Number of organisms = N = $2^{(t/30\text{ min})} = 2^{(t/0.5\text{ h})}$

   Solve for N.

   N = $2^{(72\text{ h}/0.5\text{ h})} = 2^{144} = 2.23 \times 10^{43}$ organisms

2. Find the volume per organism, assuming a spherical shape.

   Volume of one organism = $(4/3)(\pi)[(2\text{x}10^{-6}\ \mu\text{m}/2)^3](1\text{m}/10^6\ \mu\text{m})$

   $= 4.19 \times 10^{-12}\ \text{m}^3$

1. Find the theoretical mass of the accumulated organisms.

$$(2.23\,\text{x}10^{43}\ \text{organisms})\left(\frac{4.19\times10^{-12}\ \text{m}^3}{\text{organism}}\right)\left(\frac{1\,\text{kg}}{\text{L}}\right)\left(\frac{10^3\ \text{L}}{\text{m}^3}\right) = 9.34\times10^{34}\ \text{kg}$$

4. The computed number of organisms cannot occur, because the bacteria will not always be under optimal growth conditions. Nutrient supplies and oxygen supplies will be depleted, and the bacteria will begin to compete with one another. The transport of nutrients and oxygen into the cell and waste out of the cell will also limit growth. Some bacteria will die, and others will not reproduce. In terms of sheer volume, the bacteria must also fit in the space available.

PROBLEM 2-34

Problem Statement - See text, page 176

Solution

1. The volume of 2.0 μm^3 includes water, which bacteria are mostly made of. To calculate the suspended solids, the mass of water must be accounted for. The volume of organisms per liter is:

$$\left(\frac{2.0\ \mu m^3}{\text{organism}}\right)\left(\frac{10^8\ \text{organisms}}{\text{mL}}\right)\left(\frac{10^3\ \text{mL}}{\text{L}}\right)\left(\frac{1\,\text{m}}{10^6\ \mu\text{m}}\right)^3 = 2\times10^{-7}\,\text{m}^3/\text{L}$$

2. Determine the corresponding mass of organisms per liter, not including water.

$$\text{TSS} = \left(\frac{2\times10^{-7}\,\text{m}^3}{\text{L}}\right)\left(\frac{1.005\ \text{kg}}{\text{L}}\right)\left(\frac{10^3\ \text{L}}{\text{m}^3}\right)\left(\frac{10^6\ \text{mg}}{\text{kg}}\right) = 201\,\text{mg/L}$$

PROBLEM 2-35

Problem Statement - See text, page 176

Solution

1. To maximize the given equation, set the derivative of the joint probability equation equal to zero.

$y = 1/a[(1-e^{-n\lambda})^p(e^{-n\lambda})^q]$

$y' = 0 = 1/a[p(1-e^{-n\lambda})^{p-1}(-n)(-e^{-n\lambda})(e^{-n\lambda})^q + (-nq)(e^{-nq\lambda})(1-e^{-n\lambda})^p]$

$0 = (1-e^{-n\lambda})^p(e^{-nq\lambda})[(np(e^{-n\lambda})/(1-e^{-n\lambda}) - nq]$

$0 = np(e^{-n\lambda})/(1-e^{-n\lambda}) - nq$

2. Solve the above expression for λ.

$1-e^{-n\lambda} = np/nq(e^{-n\lambda}) = p/q(e^{-n\lambda})$

$e^{n\lambda} = 1+ p/q$

$\ln(e^{-n\lambda})= n\lambda = \ln[1+ p/q]$

$$\lambda = \text{MPN}/\text{mL} = \frac{\ln[1 + (p/q)]}{n}$$

$$\text{MPN}/100\ \text{mL} = \frac{100\ \ln[1 + (p/q)]}{n}$$

n = sample size

p = number of positive tubes

q = number of negative tubes = 5 - p

3. For the given sample:

$$\text{MPN}/100\ \text{mL} = \frac{100\left\{\ln[1 + (3/2)]\right\}}{0.1\ \text{mL}}$$

$$= 916\ \text{MPN}/100\text{mL}$$

PROBLEM 2-36

Problem Statement - See text, page 176

Solution

2. Using the MPN tables:

Sample	Series Used	MPN/100 mL
1	4-3-1	330
2	4-5-5	81
3	5-4-5	43
4	5-2-3	120
5	5-1-2	63
6	5-2-3	120
7	5-5-1	350

PROBLEM 2-37

Problem Statement - See text, page 177

Solution

1. The fecal coliform test has been used for many years as an indication of the bacteriological safety of surface waters and of the disinfection efficiency of

water and wastewater treatment plants. For the latter use, the test is excellent as a low coliform count in a treated effluent is also indicative of a low count of pathogenic bacterial species.

2. The use of the fecal coliform test for sampling drinking water sources is not as straightforward, however. This is because the fecal coliform group of organisms is not unique to man but is present in the gut of cattle, sheep, dogs, and other warm blooded animals. Thus, a high coliform count in a stream or lake might be due to animal contamination and not human sources.

PROBLEM 2-38

Problem Statement - See text, page 177

Solution

1. Average the counts from the 10^{-10} plates, use original and duplicates.

$$\text{Average count} = \left(\frac{60+51+38+43+56}{5}\right) = 49.6 \text{ PFU/mL}$$

2. Multiply the count by the reciprocal of the dilution

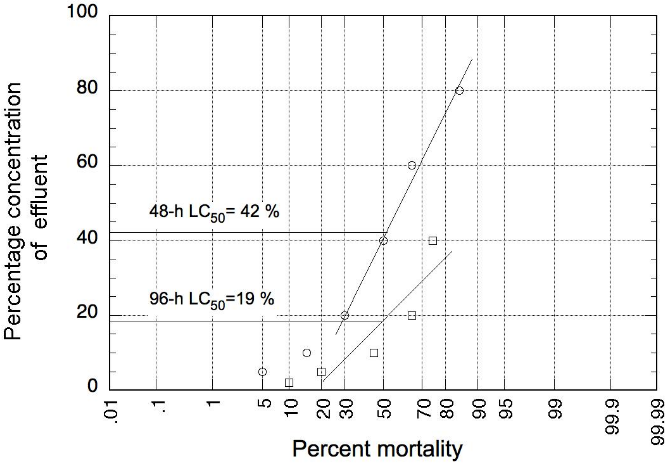
$$\text{Titer} = 49.6 \text{ PFU/mL} \times 10^{10} = 4.96 \times 10^{11}$$

PROBLEM 2-39

Problem Statement - See text, page 177

Solution

1. Plot the concentration of wastewater in percent by volume (log scale) against test animals surviving in percent (probability scale), as shown below.



2. Fit a line to the data points by eye, giving most consideration to the points lying between 16 and 84 percent mortality.

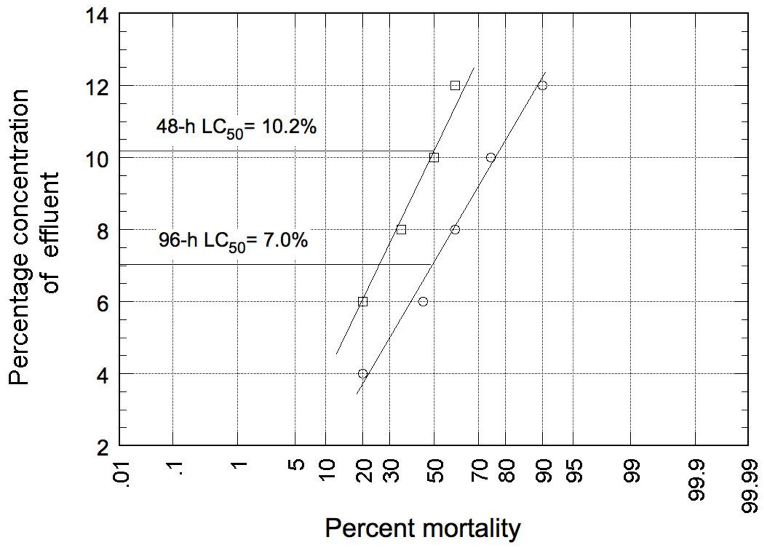
3. Find the wastewater concentrations causing 50 percent mortality. The estimated LC_{50} values, as shown in the above figure, are 42 percent for 48 h and 19 percent for 96 h.

PROBLEM 2-40

Problem Statement - See text, page 177

Solution

1. Plot the concentration of wastewater in percent by volume (log scale) against test animals surviving in percent (probability scale), as shown below.



3. Find the wastewater concentrations causing 50 percent mortality. The estimated LC_{50} values, as shown in the above figure, are 10.2 percent for 48 h and 7.0 percent for 96 h.

3

WASTEWATER FLOWRATES AND CONSTITUENT LOADINGS

PROBLEM 3-1

Problem Statement - See text, page 254

Solution

1. In determining what level of water conservation is realistic, an evaluation of the components of the wastewater is necessary, especially in determining if interior water use in the community is excessive. The average residential flowrate of 320 L/d given in the problem statement represents non-excessive domestic water use and the presence of relatively low flowrates from other sources into the sewer system. This conclusion is based on unit flowrates given in Table 3-2 that indicate for an average household size of 3 to 4 persons, a domestic flowrate of 168 to 180 L/capita•d might be expected. As reported in Table 3-9, installation of water conservation devices will reduce an average residential flowrate from about 246 to 154 L/capita•d, or a maximum reduction of 37 percent.
2. An aggressive water conservation program based on installing flow reduction devices might reasonably accomplish a flow reduction of 25 to 40 percent over time. Implementation would require the ultimate replacement of clothes washers, which would be very expensive to implement all at once.

PROBLEM 3-2

Problem Statement - See text, page 254

Instructors Note: It is suggested that flowrates be developed for more that one alternative so that alternative proposals can be compared.

Solution

1. Prepare a table of all sources of wastewater and the amount of flow expected from each of the four proposals. In the below table, flowrates for **Developers 1 and 2** are given.

Facility	Units	Flow/unit, L/user	Developer 1 No. of units	Developer 1 Total flow, L/d	Developer 2 No. of units	Developer 2 Total flow, L/d
Hotel	Guest rooms	190	120	22,800	80	15,200
	Employees	40	25	1000	16	640
Department store	Toilet rooms	1500	8	12,000	12	18,000
	Employees	40	40	1600	60	2400
Self-service laundry	Machines	1700			20	34,000
Restaurant, no bar	Seats	35	125	4375	100	3500
Restaurant, with bar	Seats	40	100	4000	125	5000
Theatre	Seats	10	500	5000	400	4000
Totals				50,775		82,740

PROBLEM 3-3

Problem Statement - See text, page 254

Solution

1. Prepare a table of all sources of wastewater and the amount of flow expected. Use typical flowrate factors from Tables 3-3 and 3-5. For the automotive service station, estimate the number of employees and include flowrate contributions.

			Area 1		Area 2	
Facility	Units	Flow/unit, L/user	No. of units	Total flow, L/d	No. of units	Total flow, L/d
Visitor center	Visitors	15	250	3750	300	4500
Motel	Guests	230			60	13,800
Resort cabins	Guests	150			100	15,000
Cottages	Guests	190	60	11,400		
Campground	Persons	95	140	13,300	120	11,400
RV park	Connections	380	40	15,200	50	19,000
Laundry	Machines	1700	8	13,600	10	17,000
Shopping center	Employees	40	10	400	15	600
	Parking spaces	8	30	240	40	320
Service station	Vehicles	40	80	3200	120	4800
	Employees	50	2	100	3	150
Restaurant	Customers	40	200	8000	300	12,000
Totals				69,190		98,570

PROBLEM 3-4

Problem Statement - See text, pages 255

Solution

1. Analyze values for **data set 1**. Assume the dormitory is fully occupied.
2. Compute the per capita wastewater generation =

$$\frac{(125{,}000 \text{ L/d})}{300 \text{ persons}} = 417 \text{ L/capita d}$$

3. Allocate sources of wastewater based on given data

a.	Toilets (assume 6 uses/capita•d) = 6 x 9 L/use =	54 L/d
b.	Faucets =	10 L/d
c.	Showers (417 – 64) L/capita•d =	353 L/d

$$\text{Average duration of shower} = \frac{(353 \text{ L/d})}{(18 \text{ L/min} \bullet \text{use})} = 19.6 \text{ min/use}$$

4. Compute water savings using low-flush toilets (6 L/use) and low-flow showerheads (11 L/min•use). (Note: data are from Table 3-6).

a.	Toilets (assume 6 uses/capita•d) = 6 x 6 L/use =	36 L/d
b.	Faucets =	10 L/d
c.	Showers = 11 min/use x 19.6 min =	216 L/d
Total		262 L/d

$$\text{Percent reduction} = \frac{[(417 - 262)\ \text{L/d}]}{(417\ \text{L/d})}(100) = 37.2$$

The percent reduction achieved by the water conservation devices greatly exceeds the flow reduction goal (15%), without affecting a life-style change, i.e., reducing the length of showers. Further flow reductions can be achieved by installing timer activated shutoff valves to limit the duration of the showers.

PROBLEM 3-5

Problem Statement - See text, pages 255

Solution

1. Prepare a table and calculate flow-weighted values for BOD and TSS.

Time	Flowrate 1	BOD		TSS	
	m^3/d	g/m^3	g/d x 1000	g/m^3	g/d x 1000
02:00	8000	130	1040	150	1200
04:00	6000	110	660	135	810
06:00	9400	160	1504	150	1410
08:00	12,800	220	2816	205	2624
10:00	13,000	230	2990	210	2730
12:00	14,400	245	3528	220	3168
14:00	12,000	225	2700	210	2520
16:00	9600	220	2112	200	1920
18:00	11,000	210	2310	205	2255
20:00	8000	200	1600	210	1680
22:00	9000	180	1620	185	1665
24:00	8400	160	1344	175	1470
Totals	121,600		24,224		23,452
Flow weighted values		199.2		192.9	

PROBLEM 3-6

Problem Statement - See text, pages 255

Solution

1. Arrange the measured data in an order of increasing magnitude, assign a rank serial number, and compute a plotting position using Eqs. (D-10).

Number	Plotting position, %	Flowrates, m^3/d			
		2007	2008	2009	2010
1	7.7	2000	1500	2800	2200
2	15.4	2400	2000	3300	3100
3	23.1	2800	2600	3800	3800
4	30.8	3200	3200	4400	4400
5	38.5	3600	3600	4800	4600
6	46.2	4000	4200	5300	5000
7	53.8	4000	4800	6000	6500
8	61.5	4800	5700	6500	7600
9	69.2	5200	6700	7300	8600
10	76.9	6200	8100	8300	10,000
11	84.6	6800	9900	9400	13,000
12	92.3	8800	13,900	11,800	18,400

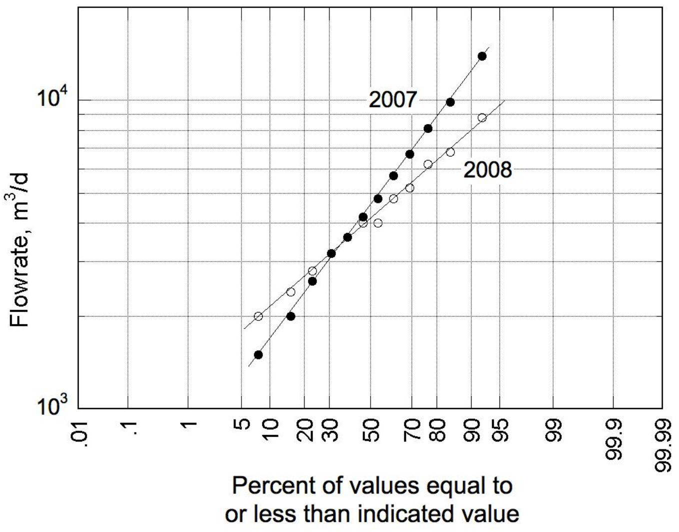
2. Plot the data in the above table on both arithmetic- and log-probability paper. Note for this problem, a log-probability plot is more appropriate. For clarity, two separate plots have been prepared as shown below: one for 2007-2008 data and one for 2009-2010 data.
   a. The data are log-normally distributed.
   b. Determine the average annual flowrate, average dry weather flowrate, and average wet weather flowrate.
      i. The average (mean) annual flowrates from the following plots are:

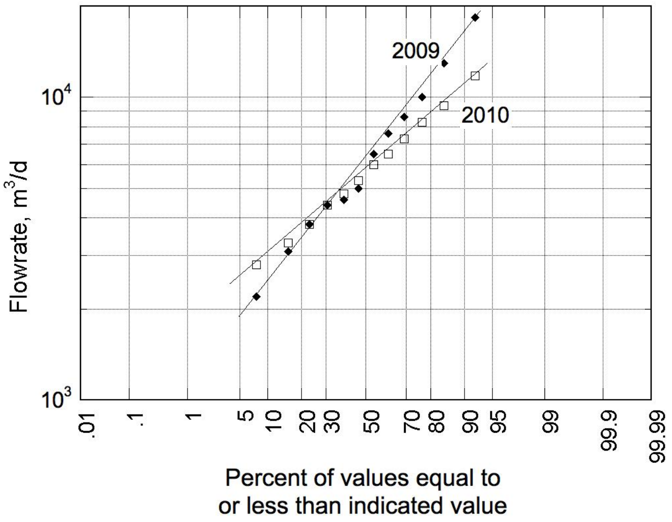
2007 = 4700 m^3/d

2008 = 4000 m^3/d

2009 = 5900 m^3/d

2010 = 6500 m^3/d.

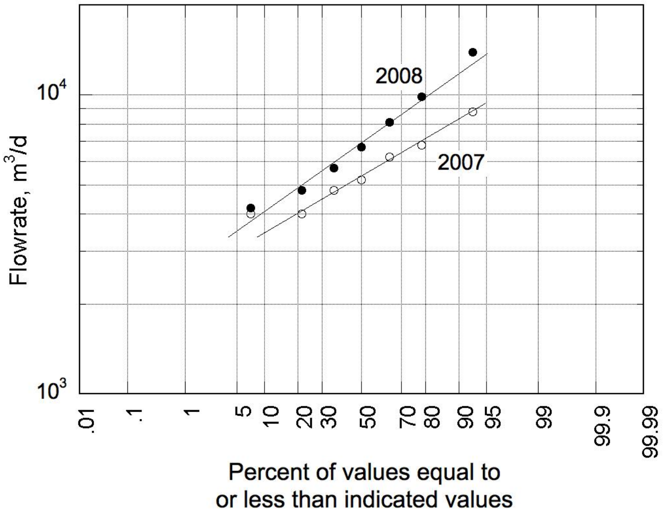




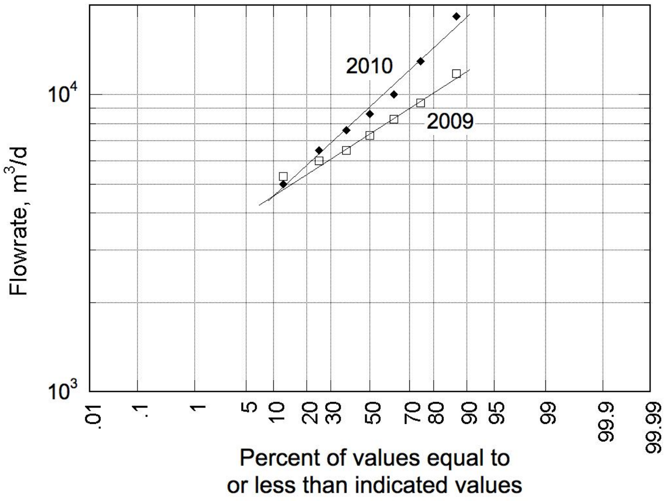
ii. Compute the AWWF. Compute the AWWF based on the highest seven months of flow records. The data are log normally distributed and the plotting positions and plots are shown below.

Number	Plotting position, %	Wet weather flowrates, m^3/d			
		2007	2008	2009	2010
1	12.5	4000	4200	5300	5000
2	25	4000	4800	6000	6500
3	37.5	4800	5700	6500	7600
4	50	5200	6700	7300	8600
5	62.5	6200	8100	8300	10,000
6	75	6800	9900	9400	13,000
7	87.5	8800	13,900	11,800	18,400

iii. Plot wet weather data for 2007 and 2008.



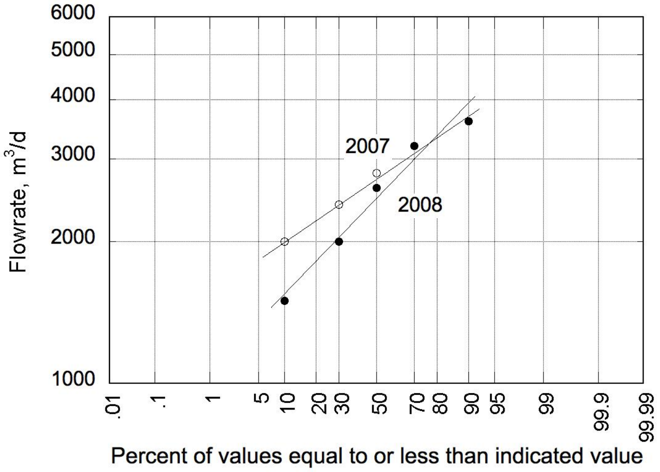
iv. Plot wet weather data for 2009 and 2010.



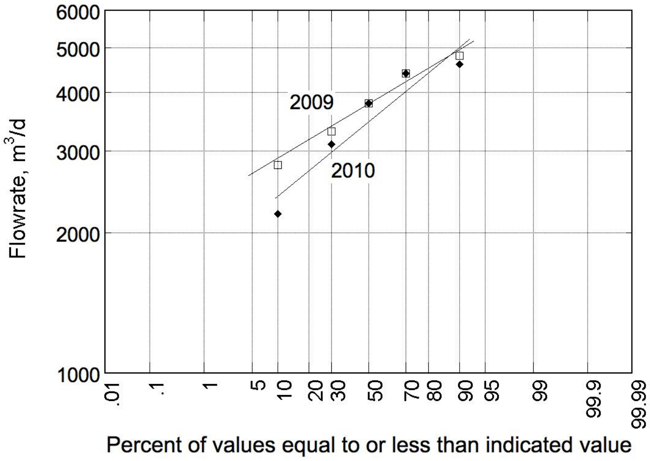
v. Compute the ADWF. Compute the AWWF based on the lowest five months of flow records. The plotting positions and plots are shown below.

Number	Plotting position, %	Wet weather flowrates, m^3/d			
		2007	2008	2009	2010
1	16.7	2000	1500	2800	2200
2	33.3	2400	2000	3300	3100
3	50	2800	2600	3800	3800
4	66.7	3200	3200	4400	4400
5	83.3	3600	3600	4800	4600

vi. Plot dry weather data for 2007 and 2008.



vii. Plot dry weather data for 2009 and 2010.



viii. Summarize data.

Year	ADWF, m^3/d	AWWF, m^3/d
1996	2800	5100
1997	2580	6900
1998	3820	7200
1999	3620	9100

3. Set up a table to compute the commercial and industrial flow.

	Year			
Item	2007	2008	2009	2010
ADWF, m^3/d	2800	2580	3820	3620
Population	8690	9400	11,030	12,280
Unit flowrate, L/capita	260	260	260	260
Domestic flowrate, m^3/d	2259	2444	2868	3193
Commercial and industrial flowrate, m^3/d	541	136	952	427

4. Set up a table using the above flowrate data and compute the infiltration/inflow.

	Year			
Item	2007	2008	2009	2010
AWWF, m^3/d	5100	6900	7200	9100
ADWF, m^3/d	2800	2580	3820	3620
I/I = AWWF – ADWF, m^3/d	2300	4320	3380	5480
Population	8690	9400	11,030	12,280
Unit I/I flowrate, L/capita•d	265	460	306	446

PROBLEM 3-7

Problem Statement - See text, pages 256

Solution

1. Estimate the average annual flowrate at buildout with an I/I contribution of 200L/capita•d.

   a. Residential flowrate = 16,000 x 300L/capita x 1 m^3/1000 L = 4800 m^3/d

b. Commercial flowrate = (1000 m^3/d)/0.80 = 1250 m^3/d

Average dry weather flow (ADWF) = 6050 m^3/d

c. I/I = 200 L/capita•d x 16,000 x 1 $m^3/10^3$ L = 3200 m^3/d

Average wet weather flow (AWWF) = 9250 m^3/d

d. Average annual flow = 6,050 m^3/d + (8/12) 3,200 m^3/d = 8183 m^3/d

2. None of the stated flowrates is acceptable for selecting the maximum design capacity. The design flowrate should also include allowances for peak flowrates. The design capacity should consist of the following, assuming a residential peaking factor of 3.4 (from Fig. 3-18):

   a. Residential flowrate = 4800 m^3/d x 3.4 = 16,320 m^3/d

   b. Commercial flowrate = 1250 m^3/d

   c. I/I = 3200 m^3/d

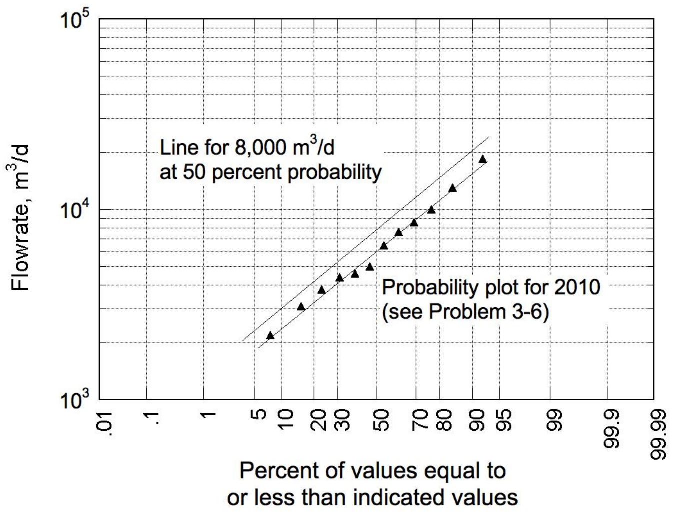
   Total = 20,770 m^3/d

PROBLEM 3-8

Problem Statement - See text, pages 256

Solution

1. See the probability plots for Problem 3-6. The wettest year of record was 2010. Using the plot for 2010, construct a line parallel to the plotted line at the 50 percentile point. The peak month (at the 92 percentile) is approximately 23,000 m^3/d.



PROBLEM 3-9

Problem Statement - See text, page 256 - 257

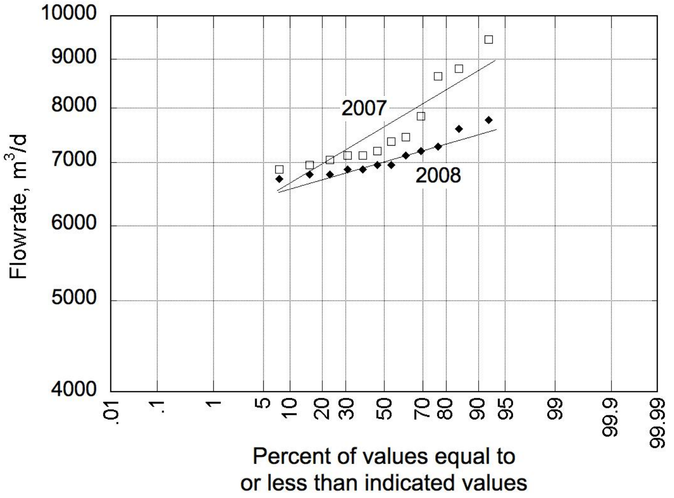
Solution

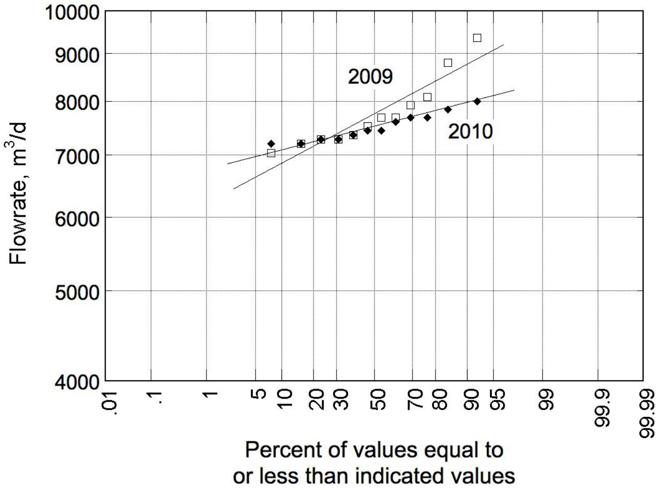
1. Arrange the data in order of increasing magnitude, assign a rank serial number, and compute a plotting position using Eq. (D-10).

Number	Plotting position, %	Flowrates, m^3/d			
		1996	1997	1998	1999
1	7.7	6880	6720	7040	7200
2	15.4	6960	6800	7200	7200
3	23.1	7040	6800	7280	7280
4	30.8	7120	6880	7280	7280
5	38.5	7120	6880	7360	7360
6	46.2	7200	6960	7520	7440
7	53.8	7360	6960	7680	7440
8	61.5	7440	7120	7680	7600
9	69.2	7840	7200	7920	7680
10	76.9	8640	7280	8080	7680
11	84.6	8800	7600	8800	7840
12	92.3	9440	7760	9360	8000

2. As noted in Problem 3-6, a log-probability plot is more appropriate. For clarity, two separate plots have been prepared as shown below: one for 2007-2008 data and one for 2009-2010 data.

   a. Determine the mean annual flowrates from the probability plots.





The data are log-normally distributed.

The average (mean) annual flowrates are:

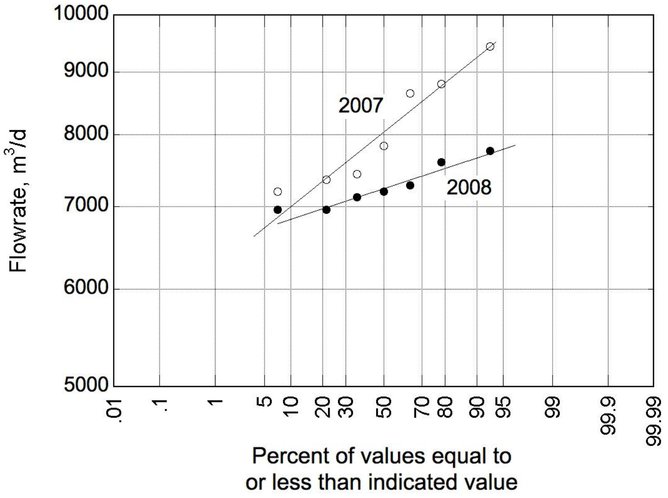
2007 = 7500 m^3/d	2009 = 7700 m^3/d
2008 = 7000 m^3/d	2010 = 7400 m^3/d

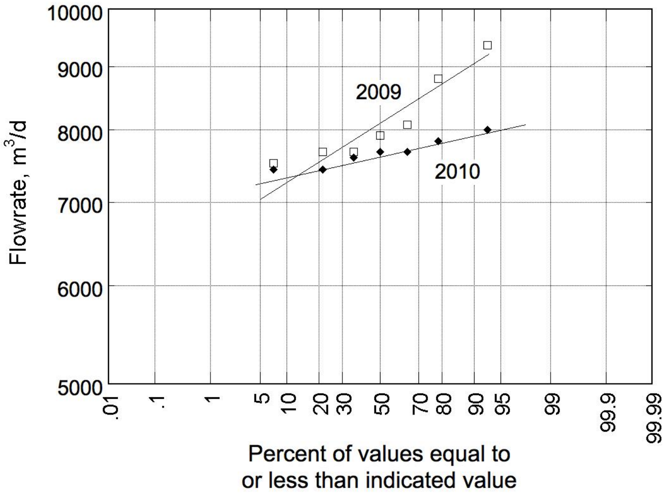
   b. Compute the AWWF and ADWF. Assume the wet season occurs from November to April and the dry season occurs from May to October.

i. Compute the AWWF based on the highest seven months of flow records. The plotting positions and plots are shown below.

Number	Plotting position, %	Wet weather flowrates, m^3/d			
		2007	2008	2009	2010
1	12.5	7200	6960	7520	7440
2	25	7360	6960	7680	7440
3	37.5	7440	7120	7680	7600
4	50	7840	7200	7920	7680
5	62.5	8640	7280	8080	7680
6	75	8800	7600	8800	7840
7	87.5	9440	7760	9360	8000

ii. Plot wet weather data.





iii. Compute and plot ADWF flowrate data in a similar manner.

iv. Summarize the mean values. (Average dry weather flowrates may be averaged as the monthly variation is small).

Year	ADWF, m^3/d	AWWF, m^3/d
2007	7000	8000
2008	6800	7300
2009	7200	8100
2010	7300	7700

5. Set up a table to compute the commercial and industrial flow. Domestic unit flowrate = 260 L/capita•d (same as Problem 3-6).

	Year			
Item	2007	2008	2009	2010
ADWF, m^3/d	7000	6800	7200	7300
Population	17,040	17,210	17,380	17,630
Unit flowrate, L/capita	260	260	260	260
Domestic flowrate, m^3/d	4430	4475	4519	4584
Commercial and industrial flowrate, m^3/d	2570	2325	2681	2716

6. Set up a table using the above flowrate data and compute the infiltration/inflow.

	Year			
Item	2007	2008	2009	2010
AWWF, m^3/d	8000	7300	8100	7700
ADWF, m^3/d	7000	6800	7200	7300
I/I = AWWF – ADWF, m^3/d	1000	500	900	400
Population	17,040	17,210	17,380	17,630
Unit I/I flowrate, L/capita•d	59	29	52	23

PROBLEM 3-10

Problem Statement - See text, page 257

Solution

1. Prepare a table of all wastewater sources and the amount of flow expected to be generated by each source. Assume 300 vehicles per day use the automobile service station and the station employs six persons per day.

Source	Number of units	Units	Flow/user, L/unit•d	Total flow, L/d
Campground (with toilets only)	200	Persons	95	19,000
Lodges and cabins	100	Persons	150	15,000
Apartments	150	Persons	230	34,500
Dining hall	300 (100 x 3)	Meals	25	7500
Cafeteria	200	Customers	10	2000
	4	Employees	40	160
Visitor center	500	Visitors	15	7500
Laundry	10	Machines	1700	17,000
Cocktail lounge	20	Seat	80	1600
Service station	300	Vehicles	40	12,000
	6	Employees	50	300
Total flow				116,560

PROBLEMS 3-11 to 3-12

Problem Statement - See text, pages 257

Instructors Note: The solutions to these problems obviously vary depending upon the location. Instructors may want to provide their students with the necessary data to use for solving these problems.

PROBLEM 3-13

Problem Statement - See text, pages 257 - 258

Solution

1. Calculate the base (dry weather flow) for flowrate **regime 1** by averaging the flowrates for the lowest months, in this case June, July, August, and September.

$$\text{Base flowrate} = \frac{(108{,}000 + 95{,}000 + 89{,}000 + 93{,}000)\ \text{m}^3/\text{d}}{4} = 96{,}250\ \text{m}^3/\text{d}$$

2. Calculate the average wet weather flowrate for the remaining months.

$$\text{WW Flowrate} = \frac{(293{,}000 + 328{,}000 + 279{,}000 + 212{,}000 + 146{,}000 + 111{,}000 + 132{,}000 + 154{,}000)\ \text{m}^3/\text{d}}{8}$$

$= 206{,}875\ \text{m}^3/\text{d}$

3. Calculate the excess flowrate by subtracting the base flow from the WW flowrate.

Excess flow = $(206{,}875 - 96{,}250)\ \text{m}^3/\text{d} = 110{,}625\ \text{m}^3/\text{d}$

4. Infiltration is estimated to be 67 percent of excess flow.

Infiltration = $(0.67 \times 110{,}625)\ \text{m}^3/\text{d} = 74{,}119\ \text{m}^3/\text{d}$

5. Infiltration will be reduced by 30 percent.

Reduction in flow = $(0.30 \times 74{,}119)\ \text{m}^3/\text{d} = 22{,}236\ \text{m}^3/\text{d}$

The reduction in flow is assumed to be approximately 10 percent per year for the first three years.

6. Estimate the value of the repair cost.

Repair cost = \$200,000/km x 300 km = \$60,000,000

7. The savings in treatment for the first year is:

$$(\$1.50/\text{m}^3)\left[\frac{(22{,}236\ \text{m}^3/\text{d})}{3}\right](8\ \text{mo})(30\ \text{d/mo}) = \$2{,}668{,}320$$

8. The number of years it will take to pay back the construction cost by savings in treatment costs can be calculated by using a spreadsheet.

Year	Treatment cost, $/m^3	Flow reduction m^3/d	Flow reduction m^3/y	Savings, $/y	Cumulative savings, $
1	1.00	7412	1,778,880	1,778,880	1,778,880
2	1.06	14,824	3,557760	3,771,226	5,550,106
3	1.12	22,236	5,336,640	5,977,037	11,527,143
4	1.19	22,236	5,336,640	6,350,602	17,877,745
5	1.26	22,236	5,336,640	6,724,166	24,601,911
6	1.34	22,236	5,336,640	7,151,098	31,753,009
7	1.42	22,236	5,336,640	7,578,029	39,331,038
8	1.50	22,236	5,336,640	8,004,960	47,335,998
9	1.59	22,236	5,336,640	8,485,258	55,821,256
10	1.69	22,236	5,336,640	9,018,922	64,840,178

As shown in the above table, the cost of the sewer repair will be paid for in less than 10 years by the savings in treatment costs.

PROBLEM 3-14

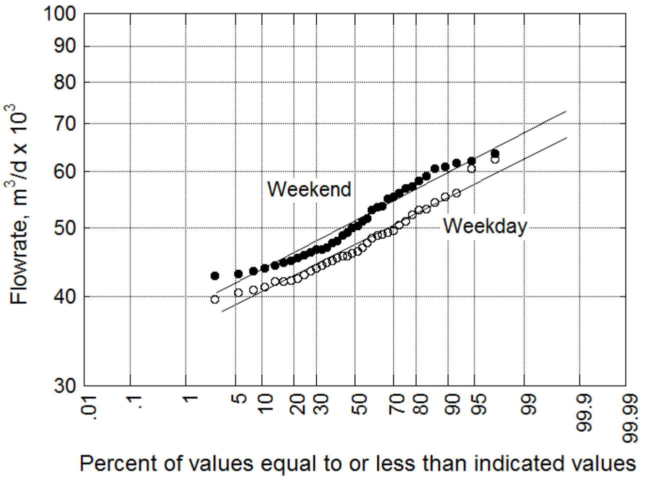
Problem Statement - See text, pages 258 - 259

Solution

1. Using the data for flowrate **regime 1**, develop a table, compute plotting positions, and plot data.

Number	Plotting position, %	Flowrate regime 1: Weekday average flowrate, m^3/d x 10^3	Flowrate regime 1: Weekend average flowrate, m^3/d x 10^3
1	2.70	39.7	42.8
2	5.41	40.5	43.1
3	8.11	40.9	43.5
4	10.81	41.3	43.9
5	13.51	42.0	44.3
6	16.22	42.1	44.7
7	18.92	42.2	45.0
8	21.62	42.4	45.4
9	24.32	42.9	45.8
10	27.03	43.5	46.2
11	29.73	43.9	46.6
12	32.43	44.3	46.7
13	35.14	44.7	46.9

14	37.83	45.0	47.7
15	40.54	45.4	47.9
16	43.24	45.6	48.8
17	45.95	45.7	49.2
18	48.65	46.0	50.0
19	51.35	46.4	50.3
20	54.05	46.9	51.1
21	56.76	47.7	51.5
22	59.46	48.4	53.0
23	62.16	48.8	53.4
24	64.86	49.0	53.7
25	67.57	49.2	54.9
26	70.27	49.6	55.3
27	72.97	50.5	56.0
28	75.68	51.1	56.8
29	78.39	52.2	57.2
30	81.08	53.0	58.3
31	83.78	53.2	59.1
32	86.49	54.3	60.6
33	89.19	55.3	60.9
34	91.89	56.0	61.7
35	94.59	60.6	62.1
36	97.30	62.5	63.6



1. The data are log-normal distributed.
2. Higher flowrates occur on the weekend.
3. The mean and 95 percentile values for weekdays are 47 and 57 x 10^3 m^3/d.
4. The mean and 95 percentile values for weekends are 51 and 63 x 10^3 m^3/d.

5. The probable one day maximum flowrate (99.7 percentile) is 72 x 10^3 m^3/d, which occurs on a weekend.

PROBLEM 3-15

Problem Statement - See text, page 259 - 260

Solution for Area 1

1. Solve the problem by use of a computation table, as follows.

Type of development	Units	Number of units	Flow, m^3/unit·d	Average flow, m^3/d	Peaking Factor	Peak flow, m^3/d
Residential	ha	125	40	5000	3.0	15,000
Commercial	ha	11	20	220	2.0	440
Industrial	ha	6	30	180	2.5	600
School	students	1500	75 L/student	113	4.0	450
Total						16,490

PROBLEM 3-16

Problem Statement - See text, page 260

Solution for City 1

1. Set up a spreadsheet and calculate the average flowrate for the 24 h period (see below). The average flowrate is 0.328 m^3/s.
2. Select a peak flowrate not to be exceeded; select **1.25** x avg for this example. The peak flowrate being discharged is 0.410 m^3/s.
3. Calculate the excess flow that has to be stored (flowrate – 0.410 m^3/s).
4. Compute the hourly volume to be stored (excess flowrate x 3600 s/h).
5. Compute the cumulative volume in storage. Consider the amount leaving storage when the average flowrate is less than 0.410 m^3/s. The peak volume in storage is the offline storage and is 819.6 m^3.

Time	Avg Flowrate m^3/s	To storage (peak-0.410) m^3/s	Filling Volume m^3	From storage (0.410-peak) m^3/s	Emptying volume m^3	Cumulative storage m^3
M-1	0.300					
1-2	0.220					
2-3	0.180					
3-4	0.160					
4-5	0.160					

5-6	0.185					
6-7	0.240					
7-8	0.300					
8-9	0.385					
9-10	0.440	0.030	106.3			106.3
10-11	0.480	0.070	250.3			356.6
11-N	0.480	0.070	250.3			606.9
N-1	0.460	0.050	178.3			785.2
1-2	0.420	0.010	34.3			**819.6**
2-3	0.390			-0.020	-73.7	745.9
3-4	0.355			-0.055	-199.7	546.2
4-5	0.331			-0.079	-286.1	260.1
5-6	0.315			-0.095	-343.7	0.0
6-7	0.320			-0.090	-325.7	
7-8	0.346			-0.064	-232.1	
8-9	0.362			-0.048	-174.5	
9-10	0.392			-0.018	-66.5	
10-11	0.360			-0.050	-181.7	
11-M	0.300			-0.110	-397.7	
Total	7.881					
Avg	0.328					
Avg x 1.25	0.410					

PROBLEM 3-17

Problem Statement - See text, page 260

Solution

1. Determine the off-line storage volume needed to equalize the flowrate

   The off-line volume required to equalize the flow is that same as the in-line volume given in Example 3-10.

2. Determine the effect of flow equalization on the BOD mass loading to the wastewater treatment plant. The computation table required to determine the BOD mass loadings is presented below.

   a. The average flowrate over the 24 h period is 0.307 m^3/s = 1,106 m^3/h

   b. The volume diverted to the storage basin is equal to:

   Diverted volume = inflow volume during a 1 h time period – 1,106 m^3

   For the time period 8-9:

V_d = 1278 m^3 – 1106 m^3 = 172 rage basin during the current time period, g/m^3 (mg/L)

V_{ic} = volume of wastewater diverted to storage basin during the current period, m^3

X_{ic} = average concentration of BOD in the inflow wastewater volume during the current period, g/m^3

V_{sp} = volume of wastewater in storage basin at the end of the previous time period, m^3

X_{sp} = concentration of BOD in wastewater in storage basin at the end of the previous time period, g/m^3

For the time period 8-9:

$$X_{ec} = \frac{(172\text{ m}^3)(175\text{ g/m}^3) + (0)(0)}{172\text{ m}^3 + 0} = 175\text{ g/m}^3$$

For the time period 9-10:

$$X_{ec} = \frac{(370\text{ m}^3)(200\text{ g/m}^3) + (172\text{ m}^3)(175\text{ g/m}^3)}{(370 + 172)\text{ m}^3} = 192\text{ g/m}^3$$

All the concentration values computed in a similar manner are reported in the computation table.

d. The third step is to compute the hourly mass loading rate using the following expression:

   i. Mass loading to the plant for treatment while the storage basin is filling:

   Mass loading rate to plant, kg/h = (V_T – V_{ic}, m^3/h) (X, g/m^3)

   where V_T = total influent flowrate

   For example, for the time period 8-9, the mass loading rate is

   = [(1278 – 172) m^3](175 g/m^3)/ 10^3 g/kg)

   = 194 kg/h (rounded)

ii. Mass loading to the plant for treatment while drawing from storage:

Mass loading to plant, kg/h = $[(V_T)(X_{ic}) + (V_{sp})(X_{sp})]/10^3$ g/kg)

For example, for the time period M-1, the mass loading rate is

= $[(990\ m^3)(150\ g/m^3) + (116\ m^3)(214\ g/m^3)]/10^3$ g/kg)

= 174 kg/h (rounded)

e. Set up a spreadsheet and computation table similar to that below.

Time period	Volume of flow during time period, m^3	Influent BOD, g/m^3	Volume diverted to (+) or from (-) storage, m^3	Cumulative volume in storage, m^3	Average BOD concentration in storage, g/m^3	BOD to plant, g/m^3	BOD mass loading to plant, kg/h
8-9	1278	175	172	172	175	175	194
9-10	1476	200	370	542	192	200	221
10-11	1530	215	424	966	202	215	238
11-N	1548	220	442	1408	208	220	243
N-1	1530	220	424	1832	211	220	243
1-2	1458	210	352	2184	210	210	232
2-3	1386	200	280	2464	209	200	221
3-4	1260	190	154	2618	208	190	210
4-5	1170	180	64	2682	207	180	199
5-6	1170	170	64	2746	207	170	188
6-7	1188	175	82	2828	206	175	194
7-8	1314	210	208	3036	206	210	232
8-9	1440	280	334	3370	213	280	310
9-10	1440	305	334	3704	222	305	337
10-11	1368	245	262	3966	223	245	271
11-M	1242	180	136	4102	222	180	199
M-1	990	150	-116	3986	222	158	174
1-2	792	115	-314	3672	222	145	161
2-3	594	75	-512	3160	222	143	158
3-4	468	50	-638	2522	222	149	165
4-5	378	45	-728	1794	222	162	179
5-6	360	60	-746	1048	222	169	187
6-7	432	90	-674	374	222	170	189
7-8	738	130	-368	6	222	161	178
Average							213

3. Does the difference in the mass loading rate justify the cost of the larger basin required for in-line storage?
   a. If flow is to be equalized, the size of the basin required is the same for in-line and off-line storage
   b. Comparing the BOD mass loading values given in the above table for off-line storage to the corresponding values given in Example 3-10 for in-line storage (see computation table given on page 250), the benefits of using in-line storage with respect to BOD mass loadings is apparent.

	BOD Mass loading	
Ratio	In-line	Off-line
Peak/averqge	271/213 = 1.27	337/213 = 1.58
Minimum/average	132/213 = 0.62	158/213 = 0.74
Peak/minimum	271/132 = 2.05	337/158 = 2.13

PROBLEM 3-18

Problem Statement - See text, page 260

Instructional Guidelines

Because an iterative solution is necessary to obtain an answer to this problem, a considerable amount of time is required to obtain a precise answer; however, a spreadsheet can facilitate the computations. It is suggested, therefore, that the students be advised that an approximate answer is acceptable.

Solution

1. Determine the required storage volume and peak-to minimum BOD loading ratio for equalized flow.

   From Example 3-10, a basin with a volume of 4110 m^3 (max. volume in storage), a peak-to-minimum BOD loading ratio of 2.05 is obtained.

2. Determine the peak-to minimum BOD loading ratio for a storage volume of ≈ 3,000 m^3 using the same procedure outlined in Example 3-10. The computations are summarized in the following computation table.

Computation Table, Basin Volume = 3000 m^3

Time period	Volume of flow in during time period, m^3	Influent BOD, g/m^3	Volume of flow out, m^3	Volume to storage, m^3	Volume in storage at end of time period, m^3	Equalized BOD during time period, g/m^3	Equalized BOD mass loading to plant, kg/h
8-9	1278	175	1106	172	172	175	194
9-10	1476	200	1106	370	542	197	218
10-11	1530	215	1106	424	966	210	233
11-N	1548	220	1106	442	1408	216	239
N-1	1530	220	1106	424	1832	218	241
1-2	1458	210	1106	352	2184	215	237
2-3	1386	200	1106	280	2464	209	231
3-4	1260	190	1106	154	2618	203	224
4-5	1170	180	1106	64	2682	196	216
5-6	1170	170	1106	64	2746	188	208
6-7	1188	175	1106	82	2828	184	203
7-8	1314	210	1142	172	3000	192	219
8-9	1440	280	1440	0	3000	221	318
9-10	1440	305	1440	0	3000	248	357
10-11	1368	245	1368	0	3000	247	338
11-M	1242	180	1242	0	3000	227	282
M-1	990	150	1106	-116	2884	208	230
1-2	792	115	1106	-314	2570	188	208
2-3	594	75	1106	-512	2058	167	185
3-4	468	50	1106	-638	1420	145	161
4-5	378	45	1106	-728	692	124	137
5-6	360	60	1052	-692	0	102	108
6-7	432	90	432	0	0	90	39
7-8	738	130	738	0	0	130	96

For a storage basin volume of 3000 m^3, the peak-to minimum BOD_5 loading ratio is:

$$\frac{\text{Peak}}{\text{Min}} = \frac{357}{39} = 9.15$$

3. Using the spreadsheet, the maximum basin volume can be changed and the volumes, mass loadings, and concentrations can be recalculated. For

example, if the basin volume is increased to 3,300 m^3, the following results will be obtained:

Time period	Volume of flow in during time period, m^3	Influent BOD, g/m^3	Volume of flow out, m^3	Volume to storage, m^3	Volume in storage at end of time period, m^3	Equalized BOD during time period, g/m^3	Equalized BOD mass loading to plant, kg/h
8-9	1278	175	1106	172	172	175	194
9-10	1476	200	1106	370	542	197	218
10-11	1530	215	1106	424	966	210	233
11-N	1548	220	1106	442	1408	216	239
N-1	1530	220	1106	424	1832	218	241
1-2	1458	210	1106	352	2184	215	237
2-3	1386	200	1106	280	2464	209	231
3-4	1260	190	1106	154	2618	203	224
4-5	1170	180	1106	64	2682	196	216
5-6	1170	170	1106	64	2746	188	208
6-7	1188	175	1106	82	2828	184	203
7-8	1314	210	1106	208	3036	192	213
8-9	1440	280	1176	264	3300	220	259
9-10	1440	305	1440	0	3300	246	354
10-11	1368	245	1368	0	3300	246	336
11-M	1242	180	1242	0	3300	228	283
M-1	990	150	1106	-116	3184	210	232
1-2	792	115	1106	-314	2870	191	211
2-3	594	75	1106	-512	2358	171	189
3-4	468	50	1106	-638	1720	151	167
4-5	378	45	1106	-728	992	132	146
5-6	360	60	1052	-692	300	113	119
6-7	432	90	732	-300	0	99	73
7-8	738	130	738	0	0	130	96

For a storage basin volume of 3000 m^3, the peak-to minimum BOD loading ratio is:

$$\frac{\text{Peak}}{\text{Min}} = \frac{354}{73} = 4.85$$

The ratio is close to the desired ratio of 5:1 indicated in the problem statement thus the equalization volume of 3300 m^3 is adequate.

4

WASTEWATER TREATMENT PROCESS SELECTION, DESIGN, AND IMPLEMENTATION

PROBLEM 4-1

Problem Statement - See text, page 300

Instructional Guidelines

If consulting engineering or other reports are available, it would be helpful to put them on reserve in the library. To avoid having each member of the class contact the local wastewater management agency individually, it would be best to organize the class into study groups. . One person can then be selected from each study group to go together to obtain the necessary information from the appropriate city or regional agency.

PROBLEM 4-2

Problem Statement - See text, page 301

Instructional Guidelines

The purpose of this problem is to expose students to the significance and importance of properly prepared environmental impact reports. It would, therefore, be appropriate if the instructor spent at least one class period discussing what is involved in the preparation of such reports. The learning value of this problem can be enhanced if example copies of both well and poorly prepared reports are available or the students to review.

PROBLEM 4-3

Problem Statement - See text, page 301

Solution

1. From Equation 4-2,

$$\text{Future cost} = \frac{\text{Projected future value of index}}{\text{Current value of index}} \times \text{Current cost}$$

Note: Construction cost indices (CCI) are available from Engineering News Record (ENR). If the ENRCCI historical and forecasted CCI are not available through your local library, check with your state transportation agency. In lieu of forecasted values, the student can make a linear projection based on historical and current values.

The most recent (2012) end-of-year national CCI value was approximately 99,412. Projected future end-of-year CCI value projecting **5 years** is approximately 196,107.

$$\text{Future cost} = \frac{196{,}107}{99{,}412} \times \$5 \times 10^6$$

$$= \$9.86 \times 10^6$$

PROBLEM 4-4

Problem Statement - See text, page 301

Instructional Guidelines

It may be appropriate for the instructor to provide the construction cost and the year the project was completed.

Solution

1. The solution to this problem involves the application of Eq. (4-1).

$$\text{Current cost} = \frac{\text{Current value of index}}{\text{Value of index at time of estimate}} \text{ x Estimated cost}$$

Although published cost indexes used to track historic cost trends are a useful tool for adjusting costs to a common past or current date, judgment is still required in selecting the appropriate index and in assuming inflation rates for future costs.

2. The average rate of inflation can be obtained from a variety of web sources including the following:

http://inflationdata.com/Inflation/Inflation/DecadeInflation.asp

http://inflationdata.com/Inflation/Inflation_Rate/HistoricalInflation.aspx

http://inflationdata.com/Inflation/Inflation_Rate/Long_Term_Inflation.asp

Although published cost indexes used to track historic cost trends are a useful tool for adjusting costs to a common past or current date, judgment is still required in selecting the appropriate index and in assuming inflation rates for future costs.

PROBLEM 4-5

Problem Statement - See text, page 301

Solution

1. Convert the treatment plant flow rate to Mgal/d:

$$\text{Flow} = (4000\ \text{m}^3/\text{d})(2.642 \times 10^{-4}\ \text{Mgal/m}^3)$$

$$= 1.057\ \text{Mgal/d}$$

2. Calculate daily energy use:

$$\text{Energy use} = (2500\ \text{kWh/Mgal})(1.057\ \text{Mgal/d})$$

$$= 2642\ \text{kWh/d}$$

3. Estimate annual energy cost
   a. Energy costs paid by wastewater treatment facilities will vary based on fees, tariffs, and electric utility rate structures including seasonal variability, tiered pricing, and time of use (TOU) periods (peak, part peak, off peak, etc.). For the purpose of this problem, an average total rate of $0.17/kWh was used. Most utilities utilize units of kWh.
   b. Calculate energy cost

$$\text{Energy cost} = (2642\ \text{kWh/d})(\$0.17/\text{kWh})(365\ \text{d/y})$$

$$= \$163{,}937\ \text{annually}$$

PROBLEM 4-6

Problem Statement - See text, page 301

Instructional Guidelines

As a starting point, suggest that students search the net by typing "Wastewater probability plots,"

The following references contain probability plots

Melcer, H., P.L. Dold, R.M. Jones, C.M. Bye, I. Takacs, H.D. Stensel, A.W. Wilson, P. Sun, and S. Bury (2003) *Methods for Wastewater Characterization in Activated Sludge Modeling.* WERF Final Report, Project 99-WWF-3, Water Environment Research Foundation, Alexandria, VA.

Mines, R.O., L.W. Lackey, and G.R. Behrend (2006) "Performance Assessment of Major Wastewater Treatment Plants (WWTPs) in the State of Georgia," *J. Environ. Sci. Health A. Tox. Hazard Subst. Environ. Eng.,* **41**, 10, 2175-2198.

Problem Analysis

1. For arithmetic-probability plots, the following relationship is used to obtain the arithmetic standard deviation (see Appendix D)

   $$s = P_{84.1} - \bar{x} \text{ or } P_{15.9} + \bar{x}$$

2. For logarithmic-probability plots the following relationship is used to obtain the geometric standard deviation (see Appendix D)

   $$s_g = \frac{P_{84.1}}{M_g} = \frac{M_g}{P_{15.9}}$$

PROBLEM 4-7

Problem Statement - See text, page 301

Solution

1. Because the not-to-exceed value was set at the highest value from six effluent samples, the probability plot concept can be applied to estimate the frequency that the process effluent will exceed the permit requirements.

   a. The plotting position on probability paper can be determined using Blom's transformation (Eq. D-11, Appendix D, page 1917).

   $$\text{Plotting position, \%} = \left(\frac{m - 3/8}{n + 1/4}\right) \text{ x } 100$$

   Where m = rank of the value when arranged from lowest to highest

   n = number of samples

   b. Determine the plotting position for the maximum value of six samples.

   $$\text{Plotting position of maximum value} = \left(\frac{6 - 3/8}{6 + 1/4}\right) \text{ x } 100 = 90\%$$

   c. Determine the frequency that the effluent constituent concentration can be expected to exceed the not-to-exceed value.

   Frequency of exceeding discharge limit = 99.9% – 90% = 9.9%

2. Clearly, the superintended should have collected more samples or negotiated with the Regulatory Agency for a more lienient effluent standard.

PROBLEM 4-8

Instructors Note: While Table 4-5, referenced in the problem statement, does provide ranges of coliphage concentrations for untreated wastewater and activated sludge effluent, more information is needed. Fig. 11-15 can be utilized to obtain distributions for primary influent and activated sludge (secondary) effluent coliphage concentrations. The geometric standard deviations, s_g, for the influent wastewater, activated sludge and reverse osmosis coliphage concentrations are 1.67, 1.67 and 1.15 pfu/100 mL, respectively.

Problem Statement - See text, page 301

Solution

1. Use the data from Fig. 11-15 to construct a plot including the reverse osmosis process. To facilitate plotting on log probability paper, use the geometric mean and standard deviation values for typical log removal of coliphage in the reverse osmosis process.

   a. From Fig. 11-15, the P_{50} can be estimated to be 2.1×10^4 pfu/100 mL for primary influent coliphage concentration and 300 for the activated sludge process. Therefore, the log removal for the activated sludge process is

   $$-\log\left(\frac{N}{N_o}\right) = -\log\left(\frac{300}{21{,}000}\right) = 1.85$$

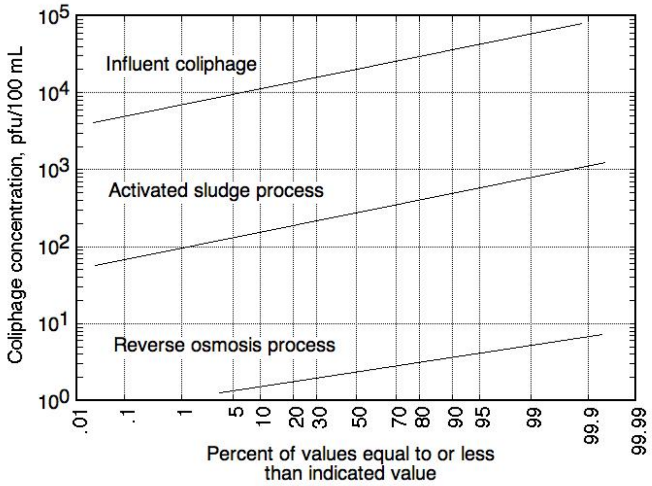
   b. The reverse osmosis process performance value of **2 log removal** (given in problem statement) and a geometric standard deviation (given in instructors note) will be used to determine the final effluent quality.

2. The plot and values shown on Fig. 11-15 can be used to for the activated sludge and reverse osmosis process.

   a. The P_{50} value for the influent coliphage concentration of **20,000 pfu/100 mL** is drawn on the plot with a slope determined using the geometric standard deviation of 1.67 (given in instructors note).

   b. The activated sludge performance is determined by drawing a line on the same plot with a P_{50} value at 283 pfu/100mL [log (20,000) – 1.85 = 2.45; $10^{2.45}$ = 283] with a slope determined using the geometric standard deviation of 1.67 (given in instructors note).

c. The reverse osmosis performance of **2.0 log removal** is also plotted with a P_{50} value of 2.83 pfu/100 mL (log (283) – 2 = 0.45; $10^{0.45}$ = 2.82), with a slope determined using the geometric standard deviation of 1.15 (given in instructors note).



3. The removal achieved at 99 and 99.9 percent reliability is 7.5 and 6 pfu/100mL, respectively.

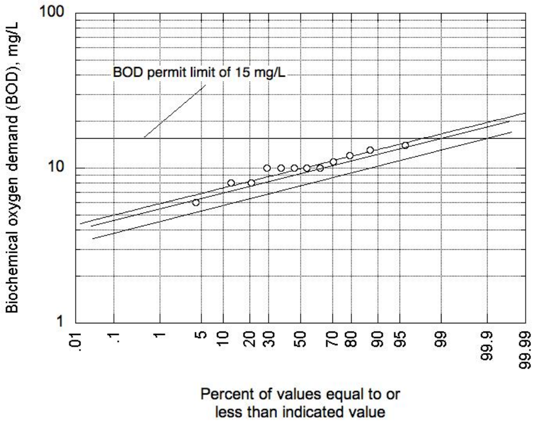
PROBLEM 4-9

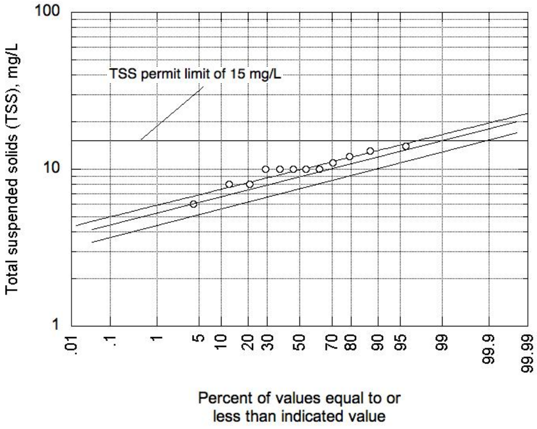
Problem Statement - See text, page 301

Solution

1. Plot the BOD and TSS values on log-probability paper. The required plots for **Plant 1** are shown below.

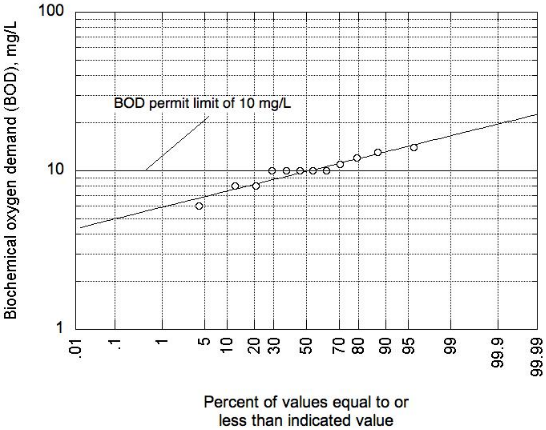
a. BOD and TSS = 15 mg/L at 99 and 99.9 percent reliability

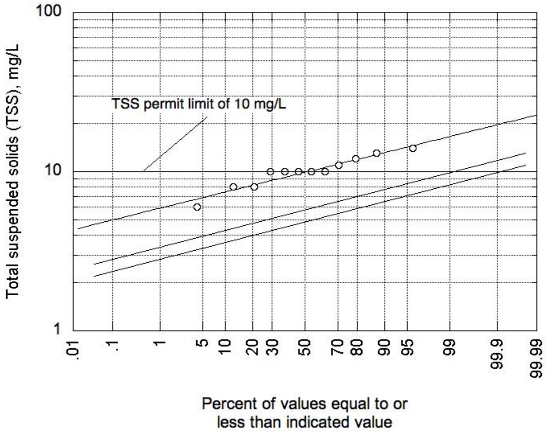




The mean design values for a BOD limit of 15 mg/L at 99 and 99.9 percent reliability are 6 and 4.2 mg/L, respectively. The mean design values for TSS at 99 and 99.9 percent reliability are 10 and 8.2 mg/L, respectively.

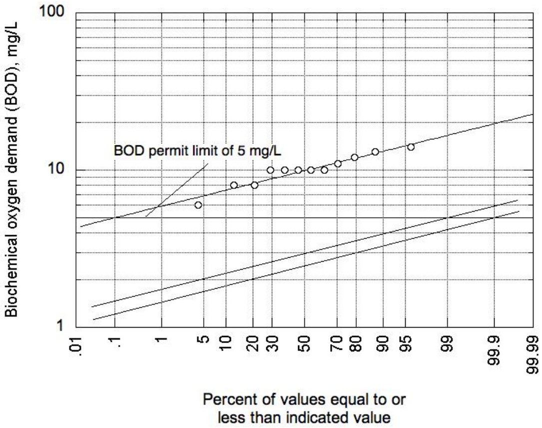
b. BOD and TSS = 10 mg/L at 99 and 99.9 percent reliability

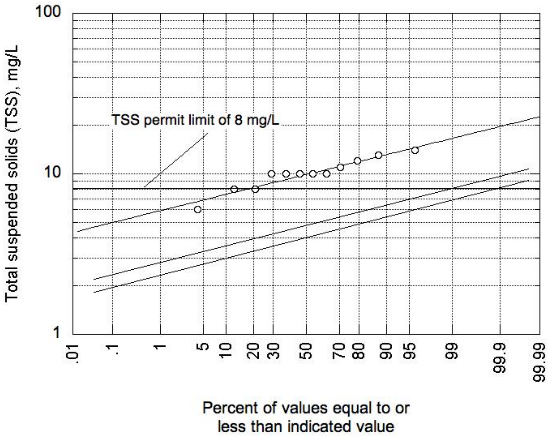




The mean design values for a BOD limit of 10 mg/L at 99 and 99.9 percent reliability are 4.1 and 3.1 mg/L, respectively. The mean design values for TSS at 99 and 99.9 percent reliability are 5.8 and 4.8 mg/L, respectively.

c. BOD = 5 mg/L and TSS = 8 mg/L at 99 and 99.9 percent reliability





The mean design values for a BOD limit of 5 mg/L at 99 and 99.9 percent reliability are 2 and 1.8 mg/L, respectively. The mean design values for TSS at 99 and 99.9 percent reliability are 4.5 and 3.8 mg/L, respectively.

2. The results for Treatment Plant 1 are summarized in the following table.

Constituent concentration,	Process reliability,	Mean design value, mg/L (percent improvement[a])

mg/L	%	BOD	TSS
5	99	2 (355)	
	99.9	1.8 (406)	
8	99		4.5 (122)
	99.9		3.8 (163)
10	99	4.1 (122)	5.8 (72)
	99.9	3.1 (194)	4.8 (108)
15	99	6 (52)	10 (0)
	99.9	4.2 (117)	8.2 (22)

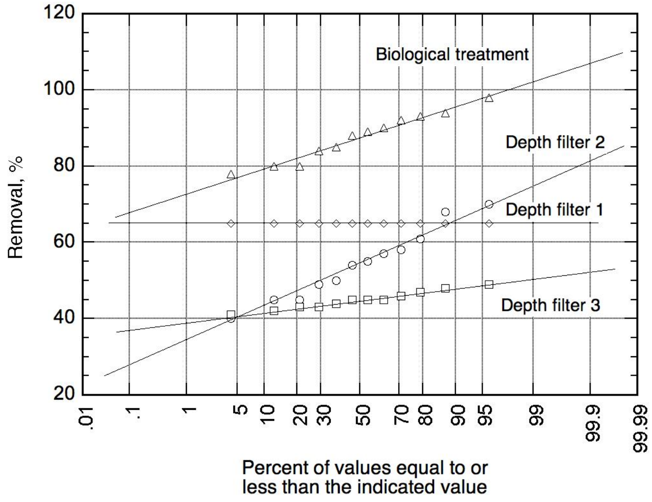
PROBLEM 4-10

Problem Statement - See text, page 302

Instructors Note: The problem statement should include the following additional question. What would be the expected constituent concentrations that could be achieved 99 and 99.9% of the time?

Solution

1. Plot the percent removals for each process on probability paper, the required plot is shown below.



2. Use the plot constructed in step 1 to determine the process performance values at 1 and 0.1 percent (99 and 99.9 percent performance, respectively). Assuming a geometric average removal for the biological

treatment process (i.e., 87 percent removal), the 99 and 99.9 percent performance for **depth filter 2** is computed as follows.

a. For the influent concentration of **150 mg/L**, the average effluent concentration from the biological process is 150 (1 - 0.87) = 19.5.

b. The 99 percent performance value (1 percent) for filter 2 is 35% removal, and an effluent concentration of 19.5 (1 – 0.35) = 12.68.

c. The 99.9 percent performance value (0.1 percent) for filter 2 is 27% removal, and an effluent concentration of 19.5 (1 – 0.27) = 14.24.

3. Summary of results for Problem 4-10.

	Effluent concentration at indicated reliability, mg/L			
	Influent constituent concentration, mg/L			
Reliability of treatment process	150	200	275	300
Mean biological treatment effluent	19.5	26	35.8	39
Depth filter A				
50%	12.68	16.90	23.24	25.35
99%	6.83	9.10	12.51	13.65
99.9%	6.83	9.10	12.51	13.65
Depth filter B				
50%	10.73	14.30	19.66	21.45
99%	12.68	16.90	23.24	25.35
99.9%	14.24	18.98	26.10	28.47
Depth filter C				
50%	8.78	11.70	16.09	17.55
99%	11.90	15.86	21.81	23.79
99.9%	12.48	16.64	22.88	24.96

PROBLEM 4-11

Problem Statement - See text, page 302

Solution

Instructional Guidelines

Some important design considerations are summarized in the table given below. Many of the design considerations may be found in Chap. 14.

Solution

The design considerations are summarized in the table below, Most of the design considerations given below may be found in Chaps. 13, 14, and 15. The reason for presenting this homework problem in this chapter before the assignment of Chaps. 13, 14, and 15 is to get students to think about what might be important. It is not expected that student would produce a list such as the one given in the table, but would identify a few of the considerations. In the classroom, the instructor could then discuss how to begin to think about the many issues involved.

Parameter	**Design consideration**
Process selection	For plant sizes less than 15,00 to18,000 m^3/d, aerobic digestion is used more commonly than anaerobic digestion, however, the selection should be compatible with existing processes in the expansion and upgrading of an existing plant.
Feed solids concentration	Low feed solids (less than 3 percent) can adversely affect performance of anaerobic digesters. High feed solids (over 4 percent) may affect the ability of the mixing and aeration system.
Thickening	Thickening may be needed to optimize performance (see feed solids concentration above).
Volatile solids destruction	Volatile solids destruction on the order of 56 to 65 percent may be achieved by anaerobic digestion compared to 38 to 50 percent by aerobic digestion.
Process performance	In colder climates, performance of aerobic digesters will be affected by changing temperatures, especially if the aerobic digestion tanks are uninsulated and open to the atmosphere. At colder temperatures, the reaction rates decrease. For colder climates, the use of the ATAD process might be a more appropriate alternative for aerobic digestion as the process generates heat. Anaerobic digesters are relatively unaffected by ambient temperature changes.
Recycle streams	Supernatant return flows from anaerobic digesters have higher concentrations of BOD and TSS than return flows from aerobic digesters. Unless the loads from return flows from the digestion, thickening, dewatering, and other solids handling processes are accounted for in the process design of the biological process, plant upsets can result.

Phosphorus removal	If phosphorus removal is included in the treatment process, anaerobic digestion should be avoided, as anaerobic decomposition will release the bound phosphorus.
Energy requirements	The requirement for electric energy for aerobic digestion for mixing and aeration will be considerably higher than the requirement for mixing in anaerobic digestion. The energy required for mixing in egg-shaped digesters will be less than that for conventional cylindrical digesters. The cost of electric power is an important consideration in evaluating the operating cost for aerobic digestion.
Energy recovery	The methane gas produced in the anaerobic digestion process can be recovered for use in digester heating, power generation, and cogeneration. Energy recovery from aerobic digestion is only possible in the ATAD process where the heat produced in oxidation of volatile solids is utilized to heat the reactor.
Operability	Operationally, conventional aerobic digestion is a somewhat less complex process to operate than anaerobic digestion. However, aerobic digester performance may be variable, especially due to seasonal effects. The ATAD process is more complex than conventional aerobic digestion, but better volatile solids destruction may be achieved.
Cost evaluation	The construction costs for anaerobic digesters are higher than aerobic digesters. The operating costs, principally for electric energy, are significantly higher for aerobic digestion. A life cycle cost analysis should be done so all of the cost factors can be evaluated in making an appropriate economic decision.

Continued on following page

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PROBLEM 4-12

Problem Statement - See text, page 302

Solution

Instructor's note: The purpose of this problem is to illustrate to junior and senior students the application of undergraduate hydraulics in the preparation of hydraulic profiles. The material needed to solve this problem was not specifically covered in this chapter. Use of hydraulic control points such as effluent weirs, for the preparation of hydraulic profiles should be discussed by the instructor before the problem is assigned. Although not stated, assume there are one primary clarifier, one secondary clarifier and one aeration tank.

Conditions:

Q_{avg} = 4000 m^3/d plus 100 percent sludge recycle

Q_{peak} = 8000 m^3/d plus 50 percent sludge recycle

Q_{low} = 2000 m^3/d plus 100 percent sludge recycle

Spacing of v-notch weirs = 600 mm

Width of aeration-tank effluent weir = 1400 mm

Number of primary and secondary clarifiers = 1 each

Problem Analysis

1. List basic assumptions.
   a. The given weir height is at the bottom of the V-notch.
   b. Concrete piping with an absolute roughness, $\varepsilon = 0.5 \times 10^{-3}$ m is to be used to interconnect treatment units.
   c. Recycled flow enters at head of aeration tanks.

2. Determine the liquid level in the secondary clarifiers.
   a. The number of V-notch weirs is:

$$\text{No. of V-notch weirs} = \frac{\text{Perimeter}}{0.60\text{ m}} = \frac{\pi \cdot d}{0.60\text{ m}} = \frac{\pi\left(15\text{ m}\right)}{0.60\text{ m}} = 79$$

   b. Find the head on the weirs
      i. Flow per weir

$$Q_{avg} = \frac{(4000\text{ m}^3/\text{d})}{\left(86{,}400\text{ s/d}\right)\left(79\right)} = 5.895 \times 10^{-4}\text{ m}^3/\text{s}$$

$$Q_{peak} = \frac{(8000\text{ m}^3/\text{d})}{\left(86{,}400\text{ s/d}\right)\left(79\right)} = 1.179 \times 10^{-3}\text{ m}^3/\text{s}$$

      ii. The V-notch weir equation is:

$$Q_{weir} = \frac{8}{15}\sqrt{2g} \cdot C_D \cdot \tan\ \phi/2 \cdot H^{5/2}$$

where C_D = discharge coefficient

= 0.585 for 90° V-notch

ϕ = angle of V = 90°

$$Q_{weir} = \frac{8}{15}\sqrt{2\left(9.8\right)} \cdot 0.585 \cdot \tan\ 90°/2 \cdot H^{5/2}$$

$$= 1.38\ H^{5/2}$$

iii. Head on weir:

a. Compute *H* for average and peak flow conditions:

$$\text{At } Q_{avg} : H = \left(\frac{Q}{1.38} \right)^{2/5}$$

$$= \left(\frac{5.895 \times 10^{-4}}{1.38} \right)^{2/5} = 0.045 \text{ m}$$

$$\text{At } Q_{peak} : H = \left(\frac{Q}{1.38} \right)^{2/5}$$

$$= \left(\frac{1.179 \times 10^{-3}}{1.38} \right)^{2/5} = 0.059 \text{ m}$$

b. Compute the liquid level in the secondary clarifiers:

i) At Q_{avg}, Elev = 518.260 + 0.045 = 518.305 m

ii) At Q_{peak}, Elev = 518.260 + 0.059 = 518.319 m

3. Determine liquid level in effluent channel from the aeration tank.

a. At Q_{avg}:

i. Minor losses

a) 2, 90° elbows

$$h_L = K_b \cdot \frac{v^2}{2g}$$

where K_b = 0.3 (varies with source)

$$v = \frac{Q_{avg} + Q_{recycle}}{A_{pipe}}$$

$$= \frac{4000 + 4000}{\frac{\pi}{4}(0.48)^2 \cdot (86{,}400 \text{ s/d})} = 0.51 \text{ m/s}$$

$$h_L = (0.3) \cdot \frac{(0.51)^2}{2(9.8)} = 0.0040 \text{ m}$$

b) Entrance

$$h_L = K_e \cdot \frac{v^2}{2g}$$

where K_e = 0.5

$$v = 0.51\,\text{m/s}$$

$$h_L = 0.5 \cdot \frac{(0.51)^2}{2(9.8)} = 0.0067\text{ m}$$

c) Exit

$$h_L = \frac{v^2}{2g} = \frac{(0.51)^2}{2(9.8)} = 0.0134\text{ m}$$

ii. Friction losses

$$h_L = f\frac{L}{D}\frac{v^2}{2g}\text{ (Darcy-Weisbach)}$$

where L = 38 m

v = 0.51 m/s

D = 0.48 m

f = 0.020 for $\varepsilon/D = 1.04 \times 10^{-3}$ from Moody diagram

$$h_L = 0.020\frac{(38)}{(0.48)}\frac{(0.51)^2}{2(9.8)} = 0.0212\text{ m}$$

ii. Total headloss

Total h_L = 0.0040 + 0.0067 + 0.0134 + 0.0212

= 0.0452 m

b. At Q_{peak}:

i. Minor losses

a) 2, 90° elbows

$$h_L = 0.3 \cdot \frac{v^2}{2g}$$

$$\text{where } v = \frac{Q_{peak} + Q_{recycle}}{A_{pipe}}$$

$$= \frac{8000 + 4000}{\frac{\pi}{4}(0.48)^2 \cdot (86{,}400\text{ s/d})} = 0.77\text{ m/s}$$

$$h_L = (0.3)\cdot\frac{(0.77)^2}{2(9.8)} = 0.0090\text{ m}$$

b) Entrance

$$h_L = K_e \cdot \frac{v^2}{2g}$$

where v = 0.77 m/s

$$h_L = 0.5 \cdot \frac{(0.77)^2}{2(9.8)} = 0.0150 \text{ m}$$

c) Exit

$$h_L = \frac{v^2}{2g} = \frac{(0.77)^2}{2(9.8)} = 0.0301 \text{ m}$$

ii. Friction losses

$$h_L = f\frac{L}{D}\frac{v^2}{2g} \text{ (Darcy-Weisbach)}$$

where v = 0.77 m/s

$$h_L = 0.020\frac{(38)}{(0.48)}\frac{(0.77)^2}{2(9.8)} = 0.0476 \text{ m}$$

iii. Total headloss

Total h_L = 0.0090 + 0.0150 + 0.0301 + 0.0476

= 0.1017 m

c. The liquid level in the aeration tank effluent channel is:

i) At Q_{avg} = 518.305 + 0.0452 = 518.350

ii) At Q_{avg} = 518.319 + 0.1017 = 518.421

4. Determine liquid level in the aeration tank.

a. Francis type weir (contracted, rectangular, sharp-crested) equation:

$$Q, \text{m}^3/\text{s} = 1.84(L - 0.1 \cdot n \cdot H)H^{3/2}$$

where 1.84 = experimentally-determined constant (metric)

L = width of weir, m

n = number of end contractions

H= head above weir, m

Given unknown head above weir, solve Francis equation for H by substituting the term $L - 0.1nH$ by L:

$$Q = 1.84 \cdot L \cdot H^{3/2}$$

$$H = \left(\frac{Q}{1.84 \cdot L}\right)^{2/3}$$

b. At Q_{avg}:

$$H=\left[\frac{(4000\ \text{m}^3/\text{d}+4000\ \text{m}^3/\text{d})}{\left(86{,}400\ \text{s/d}\right)1.84\left(1.4\ \text{m}\right)}\right]^{2/3}=0.1089\ \text{m}$$

$$\text{recomputing } L=1.4-0.2\left(0.1089\right)=1.378$$

$$H=\left[\frac{8000}{\left(86{,}400\right)1.84\left(1.386\right)}\right]^{2/3}=0.1101\ \text{m}$$

$$\text{recomputing } L=1.4-0.2\left(0.1101\right)=1.378$$

(converges after 1 iteration)

$$H=0.1101\ \text{m}$$

c. At Q_{peak}:

$$H=\left[\frac{(8000\ \text{m}^3/\text{d}+4000\ \text{m}^3/\text{d})}{\left(86{,}400\ \text{s/d}\right)1.84\left(1.4\ \text{m}\right)}\right]^{2/3}=0.1427\ \text{m}$$

$$\text{recomputing } L=1.4-0.2\left(0.1427\right)=1.371$$

$$H=\left[\frac{12{,}000}{\left(86{,}400\right)1.84\left(1.382\right)}\right]^{2/3}=0.1447\ \text{m}$$

$$\text{recomputing } L=1.4-0.2\left(0.1447\right)=1.371$$

(converges after 1 iteration)

$$H=0.1447\ \text{m}$$

Note: More accurate methods of determining the head requirement for a sharp-crested weir with end contractions have been developed by the following references:

Kindsvater, C.E., and R.W. Carter, "Discharge Characteristics of Rectangular Thin-Plate Weirs," Paper No. 3001, Transactions, American Society of Civil Engineers, vol. 124, 1959.

Ackers, W.R., J.A. Perkins, and A.J.M. Harrison, Weirs and Flumes for Flow Measurement, John Wiley & Sons, New York, 1978.

King, H.W., and E.F. Brater, Handbook of Hydraulics, fifth edition, McGraw-Hill Book Company, Inc., New York, 1963.

d. The liquid level in the aeration tank is:

i. At Q_{avg} = 519.10 + 0.1101 = 519.210 m

ii. At Q_{peak} = 519.10 + 0.1447 = 519.245 m

5. Determine liquid level in the primary clarifier effluent channel.

a. At Q_{avg}:

i. Minor losses

(a) 2, 90° elbows

$$h_L = 0.3 \cdot \frac{v^2}{2g}$$

$$\text{where } v = \frac{Q_{avg}}{A_{pipe}}$$

$$= \frac{4000}{(86{,}400)\frac{\pi}{4}(0.40)^2} = 0.37 \text{ m/s}$$

$$h_L = (0.3) \cdot \frac{(0.37)^2}{2(9.8)} = 0.0021 \text{ m}$$

(b) Entrance

$$h_L = K_e \cdot \frac{v^2}{2g}$$

where K_e = 0.5

$$v = 0.37 \text{ m/s}$$

$$h_L = 0.5 \cdot \frac{(0.37)^2}{2(9.8)} = 0.0035 \text{ m}$$

(c) Exit

$$h_L = \frac{v^2}{2g} = \frac{(0.37)^2}{2(9.8)} = 0.0069 \text{ m}$$

ii. Friction losses

$$h_L = f\frac{L}{D}\frac{v^2}{2g} \text{ (Darcy-Weisbach)}$$

where L = 46.5 m

v = 0.37 m/s

D = 0.40 m

f = 0.021 for $\varepsilon/D = 1.25 \times 10^{-3}$

from Moody diagram

$$h_L = 0.021\frac{(46.5)}{(0.40)}\frac{(0.37)^2}{2(9.8)} = 0.0169 \text{ m}$$

ii. Total headloss

Total h_L = 0.0021 + 0.0035 + 0.0069 + 0.0169

= 0.0294 m

b. At Q_{peak}:

i. Minor losses

(a) 2, 90° elbows

$$h_L = 0.3 \cdot \frac{v^2}{2g}$$

$$\text{where } v = \frac{Q_{peak}}{A_{pipe}}$$

$$= \frac{8000}{(86{,}400)\frac{\pi}{4}(0.40)^2} = 0.74 \text{ m/s}$$

$$h_L = (0.3) \cdot \frac{(0.74)^2}{2(9.8)} = 0.0083 \text{ m}$$

(b) Entrance

$$h_L = K_e \cdot \frac{v^2}{2g}$$

where v = 0.74 m/s

$$h_L = 0.5 \cdot \frac{(0.74)^2}{2(9.8)} = 0.0138 \text{ m}$$

(c) Exit

$$h_L = \frac{v^2}{2g} = \frac{(0.74)^2}{2(9.8)} = 0.0277 \text{ m}$$

ii. Friction losses

$$h_L = f\frac{L}{D}\frac{v^2}{2g} \text{ (Darcy-Weisbach)}$$

where v = 0.74 m/s

$$h_L = 0.021\frac{(46.5)}{(0.40)}\frac{(0.74)^2}{2(9.8)} = 0.0676 \text{ m}$$

iii. Total headloss

Total h_L = 0.0083 + 0.0138 + 0.0277 + 0.0676

= 0.1175 m

c. The liquid level in the primary clarifier effluent channel is:

i) At Q_{avg} = 519.210 + 0.0294 = 519.239 m

ii) At Q_{peak} = 519.245 + 0.1175 = 519.362 m

6. Determine liquid level in the primary clarifier.

a. Determine the number of weirs.

$$\text{No. of weirs} = \frac{\text{Perimeter}}{0.60 \text{ m}} = \frac{\pi \cdot d}{0.60 \text{ m}} = \frac{\pi(13.75 \text{ m})}{0.60 \text{ m}} = 72$$

b. Find the head on the weirs

i. Flow per weir

$$Q_{avg} = \frac{4000 \text{ m}^3/\text{d}}{(86{,}400 \text{ s/d})(72)} = 6.431 \times 10^{-4} \text{ m}^3/\text{s}$$

$$Q_{peak} = \frac{8000 \text{ m}^3/\text{d}}{(86{,}400 \text{ s/d})(72)} = 1.286 \times 10^{-3} \text{ m}^3/\text{s}$$

ii. Head on weir:

c. Compute H for average and peak flow conditions using the V-notch weir equation given in Part 2 above:

$$\text{At } Q_{avg} : H = \left(\frac{Q}{1.38}\right)^{2/5}$$

$$= \left(\frac{6.431 \times 10^{-4}}{1.38}\right)^{2/5} = 0.047 \text{ m}$$

$$\text{At } Q_{peak}: \; H = \left(\frac{Q}{1.38}\right)^{2/5}$$

$$= \left(\frac{1.286 \times 10^{-3}}{1.38}\right)^{2/5} = 0.061\,\text{m}$$

d. Compute the liquid level in the primary clarifiers:

i. At Q_{avg}, Elev = 519.50 + 0.047 = 519.546 m

ii. At Q_{peak}, Elev = 519.50 + 0.061 = 519.561 m

7. Summary of results

Location along hydraulic profile	Liquid Level Elevation, m	
	Q_{avg}	Q_{peak}
Primary clarifiers	519.546	519.561
Primary clarifier effluent channel	519.239	519.362
Aeration tank	519.210	519.245
Aeration tank effluent channel	518.350	518.421
Secondary clarifiers	518.305	518.319

PROBLEM 4-13

Problem Statement - See text, page 303

Instructor's note: The purpose of this problem is to illustrate to junior and senior students the application of undergraduate hydraulics in the preparation of hydraulic profiles. The material needed to solve this problem was not specifically covered in this chapter. Use of hydraulic control points such as effluent weirs, for the preparation of hydraulic profiles should be discussed by the instructor before the problem is assigned. Although not stated, assume there are two aeration tanks.

Solution

Conditions:

Q_{avg} = 7500 m^3/d plus 100 percent sludge recycle

Q_{peak} = 15,000 m^3/d plus 50 percent sludge recycle

Q_{low} = 2500 m^3/d plus 100 percent sludge recycle

Number of primary and secondary clarifiers = 2

Diameter of line from aeration tank to each clarifier = 400 mm

Spacing of v-notch weirs = 600 mm

Width of aeration-tank effluent weir = 1400 mm

Problem Analysis

1. List basic assumptions.
    a. The given weir height is at the bottom of the V-notch.
    b. Concrete piping with an absolute roughness, $\varepsilon = 0.5 \times 10^{-3}$ m is to be used to interconnect treatment units.
    c. Recycled flow enters at head of aeration tanks.
2. Determine the liquid level in the secondary clarifiers.
    a. The number of V-notch weirs is 79 as calculated in Problem 4-12 above.
    b. Find the head on the weirs
        i. Flow per weir

$$Q_{peak} = \frac{(15{,}000\ \text{m}^3/\text{d})}{2(86{,}400\ \text{s/d})(79)} = 1.105 \times 10^{-3}\ \text{m}^3/\text{s}$$

$$Q_{low} = \frac{(2500\ \text{m}^3/\text{d})}{2(86{,}400\ \text{s/d})(79)} = 1.842 \times 10^{-4}\ \text{m}^3/\text{s}$$

ii. Head on weir:

e. Compute *H* for average and peak flow conditions using the V-notch weir equation given in Problem 4-12, Part 2 above:

$$\text{At } Q_{peak}\ :\ H = \left(\frac{Q}{1.38}\right)^{2/5}$$

$$= \left(\frac{1.105 \times 10^{-3}}{1.38}\right)^{2/5} = 0.058\ \text{m}$$

$$\text{At } Q_{low}:\ H = \left(\frac{Q}{1.38}\right)^{2/5}$$

$$= \left(\frac{1.842 \times 10^{-4}}{1.38}\right)^{2/5} = 0.028\ \text{m}$$

f. Compute the liquid level in the secondary clarifiers:

i) At Q_{peak}, Elev = 518.26 + 0.058 = 518.318 m

ii) At Q_{low}, Elev = 518.26 + 0.028 = 518.288 m

3. Determine liquid level in effluent channel from the aeration tank.

   a. At Q_{peak}:

      i. Minor losses

         a) 2, 90° elbows

$$h_L = (0.3)\cdot\frac{v^2}{2g}$$

$$\text{where } v = \frac{Q_{peak} + Q_{recycle}}{2\cdot A_{pipe}}$$

$$= \frac{15{,}000 + 7500}{2\cdot\frac{\pi}{4}(0.40)^2\cdot(86{,}400\ \text{s/d})} = 1.036\ \text{m/s}$$

$$h_L = (0.3)\cdot\frac{(1.036)^2}{2(9.8)} = 0.0164\ \text{m}$$

         b) Entrance

$$h_L = (0.5)\cdot\frac{v^2}{2g}$$

where v = 1.036 m/s

$$h_L = 0.5\cdot\frac{(1.036)^2}{2(9.8)} = 0.0274\ \text{m}$$

         c) Exit

$$h_L = \frac{v^2}{2g} = \frac{(1.036)^2}{2(9.8)} = 0.0548\ \text{m}$$

      ii. Friction losses

$$h_L = f\frac{L}{D}\frac{v^2}{2g}\ \text{(Darcy-Weisbach)}$$

where v = 0.26 m/s

D = 0.40 m

f = 0.021 for $\varepsilon/D = 1.25 \times 10^{-3}$

from Moody diagram

$$h_L = 0.021\frac{(38)}{(0.40)}\frac{(1.036)^2}{2(9.8)} = 0.1093\ \text{m}$$

      ii. Total headloss

Total h_L = 0.0164 + 0.0274 + 0.0548 + 0.1093

= 0.2079 m

b. At Q_{low}:

i. Minor losses

a) 2, 90° elbows

$$h_L = (0.3)\frac{v^2}{2g}$$

$$\text{where } v = \frac{Q_{low} + Q_{recycle}}{2 \cdot A_{pipe}}$$

$$= \frac{2500 + 2500}{2 \cdot \frac{\pi}{4}(0.40)^2 \cdot (86{,}400 \text{ s/d})} = 0.173 \text{ m/s}$$

$$h_L = (0.3) \cdot \frac{(0.173)^2}{2(9.8)} = 0.0005 \text{ m}$$

b) Entrance

$$h_L = (0.5) \cdot \frac{v^2}{2g}$$

where v = 0.173 m/s

$$h_L = (0.5) \cdot \frac{(0.173)^2}{2(9.8)} = 0.0008 \text{ m}$$

c) Exit

$$h_L = \frac{v^2}{2g} = \frac{(0.173)^2}{2(9.8)} = 0.0015 \text{ m}$$

ii. Friction losses

$$h_L = f\frac{L}{D}\frac{v^2}{2g} \text{ (Darcy-Weisbach)}$$

where v = 0.173 m/s

$$h_L = 0.021\frac{(38)}{(0.40)}\frac{(0.173)^2}{2(9.8)} = 0.0030 \text{ m}$$

iii. Total headloss

Total h_L = 0.0005 + 0.0008 + 0.0015 + 0.0030

= 0.0058 m

c. The liquid level in the aeration tank effluent channel is:

i) At Q_{peak} = 518.318 + 0.2079= 518.526

ii) At Q_{low} = 518.288 + 0.0058 = 518.294

4. Determine liquid level in the aeration tank.
   a. Use Francis type weir (contracted, rectangular, sharp-crested) equation solved for H as described in Problem 4-12, Part 4 above.
   b. At Q_{peak}:

$$H = \left[\frac{(15{,}000\ \text{m}^3/\text{d} + 7500\ \text{m}^3/\text{d})}{2\left(86{,}400\ \text{s/d}\right)1.84\left(1.4\ \text{m}\right)} \right]^{2/3} = 0.1367\ \text{m}$$

$$\text{recomputing } L = 1.4 - 0.2\left(0.1367\right) = 1.373$$

$$H = \left[\frac{22{,}500}{2\left(86{,}400\right)1.84\left(1.373\right)} \right]^{2/3} = 0.1385\ \text{m}$$

$$\text{recomputing } L = 1.4 - 0.2\left(0.1385\right) = 1.372$$

$$H = 0.1385\ \text{m}$$

   c. At Q_{low}:

$$H = \left[\frac{(2500\ \text{m}^3/\text{d} + 2500\ \text{m}^3/\text{d})}{2\left(86{,}400\ \text{s/d}\right)1.84\left(1.4\ \text{m}\right)} \right]^{2/3} = 0.0502\ \text{m}$$

$$\text{recomputing } L = 1.4 - 0.2\left(0.0502\right) = 1.390$$

$$H = \left[\frac{12{,}000}{2\left(86{,}400\right)1.84\left(1.390\right)} \right]^{2/3} = 0.0504\ \text{m}$$

$$\text{recomputing } L = 1.4 - 0.2\left(0.0504\right) = 1.390$$

$$H = 0.0504\ \text{m}$$

   d. The liquid level in the aeration tank is:

i) At Q_{peak} = 519.10 + 0.1385 = 519.239 m

ii) At Q_{low} = 519.10 + 0.0504 = 519.150 m

5. Determine liquid level in the primary clarifier effluent channel.
   a. At Q_{peak}:
      i. Minor losses
         a) 2, 90° elbows

$$h_L = (0.3)\cdot\frac{v^2}{2g}$$

where $v = \frac{Q_{peak}}{A_{pipe}}$

$$= \frac{15{,}000}{2\cdot(86{,}400)\frac{\pi}{4}(0.40)^2} = 0.69 \text{ m/s}$$

$$h_L = (0.3)\cdot\frac{(0.69)^2}{2(9.8)} = 0.0073 \text{ m}$$

b) Entrance

$$h_L = (0.5)\cdot\frac{v^2}{2g}$$

where v = 0.69 m/s

$$h_L = (0.5)\cdot\frac{(0.69)^2}{2(9.8)} = 0.0122 \text{ m}$$

c) Exit

$$h_L = \frac{v^2}{2g} = \frac{(0.69)^2}{2(9.8)} = 0.0243 \text{ m}$$

ii. Friction losses

$$h_L = f\frac{L}{D}\frac{v^2}{2g} \text{ (Darcy-Weisbach)}$$

where L = 46.5 m

v = 0.69 m/s

D = 0.40 m

f = 0.021 for $\varepsilon/D = 1.25 \times 10^{-3}$
from Moody diagram

$$h_L = 0.021\frac{(46.5)}{(0.40)}\frac{(0.69)^2}{2(9.8)} = 0.0594 \text{ m}$$

ii. Total headloss

Total h_L = 0.0073 + 0.0122 + 0.0243 + 0.0594
= 0.1033 m

b. At Q_{low}:

i. Minor losses

a) 2, 90° elbows

$$h_L = (0.3) \cdot \frac{v^2}{2g}$$

$$\text{where } v = \frac{Q_{low}}{A_{pipe}}$$

$$= \frac{2500}{2 \cdot (86{,}400) \frac{\pi}{4} (0.40)^2} = 0.12 \text{ m/s}$$

$$h_L = (0.3) \cdot \frac{(0.12)^2}{2(9.8)} = 0.0002 \text{ m}$$

b) Entrance

$$h_L = (0.5) \cdot \frac{v^2}{2g}$$

where v = 0.12 m/s

$$h_L = (0.5) \cdot \frac{(0.12)^2}{2(9.8)} = 0.0003 \text{ m}$$

c) Exit

$$h_L = \frac{v^2}{2g} = \frac{(0.12)^2}{2(9.8)} = 0.0007 \text{ m}$$

ii. Friction losses

$$h_L = f \frac{L}{D} \frac{v^2}{2g} \text{ (Darcy-Weisbach)}$$

where v = 0.12 m/s

$$h_L = 0.021 \frac{(46.5)}{(0.40)} \frac{(0.12)^2}{2(9.8)} = 0.0017 \text{ m}$$

iii. Total headloss

Total h_L = 0.0002 + 0.0003 + 0.0007 + 0.0017

= 0.0029 m

c. The liquid level in the primary clarifier effluent channel is:

i) At Q_{peak} = 519.239 + 0.1033 = 519.342 m

ii) At Q_{low} = 519.150 + 0.0029 = 519.123 m

6. Determine liquid level in the primary clarifier.

a. Determine the number of weirs.

No. of weirs = 72 (from Problem 4-12, Part 6 above)

b. Find the head on the weirs

i. Flow per weir

$$Q_{peak} = \frac{(15{,}000\ m^3/d)}{2(86{,}400\ s/d)(72)} = 1.206 \times 10^{-3}\ m^3/s$$

$$Q_{low} = \frac{(2500\ m^3/d)}{2(86{,}400\ s/d)(72)} = 2.010 \times 10^{-4}\ m^3/s$$

ii. Head on weir:

g. Compute *H* for average and peak flow conditions using the v-notch weir equation given in Part 2 above:

$$\text{At } Q_{peak}\ :\ H = \left(\frac{Q}{1.38}\right)^{2/5}$$

$$= \left(\frac{1.206 \times 10^{-3}}{1.38}\right)^{2/5} = 0.060\ m$$

$$\text{At } Q_{low}\ :\ H = \left(\frac{Q}{1.38}\right)^{2/5}$$

$$= \left(\frac{2.010 \times 10^{-4}}{1.38}\right)^{2/5} = 0.029\ m$$

h. Compute the liquid level in the primary clarifiers:

i) At Q_{peak}, Elev = 519.50 + 0.060 = 519. 560 m

ii) At Q_{low}, Elev = 519.50 + 0.029 = 519. 529 m

7. Summary of results

Location along hydraulic profile	Liquid Level Elevation, m	
	Q_{peak}	Q_{low}
Primary clarifiers	519.560	519.529
Primary clarifier effluent channel	519.342	519.123
Aeration tank	519.239	519.150
Aeration tank effluent channel	518.526	518.294
Secondary clarifiers	518.318	518.288

PROBLEM 4-14

Problem Statement - See text, page 303

Instructional Guidelines

Before going on the tour, it would be helpful to discuss with the students some things to look for as the tour the plant such as:

1. Obtain information about the treatment process (flowrate, type of treatment, major unit processes, etc.) prior to the visit. If possible, obtain a plant-wide plan drawing and process flow diagram.
2. Identify major equipment driven by electric motors in the treatment plant (see Table 17-2 in Chap. 17)
3. Have the students look at the free fall at the primary and secondary sedimentation tanks and between processes.
4. What type of aeration system is being used? How long has it been used? How often is it cleaned? Has the oxygen transfer efficiency been evaluated?
5. What levels of oxygen are maintained in the process and in the effluent? How is the dissolved oxygen level controlled in the bioreactor? (If possible, ask the plant operator to show the students the SCADA monitor system during the tour and what they look for in the operation of the treatment plant.)
6. If digesters are employed, what is done with the gas? Is the gas used for heating, cogeneration, or flared?
7. Have the digesters been cleaned recently? If so, was it a grit accumulation problem?

5

PHYSICAL UNIT OPERATIONS

PROBLEM 5-1

Problem Statement - See text, page 448

Solution

Following values were given in the problem statement:

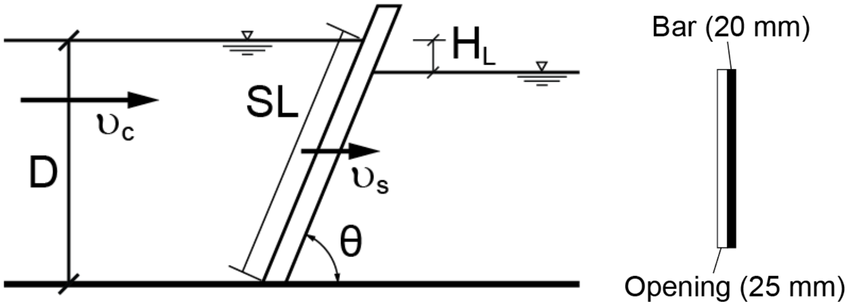
υ_c = channel velocity = 1 m/s

BW = bar width = 20 mm

CS = clear spacing = 25 mm

Θ = screen angle = 50°, 55°, 60°

Definition Sketch:



H_L = headloss

D = water depth

SL = slot length

υ_s = velocity through the screen

Following steps are taken to find the headloss, H_L. and velocity, υ_s

1. Find velocity through screen, υ_s, for one screen opening.

Water occupying the cross section area of one bar and one opening space, Q, will approach the screen, and pass through the area of one opening. Approaching velocity can be expressed as:

$$\upsilon_c = 1\,\text{m/s} = \frac{\text{(Volume of water passing one opening)}}{\text{(Area for one screen bar + one opening)}} = \frac{Q}{(BW + CS)(D)}$$

Through the opening, velocity through the slot can be written as:

$$\upsilon_s = \frac{Q}{(CS)(SL)}$$

Solve the two equations for Q to yield:

$\upsilon_c (BW + CS) D = Q = \upsilon_s (CS)(SL)$, or

$$\upsilon_s = \frac{(BW + CS)D}{(CS)(SL)} \upsilon_c$$

Given BW = 25 mm, CS = 20 mm

$$\upsilon_s = \frac{(20 + 25)D}{(25)SL} \upsilon_c$$

Where $SL = \frac{D}{(SM)\theta}$

$$\upsilon_s = \frac{45\,D}{(25)\left[\left(\frac{D}{\sin\theta}\right)\right]} \upsilon_c$$

$\upsilon_s = \frac{45\sin\theta}{25} \upsilon_c$, and υ_c = 1.0 m/s

For the θ = 50, 55 and 60°, υ_s is calculated (see the following table). As a reference, the result for θ = 90° is also shown.

	θ,°	$\upsilon_{s,}$ m/s
A	50	1.38
B	55	1.47
C	60	1.56
D	90	1.80

2. Find headloss through screen:

From Eq. 5-1 (page 317),

$$H_L = \frac{1}{C}\left(\frac{\upsilon_s^2 - \upsilon_c^2}{2g}\right)$$

Where C = discharge coefficient (from table) = 0.7 (assumed)

$$H_L = \frac{1}{0.7}\left(\frac{\upsilon_s^2 - (1.0)^2}{(2)(9.81)}\right)$$

The results are summarized below.

	Θ,°	υ_s, m/s	H_L, m
A	50	1.38	0.066
B	55	1.47	0.084
C	60	1.56	0.10
D	90	1.80	0.16

PROBLEM 5-2

Problem Statement - See text, page 448

Solution

Following values were given in the problem statement:

Q = flow = 40,000 m^3/day = 0.463 m^3/s (a)

υ_c = upstream channel velocity > 0.4 m/s

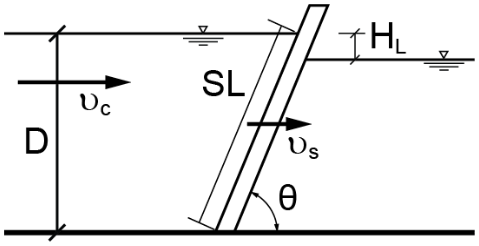
BW = bar width = 12 mm = 0.012 m

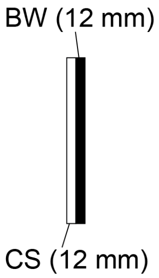
CS = clear spacing = 12 mm = 0.012 m

θ = screen angle = 75°

1. Find H_L = headloss through clean screen and through 50% clogged screen.

Design Sketch





D = water depth

SL = screen length

a. Find channel dimensions
Assume υ_c = 0.4 m/s

$$Q = \upsilon_c A$$

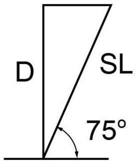
$$A = \frac{Q}{\upsilon_c} = \frac{(0.463\ \text{m}^3/\text{s})}{(0.4\ \text{m/s})} = 1.1574\ \text{m}^2$$

Where A = area of the channel

Assume channel width (w) upstream of the screen = 0.5 m

$$D = \frac{1.1574\ \text{m}^2}{0.5\ \text{m}} = 2.3148\ \text{m}$$

b. Find screen length (SL)



$$\sin 75° = \frac{D}{SL}$$

$$SL = \frac{D}{\sin 75°} = \frac{2.3148\ \text{m}}{0.9659} = 2.3965\ \text{m}$$

c. Find velocity through screen (υ_S) for clean screen
The bars are 12 mm wide and the clear spacing between bars is 12 mm. Therefore, the area of flow through the screen, A_S, is 50% of the screen area.

$$A_s = (SL)(w)(0.50) = (2.3965\text{m})(0.50\text{m})(0.50) = 0.5991\text{m}^2$$

$$\upsilon_s = \frac{(0.463\ \text{m}^3/\text{s})}{0.5991\ \text{m}^2} = 0.7727\ \text{m/s}$$

d. Find headloss through clean screen

Equation 5-1 (page 317):

$$H_L = \frac{1}{C}\left(\frac{\upsilon_s^2 - \upsilon_C^2}{2g}\right)$$

Assume C (for a clean screen) = 0.70

$$H_L = \frac{1}{0.7}\left[\frac{(0.7727\ \text{m/s})^2 - (0.4\ \text{m/s})^2}{(2)(9.81\,\text{m/s}^2)}\right] = 0.0318\text{m}$$

e. Find headloss through screen that is 50% clogged
Equation 5-1 (page 317)

$$H_L = \frac{1}{C}\left(\frac{\upsilon_s^2 - \upsilon_C^2}{2g}\right)$$

Assume C for a clogged screen = 0.60

If the screen is 50% clogged, then the velocity will double. Therefore,

$$V_s = 2(0.7727\ \text{m/s}) = 1.5455\ \text{m/s}$$

$$H_L = \frac{1}{0.6}\left[\frac{(1.5455\ \text{m/s})^2 - (0.4\ \text{m/s})^2}{(2)(9.81\,\text{m/s}^2)}\right] = 0.1893\text{m}$$

PROBLEM 5-3

Problem Statement - See text, page 448

Solution

1. Compute the Reynolds number (N_R) using Eq. (5-11) in p337.

$$N_R = \frac{D^2 n\rho}{\mu}$$

Required data:

D = 3 m

n = 30 r/min = 0.5 r/s

ρ= 995.7 kg/m^3 (Table C-1)

μ = 0.798 x 10^{-3} N•s/m^2 (Table C-1)

$$N_R = \frac{(3\,m)^2(0.5\text{ r/s})(995.7\text{ kg/m}^3)}{(0.798 \times 10^{-3}\,N\bullet s/m^2)} = 5.6 \times 10^6 \quad \text{(turbulent mixing)}$$

2. Compute the power consumption using Eq. (5-9) in p336.

   $P = N_P \rho n^3 D^5$

   Required data: N_P = 3.5 (see Table 5-11 in p338).

$$P = (3.5)(995.7\text{ kg/m}^3)(0.5\text{ r/s})^3\,(3\text{ m})^5 = 105{,}855\text{ kg}\bullet\text{m}^2/\text{s}^3\ \text{(W)}$$

PROBLEM 5-4

Problem Statement - See text, page 448

Solution

1. Determine the speed of rotation when the Reynolds number is 100,000 using Eq. (5-11) in p337.

$$N_R = \frac{D^2 n\rho}{\mu}$$

$$n = \frac{N_R\,\mu}{D^2\rho}$$

Pertinent data: D = 500 mm = 0.5 m

N_R = 100,000

μ = 1.307 x 10^{-3} N•s/m^2 (Table C-1 in Appendix C, p1915)

ρ = 999.7 kg/m^3 (Table C-1 in Appendix C, p1915)

$$n = \frac{(100{,}000)(1.307 \times 10^{-3}\,N\bullet s/m^2)}{(0.5\text{ m})^2(999.7\text{ kg/m}^3)} = 0.52\text{ r/s} = 31.4\text{ r/min}$$

2. The Reynolds number is related to both turbulence and velocity. Higher Reynolds numbers are indicative of greater turbulence and velocity. As a general rule, the greater the turbulence and the higher the velocity, the more

efficient the mixing operation will be. However, high Reynolds numbers lead to high power requirements. Rearranging Eq. (5-9) and substituting n to include the Reynolds number yields:

$P = N_P \rho n^3 D^5$

$$n = \frac{N_R \mu}{D^2 \rho}$$

$$P = \frac{N_P \mu^3 (N_R)^3}{\rho^2 D}$$

As shown, the power varies directly with the cube of the Reynolds number.

3. Determine the required motor size using the rearranged form of Eq. (5-9) derived above and the pertinent data from the problem statement and step 1.

   a. Compute theoretical power, first converting newtons to kg•m/s^2.

$$(1.307 \times 10^{-3}\ \mathrm{N \cdot s/m^2})\left[\frac{(1\,\mathrm{kg \cdot m/s^2})}{\mathrm{N}}\right] = 1.307 \times 10^{-3}\ \mathrm{kg/m \cdot s}$$

$$P = \frac{[(1.7)(1.307 \times 10^{-3}\ \mathrm{kg/m \cdot s})^3 (100{,}000)^3]}{[(999.7\ \mathrm{kg/m^3})^2 (0.5\ \mathrm{m})]}$$

$= 4.44\ \mathrm{kg \cdot m^2/s^3}$ (W)

b. Compute electric motor power requirements

$P_{motor} = P/e = 4.44\ \mathrm{W}/0.2 = 22.2\ \mathrm{W}$

PROBLEM 5-5

Problem Statement - See text, page 448

Solution

1. Solve the problem for a plug flow reactor. Let N = number of particles

   a. Write the mass balance equation for a plug flow reactor (PFR).

$$dV \frac{dN}{dt} = QN_o - Q(N_o + \frac{dN}{dt} dx) + (-kN)dV$$

assume steady state $\left(\frac{dN}{dt} = 0\right)$

$$0 = -\,QdN - kN\,dV$$

b. Solve the mass balance equation for N

$$\frac{dN}{N} = \frac{k}{Q}dV$$

$$\ln\frac{N}{N_o} = -k\frac{V}{Q}$$

$N = N_0\,e^{-kV/Q}$

let t = V/Q

$N = N_0\,e^{-kt}$

c. Compute k at t = 10

$$\ln\frac{N}{N_o} = -k\frac{V}{Q}$$

$$\ln\frac{N}{N_o} = -kt$$

Data: N = 3

$N_o = 10$

t = 10 min

$$\ln\frac{3}{10} = -k(10)$$

$k = 0.12\ \text{min}^{-1}$

d. Compute N at t = V/Q = 5 min

$N = N_0\,e^{-kt}$

$N = 10\,e^{0.12(5)}$

N = 5.49 particles/unit volume

2. Solve the problem for a batch reactor.

a. Write the mass balance equation for a batch reactor

$$V\frac{dN}{dt} = -kNV$$

$$\frac{dN}{dt} = -kN$$

b. Solve the mass balance equation for N.

$$\frac{dN}{N} = -kdt$$

$$\ln\frac{N}{N_o} = -kt$$

$$N = N_o\, e^{-kt}$$

c. Compute N at t = 5 min.

$N = 10\ e^{-0.12(5)}$

N = 5.49 particles/unit volume

PROBLEM 5-6

Problem Statement - See text, page 448

Solution

1. Write the mass balance for a complete mix reactor.

$$V\frac{dN}{dt} = QN_o - QN + (-kN)V$$

$$\frac{dN}{dt} = \frac{Q}{V}(N_o) - \frac{Q}{V}(N) + (-kN)$$

$$\frac{dN}{dt} + N\left(\frac{Q}{V} + k\right) = N_o\frac{Q}{V}$$

2. Solve the mass balance equation for N

$$\frac{dN}{dt} + N\left(\frac{Q}{V} + k\right) = N_o\frac{Q}{V}$$

This is a first-order linear differential equation and can be solved easily using the integrating factor, $e^{(Q/V + k)t.}$

The final result is:

$$N = \frac{Q}{V}\frac{N_o}{(k + Q/V)}\left[1 - e^{-(k+Q/V)t}\right] + N_o e^{-(k+Q/V)t}$$

3. Determine k at the steady state condition.

   Pertinent data:

   t = ∞

   Q/V = 1/Q = 0.1 min^{-1}

   N_o = 10

   N = 3

   $$N = 0.1\frac{10}{(k + 0.1)}(1 - 0) + 10(0)$$

   $$N = \frac{1}{(k + 0.1)}$$

   k = 0.233 min^{-1}

4. Determine N at t = 5 min

   $$N = 0.1\frac{10}{(0.233 + 0.1)}\left[1 - e^{-(0.233+0.1)5}\right] + 10e^{-(0.233+0.1)5}$$

   N = 2.43 + 1.89 = 4.32 particles/unit volume

PROBLEM 5-7

Problem Statement - See text, page 449.

Instructors Note: Assume air is released 0.25 m above the tank bottom.

Solution

1. Find the power requirement, using Eq. (5-3), page 330.

   $$G = \sqrt{\frac{P}{\mu V}}$$

   $$P = \mu V G^2$$

   Pertinent data: μ at 60°C = 0.466 x 10^{-3} N•s/m^2 (Table C-1)

   G = 60 s^{-1}

$V = 200\ m^3$

$P = (0.466 \times 10^{-3}\ N{\bullet}s/m^2)(200\ m^3)(60\ s^{-1})^2$

$= 335.5\ N{\bullet}m/s = 0.336\ kN{\bullet}m/s\ (kW)$

2. Find the required air flowrate using Eq. (5-14), page 343.

$$P = p_a V_a \ln \frac{p_c}{p_a}$$

$$V_a = \frac{P}{p_a \ln \frac{p_c}{p_a}}$$

Pertinent data:

γ at 60°C =9.642 kN/m^3 (Table C-1)

p_a = atmospheric pressure = (10.33 m H_2O)(9.642 kN/m^3)

= 99.60 kN/m^2

p_c = (p_a + depth of water above release point)•µ

= (10.33 + 3.5) m $H_2O \times \gamma$ = (13.83 m H_2O)(9.642 kN/m^3)

=133.35 kN/m^2

$$V_a = \frac{(0.336\ kN{\bullet}m/s)}{(99.60\ kN/m^2)\left[\ln\left(\frac{133.35}{99.60}\right)\right]} = 0.011.5\ m^3/s = 0.69\ m^3/min$$

PROBLEM 5-8

Problem Statement - See text, page 449

Solution

1. Find the required air flowrate using Eq. (5-14), p. 343.

$$P = p_a V_a \ln \frac{p_c}{p_a}$$

$$V_a = \frac{P}{p_a \ln \frac{p_c}{p_a}}$$

Pertinent data: P = 8543 W = 8.543 kN•m/s

γ at 15°C = 9.798 kN/m^3 (Table C-1 in Appendix C)

p_a = atmospheric pressure (10.33 m H_2O x 9.798 kN/m^3)

= 101.21 kN/m^2

p_c = (p_a + depth of water above release point) γ

= (10.33 + 3) m H_2O = 13.33 m H_2O x 9.798 kN/m^3

= 130.61 kN/m^2

$$V_a = \frac{(8.543 \text{ kN} \bullet \text{m/s})}{(101.21 \text{ kN/m}^2)\left[\ln\left(\frac{130.61}{101.21}\right)\right]} = 0.331 \text{ m}^3/\text{s} = 19.86 \text{ m}^3/\text{min}$$

PROBLEM 5-9

Problem Statement - See text, page 449

Solution

1. Derive Stokes' Law by equating Eqs. (5-16) and (5-23).

   Note: Laminar flow conditions apply

   The gravitational force on a particle is expressed by Eq. (5-16) in p. 346:

   $$F_G = (\rho_p - \rho_w)\, gV_p$$

   The frictional drag force on a particle as expressed by Eq. (5-23) in p. 346 for laminar flow conditions is:

   $$F_D = 3\pi\mu\upsilon_p d_p$$

   The drag force is equal to the gravitational force when

   $$(\rho_s - \rho)gV_p = 3\pi\mu\upsilon_p d_p$$

   But $V_p = (1/6)\pi d_p^3$

   $$[(\rho_s - \rho)gV_p][(1/6)\pi d_p^3 = 3\pi\mu\upsilon_p d_p$$

   $$\upsilon_p = \frac{(\rho_s - \rho)\, d_p^2}{18\ \mu}$$

PROBLEM 5-10

Problem Statement - See text, pages 449

Solution

1. Determine the drag coefficient using Eq. (5-19).

$$C_d = \frac{24}{275} + \frac{3}{\sqrt{275}} + 0.34 = 0.608$$

2. Determine the particle settling velocity using Eq. (5-18) and assuming the particle is spherical.

$$\upsilon_{r(t)} = \sqrt{\frac{4g(sg_p - 1)d_p}{3C_d\phi}}$$

$$\upsilon_{r(t)} = \sqrt{\frac{4(9.81\,\mathrm{m/s^2})(2.65-1)(1\,\mathrm{mm})(1\,\mathrm{m}/10^3\,\mathrm{mm})}{(3)(0.604)(1.0)}} = 0.19\,\mathrm{m/s}$$

PROBLEM 5-11

Problem Statement - See text, page 449

Solution

1. Establish a spreadsheet for determining the final settling velocity. Compute N_R using Eq. (5-21) as determined in Step 2 of Example 5-4. Use a sphericity factor of 1.0 for a spherical particle.

$$N_R = \frac{\upsilon_p d_p \psi}{\nu} = \frac{(0.224\,\mathrm{m/s})(0.5\times10^{-3}\,\mathrm{m})(1.0)}{(1.003\times10^{-6}\,\mathrm{m^2/s})}$$
$$= 111.7$$

2. Use Eq. (5-19) as shown in Step 3 of Example 5-4 and assume a settling velocity for each iteration to reach closure.

3. Calculate the drag coefficient, C_d

$$C_d = \frac{24}{N_R} + \frac{3}{\sqrt{N_R}} + 0.34 = \frac{24}{111.7} + \frac{3}{\sqrt{111.7}} + 0.34$$
$$= 0.839$$

4. Calculate the particle settling velocity

$$\upsilon_p = \sqrt{\frac{4g(sg-1)d}{3C_d}} = \sqrt{\frac{4(9.81\,m/s^2)(2.65-1)(0.5 \times 10^{-3})}{3 \times 0.839}}$$
$$= 0.113\ m/s^2$$

5. Set up a spreadsheet as follows

v_p	N_R	$24/N_R$	$\sqrt{N_R}$	$3/\sqrt{N_R}$	0.34	C_d	$(v_p)^2$	v_p
0.088	43.868	0.55	6.623	0.45	0.34	1.34	0.00805	0.0897
0.090	44.865	0.53	6.698	0.45	0.34	1.32	0.00816	0.0903

Closure has been achieved.

6. The Reynolds number, N_R, is 44.865 and coefficient of drag, C_d, is 1.32.

PROBLEM 5-12

Problem Statement - See text, page 449

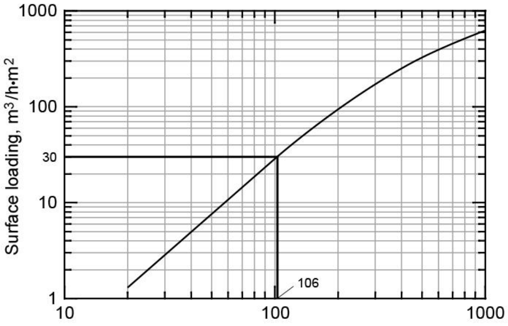
Solution

Following conditions are specified in the problem statement:

Peak flow = 40,000 m^3/d
Design SES = 106 µm

1. Find size of vortex grit removal units.

   a. Find surface loading rate. Use Fig. 5-34(b) to determine surface loading rate for SES = 106 µm.



   Select surface loading rate = 30 $m^3/h•m^2$

   b. Find area (A) required

$$A = \frac{\text{Peak flow}}{\text{Surface loading rate}}$$

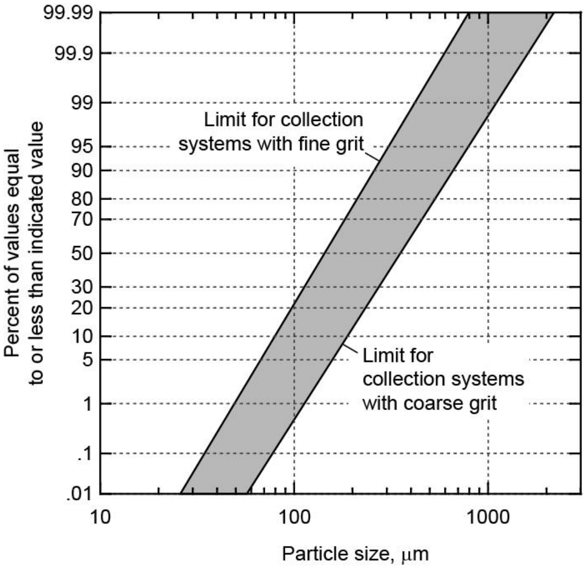
Peak flow = 40,000 m^3/d = 1667 m^3/h

$$A = \frac{(1667\ m^3/h)}{(30\ m^3/h \cdot m^2)} = 55.5\ m^2$$

In actual practice, it is necessary to review manufacturers' catalog information to determine number of units and model size to provide required settling area.

2. Determine the expected grit removal if the facility is located in an area that is known to have fine grit.

Use Fig. 5-31



The range of particle sizes for various US treatment plants is illustrated on Figure 5-31. For 106 µm SBS and fine grit (upper limit of range), about 30% of the particles will be ≤ 106 µm. Therefore, expected grit removal = (100 – 30)% = 70%.

3. To achieve 90% removal, find the Design SBS.

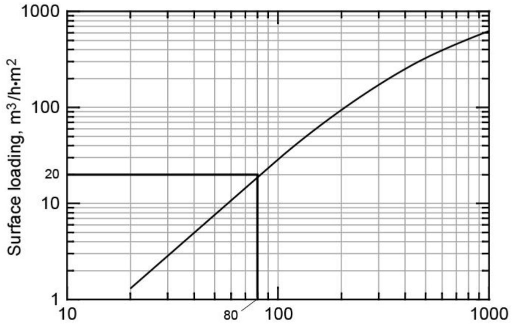
Use Fig. 5-31 (see Step 2)

To achieve 90% removal, 10% of the particles must be ≤ 80 µm.

4. Find surface loading rate for SBS = 80 µm.

Use Fig 5-34(b)

For SBS = 80 µm



Surface loading rate = 20 $m^3/h \cdot m^2$

5. Fine area required for SBS = 80 µm.

$$A = \frac{(1667\ m^3/h)}{(20\ m^3/h \cdot m^2)} = 83.35\ m^2$$

To get 90% removal, the surface area has to be increased from 55.5 m^2 to 83.35 m^3 (50% increase).

PROBLEM 5-13

Problem Statement - See text, page 449

Solution

A variety of solutions are possible. The following data have been assumed (see Table 5-17, page 374).

Detention time at Q_{max} = 3 min

Water depth = 4 m

Diffuser submergence = 3 m

Number of chambers = 2 (each channel can service 75% of the peak flow with one channel out of service)

Air supply rate = 0.3 $m^3/m \cdot min$ of length

Length to width ratio = 4:1

1. Using the data given above, determine the tank dimensions.

V/Q = 3 min at peak flowrate (20,000 m^3/d per channel)

$$V = \frac{(3\,\text{min})(20{,}000\,\text{m}^3/\text{d})}{(60\,\text{min/h})(24\,\text{h/d})} = 41.7\,\text{m}^3$$

$$A_s = \frac{41.7\,\text{m}^3}{4\,\text{m}} = 10.4\,\text{m}^2$$

Length x width = 4w x w = $4w^2$ = 10.4 m^2

Width = 1.6 m

Length = 6.4 m

2. Determine the maximum air requirement.

$$Q_{air} = \left(\frac{0.3\,\text{m}^3}{\text{m}\bullet\text{min}}\right)(6.4\,\text{m})(2\text{ channels}) = 3.84\ \text{m}^3/\text{min}$$

3. Determine the horsepower requirements. Assume the blower efficiency is 70%. The specific weight of water is 9.81 kN/m^3 (9,810 N/m^3) (Appendix C). 1 W = 1 J/s or 1 N•m/s (Table 2 in Front section) Thus, 1 kW = 1000 N•m/s.

h = 0.250 m (diffusers) + 3 m (submergence) + 0.40 m = 3.65 m

h = (3.65 m)(9810 N/m^3) = 35,806 N/m^2

$$\text{Power} = \left(\frac{Q_{air}h}{\text{efficiency}}\right)$$

$$\text{Power} = \left[\frac{(3.84\ \text{m}^3/\text{min})(35{,}806\ \text{N/m}^2)}{(0.70)(60\ \text{s/min})}\right]\left(\frac{1\,\text{kW}}{1000\ \text{Ngm/s}}\right) = 3.274\ \text{kW}$$

4. Determine the power cost. Assume the electric motor efficiency is 92%.

$$\text{Power cost} = \left[\frac{(3.724\ \text{kW})(24\,\text{h/d})}{(0.9)}\right](\$0.12/\text{kWh}) = \$10.48/\text{d}$$

Note: In the above computation, it was assumed that the blower operates at maximum capacity regardless of average flow or peak flow conditions. In small plants, this situation is often the case. Under actual operating conditions in other plants, the blower capacity is adjusted to maintain an optimum air rate, thus the power consumption may be less than that calculated in the above example.

PROBLEM 5-14

Problem Statement - See text, page 449

Solution

The given data are:

Detention time at Q_{max} = 3.5 min

Width to depth ratio = 1.5 : 1

Air supply rate = 0.4 m^3/m•min of tank length

Water depth = 3 m

Average flowrate = 0.3 m^3/s

Peak flowrate = 1 m^3/s

1. Using the data given above, determine the tank dimensions.

V/Q_{max} = 3.5 min at peak flow

V = (3.5 min)(1 m^3/s)(60 s/min) = 210 m^3

Depth = 3 m

Width = 1.5 x 3 m = 4.5 m

$$\text{Length} = \frac{210\,m^3}{3\,m \ x \ 4\,m} = 15.6\,m$$

2. Determine the air requirement assuming 0.4 m^3/m•min (see Table 5-17 on page 374).

$$Q_{air} = \frac{0.4\,m^3}{m \bullet min}(15.6\,m) = 6.2\,m^3/\,min$$

PROBLEM 5-15

Problem Statement - See text, page 449

Solution

1. The advantages and disadvantages of an aerated grit chamber as compared to a vortex grit chamber are:
    - Air flowrate can be adjusted to optimize grit removal over a wide range of wastewater flowrates
    - Grit contains relatively low amounts of organic matter, therefore, the unit does not require an external grit washer
    - Aeration may freshen wastewater and improve performance of downstream processes, however, aeration may release volatile organic compounds (VOCs) and odors, thus covering of the tanks may be required.
    - Can be used for chemical mixing and flocculation
    - No maximum size limit
    - Some short circuiting may occur thus requiring installation of internal baffling in the tanks to enhance grit removal
2. The advantages and disadvantages of a vortex grit chamber as compared to an aerated grit chamber are:
    - Unit has shorter detention time (30 s), and is compact, therefore, requires less space
    - No submerged diffusers or parts that require maintenance
    - Turbulence in the vortex may release odors and VOCs, but the area requiring covering is smaller than an aerated grit chamber.
    - Lower construction cost
    - Proprietary design; deviations from manufacturer's recommended design may void performance guarantee
    - Unit does not require an external blower system, but may require an air lift pump to remove grit
    - Air lift pumps are often not effective in removing grit from sump
    - Lower power consumption as compared to an aerated grit chamber

Reference:,

WEF (1998) *Design of Municipal Wastewater Treatment Plants*, 4th ed., vol. 2, Water Environment Federation, Alexandria, VA.

PROBLEM 5-16

Problem Statement - See text, page 449

Solution

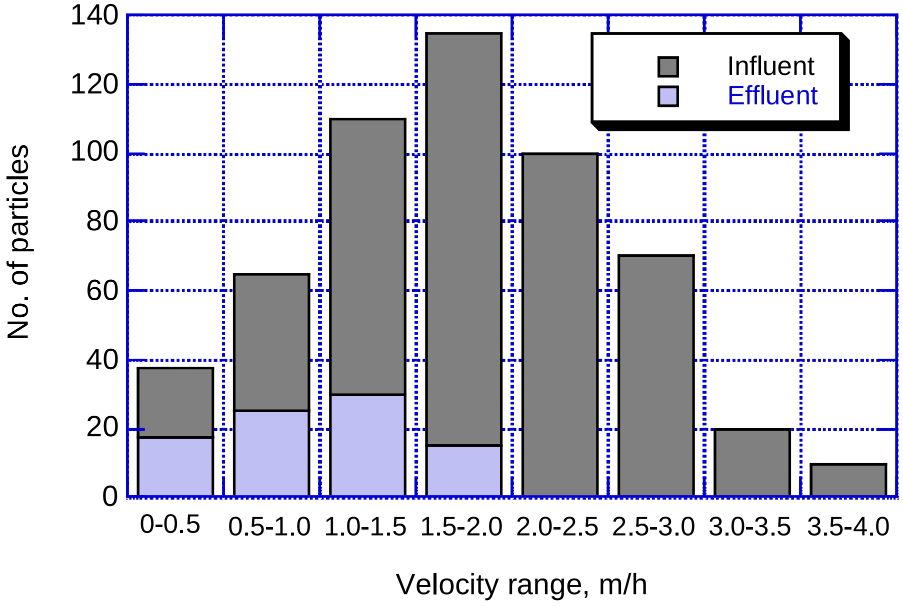
1. Prepare a computation table to determine the particle distribution in the effluent.

No. of particles in influent	V_{avg}, m/h	V_{avg},/ V_c	No. of particles removed, (V_{avg}/V_c x N_o)	No. of particles in effluent (N_o-N)
20	0.25	0.125	2.5	17.5
40	0.75	0.375	15	25
80	1.25	0.625	50	30
120	1.75	0.875	105	15
100	2.25	>1	100	0
70	2.75	>1	70	0
20	3.25	>1	20	0
10	3.75	>1	10	0
Σ = 460			372.5	87.5

2. Determine the removal efficiency.

$$\text{Percent removal} = \left(\frac{372.5}{460}\right)100 = 81.0\%$$

3. Plot the particle histogram for the influent and effluent wastewater.



PROBLEM 5-17

Problem Statement - See text, page 450

Solution

1. Determine the removal efficiency for particles with an average settling velocity of 1 m/hr and a tray depth of 1 m.

   a. The percent removal of the particles above the tray is:

   $V_{critical}$ = 1 m/1h = 1 m/h

$$\% \text{removal} = \frac{V_{solids}}{V_{critical}} \times 100 = \frac{(1 \text{ m/h})}{(1 \text{ m/h})}(100) = 100\%$$

   b. The percent removal of the particles below the tray is:

   $V_{critical}$ = 2 m/1h = 2 m/h

$$\% \text{ removal} = \frac{V_{solids}}{V_{critical}} \times 100 = \frac{(1 \text{ m/h})}{(2 \text{ m/h})}(100) = 50\,\%$$

   c. Assuming all particles are evenly distributed, the overall removal efficiency is:

$$\% \text{ removal} = \frac{(100)(1\text{m}) + (50)(2\text{m})}{3\text{m}} = 67\%$$

2. Determine the effect of tray depth, d, on removal efficiency for particles with an average settling velocity of 1 m/h.

   a. For d ≤ 1 m

   $$\% \text{removal} = \left[(1)\left(\frac{d}{3}\right) + \left(\frac{1}{3-d}\right)\left(\frac{3-d}{3}\right)\right](100) = [(d/3) + (1/3)](100)$$

   b. For 1 m ≤ d ≤ 2m

   $$\% \text{removal} = \left[\left(\frac{1}{d}\right)\left(\frac{d}{3}\right) + \left(\frac{1}{3-d}\right)\left(\frac{3-d}{3}\right)\right](100) = [(1/3) + (1/3)](100)$$

   $$= (2/3)\ (100\ \%)$$

   c. For 2 m ≥ d ≥ 3 m

   $$\% \text{ removal} = \left[\left(\frac{1}{d}\right)\left(\frac{d}{3}\right) + (1)\left(\frac{3-d}{3}\right)\right](100) = [(1/3) + 1 - (d/3)](100)$$

   $$= [(4 - d)/3](100)$$

   The maximum removal efficiency is achieved by placing the tray anywhere between 1 m and 2 m. For particles with settling velocities of 1 m/h, 66.7 percent removal efficiency is achieved. Therefore, by moving the tray from 1.0 m, the efficiency cannot be improved.

3. Determine the overall efficiency as a function of the depth of the tray for particles with a settling velocity of 0.3 m/h.

   a. For d ≥ 0.3 m

   $$\% \text{ removal} = \left[\left(\frac{1}{d}\right)\left(\frac{d}{3}\right) + \left(\frac{0.3}{3-d}\right)\left(\frac{3-d}{3}\right)\right](100)$$

   $$= [(d/3) + (0.3/3)](100) = [(d/3) + 0.1](100)$$

   b. For 0.3 m ≥ d ≥ 2.7 m

$$\%\text{removal} = \left[\left(\frac{0.3}{d}\right)\left(\frac{d}{3}\right) + \left(\frac{0.3}{3-d}\right)\left(\frac{3-d}{3}\right)\right](100)$$

= [(0.3/3) + (0.3/3)](100) = 20%

c. For 2.7 m ≥ d ≥ 3.0 m

$$\%\text{removal} = \left[\left(\frac{0.3}{d}\right)\left(\frac{d}{3}\right) + (1)\left(\frac{3-d}{3}\right)\right](100)$$

= [0.1 + 1 – (d/3)] (100) = [1.1 – (d/3)](100)

PROBLEM 5-18

Problem Statement - See text, page 450

Solution

1. Try a settling velocity of 0.085 m/s and calculate the Reynolds number. Use the Reynolds number to determine the drag coefficient, and use the drag coefficient in Newton's equation to find the settling velocity.

$$N_R = \frac{0.85(0.085\,\text{m/s})(0.5\,\text{x}10^{-3}\,\text{m})}{(1.003\,\text{x}10^{-6}\,\text{m}^2/\text{s})} = 36.0$$

$$C_d = \frac{24}{36.0} + \frac{3}{\sqrt{36.0}} + 0.34 = 1.507$$

$$\upsilon_p = \sqrt{\frac{4(9.81\,\text{m/s}^2)(2.65-1)(0.5\,\text{x}10^{-3}\,\text{m})}{3\,\text{x}1.507}} = 0.085\ \text{m/s}$$

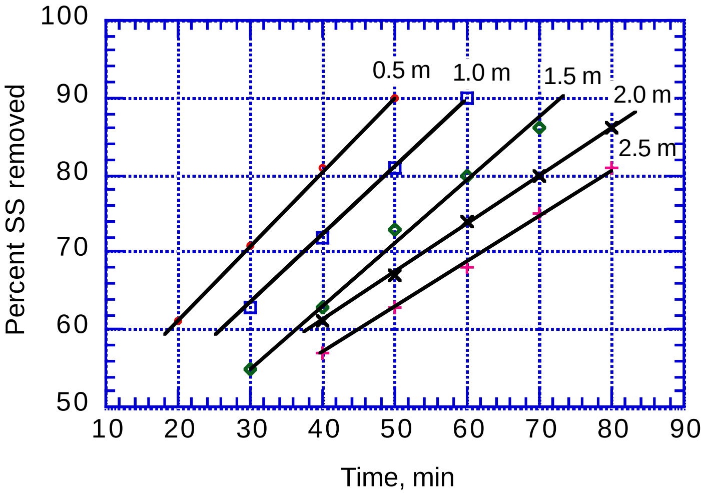
Closure has been achieved.

PROBLEM 5-19

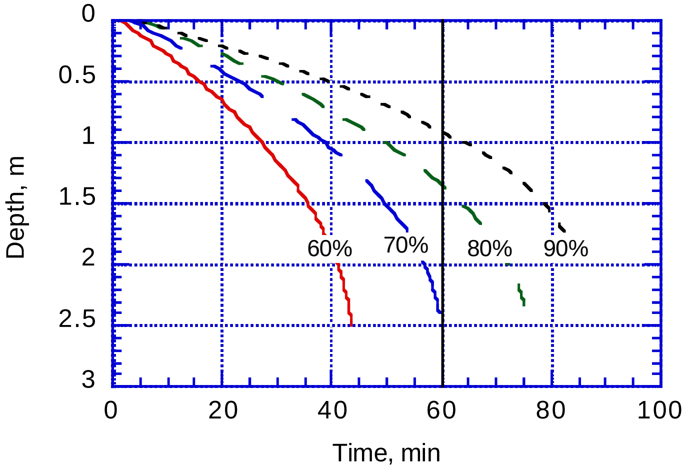
Problem Statement - See text, page 450

Solution

1. Plot the percent suspended solids removed versus time for each increment of depthas shown below.



2. From the above plot, pick off the data points at intervals of percent removal to create a particle settling curve similar to Fig. 5-234 as shown below.



3. Calculate the detention time for the basin using Eq. (5-26).

Detention time = depth/v_c

Detention time = 3 m/(3 m/h) = 1 h (60 min)

5 Determine the efficiency of removal using Eq. (5-32) and data points from the plot in step 2 at t = 60 min. Set up a table as shown below.

$\frac{\Delta h_n}{h_t} \times \frac{R_n + R_{n+1}}{2} =$ percent removal	
$\frac{0.9}{3} \times \frac{100 + 90}{2} =$	28.5
$\frac{0.4}{3} \times \frac{90 + 80}{2} =$	11.3
$\frac{1.2}{3} \times \frac{80 + 70}{2} =$	30.0
Total	69.8

PROBLEM 5-20

Problem Statement - See text, page 450

Solution

1. Assuming water velocity u = 1 m/s, calculate the settling velocity for countercurrent and cocurrent conditions. As stated in the problem statement, the inclined plates length is 2.0 m, plate specing is 75 mm.
   a. Calculate us for countercurrent using Eq. (5-35):

   $$\upsilon_s = \frac{u \circlearrowright d}{L\cos\theta + d\sin\theta}$$

   For θ = 40°

   $$\upsilon_s = \frac{(1.0\text{ m/s})(75\text{ mm})(1\text{m}/10^3\text{ mm})}{(2\text{ m})\cos(40°) + (75\text{ mm})(1\text{m}/10^3\text{ mm})\sin(40°)}$$

   $$\upsilon_s = 0.047\text{ m/s}$$

   b. Calculate υ_s for cocurrent using Eq. (5-38):

   $$\upsilon_s = \frac{u \circlearrowright d}{L\cos\theta - d\sin\theta}$$

   For θ = 40°

   $$\upsilon_s = \frac{(1.0\text{ m/s})(75\text{ mm})(1\text{m}/10^3\text{ mm})}{(2\text{ m})\cos(40°) - (75\text{ mm})(1\text{m}/10^3\text{ mm})\sin(40°)}$$

$$\upsilon_s = 0.051\,\text{m/s}$$

2. Similarly, calculate the settling velocity for 50 and 60 degrees. The results are summarized in the table below. As shown, the cocurrent arrangement results in greater settling velocities.

			Countercurrent flow Inclination angle, °			Cocurrent flow Inclination angle, °		
	Symbol	Unit	40	50	60	40	50	60
Assumed water velocity:	u	m/s	1.00	1.00	1.00	1.00	1.00	1.00
Settling velocity	υ_s	m/s	0.047	0.056	0.070	0.051	0.061	0.080

PROBLEM 5-21

Problem Statement - See text, page 450

Solution

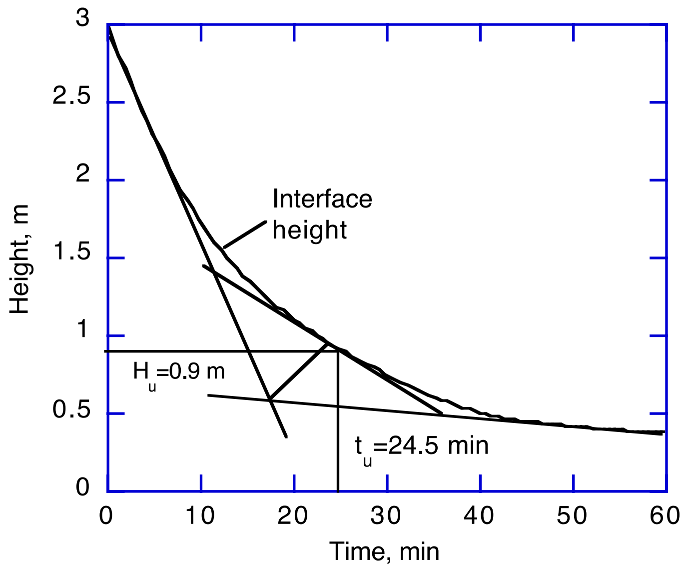
1. Determine the area required for thickening using Eq. (5-41).

   a. Determine the value of H_u

$$H_u = \frac{C_o H_o}{C_u}$$

$$H_u = \frac{(3600\,\text{g/m}^3)(3.0\,\text{m})}{(12{,}000\,\text{g/m}^3)} = 0.9\,\text{m}$$

   b. Determine t_u from the plot using the procedure described in Example 5-7.



c. Determine the thickening area.

$$A = \frac{Qt_u}{H_o} = \left[\frac{(1500\,m^3/d)(24.5\,min)}{(24\,h/d)(60\,min/h)(3\,m)}\right]$$

$$= 8.5\,m^2$$

PROBLEM 5-22

Problem Statement - See text, pages 450

Solution

1. Assumptions and design criteria:
   a. Assume primary tank is followed by secondary treatment and waste activated sludge is not returned to primary settlng tank
   b. Overflow rate at average flow = 40 $m^3/m^2{\bullet}d$
2. Determine the required surface area and volume.

$$A_s = \frac{(45{,}000\text{ persons})(400\text{ L/capita}{\bullet}\text{d})(1\text{ m}^3/10^3\text{ L})}{(40\,m^3/m^2{\bullet}d)} = 450\text{ m}^2$$

$$V = \frac{(45{,}000\text{ persons})(400\text{ L/capita}{\bullet}\text{d})(1\text{ m}^3/10^3\text{ L})(2\text{ h})}{(24\text{ h/d})} = 1500\text{ m}^3$$

3. Determine diameter and depth

$$\text{Diameter} = \sqrt{\frac{450\,\text{m}^2}{(\pi/4)}} = 23.94\text{ m}$$

Use a diameter of 24 m

$$\text{Depth} = \frac{1500\,\text{m}^3}{(\pi/4)(24\,\text{m})^2} = 3.3\text{ m}$$

Use a depth of 3.5 m

Comment: The depth is within the range of depths (3-4.9 m) given in Table 5-20. Consideration should be given to increasing the depth to 4-4.5 m if the tank is used for thickening primary sludge.

PROBLEM 5-23

Problem Statement - See text, page 450-451

Solution

1. Determine the horizontal settling velocity in the tank.

$$V_{\text{horiz}} = \frac{Q}{A_{\text{horiz}}} = \frac{(\text{Overflow rate})(A_s)}{A_{\text{horiz}}} = \frac{(30\text{ m}^3/\text{m}^2\bullet\text{d})(6\,\text{m}\times 15\,\text{m})}{(2.75\,\text{m}\times 6\,\text{m})(24\text{ h/d})(3600\text{ s/h})}$$
$$= 0.0019\,\text{m/s}$$

2. Determine the scour velocity V_H using Eq. (5-46) on page 396.

$$V_H = \left[\frac{8k(s-1)gd}{f}\right]^{1/2}$$

$$V_H = \left[\frac{(8)(0.04)(2.5-1)(9.81\text{m/s}^2)(0.1\text{mm})}{(0.03)(10^3\text{ mm}/1\text{m})}\right]^{1/2} = 0.125\text{ m/s}$$

Because the horizontal velocity in the tank is less than the scour velocity, the particles will not be scoured.

PROBLEM 5-24

Problem Statement - See text, page 451

Solution

1. Determine the percentage increase in hydraulic loading.

$$\text{Increase, \%} = \left[\frac{(200\,\text{m}^3/\text{d})}{(20{,}000\,\text{m}^3/\text{d})} \right](100) = 1\%$$

2. Determine the percentage increase in organic loading.

$$\text{Increase, \%} = \left[\frac{(200\,\text{m}^3/\text{d})(2000\,\text{g}/\text{m}^3)}{(20{,}000\,\text{m}^3/\text{d})(350\,\text{g}/\text{m}^3)} \right](100) = 5.7\%$$

3. Discuss the effect of the incremental loadings on the performance of the settling facilities.

The design overflow rate of 32 $\text{m}^3/\text{m}^2{\bullet}\text{d}$ specified in the problem is at the upper end of the design overflow rate specified in Table 5-19 for primary settling with waste sludge return at the average flowrate. The increase in hydraulic loading of 1 percent resulting from the return sludge flow is small and in itself is not significant. The overflow rate at peak hourly flow should be checked to ensure adequate settling occurs.

An additional piece of data given in the problem is the 2.8 h detention time in the clarifier, for the average flowrate. The detention time is longer than the typical value of 2.0 h given in Table 5-19. The value of the detention time in this problem is that additional clarifier depth is provided. The increased depth will provide an increased safety factor in short circuiting and sludge blanket carryover. Based on the information in the example, the probable effect on primary clarifier performance of adding the return waste activated sludge is negligible during average flow periods. During peak hourly flows, some increase in solids carryover from the primary clarifier might be expected.

In actuality, if the waste activated sludge has poor settling characteristics, performance of the primary clarifier may suffer at average flows as well as during the peak flow periods. The addition of a baffle as shown on Fig. 8-56 may retard the carryover of waste activated sludge solids. A disadvantage of not providing separate thickening for waste activated sludge is the lack of control for managing the sludge during upset or poor performance conditions.

PROBLEM 5-25

Problem Statement - See text, page 451

Instructional Guidelines

The purpose of this problem is two-fold: (1) to familiarize students with some of the additional sources of information that are available and (2) to provide insight into the range of values that will be found in the literature for a given design parameter. It will be helpful to the students if some of the standard reference publications, especially those from the Water Environment Federation, are made available or placed on reserve in the library.

PROBLEM 5-26

Problem Statement - See text, page 451

Solution

1. The advantages of circular primary sedimentation tanks are:
   - More economical to construct than rectangular tanks where site constraints are not a problem
   - Simplest mechanical equipment for sludge and scum removal
   - Collector equipment requires less maintenance than chain-and-flight mechanisms
   - Center flocculation compartment can be incorporated if combined flocculation-clarification feature is required
   - Less sensitive to rag accumulations on collector mechanisms
   - Less sensitive to flowrate surges provided tank inlet is properly baffled
2. The advantages of rectangular primary sedimentation tanks are:
   - Less space (area) required when multiple units are used
   - On large installations, common-wall construction can be used that saves construction costs

- Common pipe galleries can be used that facilitate pipe installation and equipment maintenance
- Longer travel distance for settling to occur
- Performance less affected by high winds
- Covering easier if required for odor control or VOC containment

References

Examples of references used are listed below.

AWWA/ASCE (2012): *Water Treatment Plant Design*, 5th ed., American Water Works Association/American Society of Civil Engineers McGraw-Hill, New York.

Parker, D.S., M. Sequer, M. Hetherington, A.Z. Malik, D. Robison, E.J. Wahlberg, J. Wang (2000) "Assessment and Optimization of a Chemically Enhanced Primary Treatment System," Proceedings of the WEF 73rd ACE, Anaheim, CA.

WEF (2005) *Clarifier Design, Manual of Practice FD-8*, 2nd ed., Water Environment Federation, Alexandria, VA.

WEF (2009) *Design of Municipal Wastewater Treatment Plants*, 5th ed., WEF Manual of Practice No. 8, ASCE Manual and Report on Engineering Practice No. 76, Water Environment Federation, Alexandria, VA.

WEF/IWA (2003) *Wastewater Treatment Plant Design, Student Workbook*, Water Environment Federation, Alexandria, VA.

PROBLEM 5-27

Problem Statement - See text, page 451

Instructors Note: There are many possible solutions to this problem; a range of typical values is presented below. The student should be advised that other reference sources would have to be consulted, as some of the required information cannot be found in this text**.**

Problem Analysis

		Operation	
Parameter	Unit	Sedimentation	Dissolved air flotation

Detention time		1-3 h	10-40 min
Surface loading,	$m^3/m^2 \cdot d$	25-30	60-240
Removal efficiency			
BOD	%	25-40	20-35
TSS	%	40-60	40-60
Power input,	$kWh/10^3\ m^3 \cdot d$	0.35-0.70	2.1-3.5
Application		Removal of settleable solids	Removal of finely divided suspended solids, oil and grease, and scum

PROBLEM 5-28

Problem Statement - See text, page 451

Instructors Note: The detailed solution is provided for mixed liquor. Values calculated for settled activated sludge and primary sludge with activated sludge are summarized in the table.

Solution

1. Using Eq. (5-47) compute required pressure. Assume a typical fraction of air dissolved, f = 0.5. Air solubility at temperature = 20 °C is 18.7 mg/L (see page 407).

$$\frac{A}{S} = \frac{(1.3)[S_a(f \cdot P - 1)]}{S_a}$$

$$0.02 = \frac{(1.3 \text{ x} 18.7 \text{ mL/L})[0.5(P-1)]}{(2500 \text{ mg/L})}$$

P = 6.1 atm

Gauge Pressure: $P = 6.1 \text{ atm} = \dfrac{\rho + 101.35}{101.35}$

ρ = 518 kPa

2. Determine the required surface area.

$$A = \frac{(1200\ \mathrm{m^3/d})(10^3\ \mathrm{L/1\,m^3})}{(10\ \mathrm{L/m^2 \cdot min})(1440\ \mathrm{min/d})} = 83.3\ \mathrm{m^2}$$

3. Check the solids loading rate:

Typical range is 1.2 to 3.0 → OK

		Data Set		
Item	Unit	1 Mixed liquor	2 Settled activated sludge	3 Primary + activated sludge
Solids concentration	mg/L, % solids	2500	0.75	1.00
Optimum A/S Ratio	ratio	0.02	0.03	0.03
Temperature	°C	20	20	20
Surface loading rate	$\mathrm{L/m^2 \cdot min}$	10	15	8
Flow rate	$\mathrm{m^3/d}$	1200	400	800
Fraction of saturation assumed		0.5	0.5	0.5
Solution (See Example 5-11)				
Required pressure, P	atm	6.11	20.51	26.68
Gage pressure, p	kPa	518	1977	2603
Gage pressure, p	$\mathrm{lb/in.^2}$	75.2	286.8	377.5
Required surface area, A	$\mathrm{m^2}$	83.3	18.5	69.4
Solids loading rate, SLR	$\mathrm{kg/m^2 \cdot d}$	36	162	115
Solids loading rate, SLR	$\mathrm{kg/m^2 \cdot h}$	1.5	6.75	4.8
Typical SLR (Table 14-20)	$\mathrm{kg/m^2 \cdot h}$	1.2 - 3.0	2.4 - 4.0	3.0 - 6.0
Check the loading rate		OK!	Too high, consider chemical addition	OK!

PROBLEM 5-29

Problem Statement - See text, page 451

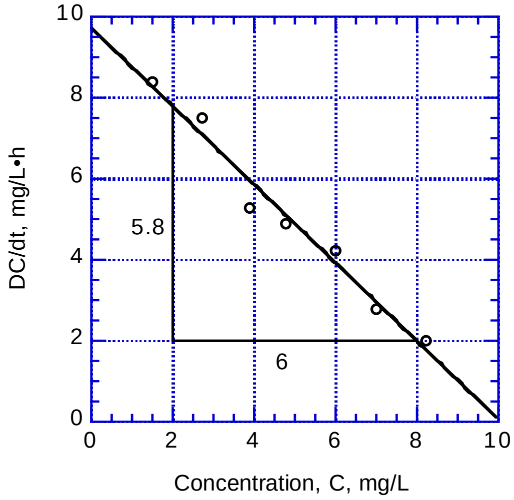
Solution

1. Determine K_La and C_S at 24°C. To determine K_La by graphical analysis, rearrange Eq. (5-61) in a linear form. Eq. (5-61) is equivalent to Eq. (5-71), except the oxygen uptake term r_M is zero.

$$r_c = \frac{dC}{dt} = K_La(C_s - C)$$

$$\frac{dC}{dt} = -K_La(C) + K_La(C_s)$$

2. Plot dC/dt versus C



The slope is equal to $-K_La$, so

$$-K_La = \frac{-5.8}{6}, K_La = 0.97\ h^{-1}$$

The y-intercept is equal to K_La (C_S), Thus C_S

$$C_s = \frac{9.7}{0.97} = 10.0\ mg/L\ at\ 24°C$$

C_s is the equilibrium dissolved-oxygen concentration in the test tank.

2. Determine K_La at 20°C. Use Eq. (5-74)

$$(K_La)_T = (K_La)_{20°C}\theta^{T-20°C}$$

$$K_La_{20°C} = 0.91\ h^{-1}$$

PROBLEM 5-30

Problem Statement - See text, page 452

Solution

1. The oxygen transfer efficiency is the amount of oxygen transferred divided by the amount of oxygen delivered to the system. At T = 20°C and C = 0, the oxygen transfer rate is at its maximum.

$$r_c = \frac{dC}{dt} = K_L a (C_s - C) = K_L a (C_s)$$

The saturation concentration of oxygen in water at 20°C and 1 atmosphere can be found in Appendix D.

C_s = 9.08 mg/L

The maximum rate of oxygen transfer, then, is

$$r_c = \frac{dC}{dt} = K_L a (C_s) = (0.91/h)(9.08\ mg/L \cdot h)$$

2. The mass of oxygen delivered can be calculated by using the ideal gas law.

$$\text{Mass } O_2 \text{ transfered} = \left(\frac{2\ m^3}{min}\right)(0.21)\left(\frac{1\ mole}{22.4 L}\right)\left(\frac{32\ g}{mole}\right)\left(\frac{10^3\ L}{m^3}\right) = 600\ g/min$$

3. For a volume of 100 m^3 and a flowrate of 2 m^3/min, the maximum oxygen-transfer efficiency can be determined using the following expression derived in Example 5-15:

$$E = \frac{(dm/dt)_{20°C,C=0}}{M}$$

where E = oxygen transfer efficiency

$(dm/dt)_{20°C,\ C\ =\ 0}$ = oxygen-solution rate at 20°C and zero dissolved oxygen

M = mass rate at which oxygen is introduced

Translating the above equation into practical terms yields

$$E = \frac{V(K_L a)(C_s - C)}{(Q_{air})(\rho_{air})(0.23)}$$

The pertinent data are:

V = 100 m^3

K_La = 0.91/h at 20°C

C_s = 9.08 mg/L

Q_{air} = 2 m^3/min

ρ_{air} = 1.2047 g/L at 20 °C and 760 mm Hg

$$E, \% = \frac{(100\ m^3)(0.91/h)(9.08 mg/L)(100)}{(2m^3/min)(1.2047 g/L)(0.23)(10^3 mg/g)(60\ min/h)} = 2.49\%$$

PROBLEM 5-31

Problem Statement - See text, page 452

Solution

1. Use the equation developed in Example 5-15.

$$Q_a = 3.53 \times 10^{-3} \frac{Q(C_s)_{20°C}}{E(1.024)^{(T-20)}}\left[\ln\left(\frac{C_s - C}{C_s - C_o}\right)\right]$$

where:

Q_a = required air flowrate, m^3/s

Q = wastewater flowrate, m^3/s

C_s = saturation concentration of oxygen at 20°C, g/m^3

C = initial dissolved oxygen concentration, g/m^3

C_o = dissolved oxygen concentration at outlet, g/m^3

E = oxygen transfer efficiency

T = water temperature, °C

2. Determine the required flowrate at 15°C.

From Appendix D, the saturation concentration of oxygen in water at 1 atm is 9.08 mg/L at 20°C, 10.07 mg/L at 15°C, and 8.24 mg/L at 25°C.

Other pertinent data are:

Q = 20,000 m^3/d = 13.89 m^3/min

E = 0.06

$$Q_a = 3.53 \times 10^{-3} \frac{(13.89\ m^3/min)(9.08\ g/m^3)}{0.06(1.024)^{(15-20)}}\left[\ln\left(\frac{10.07 - 0}{10.07 - 4.0}\right)\right] = 4.22\ m^3/min$$

3. The required flowrate at 25°C is:

$$Q_a = 3.53\times10^{-3}\,\frac{(13.89\ \text{m}^3/\text{min})(9.08\ \text{g/m}^3)}{0.06(1.024)^{(25-20)}}\left[\ln\left(\frac{8.24-0}{8.24-4.0}\right)\right] = 4.35\ \text{m}^3/\text{min}$$

PROBLEM 5-32

Problem Statement - See text, page 452

Solution

1. Determine the actual oxygen transfer rate under field conditions using Eq. (5-70)

$$\text{AOTR} = \text{SOTR}\left(\frac{\beta C_{\bar{s},T,H} - C_L}{C_{s,20}}\right)(1.024^{T-20})(\alpha)(F)$$

Neglecting the biological oxygen uptake, the average dissolved oxygen saturation concentration in clean water in aeration tank at temperature T and altitude H can be estimated using the following expression.

$$C_{\bar{s},T,H} = (C_{s,T,H})\left(\frac{P_d + P_{w,\text{mid depth}}}{P_{\text{atm},H}}\right)$$

From Appendix D, the saturation concentration of oxygen in water at 1 atm is 9.08 mg/L at 20°C. One atmosphere of pressure is equal to 10.333 m of water (see inside of back cover). Thus, the saturation concentration at the tank mid depth is:

$$C_{\bar{s},T,H} = (9.08\ \text{mg/L})\left[\frac{10.333\ \text{m} + 0.5(4.5\text{m})}{10.333\ \text{m}}\right] = 11.06\ \text{mg/L}$$

2. Determine the standard oxygen transfer rate for the ceramic domes (α = 0.64):

Assume β = 0.95, C_L = 2.0 mg/L, and F = 1.0.

$$7000\ \text{kg/d} = \text{SOTR}\left(\frac{0.95\,(11.06) - 2.0}{9.08}\right)(1.024^{20-20})(0.64)(1)$$

$$\text{SOTR} = 11{,}674\ \text{kg/d}$$

3. Determine the standard oxygen transfer rate for the non porous diffusers (α = 0.75):

   Assume β = 0.95, C_L = 2.0 mg/L, and F = 1.0.

   $$7000\ \text{kg/d} = \text{SOTR}\left(\frac{0.95\,(11.06) - 2.0}{9.08}\right)(1.024^{20-20})(0.75)(1)$$

   $$\text{SOTR} = 9{,}962\ \text{kg/d}$$

4. Estimate the air required.

   From Table 5-28, use the following oxygen transfer efficiency values

   Ceramic domes (grid pattern) = 27%

   Nonporous diffusers (dual spiral roll) = 12%

   From Appendix B, the density of air at 20°C and 1.0 atmosphere equals 1.204 g/L. Also air contains 23 percent oxygen by mass.

   a. Air requirement for ceramic domes

   $$\text{Air required} = \frac{(11{,}674\ \text{kg/d})}{(1.204\ \text{kg/m}^3)(0.23)(0.27)} = 156{,}135\ \text{m}^3/\text{d}$$

   b. Air requirement for nonporous diffusers

   $$\text{Air required} = \frac{(9{,}962\ \text{kg/d})}{(1.204\ \text{kg/m}^3)(0.23)(0.12)} = 299{,}786\ \text{m}^3/\text{d}$$

PROBLEM 5-33

Problem Statement - See text, page 452

Solution

1. Determine oxygen saturation concentration at mid-depth for winter conditions.

   From Appendix D, the saturation concentration of oxygen in water at 1 atm is 11.28 mg/L at 20°C. One atmosphere of pressure is equal to 10.333 m of water (see inside of back cover). Thus the saturation concentration at the tank mid-depth is:

   $$C_{\bar{s},T,H} = (11.28\ \text{mg/L})\left[\frac{10.333\ \text{m} + 0.5\,(4.5\text{m})}{10.333\ \text{m}}\right] = 13.74\ \text{mg/L}$$

2. Determine the standard oxygen transfer rate for the ceramic domes (α = 0.64):

   Assume β = 0.95, C_L = 2.0 mg/L, and F = 1.0.

   $$7000\ \text{kg/d} = \text{SOTR}\left(\frac{0.95\,(13.74)\ \text{-}\ 2.0}{9.08}\right)(1.024^{20-20})\,(0.64)\,(1)$$

   $$\text{SOTR} = 8{,}985\ \text{kg/d}$$

3. Determine the standard oxygen transfer rate for the non porous diffusers (□ = 0.75):

   Assume β = 0.95, C_L = 2.0 mg/L, and F = 1.0.

   $$7000\ \text{kg/d} = \text{SOTR}\left[\frac{0.95(13.74)\ \text{-}\ 2.0}{9.08}\right](1.024^{20-20})(0.75)(1)$$

   $$\text{SOTR} = 7{,}667\ \text{kg/d}$$

4. Estimate the air required.

   From Table 5-28, use the following oxygen transfer efficiency values

   Ceramic domes (grid pattern) = 27%

   Nonporous diffusers (dual spiral roll) = 12%

   From Appendix B, the density of air at 10°C and 1.0 atmosphere is:

   $$\rho_{a,20^\circ C} = \frac{(1.01325 \text{ x } 10^5\ \text{N/m}^2)(28.97\ \text{kg/kg mole})}{=[8314\ \text{Nm/(kg mole air)}\bullet\text{K}]\,[(273.15+10)\text{K}]} = 1.247\ \text{kg/m}^3$$

   a. Air requirement for ceramic domes

   $$\text{Air required} = \frac{(8985\ \text{kg/d})}{(1.247\ \text{kg/m}^3)(0.23)(0.27)} = 116{,}027\ \text{m}^3/\text{d}$$

   b. Air requirement for nonporous diffusers

   $$\text{Air required} = \frac{(7667\ \text{kg/d})}{(1.247\ \text{kg/m}^3)(0.23)(0.12)} = 222{,}767\ \text{m}^3/\text{d}$$

5. Summer/winter operation

   Because there is about a 20 percent difference between the summer and winter air requirements, four blowers and a standby could used. During the winter operation, only three of the blowers would be used.

6

CHEMICAL UNIT PROCESSES

PROBLEM 6-1

Problem Statement - See text, page 544

Solution

1. Determine the minimum alkalinity required for a ferrous sulfate dose of 25 g/m^3 using Eq. (6-12).

$FeSO_4{\bullet}7H_2O + Ca(HCO_3)_2 \rightleftarrows Fe(HCO_3)_2 + CaSO_4 + 7H_2O$

278 100 as $CaCO_3$ 178

Required alkalinity as $CaCO_3$

$$= \frac{100}{278} \text{ x } 25 \text{ g/m}^3 = 9.0 \text{ g/m}^3$$

2. Determine the amount of lime required as CaO using Eq. (6-14).

$Fe(HCO_3)_2 + 2Ca(OH)_2 \rightleftarrows Fe(OH)_2 + 2CaCO_3 + 2H_2O$

178 2 x 56 as CaO 89.9

$$\text{Required lime as CaO} = \frac{178}{278} \text{ x } (25 \text{ g/m}^3)\left(\frac{2 \text{ x } 56}{178}\right) = 10.1 \text{ g/m}^3$$

3. Determine the amount of dissolved oxygen required using Eq. (6-15).

$4Fe(OH)_2 + O_2 + 2\ H_2O \rightleftarrows 4Fe(OH)_3$

4 x 89.9 32 2 x 18

$$\text{Required DO} = \frac{89.9}{278} \text{ x } (25 \text{ g/m}^3)\left(\frac{32}{4 \text{ x } 89.9}\right) = 0.72 \text{ g/m}^3$$

PROBLEM 6-2

Problem Statement - See text, page 544

Instructors Note: As a practical matter in discussing precipitation in wastewater it should be noted that about 15 g/m^3 of $CaCO_3$ will remain in solution to satisfy the solubility product for $CaCO_3$. It should also be noted that the theoretical value calcium in solution computed using the solubility product given in Table 6-21 will be considerably lower.

Solution

1. Determine the amount of lime required as CaO for a ferrous sulfate dose of 30 g/m^3 using Eqs. (6-12) and (6-14).

$$FeSO_4{\cdot}7H_2O + Ca(HCO_3)_2 \rightleftarrows Fe(HCO_3)_2 + CaSO_4 + 7H_2O$$

278 100 as $CaCO_3$ 178

$$Fe(HCO_3)_2 + 2Ca(OH)_2 \rightleftarrows Fe(OH)_2 + 2CaCO_3 + 2H_2O$$

178 2 x 56 as CaO 89.9

Required lime as CaO (based on a $FeSO_4{\cdot}7H_2O$ dose of 30 g/m^3) =

$$= \left[\frac{(178\ \text{g/mole})}{(278\ \text{g/mole})}\right]\left[\frac{2(56\ \text{g/mole})}{(178\ \text{g/mole})}\right]\left(30\ \text{kg}/10^3\ \text{m}^3\right) = 12.1\ \text{kg}/10^3\ \text{m}^3$$

2. Determine the amount of dissolved oxygen required using Eq. (6-15).

$$4Fe(OH)_2 + O_2 + 2H_2O \rightleftarrows 4Fe(OH)_3$$

4 x 89.9 32 2 x 18

$$\text{Required DO} = \left[\frac{(89.9\ \text{g/mole})}{(278\ \text{g/mole})}\right]\left[\frac{(32\ \text{g/mole})}{4(89.9\ \text{g/mole})}\right]\left(30\ \text{kg}/10^3\ \text{m}^3\right)$$

$$= 0.9\ \text{kg}/10^3\ \text{m}^3$$

3. Determine the amount of sludge produced per 10^3 m^3.

   a. Determine the amount of $Fe(OH)_3$ formed using Eqs. (6-12), (6-14), and (6-15).

$$FeSO_4{\cdot}7H_2O + Ca(HCO_3)_2 \rightleftarrows Fe(HCO_3)_2 + CaSO_4 + 7H_2O$$

278 100 as $CaCO_3$ 178

$Fe(HCO_3)_2 + 2Ca(OH)_2 \rightleftarrows Fe(OH)_2 + 2CaCO_3 + 2H_2O$

178 2 x 56 as CaO 89.9

$4Fe(OH)_2 + O_2 + 2H_2O \rightleftarrows 4Fe(OH)_3$

4 x 89.9 4 x 106.9

Amount of $Fe(OH)_3$ formed =

$$= \left[\frac{4(106.9\ g/mole)}{4(89.9\ g/mole)}\right]\left[\frac{(89.9\ g/mole)}{(178\ g/mole)}\right]\left[\frac{(178\ g/mole)}{(278\ g/mole)}\right]\left(30\ kg/10^3\ m^3\right)$$

$$= 11.5\ kg/10^3\ m^3$$

b. Determine the amount of $CaCO_3$ formed.

$Fe(HCO_3)_2 + 2Ca(OH)_2 \rightleftarrows Fe(OH)_2 + 2CaCO_3 + 2H_2O$

178 2 x 56 as CaO 89.9 2 x 100

Amount of $CaCO_3$ formed =

$$= \left[\frac{2(100\ g/mole)}{(178\ g/mole)}\right]\left[\frac{(178\ g/mole)}{(278\ g/mole)}\right]\left(30\ kg/10^3\ m^3\right) = 21.6\ kg/10^3\ m^3$$

Assume that about 15 g/m^3 of $CaCO_3$ will remain in solution to satisfy the solubility product for $CaCO_3$. It should be noted that the theoretical value computed for calcium using the solubility product given in Table 6-21 will be considerably lower.

c. Determine the total amount of sludge produced

Sludge produced = $Fe(OH)_3$ + excess $CaCO_3$

Sludge produced = [11.5 + (21.6 - 15)] $kg/10^3\ m^3$ = 18.1 $kg/10^3\ m^3$

4. Determine the amount of alum needed (X) to obtain this same quantity of sludge using Eq. (6-9), assuming that $Al(OH)_3$ is the precipitate formed.

$Al_2(SO_4)_3 \cdot 18H_2O + 3Ca(HCO_3)_2 \rightleftarrows 2Al(OH)_3 + 6CO_2 + 3CaSO_4 + 18H_2O$

666.5 3 x 100 as $CaCO_3$ 2 x 78

$$\left[\frac{2(78\ g/mole)}{(666.5\ g/mole)}\right]\left(X\ kg/10^3\ m^3\right) = 18.0\ kg/10^3\ m^3$$

$$\text{X kg}/10^3\,\text{m}^3 = (18.0\ \text{kg}/10^3\,\text{m}^3)\left[\frac{(666.5\ \text{g/mole})}{2(78\ \text{g/mole})}\right]$$

Alum required = 76.9 kg/10^3 m^3

PROBLEM 6-3

Problem Statement - See text, page 544

Solution – Part a

1. Determine the amount of $Al(OH)_2$ sludge produced for an alum dose of 50 kg/4000 m^3 (= 12.5 kg/10^3 m^3) using Eq. (6-9)

$$Al_2(SO_4)_3{\cdot}18H_2O + 3Ca(HCO_3)_2 \rightleftarrows 2Al(OH)_3 + 6CO_2 + 3CaSO_4 + 18H_2O$$

666.5 3 x 100 as $CaCO_3$ 2 x 78

$$Al(OH)_3\text{sludge produced} = \left[\frac{2(78\ \text{g/mole})}{(666.5\ \text{g/mole})}\right]\left[\frac{(12.5\,\text{g/m}^3)}{(10^3\ \text{g/kg})}\right]$$

$$= 2.9\ \text{kg}/10^3\ \text{m}^3$$

Solution – Part b

1. Determine the amount of $Fe(HCO_3)_2$ formed using Eq. (6-12) assuming a dose of 50 kg/4000 m^3 (= 12.5 kg/10^3 m^3) of ferrous sulfate and lime

$$FeSO_4{\cdot}7H_2O + Ca(HCO_3)_2 \rightleftarrows Fe(HCO_3)_2 + CaSO_4 + 7H_2O$$

278 100 as $CaCO_3$ 178

$$Fe(HCO_3)_2\ \text{produced} = \frac{(178\ \text{g/mole})}{(278\ \text{g/mole})}\ \text{x}\ \frac{(12.5\,\text{g/m}^3)}{(10^3\ \text{g/kg})} = 8.0\ \text{kg}/10^3\,\text{m}^3$$

2. Determine the amount of $CaCO_3$ and $Fe(OH)_2$ formed using Eq. (6-14).

$$Fe(HCO_3)_2 + 2Ca(OH)_2 \rightleftarrows Fe(OH)_2 + 2CaCO_3 + 2H_2O$$

178 2 x 74 89.9 2 x 100

$$CaCO_3\ \text{produced} = \frac{2(100\ \text{g/mole})(8.0\ \text{kg}/10^3\,\text{m}^3)}{(178\ \text{g/mole})} = 9.0\ \text{kg}/10^3\,\text{m}^3$$

$$Fe(OH)_2\ \text{formed} = \frac{(89.9\ \text{g/mole})(8.0\ \text{kg}/10^3\,\text{m}^3)}{(178\ \text{g/mole})} = 4.1\,\text{kg}/10^3\,\text{m}^3$$

3. Determine the amount of lime [$Ca(OH)_2$] consumed in the reaction with $Fe(HCO_3)_2$.

$$\text{Lime used} = \frac{2(74\ \text{g/mole})(8.0\ \text{kg}/10^3\ \text{m}^3)}{(178\ \text{g/mole})} = 6.7\ \text{kg}/10^3\ \text{m}^3$$

4. Determine the amount of lime remaining.

Lime remaining = (12.5 – 6.7) kg/10^3 m^3 = 5.8 kg/10^3 m^3

5. Using Eq. (6-11) determine the amount of $CaCO_3$ formed when the remaining lime reacts with the alkalinity.

$$\underset{74}{Ca(OH)_2} + \underset{2 \times 100}{Ca(HCO_3)_2} \rightleftarrows 2CaCO_3 + 2H_2O$$

$$CaCO_3\ \text{produced} = \frac{2(100\ \text{g/mole})(5.8\ \text{kg}/10^3\ \text{m}^3)}{(74\ \text{g/mole})} = 15.7\ \text{kg}/10^3\ \text{m}^3$$

6. Determine the amount of $Fe(OH)_3$ formed using Eq. (6-15).

$$\underset{4 \times 89.9}{4Fe(OH)_2} + O_2 + 2H_2O \rightleftarrows \underset{4 \times 106.9}{4Fe(OH)_3}$$

$$Fe(OH)_3\ \text{formed} = \frac{4(106.9\ \text{g/mole})(4.1\ \text{kg}/10^3\ \text{m}^3)}{4(89.9\ \text{g/mole})} = 4.9\ \text{kg}/10^3\ \text{m}^3$$

7. Determine the total amount of sludge produced.

Sludge produced =

$$= \underset{\text{step 6}}{Fe(OH)_3} + \underset{\text{step 2}}{CaCO_3} + \underset{\text{step 5}}{CaCO_3} - 15\ \text{kg}/10^3\ \text{m}^3\ \text{dissolved}\ CaCO_3$$

Sludge produced = (4.9 + 9.0 + 15.7 - 15) kg/10^3 m^3 = 14.6 kg/10^3 m^3

PROBLEM 6-4

Problem Statement - See text, page 544-545

Solution – Part a

1. Determine the amount of $AlPO_4$ formed, and the amount of alum which reacts to form $AlPO_4$ using Eq. (6-19).

$$Al_2(SO_4)_3{\bullet}14.3H_2O + 2PO_4^{3-} \rightleftarrows 2AlPO_4 + 3SO_4^{-} + 14.3\ H_2O$$

599.7 2 x 31 as P 2 x 122

$$AlPO_4 \text{ formed} = \frac{2(122 \text{ g/mole})(10 \text{ kg}/10^3 \text{ m}^3)}{2(31.0 \text{ g/mole})} = 39.5 \text{ kg}/10^3 \text{ m}^3$$

Amount of alum reacting with P

$$\text{Alum reacting with P} = \frac{(599.7 \text{ g/mole})(10 \text{ kg}/10^3 \text{ m}^3)}{2(31.0 \text{ g/mole})} = 96.7 \text{ kg}/10^3 \text{ m}^3$$

2. Determine the amount of alum which reacts with alkalinity to form $Al(OH)_3$ and the amount of $Al(OH)_3$ formed using Eq. (6-9). Assume an alum dosage of 150 g/m^3

   Amount of alum remaining = (150 – 96.7) g/m^3 = 53.3 g/m^3

$$Al_2(SO_4)_3 \cdot 14.3H_2O + 3Ca(HCO_3)_2 \rightleftarrows 2Al(OH)_3 + 6CO_2 + 3CaSO_4 + 18H_2O$$

599.7 3 x 100 as $CaCO_3$ 2 x 78

$$Al(OH)_3 \text{ formed} = \frac{2(78 \text{ g/mole})(53.3 \text{ kg}/10^3 \text{ m}^3)}{(599.7 \text{ g/mole})} = 13.9 \text{ kg}/10^3 \text{ m}^3$$

3. Determine the amount of sludge produced.

   Sludge produced = [$AlPO_4$ + $Al(OH)_3$ + 0.95 x TSS) Q

   Q = (0.75 m^3/s x 86,400 s/d) = 64.8 x 10^3 m^3/d

   Sludge produced =

   = (39.5 + 13.9 + 0.95 x 220) g/m^3](64.8 x 10^3 m^3/d)/(10^3 g/kg)

   = 17,004 kg/d

   If sludge has a specific gravity of 1.04 and a water content of 93%, then the

   Volume of sludge produced

$$\text{Sludge volume} = \frac{(17{,}004 \text{ kg/d})}{(0.07)(1.04)(10^3 \text{ kg/m}^3)} = 233.6 \text{ m}^3/\text{d}$$

Solution – Part b

1. Determine the amount of hydroxylapatite formed, the amount of lime which reacts with the phosphorus and the amount of lime remaining after the precipitation of phosphorus. The amount of hydroxylapatite formed can be determined using Eq. (6-22).

$$10Ca(OH)_2 + 6PO_4^{3-} + 2OH \rightleftarrows Ca_{10}(PO_4)_6(OH)_2 + 18OH^-$$

10 x 74 as $Ca(OH)_2$ lime   6 x 31 as P   1004 hydroxylapatite

$$\text{Hydroxylapatite formed} = \frac{(1004\ \text{g/mole})(10\ \text{kg}/10^3\ \text{m}^3)}{6(31\ \text{g/mole})} = 54.0\ \text{kg}/10^3\ \text{m}^3$$

$$\text{Lime reacting with P} = \frac{10(74\ \text{g/mole})(10\ \text{kg}/10^3\ \text{m}^3)}{6(31\ \text{g/mole})} = 39.8\ \text{kg}/10^3\ \text{m}^3$$

Lime remaining + (450 – 39.8) kg/10^3 m^3 = 410.2 kg/10^3 m^3

2. Determine the amount of lime [$Ca(OH)_2$] which reacts with alkalinity to form $CaCO_3$ and the amount of $CaCO_3$ which precipitates.

   The amount of alkalinity present is 200 g/m^3 as $CaCO_3$.

   $$Ca(OH)_2 + Ca(HCO_3)_2 \rightleftarrows 2CaCO_3 + 2H_2O$$

   74   100 mg/L as $CaCO_3$ 2 x 100

   $$CaCO_3\ \text{formed} = \frac{2(100\ \text{g/mole})(200\ \text{kg}/10^3\ \text{m}^3)}{(100\ \text{g/mole})} = 400\ \text{kg}/10^3\ \text{m}^3$$

   Amount of $CaCO_3$ that precipitates = (400 – 20) kg/10^3 m^3 = 380 kg/10^3 m^3

3. Determine the amount of $Ca(OH)_2$ that remains in solution. The amount of $Ca(OH)_2$ that reacts with alkalinity is:

   $$Ca(OH)_2\ \text{utilized} = \frac{(74\ \text{g/mole})(200\ \text{kg}/10^3\ \text{m}^3)}{(100\ \text{g/mole})} = 148.0\ \text{kg}/10^3\ \text{m}^3$$

   Amount of $Ca(OH)_2$ that remains in solution =:

   = (410.2 – 148.0) kg/10^3 m^3 = 262.2 kg/10^3 m^3

4. Determine the amount of sludge produced.

   Sludge produced = [$Ca_{10}(PO_4)_6(OH)_2$ + $CaCO_3$ + 0.95 x TSS) Q

   Sludge produced = [54.0 + 380 + 0.95 x 220) g/m^3](64.8×10^3 m^3)/(10^3 g/kg)

   = 41,666 kg/d

   If sludge has a specific gravity of 1.05 and a water content of 92%, then the

   Volume of sludge produced

$$\text{Sludge volume} = \frac{(41{,}666\ \text{kg/d})}{(0.08)(1.05)(10^3\ \text{kg/m}^3)} = 496\ \text{m}^3/\text{d}$$

Solution – Part c

1. Determine the net increase in hardness for the treatment specified in part b. Assume calcium hardness is equal to the alkalinity

   Amount of lime remaining in solution = 262.2 g/m^3 as $CaCO_3$ (see Part b, Step 3)

   Hardness of lime remaining expressed as $CaCO_3$ =

   $$= \frac{(100\ \text{g/mole})(262.2\ \text{g/m}^3)}{(74\ \text{g/mole})} = 354.3\ \text{g/m}^3\ \text{as}\ CaCO_3$$

   Total hardness remaining = 354.3 + 20) g/m^3 = 374.3 g/m^3 as $CaCO_3$

   Net increase in hardness = (374.3 – 200) g/m^3 = 174.3 g/m^3 as $CaCO_3$

PROBLEM 6-5

Problem Statement - See text, page 545

Instructors Note: The purpose of Problem 6-5 is to introduce students to the computational procedures used to produce graphical solubility diagrams

PROBLEM 6-6

Problem Statement - See text, page 545

Instructors Note: The purpose of Problem 6-6, is to introduce the students to the computational procedures used to produce curves of residual soluble metal concentrations as function of pH.

Sources for chemical equilibrium data are:

Benefield, L. D., J. F. Judkins, Jr.,and B. L. Weand (1982) *Process Chemistry for Water and Wastewater Treatment*, Prentice-Hall, Inc., Englewood Cliffs, NJ.

Benjamin, M. M. (2001) *Water Chemistry*, McGraw-Hill, New York

Morel, F. M. M., and J. G. Hering. (199) *Principles and Applications of Aquatic Chemistry*, A Wiley-Interscience publication, New York, NY.

Pankow, J. F. (1991) *Aquatic Chemistry Concepts*, Lewis Publishers, Chelesa, MI.

Sawyer, C. N., P. L. McCarty, and G. F. Parkin (2001) *Chemistry For Environmental Engineering*, 5th ed., McGraw-Hill, Inc., New York, NY.

Snoeyink, V. L., and D. Jenkins (1980) *Water Chemistry*, John Wiley & Sons, New York, NY.

PROBLEM 6-7

Problem Statement - See text, page 545

Instructors Note: The purpose of Problem 6-7, is to introduce the students to the computational procedures used to produce curves of residual soluble metal concentrations as function of pH.

Sources for chemical equilibrium data are:

Benefield, L. D., J. F. Judkins, Jr.,and B. L. Weand (1982) *Process Chemistry for Water and Wastewater Treatment*, Prentice-Hall, Inc., Englewood Cliffs, NJ.

Benjamin, M. M. (2001) *Water Chemistry*, McGraw-Hill, New York

Morel, F. M. M., and J. G. Hering. (199) *Principles and Applications of Aquatic Chemistry*, A Wiley-Interscience publication, New York, NY.

Pankow, J. F. (1991) *Aquatic Chemistry Concepts*, Lewis Publishers, Chelesa, MI.

Sawyer, C. N., P. L. McCarty, and G. F. Parkin (2001) *Chemistry For Environmental Engineering*, 5th ed., McGraw-Hill, Inc., New York, NY.

Snoeyink, V. L., and D. Jenkins (1980) *Water Chemistry*, John Wiley & Sons, New York, NY.

PROBLEM 6-8

Problem Statement - See text, page 545

Solution

1. Determine the overall reaction by adding the two half reactions

$$\begin{array}{ll} 2H^+ + 2e^- \rightarrow H_2 & E^o = 0.00 \\ \underline{H_2 + 2OH^- \rightarrow 2H_2O + 2e^-} & E^o = 0.828 \\ 2H^+ + 2OH^- \rightarrow 2H_2O & \end{array}$$

2. Determine the $E^o_{reaction}$ for overall reaction

$$E^o_{reaction} = E^o_{reduction} - E^o_{oxidation}$$

$$E^o_{reaction} = (0.828) - (0.00) = +0.828 \text{ volts}$$

3. Determine the equilibrium constant at 25°C using Eq. (6-42)

$$\log K = \frac{n E^o_{reaction}}{0.0592} = \frac{1(0.828)}{0.0592} = 13.99$$

$K = 10^{13.99}$

The computed value is the same as the value reported in most texts at 25°C

PROBLEM 6-9

Problem Statement - See text, page 545

Instructors Note:

1. The purpose of Problems 6-9 through 6-12 is to illustrate to students why reactions used commonly in environmental engineering do occur

Solution

1. Determine the overall reaction by adding the two half reactions

$$\begin{array}{ll} 2Fe^{2+} \rightarrow 2Fe^{3+} + 2e^- & E° = -0.771 \\ \underline{H_2O_2 + 2H^+ + 2e^- \rightarrow 2H_2O + 2e^-} & E° = 1.776 \\ 2Fe^{2+} + H_2O_2 \rightarrow 2Fe^{3+} + 2H_2O & \end{array}$$

2. Determine the $E^o_{reaction}$ for overall reaction

$$E^o_{reaction} = E^o_{reduction} - E^o_{oxidation}$$

$$E^o_{reaction} = (1.776) - (-0.771) = +2.547 \text{ volts}$$

Because the $E^o_{reaction}$ for the reaction is positive, the reaction will proceed as written.

PROBLEM 6-10

Problem Statement - See text, page 545

Solution

1. Determine the overall reaction by adding the two half reactions

$$2Fe^{2+} \rightarrow 2Fe^{3+} + 2e^{-} \qquad E° = -0.771$$
$$Cl_2 + 2e^{-} \rightarrow 2Cl^{-} \qquad E° = 1.36$$
$$2Fe^{2+} + Cl_2 \rightarrow 2Fe^{3+} + 2Cl^{-}$$

2. Determine the $E^o_{reaction}$ for overall reaction

$$E^o_{reaction} = E^o_{reduction} - E^o_{oxidation}$$
$$E^o_{reaction} = (1.360) - (-0.771) = +2.131 \text{ volts}$$

Because the $E^o_{reaction}$ for the reaction is positive, the reaction will proceed as written.

PROBLEM 6-11

Problem Statement - See text, page 545

Solution

1. Determine the overall reaction by adding the two half reactions

$$H_2S \rightarrow S + 2H^{+} + 2e^{-} \qquad E° = +0.14$$
$$Cl_2 + 2e^{-} \rightarrow 2Cl^{-} \qquad E° = 1.36$$
$$H_2S + Cl_2 \rightarrow S + 2HCl^{-}$$

2. Determine the $E^o_{reaction}$ for overall reaction

$$E^o_{reaction} = E^o_{reduction} - E^o_{oxidation}$$
$$E^o_{reaction} = (1.36) - (0.14) = +1.22 \text{ volts}$$

Because the $E^o_{reaction}$ for the reaction is positive, the reaction will proceed as written.

PROBLEM 6-12

Problem Statement - See text, page 545

Solution

1. Determine the overall reaction by adding the two half reactions

$$\begin{array}{rcll} H_2S & \rightarrow & S + 2H^+ + 2e^- & E° = +0.14 \\ O_3 + 2H^+ + 2e^- & \rightarrow & O_2 + H_2O & E° = 2.07 \\ \hline H_2S + O_3 & \rightarrow & S + O_2 + H_2O & \end{array}$$

2. Determine the $E^o_{reaction}$ for overall reaction

$$E^o_{reaction} = E^o_{reduction} - E^o_{oxidation}$$
$$E^o_{reaction} = (2.07) - (0.14) = +1.93 \text{ volts}$$

Because the $E^o_{reaction}$ for the reaction is positive, the reaction will proceed as written.

PROBLEM 6-13

Problem Statement - See text, page 545

Solution

1. Convert the given data for **Sample 3** for use in determinng the Langelier and Ryzner indexes

   a.. Given data

Constituent	Unit	Sample 3
Ca^{2+}	mg/L as $CaCO_3$	245
HCO_3^-	mg/L as $CaCO_3$	200
TDS	mg/L	600
pH	unitless	6.9

   b. Converted data

Constituent	mg/L	mole/L
Ca^{2+}	98.20	2.45×10^{-3}
HCO_3^-	244.0	4.07×10^{-3}

2. Determine the ionic strength of the treated water using Eq. (2-11)

   $I = 2.5 \times 10^{-5} \times TDS$

   $I = 2.5 \times 10^{-5} \times 600 \text{ mg/L} = 1.5 \times 10^{-2}$

3. Determine the activity coefficients for calcium and bicarbonate using Eq. (2-12).

a. For calcium

$$\log \gamma_{Ca^{2+}} = -0.5\,(Z_i)^2\left(\frac{\sqrt{I}}{1+\sqrt{I}} - 0.3\ I\right)$$

$$= -0.5(2)^2\left[\frac{\sqrt{1.5\,x10^{-2}}}{1+\sqrt{1.5\,x10^{-2}}} - 0.3\left(1.5\,x10^{-2}\right)\right]$$

$$= -0.2092$$

$\gamma_{Ca^{2+}}$ = 0.6177

b. For bicarbonate

$$\log \gamma_{HCO_3} = -0.5\,(Z_i)^2\left(\frac{\sqrt{I}}{1+\sqrt{I}} - 0.3\ I\right)$$

$$= -0.5(1)^2\left[\frac{\sqrt{1.5\,x10^{-2}}}{1+\sqrt{1.5\,x10^{-2}}} - 0.3\left(1.5\,x10^{-2}\right)\right]$$

$$= -0.0523$$

γ_{HCO_3} = 0.8865

4. Determine the saturation pH_S at 20°C using Eq. (6-73).

$$pH_s = -\log\left(\frac{K_{a2}\gamma_{Ca^{2+}}\left[Ca^{2+}\right]\gamma_{HCO_3^-}\left[HCO_3^-\right]}{K_{sp}}\right)$$

$$pH_s = -\log\left[\frac{\left(4.17\ x\ 10^{-11}\right)\left(0.6177\right)\left(2.45\ x\ 10^{-3}\right)\left(0.8865\right)\left(4.07\ x\ 10^{-3}\right)}{5.25\ x\ 10^{-9}}\right]$$

$$pH_s = -\log\left(4.89\ x\ 10^{-8}\right) = 7.31$$

5. Determine the Langelier and Ryzner indexes using Eqs. (6-71) and (6-72)

a. Langelier Saturation Index

LSI = pH – pH_S = 6.9 – 7.31 = – 0.41

LSI < 0 (Water is undersaturated with respect to calcium carbonate)

b. Ryzner Stability Index

RSI = $2pH_S$ – pH = 2(7.31) – 6.9 = 7.72

6.8 < (RSI = 7.72) < 8.5 (Water is aggressive)

Comment

Although both indexes are used, the Langelier Saturation Index is used most commonly in the water and wastewater field while the Ryzner Stability Index is used most commonly in industrial applications.

PROBLEM 6-14

Problem Statement - See text, page 545

Solution

1. Determine the ionic strength of **Sample 1** using Eq. (2-10)

   a. Prepare a computation table to determine the summation term in Eq. (2-10).

Ion	Conc., C, mg/L	C x 10^3, mole/L	Z^2	CZ^2 x 10^3
Ca^{2+}	121.3	3.026	4	12.104
Mg^{2+}	36.2	1.489	4	5.956
Na^+	8.1	0.352	1	0.352
K^+	12	0.307	1	0.307
HCO_3^-	280	4.590	1	4.590
SO_4^{2-}	116	1.208	4	4.832
Cl^-	61	1.721	1	1.721
NO_3^-	15.6	0.252	1	0.252
Sum				30.114

   b. Determine the ionic strength for the concentration C

$$I = \frac{1}{2}\sum C_i Z_i^2 = \frac{1}{2}(30.114 \text{ x } 10^{-3}) = 15.057 \text{ x } 10^{-3}$$

2. Determine the activity coefficients for the monovalent and divalent ions using Eq. (2-12).

   a. For monovalent ions

$$\log\gamma = -0.5\,(Z_i)^2\left(\frac{\sqrt{I}}{1+\sqrt{I}} - 0.3\,I\right)$$

$$= -0.5(1)^2\left[\frac{\sqrt{15.057 \text{ x } 10^{-3}}}{1+\sqrt{15.057 \text{ x } 10^{-3}}} - 0.3\left(15.057 \text{ x } 10^{-3}\right)\right]$$

$$= -0.0524$$

$\gamma = 0.8864$

b. For divalent ions

$$\log\gamma = -0.5\,(Z_i)^2\left(\frac{\sqrt{I}}{1+\sqrt{I}} - 0.3\,I\right)$$

$$= -0.5(2)^2\left[\frac{\sqrt{15.057 \text{ x } 10^{-3}}}{1+\sqrt{15.057 \text{ x } 10^{-3}}} - 0.3\left(15.057 \text{ x } 10^{-3}\right)\right]$$

$$= -\ 0.2096$$

$\gamma = 0.6172$

3. Determine the saturation pH_S at 20°C using Eq. (6-73).

$$pH_s = -\log\left(\frac{K_{a2}\,\gamma_{Ca^{2+}}\left[Ca^{2+}\right]\gamma_{HCO_3^-}\left[HCO_3^-\right]}{K_{sp}}\right)$$

$$pH_s = -\log\left[\frac{\left(4.17 \text{ x } 10^{-11}\right)(0.8864)\left(3.026 \text{ x } 10^{-3}\right)(0.6172)\left(4.590 \text{ x } 10^{-3}\right)}{5.25 \text{ x } 10^{-9}}\right]$$

$$pH_s = -\log\left(6.80 \text{ x } 10^{-8}\right) = 7.17$$

4. Determine the Langelier and Ryzner indexes

a. Langelier Saturation Index

$LSI = pH - pH_S = 7.2 - 7.17 = -0.0327$

LSI ≈ 0 Water is essentially neutral (i.e., neither scale forming or scale removing with respect to calcium carbonate)

b. Ryzner Stability Index

$RSI = 2pH_S - pH = 2(7.17) - 7.2 = 7.13$

$6.8 < (RSI = 7.13) < 8.5$ (Water is aggressive)

Comment

Although both indexes are used, the Langelier index is used most commonly in the water and wastewater field while the Ryzner index is used most commonly in industrial applications.

PROBLEM 6-15

Problem Statement - See text, page 546

Solution

1. Langelier Saturation Index

   $LSI = pH - pH_S$

   The Langelier Saturation Index was developed from a consideration of carbonate equilibrium (i.e., the effect of pH on the precipitation of calcium carbonate). The pH value at which $CaCO_3$ will neither be deposited or dissolved is defined as the pH_S value. Thus, if the LSI value is positive, the water is supersatured with respect to $CaCO_3$ and scale formation may occur. Similarly if the LSI value is negative, the water is undersaturated and existing to $CaCO_3$ coatings may be dissolved.

2. Ryzner Stability Index

   $RSI = 2pH_S - pH$

   The Ryzner Stability Index was developed from empirical observations of the dissolution or formation of film in heated water pipes and glass coils.

3. An excellent discussion of the relative merits of the two indexes may be found in:

   Schock, M R. (1999) Chapter 17: "Internal Corrosion and Deposition Control," in R. D. Letterman, ed., *Water Quality And Treatment: A Handbook of Community Water Supplies*, 5th ed., American Water Works Association, McGraw-Hill, New York, NY.

PROBLEM 6-16

Problem Statement - See text, page 546

Instructors Note: Students will need to research and find, or be provided with the required molecular weight and hydroxyl radical rate constant for the compound of interest. If desired, the compounds and concentrations may be varied to demonstrate processes that may not be feasible due to insufficient concentrations of HO• (i.e., concentrations which fall outside of the range that can be transferred to water).

Solution

1. Develop a relationship to find the required reaction rate for the given reaction time. A sample computation for chlorobenzene is shown below.

$$r_R = \frac{\text{moles of R lost or gained due to reaction}}{\text{volume x time}}$$

$$r_R = \frac{(0.095\ \text{mg/L})/(112560\ \text{mg/mole})}{10\ \text{s}} = 8.44\text{x}10^{-8}\ \text{mole/L}\bullet\text{s}$$

2. Rearrange Eq. (6-57) to solve for the hydroxyl radical concentration required to carry out the reaction.

$$C_{HO\cdot} = \frac{r_R}{k_R C_R} = \frac{(8.44\text{x}10^{-8}\ \text{mole/L}\bullet\text{s})}{(4.5\text{x}10^{9}\ \text{L/mole}\cdot\text{s})(8.88\text{x}10^{-7}\ \text{mole/L})}$$
$$= 2.1\text{x}10^{-11}\ \text{mole/L}$$

3. Evaluate the feasibility of the reaction.

   Because the required hydroxyl radical concentration is within the range attainable using current technology (e.g., 109 to 1011), the process is considered to be feasible. A summary table of hydroxyl radical concentrations for other compounds given in the problem statement are given below. As stated, all of the processes are considered feasible, however, interferences and other non-idealities may inhibit a given process. Pilot testing is recommended to evaluate an AOP process for a given water.

Compound	Molecular	Rate constant,	HO• concentration, mole/L

	weight, g/mole	L/mole•s	Water A	Water B
Clorobenzene	112.56	4.50E+09	2.1E-11	2.1E-11
Chloroethene	62.498	1.20E+10	7.9E-12	8.1E-12
TCE	131.39	4.20E+09	2.3E-11	2.2E-11
Toluene	92.14	3.00E+09	3.2E-11	3.1E-11

PROBLEM 6-17

Problem Statement - See text, page 546

Instructors Note: Students should be assigned a constituent from Table 6-17 for purposes of solving the problem.

Solution

1. Develop an expression for the concentration of the constituent as a function of time in a completely mixed batch reactor (CMBR). Note that the residence time for an ideal plug flow reactor is equivalent to the residence time in a completely mixed batch reactor. The required computation for chlorobenzene is given below.

   a. Using Eq. (6-58), the rate expression for a CMBR, where C_R represents the concentration of the selected constituent is given by

   $$r_R = \frac{dC_R}{dt} = -k_R C_{HO\bullet} C_R = -k' C_R$$

   where $k' = k_R C_{HO\bullet}$

   b. The integrated form of the rate expression for a CMBR is:

   $$\int_{C_{R0}}^{C_R} \frac{dC_R}{C_R} = -\int_0^t k' t$$

   $$C_R = C_{R0} e^{-k't}$$

2. Calculate the time it would take to achieve a concentration of 1.25 μg/L (25 μg/L x 0.05) using the equation developed in step 1.

a. Rearrange the above equation to solve for t.

$$t = \frac{1}{k'} \ln \frac{C_{R0}}{C_R}$$

b. Solve for the reaction time. The reaction time is given below for several hydroxyl radical concentrations that may be attained using different reactor designs.

Using the value of k' from step 1 and an HO· concentration of 10^{-9} mole/L, the reaction time is calculated for the selected constituent (**chloride ion**):

$$k' = k_R C_{HO\bullet} = (4.30 \times 10^9 \text{ L/mole}\bullet\text{s})(10^{-9} \text{ mole/L}) = 4.3 \text{ 1/s}$$

$$t = \frac{1}{(4.3)} \ln\left(\frac{25}{1.25}\right) = 0.70 \text{ s}$$

For an HO· concentration of 10^{-10} mole/L, the reaction time is

$$k' = k_R C_{HO\bullet} = (4.3 \times 10^9 \text{ L/mole}\bullet\text{s})(10^{-10} \text{ mole/L}) = 0.43 \text{ 1/s}$$

$$t = \frac{1}{(0.43)} \ln\left(\frac{25}{1.25}\right) = 7.0 \text{ s}$$

For an HO· concentration of 10^{-11} mole/L, the reaction time is

$$k' = k_R C_{HO\bullet} = (4.3 \times 10^9 \text{ L/mole}\bullet\text{s})(10^{-11} \text{ mole/L}) = 0.043 \text{ 1/s}$$

$$t = \frac{1}{(0.043)} \ln\left(\frac{25}{1.25}\right) = 70 \text{ s}$$

3. Size the reactor for a flowrate of 3800 m^3/d.

a. For the HO· concentration of 10^{-9} mole/L, the reactor size (assuming ideal hydraulics) would be

$$V = Q \cdot t = \frac{(3800 \text{ m}^3\text{/d})}{(86400 \text{ s/d})}(0.70 \text{ s}) = 0.03 \text{ m}^3 \text{ or } 30 \text{ L}$$

b. For the HO· concentration of 10^{-10} mole/L, the reactor size would be

$$V = Q \cdot t = \frac{(3800\ m^3/d)}{(86400\ s/d)}(7.0\ s)\ =\ 0.3\ m^3\ \text{or}\ 300\ L$$

c. For the HO• concentration of 10^{-11} mole/L, the reactor size would be

$$V = Q \cdot t = \frac{(3800\ m^3/d)}{(86400\ s/d)}(70\ s)\ =\ 3\ m^3\ \text{or}\ 3000\ L$$

PROBLEM 6-18

Problem Statement - See text, page 546

Solution

1. Calculate the photonic energy input per unit volume of the reactor.

   a. Calculate the total lamp power:

   P = (25 lamps x 500 W/lamp) = 12,500 W = 12,500 J/s

   b. Calculate the photonic energy input for the reactor using Eq. (6-63)

$$P_R = \frac{(12{,}500\ J/s)(0.3)(254 \times 10^{-9}\ m)}{(6.023 \times 10^{23}\ 1/\text{einstein})(6.62 \times 10^{-34}\ J \bullet s)(3.0 \times 10^{8}\ m/s)(250L)}$$
$$= 3.185 \times 10^{-5}\ \text{einstein}/L \bullet s$$

2. Calculate the rate constant for NDMA.

   a. The extinction coefficient of NDMA at 254 nm can be obtained from Table 6-18

   $\varepsilon(254)$ = 1974 L/mole•cm

   $\varepsilon'(254) = 2.303\varepsilon(254)$ = 2.303 x 1974 = 4546 L/mole•cm

   b. The quantum yield for NDMA can be obtained from Table 6-18.

   $\phi(\lambda)_{NDMA}$ = 0.3 mole/einstein

   c. Compute k_{NDMA} using Eq. (6-66).

$$k_{NDMA} = \phi(\lambda)_{NDMA} P_R \frac{\varepsilon'(\lambda)_{NDMA}}{k'(\lambda)}$$

$$= (0.3 \text{ mole/einstein})\ (3.185 \times 10^{-5} \text{ einstein/L} \cdot \text{s}) \left[\frac{(4546 \text{ L/mole} \bullet \text{cm})}{(0.01/\text{cm})} \right]$$

$$= 4.34 \text{ 1/s}$$

3. Calculate the flow rate that can be treated per reactor.

   a. Calculate hydraulic detention time for the reactor.

$$\tau = \frac{n\left[\left(C_{NDMA,o} / C_{NDMA,e}\right)^{1/n} - 1\right]}{k_{NDMA}} = \frac{4\left[(100/10)^{1/4} - 1\right]}{4.34 \text{ 1/s}} = 0.717 \text{ s}$$

   b. Calculate the flow rate that can be processed by one reactor.

$$Q = \frac{V}{\tau} = \frac{250 \text{ L}}{0.717 \text{ s}} = 349 \text{ L/s}$$

4. Determine the number of reactors needed to treat the full flow.

   a. The total flow to be treated is 1 x 10^5 m^3/d = 1157 L/s

   b. The number of reactors needed is (1157 L/s) / (349 L/s) = 3.3 (use 4)

   c. The actual number of reactors needed will be greater than the computed value to compensate for lamp failure, fouling, and so that one or more reactors can be taken off line for lamp maintenance without interrupting the flow. It should be noted that the extra reactors will not be in continuous operation, but will only be used when needed or in a service rotation to reduce costs.

5. Calculate the EE/O for the photolysis process.

$$\mathrm{EE/O} = \frac{P}{Q\log\left(\frac{C_i}{C_f}\right)}$$

$$= \frac{(12.5\ \mathrm{kW})\left(10^3\ \mathrm{L/m^3}\right)}{(349\ \mathrm{L/s})\left[\log\left(\frac{100\ \mathrm{ng/L}}{10\ \mathrm{ng/L}}\right)\right](3600\ \mathrm{s/h})} = 0.01\ \mathrm{kWh/m^3}$$

The computed EE/O value is low compared to the typical range for ground and surface waters because of the high quality effluent from the RO process. Reverse osmosis removes or reduces many of the constituents that would interfere with photolysis of specific constituents and can produce effluent with low absorbance, improving the efficiency of the photolysis process.

6. Estimate the overall daily energy usage for the process.

For the two operational reactors, the estimated energy usage is

(4 reactors)(12.5 kW)(24 h/d) = 1200 kWh/d

7. Prepare a summary table of results for various absorptivity values.

As shown in the following table, absorptivity has a significant effect on the number of reactors and energy required for photolysis.

Absorptivity, $\mathrm{cm^{-1}}$	K_{NDMA}, 1/s	$Q_{Reactor}$, L/s	Number of reactors (rounded up)	EE/O, $\mathrm{kWh/m^3}$	Energy usage, kWh/d
0.01	4.34	349	4	0.01	1200
0.05	0.869	70	17	0.05	5100
0.1	0.434	35	34	0.1	10,200

PROBLEM 6-19

Problem Statement - See text, page 546

Instructors Note: Students will need to make assumptions about the process, including the absorptivity coefficient and reactor characteristics. Thus, responses will be dependant on the various assumptions made and degree of process optimization.

Solution

1. Calculate the amount of energy required using the procedure outlined in Example 6-8. Assuming that three reactors (as described in Example 6-8) are needed to accomplish the required treatment, the resulting EE/O value is computed as follows:

$$Q = \frac{V}{\tau} = \frac{242\ \text{L}}{4.22\ \text{s}} = 57.4\ \text{L/s}$$

$$\text{EE/O} = \frac{\text{P}}{\text{Q}\log\left(\dfrac{\text{C}_\text{i}}{\text{C}_\text{f}}\right)} = \frac{(14.4\ \text{kW})(10^3\ \text{L/m}^3)}{(57.4\ \text{L/s})\left\{\log\left[\dfrac{(100\ \text{ng/L})}{(1\ \text{ng/L})}\right]\right\}(3600\ \text{s/h})} = 0.035\ \text{kWh/m}^3$$

Using an electricity cost of \$0.13/kWh, the cost is computed as follows.

$$(\$0.13/\text{kWh})(0.035\ \text{kWh/m}^3)(3800\ \text{m}^3/\text{d}) = \$17.22/\text{d}$$

PROBLEM 6-20

Problem Statement - See text, page 546

Solution

1. Prepare a table to summarize the chemical properties of importance for determining the advanced treatment process that should be considered. For some of the compounds to be investigated, Table 16-12, page 1769, may be used to find chemical properties, other compounds will require review of other literature references.

Compound	Formula	mw	H, m^3-atm/mole	Solubility, mg/L
Benzene	C_6H_6	78.1	5.5 E-3	1,780
Chloroform	$CHCl_3$	119.4	3.1 E-3	7,840

Dieldrin	$C_{12}H_8Cl_6O$	380.9	1.0 E-5	0.195
Heptachlor	$C_{10}H_5Cl_7$	373.3	2.9 E-4	0.18
N-Nitrosodi-methylamine	$C_2H_6N_2O$	74.1	2.63 E-7	1,000,000
Trichloroethylene	C_2HCl_3	131.4	9.9 E-3	1,280
Vinyl chloride	C_2H_3Cl	62.5	2.8 E-2	8,800

2. Prepare a table to summarize the compounds and the treatment processes that are expected to be effective for removal of that compound. The information in Table 6-1 may be useful as a guide in process selection.

Compound	Advanced treatment processes for removal of specified compound[a]
Benzene	Advanced oxidation, ozonation
Chloroform	Advanced oxidation
Dieldrin	Advanced oxidation
Heptachlor	Advanced oxidation
N-Nitrosodi-methylamine	Advanced oxidation, photolysis
Trichloroethylene	Advanced oxidation
Vinyl chloride	Advanced oxidation

[a] Descriptions of the various processes are presented in the following table

Note: The problem statement as written refers to treatment methods discussed in Chap. 6 only (e.g., advanced oxidation, chemical oxidation, chemical coagulation, and chemical precipitation). An identical question is provided in Chap. 11 for separation processes (i.e., filtration processes, reverse osmosis, electrodialysis, ion exchange and adsorption).

Advanced treatment process discussed in Chap. 6 and their applications.

Advanced treatment process	Typical applications
Conventional chemical oxidation	Removal of trace organic compunds using ozone (O_3)
Advanced oxidation	Removal of dissolved organic compounds using hydroxyl radicals for oxidation.
Photolysis	Removal of trace organic constituents using exposure to UV light

7

FUNDAMENTALS OF BIOLOGICAL TREATMENT

Instructors Note: In many of the problems where constituent concentrations are used, the units mg/L and g/m^3 are used interchangeably to facilitate computations without introducing additional conversion factors.

PROBLEM 7-1

Problem Statement – see text, page 674

Solution

1. Determine the amount of biomass in mg TSS/d **for 500 mg VSS/d** and then use Table 7-3, which gives fraction of inorganic constituents on a dry weight basis, to compute the required amounts of the essential elements.

   a. From page 557, about 90 percent of the biomass is organic. The total

   $$\text{biomass production} = \frac{(500\text{ mg VSS/d})}{(0.9\text{ g VSS/g TSS})} = 555.6\text{ mg TSS/d}$$

   b. From Table 7-3, the required amounts of essential inorganic elements are as follows:

Element	Fraction of dry weight	Biomass dry weight as mg/d	Required amount of essential element, mg/d
Nitrogen	0.12	555.6	66.7
Phosphorus	0.02	555.6	11.1
Sulfur	0.01	555.6	5.6
Potassium	0.01	555.6	5.6
Sodium	0.01	555.6	5.6
Calcium	0.005	555.6	2.8
Magnesium	0.005	555.6	2.8
Chloride	0.005	555.6	2.8
Iron	0.002	555.6	1.1

2. Prepare the recipe for the inorganic medium using stoichiometric relationships between the element and compound used and a feed rate of 1 L/d. The calculations for the results shown in the table are provided below the table.

Element	Required recipe concentration, mg/L	Required compound	Compound concentration, mg/L
Nitrogen	66.7	NH_4Cl	254.8
Phosphorus	11.1	KH_2PO_4	48.7
Sulfur	5.6	Na_2SO_4	24.9
Potassium	5.6	Sufficient in KH_2PO_4	
Sodium	5.6	Sufficient in Na_2SO_4	
Calcium	2.8	$CaCl_2$	7.8
Magnesium	2.8	$MgCl_2$	11.0
Chloride	2.8	Sufficient, other compounds	
Iron	1.1	$FeCl_3$	3.2

(N) MW: $NH_4Cl = 14 + 4(1) + 35.5 = 53.5$

$NH_4Cl = (53.5/14)(66.7 \text{ mg/L}) = 254.8 \text{ mg/L}$

(P) MW: $KH_2PO_4 = 39.1 + 2 + 31 + 4(16) = 136.1$

$KH_2PO_4 = (136.1/31)(11.1 \text{ mg/L}) = 48.7 \text{ mg/L}$

(S) MW: $Na_2SO_4 = 2(23) + 32 + 4(16) = 142$

$Na_2SO_4 = (142/32)(5.6 \text{ mg/L}) = 24.9 \text{ mg/L}$

(K) Check potassium in KH_2PO_4

MW: $K = 39.1$

$K = (39.1/136.1)(48.7 \text{ mg/L}) = 14.0 \text{ mg/L}$ (amount is sufficient)

(Na) Check sodium in Na_2SO_4

MW: $Na = 23$

$Na = (46/142)(24.9 \text{ mg/L}) = 8.1 \text{ mg/L}$ (amount is sufficient)

(Ca) MW: $CaCl_2 = 40.1 + 2(35.5) = 111.1$

$CaCl_2 = (111.1/40.1)(2.8 \text{ mg/L}) = 7.8 \text{ mg/L}$

(Mg) MW: $MgCl_2 = 24.3 + 2(35.5) = 95.3$

$MgCl_2 = (95.3/24.3)(2.8 \text{ mg/L}) = 11.0 \text{ mg/L}$

(Fe) MW: $FeCl_3 = 55.8 + 3(35.5) = 162.3;$

$FeCl_3 = (162.3/55.8)(1.1 \text{ mg/L}) = 3.2 \text{ mg/L}$

PROBLEM 7-2

Problem Statement – see text, page 675

Solution

1. The key cell components involved in protein production for enzyme synthesis are:

Component	Role
DNA	Genetic information
Messenger (m) RNA	Copies and transfers segment (gene) of DNA
Transfer (t) RNA	Translates mRNA information
Ribosome	Site where protein is produced

A relatively small segment (gene) of the cell DNA is unraveled to form a single strand. Through complementary base-pairing of nucleic acids (adenine with uracil, quanine with cytosine), mRNA is produced. In the ribosome, the mRNA is matched and translated by tRNA. For every three nucleotide sequence in the tRNA, an amino is produced. The three nucleotide sequence is termed a codon and each codon selects for a specific one of the 21 amino acids. A series of amino acids is formed and the amino acids are termed peptides, and polypeptides are formed. The polypeptides fold and connect at various locations to form the protein structure.

PROBLEM 7-3

Problem Statement – see text, page 675

Instructors Note: The purpose of this problem is to have the students familiarize themselves with appropriate literature for developing responses to the problem statement.

PROBLEM 7-4

Problem Statement – see text, page 675

Instructors Note: The purpose of this problem is to have the students familiarize themselves with appropriate literature for developing responses to the problem statement.

PROBLEM 7-5

Problem Statement – see text, page 675

Solution

1. Prepare a COD balance to determine the amount of casein COD oxidized (O_2 consumed)

   g COD cells + g COD oxidized = g COD removed

2. **Determine COD of 22 g casein removed**

   a. Basic equation for casein oxidation:

      $C_8H_{12}O_3N_2 + O_2 \rightarrow CO_2 + H_2O + NH_3$

   b. Balance equation

      $C_8H_{12}O_3N_2 + 8.0\ O_2 \rightarrow 8\ CO_2 + 3\ H_2O + 2\ NH_3$

      8.0 moles O_2 / mole casein

   c. Compute g COD removed

      MW casein: 8(12) + 12(1) + 3(16) + 2(14) = 184

      $$\text{g COD/g casein} = \frac{8.0(32)}{184} = 1.39$$

      g COD removed = (1.39 g COD/g casein)(22g) = 30.6 g

3. Compute the amount of oxygen required
   a. Compute g COD in cells:
      Given: 18 g cells/50 g casein = 0.36 g cells/g casein
      g cells = (0.36 g/g)(22 g casein) = 7.92 g cells
      From Eq. (7-5), 1.42 g COD/g cells
      g COD in cells = (1.42 g/g)(7.92 g cells) = 11.25 g COD into cells
   b. g COD oxidized = g COD removed – g COD cells
      = (30.6 – 11.25) g = 19.35 g
   b. Oxygen required = 19.4 g

*__Alternative solution approach using substrate use and biomass production mass balance equation__*__.__

1. Determine stoichiometry of oxygen used and biomass produced during casein metabolism.

Note: Casein + oxygen = biomass + carbon dioxide + ammonia + water

a. General for reactions and products:

$C_8H_{12}O_3N_2 + O_2 = C_5H_7NO_2 + CO_2 + NH_3 + H_2O$

Given: 18 g biomass produced per 50 g of casein used, determine the molar ratios

$$\frac{50\text{ g casein}}{(184\text{ g/mole})} = 0.272\text{ mole casein used, } \frac{18\text{ g biomass}}{(113\text{ g/mole})} = 0.159\text{ mole biomass}$$

Thus, 0159 mole biomass produced per 0.272 mole casein used. Balance above reaction equation:

$$0.272\ C_8H_{12}O_3N_2 + 1.381\ O_2 = 0.159\ C_5H_7NO_2 + 1.381\ CO_2 + 0.385\ NH_3 + 0.495\ H_2O$$

From balanced equation the ratio of g oxygen used per g casein consumed is determined: $\dfrac{1.381(32)}{0.272(184)} = 0.883\text{ g }O_2\text{/g casein}$

2. Determine oxygen used for 22 g of casein biodegradation

O_2 used = (22 g)(0.883 g O_2/g casein) = 19.4 g

PROBLEM 7-6

Problem Statement – see text, page 675

Solution

1. Determine amount of BOD removed and calculate yield **for wastewater A**
    a. Calculate BOD removed (BOD_R)

    BOD_R = (200 – 2.5) mg/L = 197.5 mg/L

    b. Calculate observed yield for BOD removal

    VSS produced = 100 mg/L

    g VSS/g BOD_R = 100/197.5 = 0.51

    From text, use 0.85 g VSS/g TSS for biomass:

    $$\text{g TSS / g BOD}_R = \frac{(0.51\,\text{g VSS / g BOD}_R)}{(0.85\text{ g VSS / g TSS})} = 0.60$$

    c. Calculate observed yield for COD removal.

    Influent is all soluble COD = 450 mg/L

    Effluent COD = (Influent COD – 1.6(BOD_R) + COD biomass produced

    Effluent COD = [450.0 – 1.6(200 – 2.5)] + 1.42(100 mg VSS/L) = 276.0 mg/L

    Observed COD removed = 450 – 276 = 174 mg/L

    Observed yield = 100/174 = 0.57 g VSS/g COD_R

2. Determine effluent sCOD from nonbiodegradable COD (nbsCOD) and biodegradable COD (bsCOD) using BOD and COD information provided:

    Influent nbsCOD = [450 – (1.6 g COD/g BOD)(200)] mg/L = 130 mg/L

    Effluent bsCOD = (1.6 g COD/g BOD)(2.5 mg BOD/L) = 4.0 mg/L

    Total effluent sCOD = 130 + 4.0 = 134.0 mg/L

3. The fraction of influent BOD oxidized is the difference between the amount of BOD or degradable COD removed and the amount that is incorporated into biomass:

    Influent biodegradable COD (bCOD) = 1.6(200 mg/L) = 320 mg/L g bCOD removed = g COD oxidized + g COD cells

g COD oxidized = g COD removed – g COD cells

g bCOD removed = (320 – 4.0) mg/L = 316 mg/L

g COD cells = (100 mg VSS/L)(1.42 g O_2/g VSS) = 142 mg/L

g COD oxidized = (316 – 142) mg/L = 174 mg/L

Fraction of influent degradable COD or BOD oxidized = 174/320 = 0.54

PROBLEM 7-7

Problem Statement – see text, page 675

Solution

1. Compute hydraulic retention time, τ

   τ = V/Q = (1000 L)/(500 L/d) = 2.0 d

2. Compute oxygen used per d **for wastewater A**, which is equal to the g COD oxidized,

   O_2 used/d = (oxygen uptake rate)(volume)

   = (10 mg/L • h)(24 h/d)(1000 L)(1 g/10^3 mg)

   = 240 g/d

3. Compute the effluent VSS concentration.

   The soluble COD removed is equal to the amount of oxygen used plus the COD of the biomass produced. The influent flow contained no VSS, so the biomass produced is observed here as the effluent VSS concentration. For a completely mixed reactor with no recycle, effluent VSS concentration is equal to the reactor concentration.

   g COD removed = g COD oxidized + g COD cells

   g COD cells = gCOD removed + g COD oxidized

   g COD removed/d = [(1000 – 10) mg/L](500 L/d)(1 g/10^3 mg) = 495 g/d

   g COD cells/d = (495 – 240) g/d = 255 g/d

   $$\text{g cells as VSS/d} = \frac{(255\text{ g COD cells/d})}{(1.42\text{ g COD/g VSS})} = 179.6\text{ g VSS/d}$$

   All the biomass will be in the effluent flow (no settling and no recycle)

$$\text{Effluent VSS} = \frac{(179.6\text{ g VSS/d})}{(500\text{ L/d})} = 0.359\text{ g/L} = 359.2\text{ mg/L}$$

4. The observed yield in this example is based on the COD removed and the amount of oxygen consumed. For an actual real system, one would simply measure the effluent VSS concentration to determine the observed yield.

Observed yield = g VSS/g COD removed

??

$$= \frac{179.6\text{ g VSS/d}}{495\text{ g COD/d}} = 0.363\text{ gVSS/g COD removed}$$

Based on effluent VSS measurement,

???

$$\text{Observed yield} = \frac{359.2\text{ g VSS/L}}{[(1000-10)\text{ mg COD/d}]}$$
$$= 0.363\text{ g VSS/g COD removed}$$

PROBLEM 7-8

Problem Statement – see text, page 675, solve for methanol

Solution

Use half-reaction equations and free energy values in Table 7-6.

1. Solve for the energy produced and captured by **methanol.** Methanol is electron donor and oxygen is the electron acceptor. Use reaction No. 14 for methanol and reaction No. 4 for oxygen in Table 7-6 to obtain energy produced.

		ΔG kJ/mole e^-
No. 14	$\frac{1}{6}CH_3OH + \frac{1}{6}H_2O \rightarrow \frac{1}{6}CO_2 + H^+ + e^-$	-37.51
No. 4	$\frac{1}{4}O_2 + H^+ + e^- \rightarrow \frac{1}{2}H_2O$	-78.14
	$\frac{1}{6}CH_3OH + \frac{1}{4}O_2 \rightarrow \frac{1}{6}CO_2 + \frac{1}{3}H_2O$	ΔG_R = -115.65

Energy captured by cell:

$K(\Delta G_R)$ = 0.60 (-115.65) = -69.39 KJ/mole e^-

2. Solve for the energy needed per electron mole of cell growth (ΔG_S)

ΔG_C = 31.4 kJ/mole e^- cells

ΔG_N = 0 (NH_3 is available)

ΔG_P from methanol (reaction No. 14) to pyruvate (reaction No. 15)

		ΔG kJ/mole e^-
No. 14	$\frac{1}{6}CH_3OH + \frac{1}{6}H_2O \rightarrow \frac{1}{6}CO_2 + H^+ + e^-$	-37.51
No. 15	$\frac{1}{5}CO_2 + \frac{1}{10}HCO_3^- + H^+ + e^- \rightarrow \frac{1}{10}CH_3COCOO^- + \frac{2}{5}H_2O$	+35.78
	$\frac{1}{6}CH_3OH + \frac{1}{30}CO_2 + \frac{1}{10}HCO_3^- \rightarrow \frac{1}{10}CH_3COCOO^- + \frac{7}{30}H_2O$	ΔG_P=-1.73

Because ΔG_P is negative, the exponent m = -1 in Eq. (7-8)

$$\Delta G_S = \left[\frac{-1.73}{(0.6)^{-1}} + 31.41 + 0\right] = 30.37 \text{ KJ/mole e}^-$$

3. Determine f_e and f_s using Eq. (7-9)

$$\frac{f_e}{f_s} = \frac{-\Delta G_S}{K\Delta G_R} = \frac{-30.37}{-69.39}$$

$$\frac{f_e}{f_s} = 0.438$$

$f_e + f_s = 1.0$

Solving for f_e and f_s: $f_e = 0.31$ and $f_s = 0.69 \dfrac{\text{g cell COD}}{\text{g COD used}}$

??Thus, yield = $\dfrac{0.69 \text{ g COD/g COD}}{1.42 \text{ g COD/g VSS}} = 0.49 \dfrac{\text{g VSS}}{\text{g COD}}$

4. With nitrate as electron acceptor, the same calculation steps follow with the change that reaction No. 5 in Table 7-6 is used in the first step above to calculate ΔG_R.

				ΔG kJ/mole e^-
No. 14	$\frac{1}{6}$ CH_3OH + $\frac{1}{6}$ H_2O	$\rightarrow$	$\frac{1}{6}$ CO_2 + H^+ + e^-	-37.51
No. 5	$\frac{1}{5}$ NO_3^- + $\frac{6}{5}$ H^+ + e^-	$\rightarrow$	$\frac{1}{10}$ N_2 + $\frac{3}{5}$ H_2O	-71.67
	$\frac{1}{6}$ CH_3OH + $\frac{1}{5}$ NO_3^- + $\frac{1}{5}H^+$	$\rightarrow$	$\frac{1}{6}$ CO_2 + $\frac{1}{10}$ N_2 + 13 H_2O	ΔG_R = -109.18

$K\Delta G_R$ = 0.60(-109.18) = -65.50 KJ/mole e^-

ΔG_P = -1.73 KJ/mole e^- cell (same as with O_2 as e acceptor)

Using Eq. (7-8), ΔG_S = 30.37 KJ/mole e^-

$$\frac{f_e}{f_s} = \frac{-30.37}{-65.50} = 0.46 \quad (f_e + f_s = 1.0)$$

$f_e = 0.32 \qquad\qquad f_s = 0.68\ \dfrac{\text{g cell COD}}{\text{g COD used}}$

$$\text{Yield} = \frac{0.68}{1.42} = 0.48\ \frac{\text{g VSS}}{\text{g COD}}$$

5. Comparison: The yields using oxygen and nitrate as the electron acceptors are similar because the energy production values from organic substrate oxidation are very close. However, literature suggests that much lower yields are observed for nitrate reduction versus oxygen respiration (about 2/3 of that for oxygen). The difference between the theoretical yield and actual yields observed may be due to the actual energy capture efficiency (K) of the nitrate reducing bacteria.

PROBLEM 7-9

Problem Statement – see text, page 676, solve for methanol.

Use half-reaction equations and free energy values in Table 7-6.

Note that the biomass yield with nitrate as the electron acceptor has been determined in Problem 7-8.

$$\text{Yield with nitrate} = 0.48\ \frac{\text{g VSS}}{\text{g COD}}$$

Solve for the biomass yield using nitrite as the electron acceptor.

2. Solve for the energy produced and captured by **methanol.** Methanol is electron donor and **nitrite** is the electron acceptor. Use reaction No. 14 for methanol and reaction No. 3 for nitrite in Table 7-6 to obtain energy produced.

		ΔG kJ/mole e^-
No. 14	$\frac{1}{6}CH_3OH + \frac{1}{6}H_2O \rightarrow \frac{1}{6}CO_2 + H^+ + e^-$	-37.51
No. 3	$\frac{1}{3}NO_2^{2-} + \frac{4}{3}H^+ + e^- \rightarrow \frac{1}{6}N_2 + \frac{2}{3}H_2O$	-92.23

$$\frac{1}{6}CH_3OH + \frac{1}{3}NO_2^{2-} + \frac{1}{3}H^+ \rightarrow \frac{1}{6}N_2 + \frac{1}{6}CO_2 + \frac{1}{2}H_2O \qquad \Delta G_R = -129.74$$

Energy captured by cell:

$K(\Delta G_R) = 0.60\ (-129.74) = -77.84$ KJ/mole e^-

2. Solve for the energy needed per electron mole of cell growth (ΔG_S)

$\Delta G_C = 31.4$ kJ/mole e^- cells

$\Delta G_N = 0$ (NH_3 is available)

ΔG_P from methanol (reaction No. 14) to pyruvate (reaction No. 15)

		ΔG kJ/mole e^-
No. 14	$\frac{1}{6}CH_3OH + \frac{1}{6}H_2O \rightarrow \frac{1}{6}CO_2 + H^+ + e^-$	-37.51
No. 15	$\frac{1}{5}CO_2 + \frac{1}{10}HCO_3^- + H^+ + e^- \rightarrow \frac{1}{10}CH_3COCOO^- + \frac{2}{5}H_2O$	+35.78
	$\frac{1}{6}CH_3OH + \frac{1}{30}CO_2 + \frac{1}{10}HCO_3^- \rightarrow \frac{1}{10}CH_3COCOO^- + \frac{7}{30}H_2O$	ΔG_P=-1.73

Because ΔG_P is negative, the exponent m = -1 in Eq. (7-8)

$$\Delta G_S = \left[\frac{-1.73}{(0.6)^{-1}} + 31.41 + 0\right] = 30.37\ \text{KJ/mole}\ e^-$$

3. Determine f_e and f_s using Eq. (7-9)

$$\frac{f_e}{f_s} = \frac{-\Delta G_S}{K\Delta G_R} = \frac{-30.37}{-77.84}$$

$$\frac{f_e}{f_s} = 0.39$$

$f_e + f_s = 1.0$

Solving for f_e and f_s: $f_e = 0.28$ and $f_s = 0.72\ \frac{\text{g cell COD}}{\text{g COD used}}$

$$\text{Thus, yield with nitrite} = \frac{0.72\ \text{g COD/g COD}}{1.42\ \text{g COD/g VSS}} = 0.507\ \frac{\text{g VSS}}{\text{g COD}}$$

From above, yield with nitrate = $0.48\ \frac{\text{g VSS}}{\text{g COD}}$

The biomass yield with nitrite is higher because of the higher energy production with nitrite as an electron acceptor.

4. Determine the amount of COD needed per g NO_2-N reduced
   a. Determine the amount of oxygen equivalent needed per g COD used with nitrite as the electron acceptor.

   From above f_e = 0.28 e^-mole of substrate oxidized per e^- mole of substrate used = $\frac{0.28\text{ g }O_2}{\text{g COD used}}$

   b. Determine the oxygen equivalent of NO_2-N

From electron acceptor equations in Table 7-6, Equate reactions 3 and 4 for one mole of electron transfer:

$$\frac{1}{3}NO_2^- + \frac{4}{3}H^+ + e^- = \frac{1}{4}O_2 + H^+ + e^-$$

1/3 mole N = 1/4 mole of O_2

$$\frac{1}{3}\text{ mole N}\left(\frac{14\text{ g }NO_2^-\text{-N}}{\text{mole }NO_2^-}\right) = \frac{1}{4}\text{ mole Oxygen}\left(\frac{32\text{ g O}}{\text{mole }O_2}\right)$$

1 g NO_2^--N = 1.71 g Oxygen

c. Determine the g COD used per g NO_2-N removed

From steps 4 and 5:

$$\left(\frac{0.28\text{ g }O_2}{\text{g COD used}}\right)\left(\frac{\text{g }NO_2^-\text{-N}}{1.71\text{ g }O_2}\right) = 0.164\ \frac{\text{g }NO_2^-\text{-N}}{\text{g COD used}}$$

$$\frac{\text{g COD used}}{\text{g }NO_2^-\text{-N}} = 6.1$$

5. For nitrate as the electron acceptor, determine the amount of COD needed per g NO_3-N reduced
   b. Determine the amount of oxygen equivalent needed per g COD used with nitrite as the electron acceptor.

From Problem 7-8, f_e = 0.32 e^-mole of substrate oxidized per e^- mole of substrate used = $\frac{0.32\text{ g }O_2}{\text{g COD used}}$

b. Determine the oxygen equivalent of NO_2-N

From electron acceptor equations in Table 7-6, Equate reactions 5 and 4 for one mole of electron transfer:

$$\frac{1}{5}NO_3^- + \frac{6}{5}H^+ + e^- = \frac{1}{4}O_2 + H^+ + e^-$$

1/5 mole N = 1/4 mole of O_2

$$\frac{1}{5}\text{ mole N}\left(\frac{14\text{ g N}}{\text{mole }NO_3^-}\right) = \frac{1}{4}\text{ mole Oxygen}\left(\frac{32\text{ g O}}{\text{mole }O_2}\right)$$

1 g NO_3^--N = 2.86 g Oxygen

c. Determine the g COD used per g NO_2-N removed

From steps 4 and 5:

$$\left(\frac{0.32\text{ g }O_2}{\text{g COD used}}\right)\left(\frac{\text{g }NO_3^-\text{-N}}{2.86\text{ g }O_2}\right) = 0.11\ \frac{\text{g }NO_3^-\text{-N}}{\text{g COD used}}$$

$$\frac{\text{g COD used}}{\text{g }NO_3^-\text{-N}} = 9.1$$

The methanol need in g COD per g N reduced is higher for nitrate as the electron acceptor due to the higher synthesis yield with nitrate. The amount of COD needed for nitrogen removal by denitrification is lower if nitrite is reduced instead of nitrate by about 33 percent based on the calculations (6.1 g COD/g N versus 9.1 g COD/g N).

In actual measurements the biomass yields are lower than determined by these energetic calculations and thus the g COD needed per g N reduced is lower. For methanol with nitrate reduction the COD/N ratio is typically about 5.5 g COD/g N instead of 9.1.

PROBLEM 7-10

Problem Statement – see text, page 676

Solution

1. From Table 7-6, it is clear that the energy production for bacteria using nitrate as the electron acceptor is much greater than that for bacteria using sulfate as an electron acceptor (ΔG = -78.14 versus +21.27 KJ/mole e^-). With more energy available, the cell yield for the bacteria using nitrate will be greater so that with time the proportion of nitrate-reducing biomass will continue to increase. The biomass will continue to consume an ever-increasing proportion of the feed substrate, with the result that the sulfate-reducing bacteria will receive a decreasing portion of the substrate. Because the sulfate-reducing bacteria will lose the competition for substrate, their population will diminish by endogenous decay and lack of growth.

PROBLEM 7-11

Problem Statement – see text, page 676

Solution

1. Apply the stoichiometric relationship for electron acceptors, donor and biomass growth [Eq. (7-11)]

   $R = f_eR_a + f_sR_{cs} - R_d$

   From Example 7-3, $f_e = 0.954$ and $f_s = 0.046$

   R_a = Reaction No. 8, R_d = Reaction No. 18, and R_{cs} = Reaction No. 1, assuming NH_3 as the nitrogen source

   Thus, the equations are listed as follows:

   R = 0.954 (No. 8) + 0.046 (No. 1) – No. 18

   0.954 (No. 8) = $0.1193\ CO_2 + 0.954H^+ + 0.954e^- \rightarrow 0.1193\ CH_4 + 0.2385\ H_2O$

   0.046 (No. 1) = $0.0092\ CO_2 + 0.0023\ HCO_3^- + 0.0023\ NH_4^+ + 0.046\ H^+ + 0.046\ e^-$
   $\rightarrow 0.0023\ C_5H_7O_2N + 0.0207\ H_2O$

   - No. 18 = $0.125\ CH_3COO^- + 0.375\ H_2O \rightarrow 0.125\ CO_2 + 0.125\ HCO_3^- + H^+ + e^-$

$$R = 0.125\ CH_3COO^- + 0.0023\ NH_4^+ + 0.0035\ CO_2 + 0.3543\ H_2O$$

$$\rightarrow 0.0023\ C_5H_7O_2N + 0.1227\ HCO_3^- + 0.1193\ CH_4$$

PROBLEM 7-12

Problem statement – see text, page 676

Solution

Table 7-7

Growth condition	Electron donor	Electron acceptor	Synthesis yield
Aerobic	Organic compound	Oxygen	0.45 g VSS/g COD
Aerobic	Ammonia	Oxygen	0.12 g VSS/g NH_4-N
Anoxic	Organic compound	Nitrate	0.30 g VSS/g COD
Anaerobic	Organic compound	Organic compound	0.06 g VSS/g COD
Anaerobic	Acetate	Carbon dioxide	0.05 g VSS/g COD

1. Use the definition of f_s with yields given for organic compound degradation to obtain the f_s values

   a. Aerobic growth, organic compound

      y = 0.45 g VSS/g COD used

      From Eq. (7-10), f_s = e^- mole of substrate used for cells per e^- mole substrate consumed or on COD basis, $f_s = \frac{\text{g COD cell}}{\text{g COD used}}$

      From Eq (7-5), 1.42 g COD/g cell VSS

      $$f_s = y\left(1.42\ \frac{\text{g COD}}{\text{g VSS}}\right) = \left(0.45\ \frac{\text{g VSS}}{\text{g COD}}\right)\left(1.42\ \frac{\text{g COD}}{\text{g VSS}}\right)$$

      $$f_s = 0.64\ \frac{\text{g COD cells}}{\text{g COD used}}$$

      $$f_e + f_s = 1.0,\ f_e = 1.0 - 0.64 = 0.36\ \frac{\text{g COD oxidized}}{\text{g COD used}}$$

   b. Anoxic, organic compound

$$f_S = y\left(1.42\ \frac{\text{g COD}}{\text{g VSS}}\right) = \left(0.30\ \frac{\text{g VSS}}{\text{g COD}}\right)\left(1.42\ \frac{\text{g COD}}{\text{g VSS}}\right)$$

$$f_S = 0.43\ \frac{\text{g COD cells}}{\text{g COD used}}$$

$$f_e = 1.0 - 0.43 = 0.57\ \frac{\text{g COD oxidized}}{\text{g COD used}}$$

c. Anaerobic, organic compound

$$f_S = \left(0.06\ \frac{\text{g VSS}}{\text{g COD}}\right)\left(1.42\ \frac{\text{g COD}}{\text{g VSS}}\right)$$

$$f_S = 0.09\ \frac{\text{g COD cells}}{\text{g COD used}}$$

$$f_e = 1.0 - 0.09 = 0.91\ \frac{\text{g COD oxidized}}{\text{g COD used}}$$

d. Anaerobic, acetate

$$f_S = \left(0.05\ \frac{\text{g VSS}}{\text{g COD}}\right)\left(1.42\ \frac{\text{g COD}}{\text{g VSS}}\right)$$

$$f_S = 0.07\ \frac{\text{g COD cells}}{\text{g COD used}}$$

$$f_e = 1.0 - 0.07 = 0.93\ \frac{\text{g COD oxidized}}{\text{g COD used}}$$

PROBLEM 7-13

Problem statement – see text, page 676

Solution

1. Prepare a summary table

Biological metabolism	Electron acceptor	End products	Relative synthesis yield
Aerobic	Oxygen	$CO_2 + H_2O$	Decreasing
Fermentation	Organic compound	Volatile fatty acid	Decreasing
Methanogenesis	CO_2	Methane	Decreasing

The bacteria metabolic end products are less oxidized compounds as the electron acceptor goes from oxygen to an organic compound and to CO_2. Thus, the energy available from the organic substrate utilized decreases. The cell yield per unit of substrate used is less in the direction indicated above, as a certain amount of energy is needed per unit of cell production and less energy is available per g substrate COD used.

PROBLEM 7-14

Problem statement – see text, page 676

Solution for diameter = 1 μm

1. Cells are assumed spherical so that the mass per cell can be estimated using the volume of a sphere and specific gravity of the cells.

   a. Volume of a sphere = $\frac{4}{3}\pi r^3 = \frac{\pi D^3}{6}$

   Volume = $\frac{\pi}{6}(1 \times 10^{-6}\ \text{m})^3 = 0.524 \times 10^{-18}\ \text{m}^3/\text{cell}$

   Specific gravity for cell ~ 1.0

   Mass/cell = $(0.524 \times 10^{-18}\ \text{m}^3)(1.0\ \text{g/cm}^3)(1000\ \text{mg/g})(100\ \text{cm/m})^3$

   $= 0.524 \times 10^{-9}\ \text{mg/cell}$

   b. 1 L @ 100 mg VSS / L = 100 mg VSS cell mass

   Organic mass/cell @ 90% volatile (given)

   Number cells = $\dfrac{100\ \text{mg}}{\left(0.90\,\dfrac{\text{g VSS}}{\text{g cell}}\right)\left(0.524 \times 10^{-9}\,\dfrac{\text{mg}}{\text{cell}}\right)} = 2.12 \times 10^{11}$ cells

---

PROBLEM 7-15

Problem statement – see text, page 676

Solution for generation time of 20 min

1. Using the generation time given, the maximum specific growth rate can be determined and used in zero-order growth rate model to obtain the population size versus time.

Generation time = time to double population

Cells are growing at their maximum specific growth rate, thus:

$$\frac{dN}{dt} = \mu_m N \qquad \text{(N equals number of cells)}$$

Given that N = 20 at time = 0

Integrate from t = 0 to t = t

$$N = N_o e^{\mu_m t}$$

At 1 generation time N = 2 N_o

$$2N_o = N_o e^{\mu_m (20 \text{ min})}$$

ln 2 = μ_m(20 min) (1 h/60 min) = μ_m (0.333) h

μ_m = ln 2 / 0.333 hr = 2.0815 / h

$$N = N_o e^{2.08(t)} = 20 e^{2.08(t)}$$

At 12 hrs, $N = 20\ e^{2.08(12)} = 1.409 \times 10^{12}$ cell

From Problem 7-13, the mass/cell = 0.524 x 10^{-9} mg/cell, thus

mg VSS = 1.409 x 10^{12} cells (0.90 g VSS/g TSS) (0.524 x 10^{-9} mg/cell)

= 0.66 x 10^3 mg = 660 mg

PROBLEM 7-16

Problem statement – see text, page 676

Solution (data set #1)

1. Define equations for substrate utilization and growth and solve with computer spreadsheet.

   a. Substrate utilization; modify Eq. (7-24) for ammonia-N oxidation:

$$r_{su} = \left[\frac{\mu_{N,max} N}{Y_N (K_N + N)}\right]\left(\frac{S_o}{K_o + S_o}\right) X_N$$

N = NH_3-N concentration, mg/L

So = Dissolved oxygen concentration, mg/L

Values for K_N and K_o are given in table of inputs for problem

$\mu_{N,max}$ = 0.60 g VSS/ g VSS•d = 0.025/h

K_N = 0.50 mg/L, K_o = 0.50 mg/L, Y_N = 0.12 g VSS/g NH_3-N oxidized

b. Net cell growth, Eq. (7-21)

$r_X = Y_N r_{su} – bX_N$

b = 0.08 g VSS/g VSS•d = 0.00333/h

2. Develop a spreadsheet solution. The substrate (NH_3-N) concentration and biomass concentration are solved at incremental times using the Euler numerical method. A time increment of 0.25 hours is used in an Excel spreadsheet for this solution. Other time increments may be acceptable.

a. Ammonia-N (N, where, t = time, h)

$$N_t = N_{t-1} -– r_{su}(\Delta t)$$

$$N_t = N_{t-1} - \Delta t\left[\frac{\mu_{N,max}N_{t-1}}{Y_N(K_N+N_{t-1})}\right]\left[\frac{S_o}{K_o+S_o}\right]X_{N,t-1}$$

$$N_t = N_{t-1} - \Delta t\left[\frac{0.025(N_{t-1})}{0.12(0.5+N_{t-1})}\right]\left[\frac{3.0}{(0.5+3.0)}\right](X_{N,t-1})$$

b. Ammonia-oxidizing bacteria (X_N, where, t=time, h)

$$X_{N,t} = X_{N,t-1} + r_X(\Delta t)$$

$$X_{N,t} = X_{N,t-1} + \left\{\left[\frac{\mu_{N,max}X_{N,t-1}N_{t-1}}{(K_N+N_{t-1})}\right]\left[\frac{S_o}{K_o+S_o}\right] - b(X_{N,t-1})\right\}\Delta t$$

$$X_{N,t} = X_{N,t-1} + \left\{\left[\frac{0.025X_{N,t-1}N_{t-1}}{(0.5+N_{t-1})}\right]\left[\frac{S_o}{0.5+S_o}\right] - 0.00333(X_{N,t-1})\right\}\Delta t$$

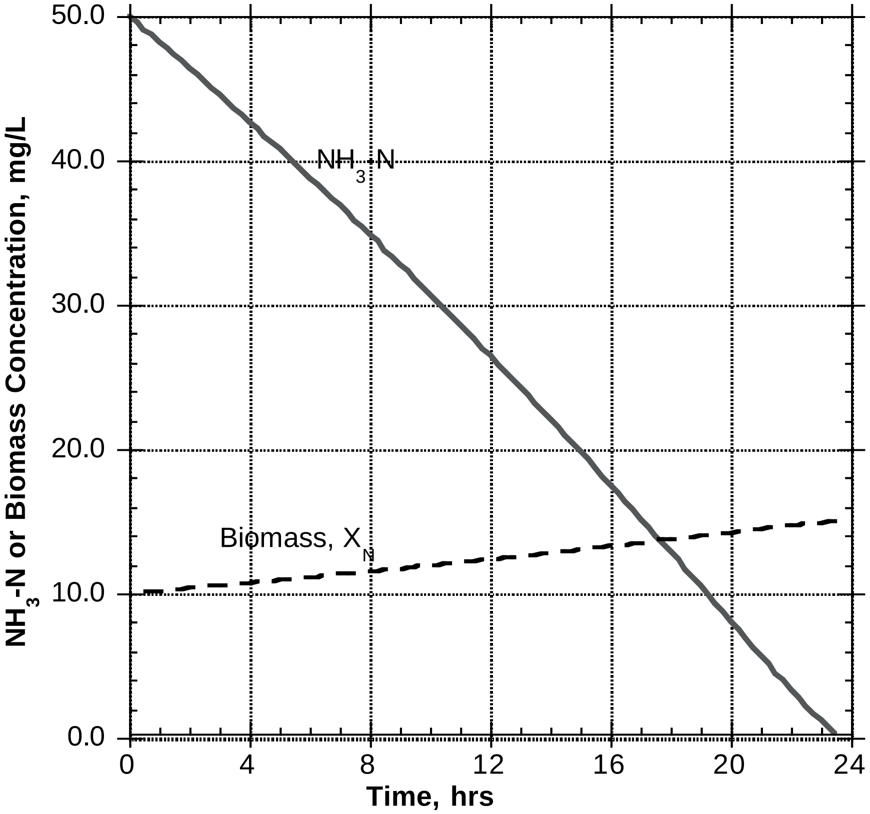
Solve on excel spreadsheet, N_o = 50 mg N/L, X_o = 10 mg/L use $\Delta t = 0.25$ h

c. Tabulate spreadsheet results for hourly values. Only the hourly values for NH_3-N and X_N are tabulated here.

At 0.50 d, NH_3-N = 26.48 mg/L and X_N = 12.38 mg/L

Time, h	N, (NH_3-N), mg/L	X_N (Biomass), mg/L
0.00	50.00	10.00
1.00	48.22	10.18
2.00	46.41	10.36
3.00	44.57	10.55
4.00	42.69	10.74
5.00	40.78	10.93
6.00	38.84	11.13
7.00	36.87	11.33
8.00	34.86	11.53
9.00	32.82	11.74
10.00	30.74	11.95
11.00	28.63	12.16
12.00	26.48	12.38
13.00	24.30	12.60
14.00	22.08	12.82
15.00	19.83	13.05
16.00	17.54	13.28
17.00	15.23	13.51
18.00	12.88	13.75
19.00	10.51	13.99
20.00	8.12	14.23
21.00	5.73	14.47
22.00	3.38	14.70
23.00	1.19	14.91
24.00	<0.1	~15.01

Plot substrate and biomass concentration versus time up through 23 hours



PROBLEM 7-17

Problem statement – see text, page 677

Solution

Analyze the growth rates for the two types of bacteria. The y axis on the curve shows the specific growth rate for bacteria A and B. Note at steady state, the specific growth rate is the inverse of the SRT

a. For Experiment I, at a high SRT (say at 10 d, the specific growth rate (μ) will be low at 0.10 $d^{-1)}$. At this low μ, the reactor substrate concentration as shown on the curve will be lower for A than B. Thus, the bacteria represented by A will be more competitive and will consume more substrate than B; A will grow more and dominate.

b. For Experiment II, at an SRT of 1.1 d the steady state specific growth rate will be 0.9 d^{-1}. At this specific growth rate only B will be present. The maximum specific growth rate for A is 0.6 g/g•d as shown on the curve. Thus, the bacteria can not grow fast enough to stay in the reactor at the 1.1 d SRT.

PROBLEM 7-18

Problem Statement – see text, page 677

Solution (data set #1)

1. Determine the minimum hydraulic retention time using the kinetic coefficients. For a system with no solids recycle, τ = SRT.

   a. Calculate the washout SRT at 20°C using Eq. (7-71)

$$\frac{1}{\mathrm{SRT_{min}}} = \mathrm{Yk} - \mathrm{b}$$

$$\frac{1}{\mathrm{SRT_{min}}} = (0.45\ \mathrm{g\ VSS/g\ phenol})(0.90\ \mathrm{g\ phenol/g\ VSS{\bullet}d})$$

$$- 0.10\ \mathrm{g\ VSS/g\ VSS{\bullet}d}$$

$$= 0.305/\mathrm{d}$$

@20°C, SRT = τ = 1/0.305 = 3.28 d

   b. To solve the problem for a 10^0C temperature, first calculate the values for the coefficients, k and b using temperature coefficients given

in Eq. (1-44)

$$\mathrm{k_T} = \mathrm{k_{20}}(\theta)^{\mathrm{T}-20} = 0.90(1.07)^{10-20} = 0.46$$

$$\mathrm{b} = 0.10(1.04)^{10\text{-}20} = 0.068\ \mathrm{g\ VSS/g\ VSS{\bullet}d}$$

$$\frac{1}{\mathrm{SRT_{min}}} = (0.45)(0.46) - 0.068 = 0.137\,/\mathrm{d}$$

@10°C, $\mathrm{SRT_{min}}$ = 1/0.137 = 7.25 d

c. Apply steady state equations for effluent substrate and biomass concentrations as a function of SRT. Use Eq. (7-46) for steady state effluent phenol concentration.

$$S = \frac{K_S[1+b(SRT)]}{SRT(Yk-b)-1} = \frac{0.20[1+(0.10)(0.40)]}{4[0.45(0.90)-0.10]-1}$$

S = 1.27 mg/L (g/m^3) phenol

Use Eq. (7-42) for biomass concentration, (SRT = τ)

$$X = \frac{Y(S_O-S)}{1+b(SRT)}\left(\frac{SRT}{t}\right) = \left\{\frac{0.45(100-1.27)}{[1+(0.10)4.0]}\right\}\left(\frac{4.0}{4.0}\right)$$

X = 31.7 mg/L biomass as VSS

d. Apply COD balance to determine oxygen required, Eq. (7-61). Note substrate concentration is as COD

$R_o = Q(S_O - S) - 1.42\ P_{X,bio}$

Determine COD of phenol by stoichiometric balance

$C_6H_6O + 7O_2 \rightarrow 6CO_2 + 3H_2O$

$$\frac{g\ O_2}{g\ phenol} = \frac{7(32)}{(1)[72+6+16]} = 2.38\ g\ O_2/g\ P$$

S_o = 2.38(100 g/m^3) = 238 g/m^3 COD

S = 2.38 (1.27 g/m^3) = 3.02 g/m^3 COD

Determine $P_{X,bio}$ (solids wasted)

Solids are wasted via effluent flow

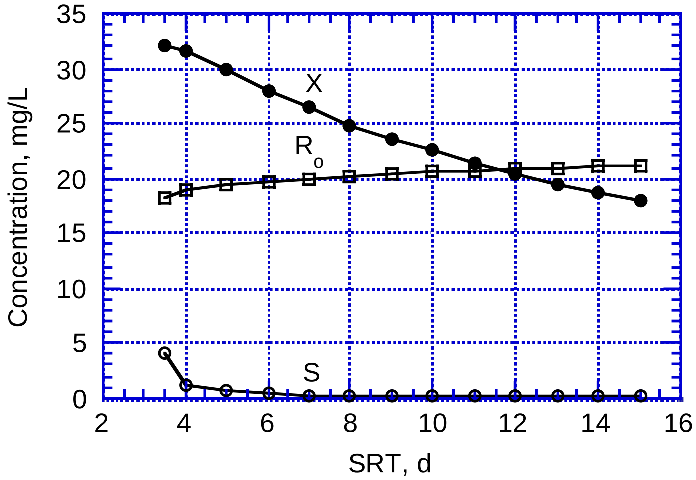
$P_{X,bio}$ = Q(X) = 100 m^3/d(31.7 g VSS/m^3)

R_O = [(100 m^3/d)[(238 - 3.02) g/m^3] – 1.42(100 m^3/d)(31.7 g/m^3)](1 kg/10^3 g)

$R_o = 19.0 \text{ kg } O_2/\text{d}$

2. Solve for S, X, and R_O for different SRTs using previous equations for parts c and d using a computer spreadsheet. The values are as follows:

SRT, d	S, mg/L	X, mg/L	R_O, kg/d
3.5	4.00	32.0	18.3
4	1.27	31.7	19.0
5	0.57	29.8	19.4
6	0.39	28.0	19.7
7	0.30	26.4	20.0
8	0.25	24.9	20.2
9	0.22	23.6	20.4
10	0.20	22.5	20.6
11	0.18	21.4	20.7
12	0.17	20.4	20.9
13	0.16	19.5	21.0
14	0.15	18.7	21.1
15	0.14	18.0	21.2



PROBLEM 7-19

Problem statement – see text, page 677

Solution

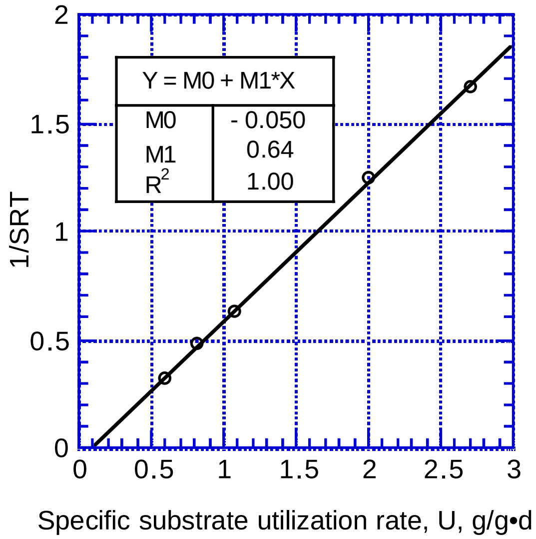
1. Compute Y and b by a linear regression to values calculated for 1/SRT and r_{su} in Eqs. (7-39) and (7-40)

$$\frac{1}{SRT} = Y\left(\frac{r_{su}}{X}\right) - b$$

$$r_{su} = \frac{Q(S_o - S)}{V}$$

Test no.	SRT, d	1/SRT, d^{-1}	r_{su}/X, d^{-1}
1	3.1	0.323	0.591
2	2.1	0.476	0.806
3	1.6	0.625	1.081
4	0.8	1.250	1.999
5	0.6	1.667	2.707

1. Determine Y and b from a linear fit of $\frac{1}{SRT}$ versus r_{su}/X as shown on the following plot



From graphs and linear fit: b = 0.05 g/g • d

Y = 0.64 g VSS/g COD

2. Use Eq. (7-12) to determine k and K_s from the data.

$$r_{su} = \frac{kXS}{K_s+S}$$

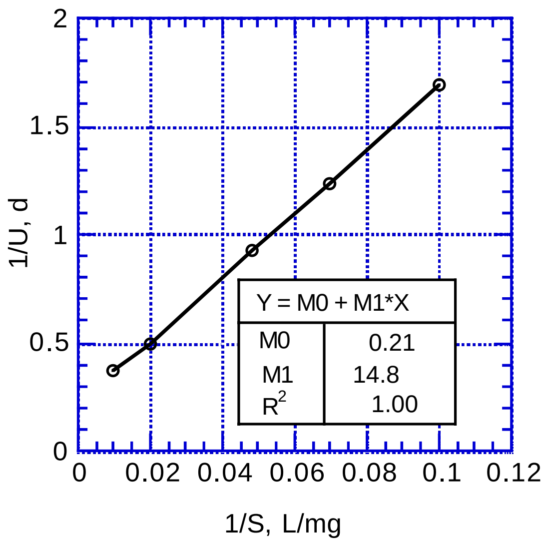
$\frac{r_{su}}{X} = \frac{kS}{K_s+S}$, $U = \frac{r_{su}}{X}$, specific substrate utilization rate

$U = \frac{kS}{K_s+S}$ and

$$\frac{1}{U} = \left(\frac{Ks}{k}\right)\left(\frac{1}{S}\right) + \frac{1}{k}$$

SRT (d)	1/U (d)	1/S (L/mg)
3.1	1.691	0.100
2.1	1.240	0.070
1.6	0.925	0.048
0.8	0.500	0.020
0.6	0.369	0.010

4. Plot 1/U vs. 1/S



From data fit

$$\frac{1}{k} = 0.21,\ k = 4.76\ \text{g/g} \bullet \text{d}$$

$$\frac{K_s}{k} = 14.8$$

K_s = 14.8 (4.76) = 70.5 mg/L

5. Now calculate μ_m from Eq. (7-16).

   μ_m = Yk = 0.64 (4.76) = 3.05 d

Note: calculate the sludge production

Eq. (7-21):

$$r_x = Yr_{su} - bx$$

$$r_{su} = \frac{Q(S_0 - S)}{V},\ \frac{V}{Q} = \tau$$

$$r_x = Y\frac{Q(S_0 - S)}{V} - bx$$

$$r_x = Y\frac{(S_0 - S)}{\tau} - bx,\ \text{g/m}^3\text{-d}$$

this is the production in g//d per unit of reactor volume

can not get it in g/d because flowrate and volume were not given

Another approach you can take is to calculate the amount of solids per unit flow

eq. for X:

$$X = \frac{QY(S_0\text{-}S)SRT}{(1\text{+}bSRT)V}$$

$$P_x = \frac{VX}{SRT},\ \text{multiply the above eq. by V/SRT}$$

$$\frac{P_x}{Q} = \frac{Y(S_0\text{-}S)}{(1\text{+}bSRT)}$$

Test	SRT d	So So, mg/L	S mg/L	X mg/L	HRT d	Y gVSS/gCOD	b g/g-d	r_x mg/L-d	Px/Q g/m^3
1	3.1	400	10.0	3950	0.167	0.64	0.05	1297.1	216.1
2	2.1	400	14.3	2865	0.167	0.64	0.05	1334.8	223.3

3	1.6	400	21.0	2100	0.167	0.64	0.05	1347.4	224.6
4	0.8	400	49.5	1050	0.167	0.64	0.05	1290.7	215.7
5	0.6	400	101.6	660	0.167	0.64	0.05	1110.5	185.4

The sludge production increases as the SRT is increased from 0.80 to 1.6 days because the growth from the increase in the amount of COD removed is greater than the loss by endogenous decay. But for 2.1 days and higher the loss by endogenous decay is more than the growth from additional substrate removal, so the sludge production rate decreases with the higher SRT.

PROBLEM 7-20

Problem statement – see text, page 678

Solution

1. Determine the pertinent equations to compute Y and b.

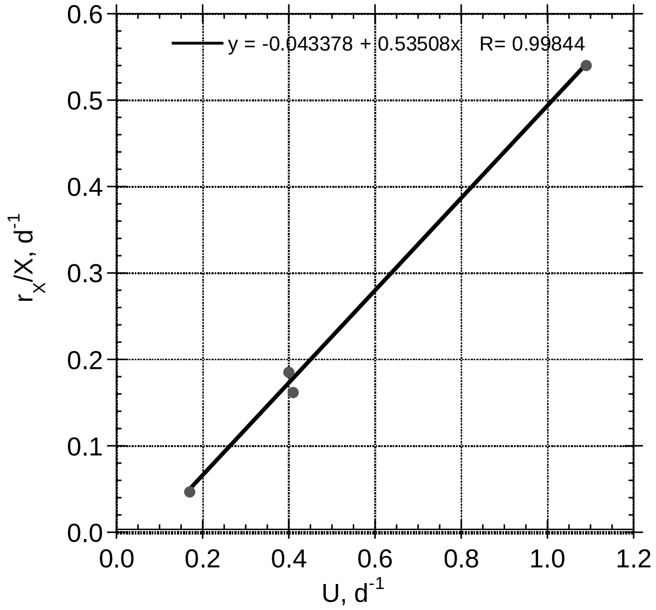
$r_X = Yr_{su} - bX$ Eq. (7-21)

$$\frac{r_X}{X} = Y\left(\frac{r_{su}}{X}\right) - b$$

$$\frac{r_X}{X} = Y(U) - b$$

$\frac{r_X}{X}$, d^{-1}	U, d^{-1}
0.0468	0.17
0.1619	0.41
0.1856	0.40
0.5398	1.09

3. Prepare a linear fit of a plot of r_X/X versus U to determine Y and b.



From plot Y = 0.54 g VSS/g BOD

b = 0.043 g VSS/g VSS • d

PROBLEM 7-21

Problem statement – see text, page 678

Solution (for data set #1)

1. Determine SRT from aeration basin solids inventory and solids wasting rate

Eq. (7-56) $P_{X,VSS} = \frac{(X_{VSS})(V)}{SRT}$

$$P_{X,VSS} = \left(59\ m^3/d\right)\left(8000\ g/m^3\right) = 472{,}000\ g/d$$

$$???SRT = \frac{(3000\ g/m^3)(1000\ m^3)}{472{,}000\ g/d} = 6.36\ d$$

2. Determine oxygen required from COD balance.

Eq. (7-61) $R_o = Q(S_O - S) - 1.42\ P_{X,bio}$

Influent wastewater is all soluble so $P_{X,bio} = P_{X,VSS}$

$R_o = \{(5000\ m^3/d)[(400 - 5)mg/L] - [1.42\ (472{,}000\ g/d)]\}(1\ kg/10^3\ g)$

$R_o = 1304.8\ kg/d$

3. Divide the oxygen consumption rate in kg/d by the aeration tank volume to obtain the OUR, assuming steady state conditions

$$\text{OUR} = \frac{(1304.8\ \text{kg O}_2/\text{d})(10^6\ \text{mg/kg})}{(1000\,\text{m}^3)(1000\,\text{L/m}^3)(24\,\text{h/d})} = 54.4\ \text{mg/L}\cdot\text{h}$$

PROBLEM 7-22

Problem Statement – see text, p. 678

Solution (for MLSS = 2800 mg/L)

1. Determine the SRT from the aeration basin inventory and sludge removal daily from system via effluent and wasting for a process with a MLSS concentration of 2800 mg/L.

Eq. (7-57) $\text{SRT} = \dfrac{(X_{TSS})(V)}{P_{X,TSS}}$

$P_{X,TSS} = Q_e(X_e) + Q_w X_R,\quad Q_e = Q - Q_w$

$P_{X,TSS} = [(1000 - 85.5)\ \text{m}^3/\text{d}]\ (20\ \text{g/m}^3) + (85.5\ \text{m}^3/\text{d})\ (10{,}000\ \text{g/m}^3)$

$= 873{,}290\ \text{g/d}$

$\tau = \dfrac{V}{Q}$ V = (1000 m^3/d) (1 d) = 1000 m^3

$$\text{SRT} = \frac{(2800\,\text{g/m}^3)(1000\,\text{m}^3)}{(873{,}290\,\text{g/d})} = 3.2\ \text{d}$$

2. Determine F/M ratio (g BOD/g MLVSS • d) and BOD loading using appropriate equation and VSS/TSS ratio.

$\text{F/M} = \dfrac{QS_o}{XV}$, Eq. (7-62)

$$\text{F/M} = \frac{QS_o}{XV} = \frac{(1000\ \text{m}^3/\text{d})(1875\ \text{g/m}^3)}{(2800\ \text{g/m}^3)(0.80)(1000\ \text{m}^3)} = 0.84\ \text{g BOD/g MLVSS}\bullet\text{d}$$

$L_{org} = \dfrac{QS_o}{(V)(10^3\,\text{g/kg})}$, Eq. (7-69)

$$L_{org} = \frac{(1000\ \text{m}^3/\text{d})(1875\ \text{g/m}^3)}{(1000\ \text{m}^3)(10^3\,\text{g/kg})} = 1.875\ \text{kg BOD/m}^3\cdot\text{d}$$

3. Calculate the observed yield based on solids produced in system and amount of COD or BOD removed. Assume the concentration of effluent soluble COD and BOD is not significant.

$$P_{X_T,TSS} = 873{,}290 \text{ g TSS/d}$$

$$y_{obs,COD} = \frac{(873{,}290 \text{ g TSS / d})}{(1000 \text{ m}^3)(3000 \text{ g / m}^3)} = 0.29 \text{ g TSS / g COD}$$

$$y_{obs,BOD} = \frac{(873{,}290 \text{ g TSS / d})}{(1000 \text{ m}^3)(1875 \text{ g / m}^3)} = 0.47 \text{ g TSS / g BOD}$$

4. Determine synthesis yield from Eq. (7-54) that accounts for solids production, synthesis yield, endogenous decay, and cell debris. No influent non-degradable VSS is indicated from the problem statement.

$$P_{X,VSS} = \frac{QY(S_o - S)}{1 + b(SRT)} + \frac{(f_d)(b)YQ(S_o - S)SRT}{1 + b(SRT)} + Q(X_{Qi})$$

For COD Basis:

$$0.80(873{,}290 \text{ g/ d}) = \frac{(1000 \text{ m}^3 / \text{d})Y(3000\text{g/ m}^3)}{[1 + (0.10 \text{ d}^{-1})(3.2 \text{ d})]}$$

$$+ \frac{0.15(0.10 \text{ d}^{-1})(Y)(1000 \text{ m}^3 / \text{d})(3000 \text{ g / m}^3)(3.2 \text{ d})}{[1 + (0.10 \text{ d}^{-1})(3.2 \text{ d})]}$$

698,632 = 2,272,727Y + 109,091Y

Y = 0.29 g VSS/g COD

For BOD Basis:

$$0.80(873{,}290 \text{ g / d}) = \frac{(1000 \text{ m}^3 / \text{d})(Y)(1875 \text{ g/ m}^3)}{[1 + (0.10 \text{ d}^{-1})(3.2 \text{ d})]}$$

$$+ \frac{0.15(0.10 \text{ d}^{-1})(Y)(1000 \text{ m}^3 / \text{d})(1875 \text{ g / m}^3)(3.2 \text{ d})}{[1 + (0.10 \text{ d}^{-1})(3.2 \text{ d})]}$$

698,632 = 1,420,455Y + 68,182Y

Y = 0.47 g VSS/g BOD

PROBLEM 7-23

Problem Statement – see text, page 678

Solution (For SRT = 8 d)

1. Based on the reactor volume, MLSS concentration and SRT the steady state sludge production rate is calculated from Eq. (7-57).

$$P_{X,TSS} = \frac{(X)(V)}{SRT} = \frac{(3000\ g/m^3)(8000\ m^3)}{8\ d} = 3{,}000{,}000\ g/d = 3000\ kg/d$$

2. If wasting is done from the reactor, the waste sludge concentration = 3,000 mg/L (3000 g/m^3)

$$P_{X,TSS} = (3000\ g/m^3)(Q_w) = 3{,}000{,}000\ g/d$$

$Q_w = 1000\ m^3/d$

3. If wasting is done from the recycle line, the waste sludge concentration = 10,000 mg/L (g/m^3)

$$P_{X,TSS} = (10{,}000\ g/m^3)\ (Q_w) = 3{,}000{,}000\ g/d$$

$Q_w = 300\ m^3$

PROBLEM 7-24

Problem statement – see text, page 678

Solution (For influent VSS = 400 mg/L and SRT = 3 d)

1. Develop mass balance equations for particulates and biomass using Eq. (7-20) for the particulate degradation kinetics (let X_s = P and X_H = X). Assume that the level of soluble COD remaining from the particulate conversion is very small so that the rate of soluble COD utilization for biomass growth is equal to the rate of particulate COD conversion. Note that the SRT of the particulates is the same as that for the biomass and the suspended solids for a steady state homogenous system.

   a. Particulate (P) mass balance. Let P_o = influent particulate concentration and P = effluent particulate concentration:

$$V\frac{dP}{dt} = \text{In – out + P production or utilization}$$

$$V\frac{dP}{dt} = QP_o - \frac{PV}{SRT} - \frac{k_h(P/X)XV}{(K_X + P/X)}$$

At steady state, $V\frac{dP}{dt} = 0$

$$QP_o = \frac{PV}{SRT} + \frac{k_h(P/X)XV}{(K_X + P/X)}$$

b. Mass balance for biomass (X):

$$V\frac{dX}{dt} = QX_o - \frac{XV}{SRT} - \frac{(Y)k_h(P/X)XV}{(K_X + P/X)} - bX$$

$QX_o = 0$

$$QPo - QPo - \frac{PV}{SRT} = \frac{k_h(P/X)XV}{(K_X + P/X)}$$

At steady state and substituting for $r_{sc,P}$

$$0 = -\frac{XV}{SRT} + Y\left(QP_o - \frac{PV}{SRT}\right) - bXV$$

$$\frac{XV}{SRT} + bXV = Y\left(QP_o - \frac{PV}{SRT}\right)$$

$$X = \frac{Y\left(QP_o - \frac{PV}{SRT}\right)SRT}{V + b(SRT)V}$$

2. To solve for P, the equation for X can be substituted, but first the steady state equation for P is rearranged.

$$QP_o - \frac{PV}{SRT} = \frac{k_hPV(X)}{K_x(X) + P}$$

$$\frac{QP_o - \frac{PV}{SRT}}{k_hPV} = \frac{X}{K_x(X) + P}$$

$$\frac{k_hPV}{QP_o - \frac{PV}{SRT}} = K_x + \frac{P}{X}$$

$$\frac{P}{X} = \frac{k_hPV}{QP_o - \frac{PV}{SRT}} - K_x$$

Substitute equation for X

$$\frac{P[V+b(SRT)V]}{Y\left(QP_o-\dfrac{PV}{SRT}\right)SRT}=\frac{k_hPV}{QP_o-\dfrac{PV}{SRT}}-K_x$$

Rearranging:

$$P=\frac{-K_xYQP_o(SRT)}{[V+b(SRT)V]-k_hVY(SRT)-K_xYV}$$

$$\frac{P}{P_o}=\frac{-K_xYQ(SRT)}{[V+b(SRT)V]-k_hVY(SRT)-K_xYV}$$

3. Solve for P at P_o = 400 mg/L and X at SRT = 3 d

$$\frac{P}{P_o}=\frac{(-0.15\text{ g/g})(0.5\text{ g /g})(2000\text{ m}^3\text{/d})(3\text{ d})}{[500\text{ m}^3+(0.10\text{ g/g}\cdot\text{d})(3\text{ d})(500\text{ m}^3)]-[(2.2\text{ g/g}\cdot\text{d})(500\text{ m}^3)(0.5\text{ g/g})(3\text{ d})-[(0.15\text{ g/g})(0.5\text{ g/g})(500\text{ m}^3)}$$

$$\frac{P}{P_o}=0.43$$

P = 0.43 (400 mg/L) = 172 mg/L = 172 g/m^3

$$X=\frac{(0.5\text{ g/ g})\left[(2000\text{ m}^3/\text{d})(400\text{ g/m}^3)-\dfrac{(172\text{ g/m}^3)(500\text{ m}^3)}{3\text{ d}}\right]3\text{ d}}{[500\text{ m}^3+(0.10\text{ g/g}\cdot\text{d})(3\text{ d})(500\text{ m}^3)]}$$

$$=1780\text{ g/m}^3$$

4. Compute percent removal

Percent removal = [(g P/d$_{In}$ – g P/d$_{out}$)(100)/gP/d$_{IN}$]

$$\text{Percent removal} = \frac{\left(QP_o - Q_wP_w\right)100}{QP_o},\quad Q_wP_w = \frac{VP}{SRT}$$

$$\text{Percent removal} = \left(1-\frac{Q_wP_w}{QP_o}\right)100 = \left(1-\frac{VP}{SRT\left(Q\right)P_o}\right)100$$

At P_o = 400 mg/L, SRT = 3 d

$$\text{Percent removal} = \left[1-\frac{(500\text{ m}^3)(172\text{ g/m}^3)}{(3.0\text{ d})(2000\text{ m}^3\text{/d})(400\text{ g/m}^3)}\right]100 = 96.4\%$$

5. Other solutions are tabulated below:

SRT, d	P/P$_o$	P, mg/L	X, mg/L	% P removal

3	0.43	172	1780	96.4
5	0.37	147	2618	98.2
10	0.33	132	3967	99.2

PROBLEM 7-25

Problem statement – see text, page 679

Solution

Note that it is not necessary to carry out a numerical solution as the problem is basically asking how an increase in SRT from 10.5 d to 15 d will affect the values for the listed parameters in (a) through (f). One can assume that the temperature and DO concentration are constant. Answers are (**I**) for increase, (**D**) for decrease, and (**S**) for remain the same.

1. Sludge production rate **(D)**

   The relevant relationship is shown in Eq. (7-54).

$$P_{X,VSS} = \underbrace{\frac{QY(S_o - S)}{1 + b(SRT)}}_{(A)} + \underbrace{\frac{(f_d)(b)YQ(S_o - S)SRT}{1 + b(SRT)}}_{(B)} + \underbrace{Q(X_{o,i})}_{(C)}$$

   As SRT increases the value for (A) decreases and the value for (B) increases but (B) represents only a fraction of the solids lost by endogenous decay or decrease in A, so the net effect is a decrease in $P_{X,VSS}$.

2. Oxygen consumption rate **(I)**.

   The relevant relationships are shown in Eq. (7-61) and Eq. (7-46), and those shown in Fig. 7-13.

   $R_o = Q(S_o – S) – 1.42\ P_{X,bio}$, Eq. (7-61)

$$S = \frac{K_s[1 + b(SRT)]}{SRT(Yk - b) - 1}, \text{ Eq. (7-46)}$$

   As the SRT increased per Step 1, $P_{X,bio}$ (A + B) decreases and the effluent bsCOD only decreases slightly from an SRT of 10.5 to 15 d (Figure 7-13). Thus, R_o must increase.

3. Effluent soluble biodegradable COD concentration **(D)**

Per Eq. (7-46) and Fig. 7-13, it will decrease slightly.

4. Aeration tank MLSS concentration **(I)**

   The relevant relationships are Eq. (7-57) and Eq. (7-55):

   $$X_{TSS} = \frac{P_{X,TSS}(SRT)}{V}, \text{ Eq. (7-57)}$$

   $$P_{X,TSS} = \frac{A}{0.85} + \frac{B}{0.85} + C + Q(TSS_o - VSS_o) \text{ , Eq. (7-55)}$$

   A, B, and C are shown in Step 1.

   V = constant. Per Eq. (7-57), X_{TSS} increases in a linear proportion to SRT. $P_{X,TSS}$ decreases with SRT but less than a linear ratio, so the net effect is that X_{TSS} will increase.

5. Effluent NH_3-N concentration **(D)**

   The relevant relationships are Eq. (7-46) shown in Step 2 and Fig. 7-13. The S in Eq. (7-46) is a degradable growth substrate and can be NH_3-N, which is oxidized by ammonia-oxidizing bacteria to nitrite. Thus, as shown in Step 3, as the SRT increases, the effluent NH_3-N concentration will decrease.

6. Effluent NO_2-N concentration **(D)**

   This is for same reasons as for Step 3 and Step 5.

PROBLEM 7-26

Problem statement – see text, page 679

Solution

1. Use Eq. (7-58) to calculate observed yield and various solids fractions contributing to the yield. Assume $S_o - S \approx S_o$

   $$Y_{obs} = \underbrace{\frac{Y}{1+b(SRT)}}_{\text{biomass}} + \underbrace{\frac{(f_d)(b)Y(SRT)}{1+b(SRT)}}_{\text{cell debris}} + \underbrace{\frac{X_{o,i}}{S_o - S}}_{\text{non-biodegradable influent VSS}}$$

   a. Prepare an example calculation for SRT = 4 d and **coefficient set #1**

$$Y_{obs} = \frac{(0.40\ g/g}{[1+(0.10\ g/g\bullet d)(4\ d)]}) + \frac{(0.10\ g/g)(0.10\ g/g\bullet d)(0.40\ g/g)(4\ d)}{[1+0.10\ g/g\bullet d)(4\ d)]}$$

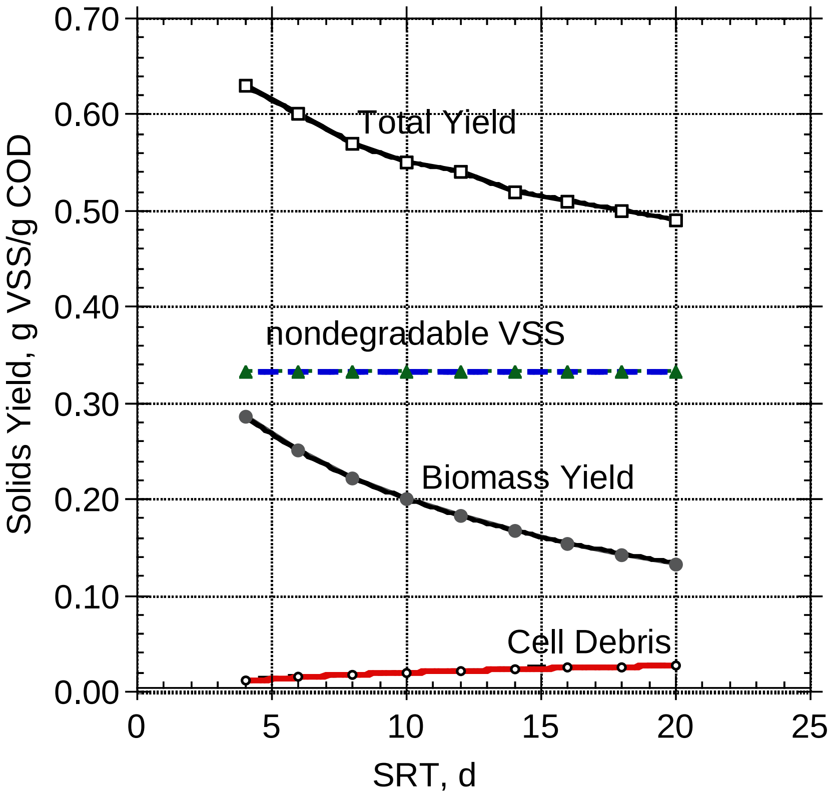
$$+\frac{(100\ g/m^3)}{(300\ g/m^3)}$$

$$Y_{obs} = 0.286 + 0.011 + 0.333 = 0.63$$

b. Prepare a spreadsheet for SRTs ranging from 4 to 20 d

SRT	Biomass yield	Cell debris	Nondegradable VSS	Total yield g VSS/g COD
4	0.286	0.011	0.333	0.63
6	0.250	0.015	0.333	0.60
8	0.222	0.018	0.333	0.57
10	0.200	0.020	0.333	0.55
12	0.182	0.022	0.333	0.54
14	0.167	0.023	0.333	0.52
16	0.154	0.025	0.333	0.51
18	0.143	0.026	0.333	0.50
20	0.133	0.027	0.333	0.49

a. Plot solids yield vs. SRT



2. Determine oxygen required and divide by COD removed to obtain g O_2/g COD removed

   a. Determine the equation for oxygen required

   $R_o = Q(S_o - S) - 1.42\, P_{X,bio}$ Eq. (7-61)

   $P_{X,bio} = Y_{bio}(Q)(S_o - S)$

   $$Y_{bio} = \frac{Y}{1 + b(SRT)}$$

   $R_o = Q(S_o - S) - 1.42\, Y_{bio}(Q)\,(S_o - S)$

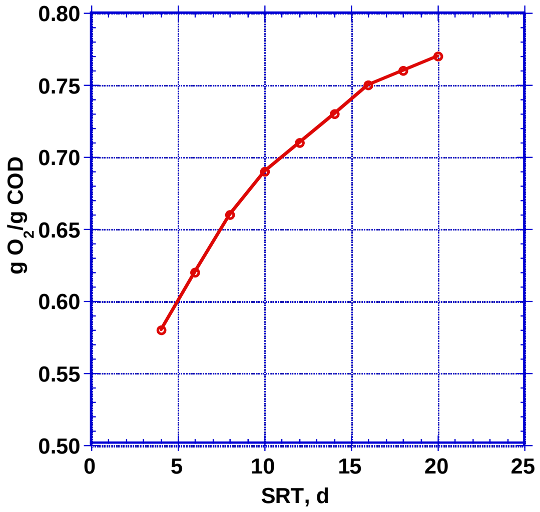
   b. Determine g O_2/g COD

   $$\frac{g\ O_2}{g\ COD} = \frac{R_o}{Q(S_o - S)} = 1 - 1.42 Y_{bio}$$

   c. Prepare a spreadsheet ($Y_{bio} = Y_{biomass} + Y_{cell\ debris}$)

SRT	Y_{bio}	g O_2/g COD
4	0.297	0.58
6	0.265	0.62
8	0.240	0.69
10	0.220	0.71
12	0.204	0.71
14	0.190	0.73
16	0.179	0.75
18	0.169	0.76
20	0.160	0.77

d. Plot oxygen demand vs. SRT



PROBLEM 7-27

Problem Statement – see text, page 679

Solution

1. Combine Eqs. (7-54), (7-55), and (7-57) to obtain the aeration tank volume and use Eq. (7-46) to determine the effluent soluble bCOD concentration value needed to solve for V, given X_{TSS}.

$$(X_{TSS})(V) = \frac{QY(S_o - S)(SRT)}{[1+b(SRT)](0.85)} + \frac{(f_d)(b)YQ(S_o - S)(SRT)(SRT)}{[1+b(SRT)](0.85)}$$

$$+QX_{o,i}(SRT) + Q(TSS_o - VSS_o)(SRT)$$

$$S = \frac{K_s[1+b(SRT)]}{[(SRT)(Yk-b)]-1}$$

a. Solve for S.

As indicated by the problem statement, the influent contains soluble BOD, no degradable VSS, and no inorganic suspended solids (TSS – VSS). The SRT is given and Yk = μ_m, therefore:

$$S = \frac{20\ g/m^3[1+(0.10 g/g\bullet d)(10\ d)]}{[(10\ d)(2.5\ g/g\bullet d) - (0.10\ g/g\bullet d)] - 1} = 1.7\ g/m^3 = 1.7\ mg\ COD/L$$

b. Solve for S_o for **wastewater #1.**

As the coefficients are given in terms of bCOD, the influent (S_o) must be converted to bCOD**.**

S_o = (1.6 mg bCOD/mg BOD)(800 mg/L BOD) = 1280 mg bCOD/L

c. Solve for V.

$$(2500\ g/m^3)V = \frac{(4000\ m^3/d)(0.45\ g/g)[(1280-1.7)g/m^3)](10\ d)}{[1+(0.10\ g/g\bullet d)(10\ d)](0.85)]}$$

$$+\frac{(0.10\ g/g)(0.10\ g/g\bullet d)(0.45\ g/g)(4000\ m^3/d)[(1280-1.7)g/m^3)](10\ d)^2}{[1+(0.10\ g/g\bullet d)(10\ d)](0.85)]}$$

$$+ (4000\ m^3/d)(200\ g/m^3)(10\ d)$$

$(2500\ g/m^3)V = 22{,}888{,}435\ g/m^3\ (m^3)$

$V = 9{,}155\ m^3$

2. Determine the amount of waste solids using Eq. (7-57)

$$P_{x,TSS} = \frac{X_{TSS}(V)}{SRT} = \frac{(2500\ g/m^3)(9155\ m^3)(1\ kg/10^3 g)}{10\ d} = 2{,}288.8\ kg/d$$

3. Determine the oxygen requirement using Eq. 7-61

$R_o = Q(S_o - S) - 1.42\,P_{X,bio}$, where $P_{X,bio}$ is determined from terms A and B in Eq. (7-54)

$$P_{X,bio} = \frac{QY(S_o - S)}{1 + b(SRT)} + \frac{(f_d)(b)YQ(S_o - S)SRT}{1 + b(SRT)}$$

$$P_{X,bio} = \frac{(4000\ \mathrm{m^3/d})(0.45\ \mathrm{g/g})[(1280 - 1.7)\mathrm{g/m^3}]}{[1 + (0.10\ \mathrm{g/g \cdot d})(10\ \mathrm{d})]}$$

$$+ \frac{(0.10\ \mathrm{g/g})(0.10\ \mathrm{g/g \cdot d})(0.45\ \mathrm{g/g})(4000\ \mathrm{m^3/d})[(1280 - 1.7)\ \mathrm{g/m^3}](10\ \mathrm{d})}{[1 + 0.10\ \mathrm{g/g \cdot d})(10\ \mathrm{d})]}$$

= 1,265,517 g/d

$R_o = (4000\ \mathrm{m^3/d})[(1280 - 1.7)\mathrm{g/m^3}] - (1.42)(1{,}265{,}517\ \mathrm{g/d})$

= 3,316,165 g/d = 3316 kg/d

Volumetric oxygen uptake rate = R_o/V

$= (3{,}316{,}165\ \mathrm{g/d}) / (9155\ \mathrm{m^3})(24\ \mathrm{h/d})$

$= 15.1\ \mathrm{g/m^3 \bullet h} = 15.1\ \mathrm{mg/L \bullet h}$

4. Determine the effluent soluble BOD concentration from the effluent soluble bCOD concentration.

   Effluent sBOD = 1.7 / (1.6 g COD/g BOD)

   = 1.1 mg/L sBOD

5. Determine the return sludge recycle ratio by mass balance, accounting for the solids entering and leaving the final clarifier, where return sludge flow = Q_R and the recycle ratio, $R = Q_R/Q$ (ignore solids wasting which is a small fraction of rate of solids mass)

   Rate of mass in = Rate of mass out

   $(Q_R + Q)(2500\ \mathrm{mg/L}) = Q_R(8000\ \mathrm{mg/L}) + (Q - Q_R)(15\ \mathrm{mg/L})$

   $(R + 1)(2500\ \mathrm{mg/L}) = R(8000\ \mathrm{mg/L}) + (1 - R)(15\ \mathrm{mg/L})$

   Solving for R: R = 0.45

4. Determine the MLVSS/MLSS ratio by first calculating the MLVSS concentration by combining Eqs. (7-54) and (7-56).

   MLVSS = $P_{X,VSS}$ (SRT)/ V

$$P_{X,VSS} = \frac{QY(S_o - S)}{1 + b(SRT)} + \frac{(f_d)(b)YQ(S_o - S)SRT}{1 + b(SRT)} + Q(X_{o,i})$$

$$MLVSS = \frac{(4000\ m^3/d)(0.45\ g/g)[(1280 - 1.7)g/m^3](10\ d)}{[1 + (0.10\ g/g \bullet d)(10\ d)](9155\ m^3)]}$$

$$+ \frac{(0.10\ g/g)(0.10 g/g \bullet d))(0.45\ g/g)(4000\ m^3/d)[(1280 - 1.7)g/m^3)(10\ d)^2}{[1 + (0.10\ g/g \bullet d)(10\ d)](9155\ m^3)]}$$

$$+ \frac{(4000\ m^3/d)(200\ g/m^3)(10\ d)}{9155\ m^3} = 2256\ g/m^3$$

   MLVSS/MLSS = (2256 g/m^3)/(2500 g/m^3) = 0.90

5. Determine the N and P requirements, based on the biomass produced/day.

   $P_{X,bio}$ = 1,265,567 g/d

   a. N required = 0.12 g N/g biomass

      = (0.12)(1,265,562 g) = 151,862 g

      Based on influent flow = 151,862 g/(4000 m^3/d) = 37.97 mg/L• d

      Influent flow TKN = 30 mg/L, so nitrogen must be added at 8 mg/L as N.

   c. P required = 0.02 g P/g biomass

      = 0.02 (1,265,567 g) = 25,310 g/d

      Based on influent flow = 25,310 g/(4000 m^3/d) = 6.33 mg/L

      There is sufficient P in the influent (8 mg/L).

PROBLEM 7-28

Problem statement – see text, page 680

Solution

1. The PAC is not biodegradable and will not ignite at the temperature (550°C) used for the VSS test, so it can be treated as a solids equivalent to an inorganic material or non-volatile TSS. The solution in Problem 7-27 is modified by adding the solids produced from the PAC.

   $P_{X,PAC} = Q\ (TSS_o) = 4000\ (50) = 200{,}000\ g/d$

   The sludge production as TSS in Problem 7-27 was 2288.8 kg/d = 2,288,800 g/d

   The new sludge production $P_{X,TSS} = 2{,}288{,}800 + 200{,}000 = 2{,}488{,}800\ g/d = 2488.8\ kg/d$

2. The MLSS concentration is determined from the definition of solids wasting at steady state [Eq. (7-57)]:

   $$P_{X,TSS} = \frac{X_{TSS}(V)}{SRT}$$

   $$MLSS = X_{TSS} = P_{X,TSS}(SRT)/V = \frac{(2{,}488{,}800\ g/d)(10\ d)}{9155\ m^3} = 2719\ mg/L$$

   MLVSS in Problem 7-27 = 2256 mg/L

   MLVSS/MLSS = (2256 mg/L)/(2719 mg/L) = 0.83

Book Problem 7-29

Problem Statement – see text, page 680

Solution

1. The aeration capacity must equal the oxygen required per Eq. (7-61). Equate the aeration capacity to the oxygen required and solve for SRT.

   Assume f_d = 0.10 g VSS/g VSS. (Note that nitrification is assumed insignificant.) Solve for **wastewater #1.**

   Aeration capacity = $R_o = Q\ (S_o - S) - 1.42\ P_{X,bio}$

   Assume $S_o - S \approx S_o$

   $R_o = 52\ kg/h\ (24\ h/d)\ (10^3\ g/kg) = 1{,}248{,}000\ g/d$

   $$P_{X,bio} = \frac{QY(S_o - S)}{1 + b(SRT)} + \frac{(f_d)(b)YQ(S_o - S)SRT}{1 + b(SRT)}$$

1,248,000 g/d = (6000 m^3/d)(300 g/m^3)

$$-1.42\left[\frac{(6000\ m^3/d)(0.40\ g/g)(300\ g/m^3)}{[1+(0.10\ g/g\bullet d)(SRT)]}+\frac{(0.10\ g/g)(0.10\ g/g\bullet d)(0.40\ g/g)(6000\ m^3/d)(300\ g/m^3)SRT}{[1+(0.10\ g/g\bullet d)(SRT)]}\right]$$

1,248,000 g/d = 1,800,000 g/d - $\left[\frac{1{,}022{,}400}{1+0.10(SRT)}+\frac{10{,}224(SRT)}{1+0.10(SRT)}\right]$

SRT = 10.5 days

Note: To show effect of SRT, the oxygen required at an SRT of 15 d is 1,329,696 g/d = 55.4 kg/h (an amount greater by 7%)

PROBLEM 7-30

Problem statement – see text, page 680

Solution

1. For a complete-mix reactor the mass balances for substrate and biomass are as follows, where r_{su} = kXS

   Mass rate of change = rate of mass in – rate of mass out

   + rate of generation – rate of depletion

   Substrate: $\frac{dS}{dt}V = QS_o - QS - r_{su}V$

   At steady state and r_{su} = kXS

   $QS_o - QS = kXSV$

   $S_o - S = kXS\frac{V}{Q} = kXS\,\tau$

   $kXS\,\tau + S = S_o$

   $S = S = \frac{S_o}{(1+kX\tau)}$ Eq. (A)

   Biomass:

   $$\frac{dX}{dt}V = QX_o - \frac{XV}{SRT} + Yr_{su}V - bXV$$

   At steady state and X_o = 0 and r_{su} = kXS

$r_{su}V$ = substrate utilization rate = $Q(S_o - S)$

$$0 = -\frac{XV}{SRT} + YQ(S_o - S) - bXV$$

$$XV\left(\frac{1}{SRT} + b\right) = -YQ(S_o - S)$$

$$X = \frac{YQ(S_o - S)SRT}{[1 + b(SRT)]V} = \frac{SRT}{\tau}\left[\frac{Y(S_o - S)}{1 + b(SRT)}\right] \qquad \text{Eq. (B)}$$

This equation is the same as Eq. (7-42), p. 600

2. Using S = 1.0 mg/L, substitute values into Eq. (A) above and solve for X. Substitute X into Eq. (B) above and solve for SRT.

$$1.0 = \frac{500}{[1 + (0.504X)(0.25)]} = \frac{500}{(1 + 0.126X)}$$

X = 3960.3 mg VSS/L

$$3960.3 = \frac{SRT}{0.25}\left[\frac{0.50(500 - 1.0)}{1 + (0.06)SRT}\right]$$

$$3960.3 = \frac{SRT(998)}{1 + (0.06)SRT}$$

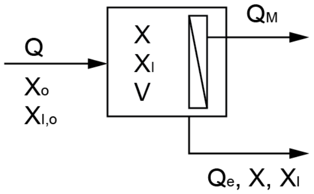
SRT = 5.2 d

PROBLEM 7-31

Problem statement – see text, p. 650

Solution

1. Write mass balance for X (biomass concentration) and show a steady state equation to solve for X.



Rate of change = rate in – rate out + rate of production – rate of depletion

$$V\frac{dX}{dt} = QX_o - Q_E X - (r_{xd})V$$

Steady state: $V\frac{dX}{dt} = 0$, r_{xd} = bX

$$QX_o = Q_E X + bXV$$

$$X_o = \frac{Q_E}{Q}(X) + bX\left(\frac{V}{Q}\right), \qquad \tau = \frac{V}{Q}$$

$$X_o = \frac{Q_E}{Q}(X) + bX\left(\frac{V}{Q}\right)$$

$$X_o = \left[\frac{Q_E}{Q} + b\tau\right]X$$

$$X = \frac{X_o}{\left[Q_E / Q + b\tau\right]}$$

2. Write a mass balance equation for the inert suspended solids, X_I, and give equation to solve for X_I.

$$V\frac{dX_I}{dt} = QX_{I,o} - Q_E X_I$$

Steady state: $Q_E X_I = Q_E X_{I,o}$

$$X_I = \left(\frac{Q}{Q_E}\right)X_{I,o}$$

3. SRT = mass present / mass wasted per day

$$SRT = \frac{V(X)}{Q_E(X)}, \quad SRT = \frac{V}{Q_E}$$

4. Solve for X, $X_{I,o}$, and SRT at Q_M = 0.5Q

From (1), $X = \frac{X_o}{\left[Q_E / Q + b\tau\right]}$

Q_E + Q_M = Q, Q_M = 0.50Q

Q_E = 0.50Q, τ = V/Q = 20 d

$$X = \frac{(24 \text{ g VSS} / \text{L})}{\left[(0.50Q / Q) + (0.10 \text{ g VSS} / \text{g VSS•d})(20 \text{ d})\right]} = 9.6 \text{ g VSS} / \text{L}$$

From (2), $X_I = \left(\frac{Q}{Q_E}\right)X_{I,o}$

$$X_I = \left(\frac{Q}{0.50Q}\right)(6\ \text{g VSS/L}) = 12.0\ \text{g VSS/L}$$

From (3), $\text{SRT} = \frac{V}{Q_E}$

$$\text{SRT} = \frac{V}{0.50Q} = 2\left(\frac{V}{Q}\right)$$

$$\text{SRT} = 2(20\ \text{d}) = 40\ \text{d}$$

PROBLEM 7-32

Problem statement – see text, p. 681

Solution

1. Use Eq. (7-84) to relate surface flux limitations between the election acceptor and electron donor:

$$S_{ba} < \frac{D_{wd}\nu_a mw_a}{D_{wa}\nu_d mw_d}(S_{bd})$$

S_{ba} = 2.0 mg/L DO

From Example 7-4, $\frac{\nu_a}{\nu_d} = 0.103\ \text{mole}\,O_2 / 0.125\ \text{mole acetate}$

mw_d = 60 g/mole acetate

mw_a = 32 g/mole O_2

$$S_{ba} < \frac{0.90}{2.6}\left(\frac{0.103}{0.125}\right)\left(\frac{32}{60}\right)(S_{bd})$$

$S_{ba} < 0.152\ S_{bd}$

$\frac{2.0}{0.152} < S_{bd}$, $13.2 < S_{bd}$

If S_{bd} is 13.2 mg/L of acetate concentration or less, the acetate removal in the biofilm is not limited by a bulk liquid DO concentration of 2.0 mg/L.

For Example 7-7, at a DO = 2.0 mg/L, the bulk liquid NH_4-N concentration = (2.0 mg/L)/2.8 = 0.71 mg/L or less where the reaction is not surface flux DO limited. There are two reasons why at a DO of 2.0 mg/L the NH_4-N concentration must be so much lower than that for acetate to prevent surface flux limitation of the electron acceptor. These are:

1. The g O_2/g electron donor is much greater for NH_4-N utilization compared to acetate (4.57 vs. $\left[\frac{0.103(32)}{0.125(60)}\right]$ or 0.44 g O_2 /g H_{AC}.
2. NH_4-N has a higher diffusivity coefficient than acetate.

PROBLEM 7-33

Problem statement – see text, page 681

Solution

1. To consider the possible causes for the decline in nitrification performance, summarize the factors related to nitrification kinetics and biomass growth.

Factors affecting nitrification	Comment
SRT and temperature	Was not changed, still at 10 d and 18°C. SRT is long enough at that temperature.
pH	Low pH can inhibit performance – check
Toxicity	Toxicity can hinder nitrification rates – perform bioassay on wastewater using nitrifier enrichments
DO concentration	Check to see if enough aeration is being supplied and if basin DO concentration is > 2.0 mg/L, or has changed
Peak NH_4-N loading	Check to see if high NH_4-N concentration recycle streams are entering system to create transient overloads and periods of high effluent NH_4-N concentration

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PROBLEM 7-34

Problem Statement – see text, page 682

Solution

1. Determine the SRT of the aerobic system at steady state for a completely mixed activated sludge system at 20 ºC by combining Eq. (7-94) and Eq. (7-98) and assuming no limitation by dissolved oxygen.

$$\frac{1}{SRT} = \mu_{max,AOB}\left(\frac{S_{NH_4}}{S_{NH_4} + K_{NH_4}}\right) - b_{AOB}$$

From Table 7-13 for AOB at 20 ºC:

$\mu_{max} = 0.90\ g\ VSS / g\ VSS•d$

$K_{NH_4} = 0.50\ mg\ NH_3\text{-}N / L$

$$\frac{1}{SRT} = (0.90\ g\ VSS / g\ VSS \circlearrowright d)\left(\frac{1.0\ mg\ N/L}{1.0\ mg\ N/L + 0.50\ mg\ N/L}\right)$$

$$- 0.17\ g\ VSS / g\ VSS \circlearrowright d$$

$$\frac{1}{SRT} = 0.43\ d^{-1}$$

SRT = 2.33 d

2. Determine the SRT of the anaerobic completely mixed system at 30 ºC with limitation by nitrite. The same kinetics relationship as used in Step 1 for AOB applies.

From Table 7-13 at 30 ºC, using average of values shown.

$\mu_{max} = 0.065\ g\ VSS / g\ VSS•d$

$K_{NH_4} = 0.085\ mg\ NH_3\text{-}N / L$

$$\frac{1}{SRT} = (0.065\ g\ VSS / g\ VSS \circlearrowright d)\left(\frac{1.0\ mg\ N/L}{1.0\ mg\ N/L + 0.085\ mg\ N/L}\right) - 0.03\ g\ VSS / g\ VSS \circlearrowright d$$

$$= 0.0299\ d^{-1}$$

SRT = 33.4 d

PROBLEM 7-35

Problem Statement – see text, page 682

Solution

1. Compare the moles of nitrite and oxygen used for 1 mole electron transfer in Eq. 3 and Eq. 4, respectively, in Table 7-6.

   Electron Acceptors:

   $$\frac{1}{3}NO_2^- + \frac{4}{3}H^+ + e^- = \frac{1}{6}N_2 + \frac{2}{3}H_2O$$

   $$\frac{1}{4}O_2 + H^+ + e^- = \frac{1}{2}H_2O$$

   $$\frac{1}{3}NO_2^- = \frac{1}{4}O_2 \text{ for equal moles electron acceptor}$$

   $$\frac{\text{g } O_2 \text{ equiv}}{\text{g } NO_2-N} = \frac{32(1/4)}{14(1/3)} = 1.7\frac{\text{g } O_2}{\text{g } NO_2-N}$$

PROBLEM 7-36

Problem Statement – see text, page 682

Solution

1. Provide mass balance for NO_3-N removed

   NO_3-N is removed to provide oxygen equivalent for COD degradation and to provide N for biomass synthesis.

   Eq. (7-61) where Ro = oxygen needed:

   $R_o = Q(S_o - S) - 1.42\ P_{,bio}$

   NO_3-N removed = NO_3-N for supply of oxygen equiv. + biomass synthesis

   $$NO_3\text{-N removed} = Q(No - N) = \frac{R_o}{2.86} + 0.12P_{X,bio}$$

   $$Q(No - N) = (4000\ m^3/d)(40.5 - 0.5)g/m^3 = 160{,}000\text{ g } NO_3\text{-N/d}$$

   $$160{,}000\text{ g } NO_3\text{-N/d} = \frac{R_o}{2.86} + 0.12P_{X,bio}$$

   $$160{,}000\text{ g } NO_3\text{-N/d} = \frac{[Q(So - S) - 1.42P_{X,bio}]}{2.86} + 0.12P_{X,bio}$$

   $$P_{X,bio} = \frac{QY(S_o - S)}{1 + b(SRT)} + \frac{(f_d)(b)YQ(S_o - S)SRT}{1 + b(SRT)}$$

160,000 g NO_3-N/d =

$$\frac{[Q(So-S)-1.42[\frac{QY(S_o-S)}{1+b(SRT)}+\frac{(f_d)(b)YQ(S_o-S)SRT}{1+b(SRT)}]}{2.86}$$

$$+\ 0.12[\frac{QY(S_o-S)}{1+b(SRT)}+\frac{(f_d)(b)YQ(S_o-S)SRT}{1+b(SRT)}]$$

160,000 g NO_3-N/d =

$$\left[\frac{Q(S_o-S)}{2.86}\right]+\left(\frac{-1.42}{2.86}+0.12\right)\left[\frac{QY(S_o-S)}{1+b(SRT)}+\frac{(f_d)(b)YQ(S_o-S)SRT}{1+b(SRT)}\right]$$

2. Use information given for Y, b, f_d, Q, and SRT to calculate the acetate used as COD

160,000 g NO_3-N/d =

$$\left[\frac{\left(4000\ m^3/d\right)(So-S)\,g/m^3}{2.86}\right]$$

$$+\left(\frac{-1.42}{2.86}+0.12\right)\left\{\frac{\left(4000\ m^3/d\right)\left(0.42\ g\ VSS/g\ COD\right)(S_o-S)}{[1+\left(0.08\ g\ VSS/g\ VSS\text{-}d\right)(5\ d)]}+0\right\}$$

$$160{,}000 = 1398.6(So-S)-(0.3766)(1200)(So-S)$$

So – S = 169.0 mg/L COD

3. Determine the COD of acetate and amount of acetate used

$CH_3COOH + 2O_2 = 2CO_2 + 2H_2O$

$Acetate_{MW}$ = 2(12) + 4(1) + 2(16) = 60

$$\frac{g\ COD}{g\ acetate}=\frac{2(32)}{60}=1.067\ g\ COD/g\ acetate$$

$$\text{Acetate used} = \frac{169.0\ mg\ COD/L}{1.067\ mg\ COD/mg\ acetate}=158.4\ mg/L\ acetate$$

4. Determine the acetate dose and amount needed, kg/d

Given effluent acetate concentration = 2.0 mg/L

(So – 2.0) = 158.4 mg/L acetate

So = dose = 160.4 mg/L acetate

Amount added per day = (160.4 g/m^3)(4000 m^3/d) = 641,600 g/d

Amount per day = 641.6 kg/d acetate

5. Determine the biomass production rate, kg/d

   The biomass production rate is $P_{X,bio}$

$$P_{X,bio} = \frac{QY(S_o - S)}{1 + b(SRT)} + \frac{(f_d)(b)YQ(S_o - S)SRT}{1 + b(SRT)}$$

$$P_{X,bio} = \frac{\left(4000\ m^3/d\right)\left(0.42\ g\ VSS/g\ COD\right)(169.0)\,g\ COD/m^3}{[1+0.08\ g\ VSS/g\ VSS\text{-}d(5\ d)]} + 0$$

$$P_{X,bio} = 202{,}800\ g\ VSS/d$$

$$P_{X,bio} = 202.8\ kg\ VSS/d$$

$$P_{X,bio} = \frac{202.8\ kg\ VSS/d}{0.85\ g\ VSS/g\ TSS} = 238.6\ kg\ TSS/d$$

6. Provide a steady state mass balance for reactor biomass concentration

   This is a steady state completely mixed reactor so Eq. (7-42) applies

$$X = \left(\frac{SRT}{\tau}\right)\left[\frac{Y\left(S_o - S\right)}{1 + b\left(SRT\right)}\right]$$

   The reactor volume would have to be given to solve for X or if a concentration is assumed, the hydraulic retention time can be determined.

PROBLEM 7-37

Problem statement – see text, page 682

Solution (100 mg/L acetate)

1. Determine the reactor MLVSS concentration by combining and using appropriate terms in Eqs. (7-56) and (7-54). With that, the amount of solids wasted can be calculated, which, in turn, is used to account for the phosphorus removed. The phosphorus removal is equal to the removal as mg/L times the flowrate. The VSS/TSS ratio is used to calculate the MLSS concentration.

   X_{VSS} (V) = $P_{X,VSS}$ (SRT), Eq. (7-56)

$$\text{MLVSS(V)} = \left[\frac{QY(S_o - S)}{1 + b(SRT)} + \frac{(f_d)(b)YQ(S_o - S)SRT}{1 + b(SRT)}\right]SRT$$

Divide by V and assume $S_o - S \approx S_o$

Acetate as COD = 1.07 g COD/g H_{AC} (100 mg/L) = 107 mg/L

$$\text{MLVSS} = \left\{\frac{Y(S_o)}{[1 + b(SRT)]\tau} + \frac{(f_d)(b)Y(S_o)SRT}{[1 + b(SRT)]\tau}\right\}SRT$$

$$\tau = 3\text{ h}\left(\frac{1\text{ d}}{24\text{ h}}\right) = 0.125\text{ d}$$

$$\text{MLVSS} = \left\{\begin{aligned}&\frac{(0.4\text{ g/g})(107\text{ g/m}^3)}{[1 + (0.10\text{ g/g}\cdot\text{d})(5\text{ d})](0.125\text{ d})}\\ &+ \frac{(0.10\text{ g/g})(0.10\text{ g/g}\cdot\text{d})(0.4\text{ g/g})(107\text{ g/m}^3)(5\text{ d})}{[1 + (0.10\text{ g/g}\cdot\text{d})(5\text{ d})](0.125\text{ d})}\end{aligned}\right\}(5\text{ d})$$

MLVSS = 1198.4 g/m^3

$$\text{g VSS/d wasted} = \frac{\text{(MLVSS)V}}{\text{SRT}}$$

$$\text{g P removed / d} = \frac{\text{g P}}{\text{g VSS}}\text{(g VSS / d wasted)}$$

$$Q(\Delta P) = \text{g P removed / d}$$

a. For anaerobic / aerobic system:

$$Q\ (\Delta P) = \frac{0.25\ \text{(MLVSS)V}}{\text{SRT}}$$

$$\Delta P = \frac{0.25\ \text{(MLVSS)(V/Q)}}{\text{SRT}} = \frac{0.25\ \text{(MLVSS)}\tau}{\text{SRT}}$$

$$= \frac{(0.25\text{ g/g})(1198.4\text{ g/m}^3)\ 0.125\text{ d}}{5\text{ d}} = 7.5\text{ g/m}^3$$

P removal from influent for anaerobic/aerobic system = 7.5 mg/L

$$\text{MLSS} = \frac{\text{(1198.4 mg VSS/L)}}{\text{(0.65 g VSS/g TSS)}} = 1843.7\text{ g/m}^3$$

b. For aerobic only system

$$\Delta P = \frac{0.015\ (\text{MLVSS})\ \tau}{\text{SRT}}$$

$$= \frac{(0.015\ \text{g/g})(1198.4\ \text{g/m}^3)(0.125\ \text{d})}{5\ \text{d}} = 0.45\ \text{g/m}^3$$

$$\text{MLSS} = \frac{(1198.4\ \text{g/m}^3)}{0.85} = 1409.9\ \text{g/m}^3$$

PROBLEM 7-38

Problem statement – see text, page 682

Solution

1. From page 652, the molar ratios of cations to P removal are 0.28, 0.26, and 0.09 Mg^{2+}, K^+, and Ca^{2+}, respectively. Use these ratios to determine minimum concentrations needed in the influent wastewater for 10 mg/L P removal.

   mmole P removal = (10 mg/L)/(31 mg/mmole P) = 0.323 mmole P/L

Mg^{2+} = (0.323 mmole P/L)(0.28 mmole Mg/mmole P)(24.2 mg Mg/mmole Mg) = 2.2 mg/L

K^+ = (0.323 mmole P/L)(0.26 mmole K/mmole P)(39.1 mg K/mmole K) = 3.3mg/L

Ca^{2+} = (0.323 mmole P/L)(0.09 mmole Ca/mmole P)(40 mg Ca/mmole Ca) = 1.2 mg/L

PROBLEM 7-39

Problem statement – see text, page 682

Solution

a. An increase in the system SRT and occurrence of nitrification will result in less P removal for the anaerobic/aerobic process shown in Fig. 7-23 and thus the effluent P concentration will increase (I).

The reason is that nitrate in the recycle stream to the anaerobic contact zone will be used as an electron acceptor by facultative heterotrophic bacteria as they consume influent rbCOD. They are very competitive for substrate versus the PAOs. This leaves less rbCOD for PAOs and subsequently less PAO growth and less EBPR.

b. An increase in the fraction of rbCOD from 20 to 35 percent of the influent biodegradable COD will result in more P removal by EBPR and thus the effluent P concentration will decrease (D).

The reason is that PAOs take up rbCOD in the anaerobic zone to intracellular storage and then use the stored carbon for cell growth in the aerobic zone. Thus, with an increase in influent rbCOD concentration, more PAO growth will occur, and thus more P will be removed by EBPR.

c. The higher temperature and lower pH will result in less P removal by EBPR so that the effluent P concentration will increase (I).

The reason is that the higher temperature and lower pH provides more favorable conditions for the GAOs. On page 652 it is noted that GAOs can greatly outcompete PAOs at higher temperature and lower pH.

d. The decrease in DO concentration from 2.0 to a range of 0.30 to 0.50 mg/L will result in less EBPR and thus an increase in effluent P concentration (I).

The reason is that the oxidation of the stored substrate by the PAOs will be at a reduced rate due to the oxygen-limited condition. Because the system SRT is low as noted for the base case, there is not excess aeration time to off set the decreased rate of stored carbon oxidation so that the amount of PAO growth will decrease and the P release in the anaerobic zone will be less. The combined effect of less growth and less P release in the anaerobic zone will results in less EBPR.

PROBLEM 7-40

Problem statement – see text, page 683

Solution (Influent COD = 2000 mg/L)

1. Determine the amount of COD converted to methane based on the COD_{in} minus the COD in the effluent minus the COD in the biomass produced.

   $COD_{in} = COD_{eff} + COD_{cells} + COD_{methane}$

   $COD_{eff} = (1 – 0.95)\ Q\ (S_o)$

   $= (1 – 0.95)(500\ m^3/d)(2000\ g/m^3) = 50{,}000\ g/d$

   $COD_{in} = (500\ m^3/d)(2000\ g/m^3) = 1{,}000{,}000\ g/d$

   $$COD_{cells} = 1.42\ \left(\frac{0.04\ g\ VSS}{g\ COD}\right)(1{,}000{,}000 – 50{,}000)\ g/d$$

   $= 53{,}960\ g/d$

   $COD_{methane} = (1{,}000{,}000 – 50{,}000 – 53{,}960)\ g/d = 896{,}040\ g/d$

2. Methane production is based on

   $0.35\ L\ CH_4/gCOD$ at 0°C

   CH_4 at 0°C $= (0.35\ L/g)(896{,}040\ g/d)(1\ m^3/10^3\ L) = 313.6\ m^3/d$

3. Calculate the methane gas volume at 30°C and 1 atm

   $$V_2 = V_1\left(\frac{T_2}{T_1}\right) = \frac{(313.6\ m^3/d)(273.15 + 30)K}{(273.15)K} = 348\ m^3/d$$

   $$\text{Total gas flow} = \frac{(348\ m^3/d)}{0.65} = 535.5\ m^3/d$$

4. Determine energy value at 50.1 kJ/g CH_4 by determining CH_4 production in g/d.

   At 0°C, 22,414 L CH_4/mole, 16 g/mole

   Moles $CH_4 = (313.6\ m^3/d)(10^3\ L/m^3)(1\ mole/22{,}414\ L)(16\ g/mole)$

   $= 223{,}860\ g\ CH_4/d$

   Energy $= (50.1\ kJ/g\ CH_4/(223{,}860\ g\ CH_4/d) = 11{,}215{,}390\ kJ/d$

PROBLEM 7-41

Problem statement – see text, page 683

Solution

The problem addresses two options for the processing of food waste: (1) anaerobic digestion and (2) composting.

(1) When added to a municipal anaerobic digester, it is converted to methane and carbon dioxide. A check of the literature will show that food waste is highly degradable with potential for over 90 percent conversion. About 95 percent of the COD converted will show up as methane, so a large portion of the food waste can be converted to a methane fuel. The methane can be used in place of other fuels so that the net addition of greenhouse gases from the digestion is minimized when considering it is being substituted for another fuel. There is some increase in CO_2 emission as the digester gas typically contains 30 to 35 percent CO_2.

(2) In composting, a large portion of the COD is oxidized to CO_2 and water, as it is an aerobic process. The net effect is more CO_2 production than that from anaerobic digestion, so its greenhouse gas contribution is greater.

I would agree with the professor.

PROBLEM 7-42

Problem statement – see text, page 683

Solution

1. Literature sources should be identified and interpreted to describe syntrophic relationship between methanogenic bacteria and acid formers. If hydrogen is not utilized at a fast enough rate by the methanogens, the conversion of propionate and butyrate to acetate and hydrogen will be inhibited. The accumulation of these fatty acids will cause inhibition of methanogenic activity and a drop in pH. The direction of changes in parameters listed for this problem for such an upset condition is given in the table below.

Parameter	Change
Gas Production Rate	Decrease

Percent Methane	Decrease
VFA Concentration	Increase
pH	Decrease

PROBLEM 7-43

Problem Statement – see text, page 683

Solution

1. Substitute the first order kinetics substrate utilization relationship ($r_{su} = kSX_S$) in the Monod term $(1/Y)(\mu_m S/K_s + S)X_S$ in Eq (7-156) and develop a new relationship for S_o.

$$S_o = kS(X_S)\tau + K_p S X_T\left(\frac{\tau}{SRT}\right) + K_L a_s\ S(\tau) + S$$

2. Because the net biomass production depends on the substrate removed for biodegradation, the specific endogenous decay rate, and the SRT, Eq. (7-157) is not changed.

$$X_S = \frac{Y[(S_o - S) - K_p S X_T(\tau / SRT) - K_L a_s S(\tau)]}{(b)(\tau) + (\tau / SRT)}$$

3. It is not possible to develop an equation to replace Eq. (7-158) as the effluent substrate concentration S is a function of all the factors affecting its fate in the reactor. Revised Eq. (7-156) and Eq. (7-157) must be solved simultaneously to develop a solution.

PROBLEM 7-44

Problem statement – see text, page 683

Solution

1. Assuming the loss due to volatilization is negligible, solve for the substrate concentration, S, as a function of SRT [Eq. (7-158)]. **Solve for SRT = 5 d.**

$$S = \frac{K_S[1 + b(SRT)]}{(SRT)(\mu_m - b) - 1} = \frac{(0.4\ g/m^3)[1 + (0.08\ g/g{\bullet}d)(5d)]}{(5d)[(2.0 - 0.08)\ g/g{\bullet}d] - 1} = 0.065\ g/m^3$$

2. Determine X_S using Eq. (7-157), again assuming the loss due to volatilization is negligible.

$$X_S = \frac{Y[(S_o - S) - K_p S X_T(\tau / SRT)]}{(b)(\tau) + (\tau / SRT)}$$

$$X_S = \frac{(0.6\, g/g)\{[(5.0 - 0.065) g/m^3] - (0.015\, m^3/g)(0.065\, g/m^3)(2000\, g/m^3)(0.25\, d/5\, d)\}}{(0.08\, g/g{\cdot}d)(0.25\, d) + (0.25\, d/5\, d)}$$

$= 41.4\ g/m^3$

3. Determine the losses due to sorption, removal in the effluent, and biodegradation:

   a. Sorption and waste sludge portion in Eq. (7-156)

   $K_p S X_T(\tau/SRT) = (0.015\ m^3/g)(0.065\ g/m^3)(2000\ g/m^3)(0.25\ d)(5\ d)$

   $= 0.0975\ g/m^3$

   b. Removal in effluent, $S = 0.065\ g/m^3$

   c. Biodegradation using the biodegradation portion in Eq. (7-156)

$$??\left(\frac{1}{Y}\right)\left(\frac{\mu_m S}{K_s + S}\right)(X_s)\ \tau = \left(\frac{1}{0.6\ g/g}\right)\frac{(2.0\ g/g \bullet d)(0.065\ g/m^3)(41.4\ g/m^3)(0.25\ d)}{[(0.4 + 0.065) g/m^3]}$$

$= 4.823\ g/m^3$

   d. Check quantities with mass balance

   Mass balance = $(0.0975 + 0.065 + 4.832)\ g/m^3 = 5.0\ g/m^3$ (checks)

4. Repeat calculations with μ_m three times greater: $\mu_m = 6.0\ g/g \bullet d$.

   $X_s = 42.4\ g/m^3$

   Sorption: $= 0.0294\ g/m^3$

   Effluent $= 0.0196\ g/m^3$

   Biodegradation: $= 4.951\ g/m^3$

   Mass balance = $(0.0294 + 0.0196 + 4.951)\ g/m^3 = 5.0\ g/m^3$ (checks)

8

SUSPENDED GROWTH BIOLOGICAL TREATMENT PROCESSES

Instructors Note: In many of the problems where constituent concentrations are used, the units mg/L and g/m^3 are used interchangeably to facilitate computations without introducing additional conversion factors.

PROBLEM 8-1

Problem Statement – see text, page 919

Solution

1. Use Eq. (8-4) in page 711 to obtain the bCOD concentration:

$$\frac{\text{bCOD}}{\text{UBOD}} = \frac{1}{1.0 - 1.42\ f_d(Y_H)}$$

$$\frac{\text{bCOD}}{\text{UBOD}} = \frac{1}{1.0 - 1.42(0.15\,\text{g/g})(0.40\,\text{g/g})} = 1.093$$

bCOD = 1.093(180 mg/L) = 196.8 mg/L

PROBLEM 8-2

Problem Statement – see text page 920

Solution (Wastewater 1)

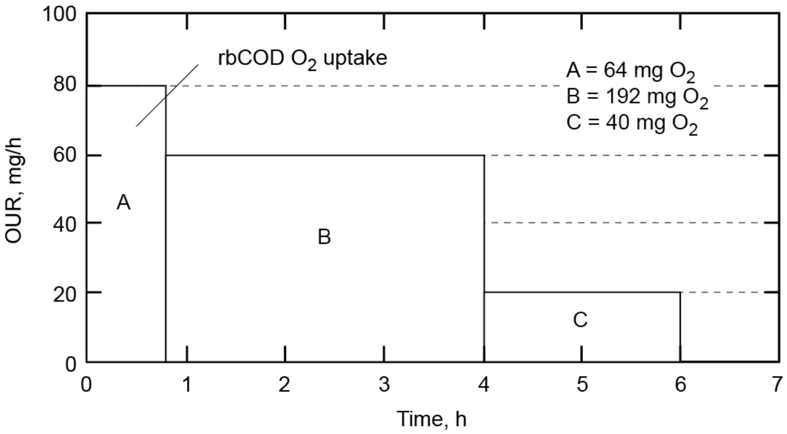
1. Develop a diagram illustrating the three phases of oxygen consumption.
   a. Compute the oxygen consumption for each phase.

      Phase A OUR = 64 mg/0.8 h = 80 mg/h

      Phase B OUR = 192 mg/3.2 h = 60 mg/h

      Phase C OUR = 40 mg/2 h = 20 mg/h

   b. Plot oxygen consumption versus time as illustrated below.



2. Compute the oxygen consumption for rbCOD and the rbCOD concentration in the wastewater.

   a. Compute the rbCOD oxygen consumption. The oxygen consumed for biological uptake of the rbCOD is illustrated as the upper section of Area A in the above graph between 60 and 80 mg/h. Determine that area by subtracting the uptake rate due to the activity associated with area B.

      rbCOD area OUR = (80 – 60) mg/h = 20 mg/h

      O_A = oxygen used for rbCOD uptake = 20 mg/h (0.8 h) = 16.0 mg

      The total test volume was 1.0 L so the uptake concentration is 16.0 mg/L

   b. Compute the rbCOD concentration in the wastewater.

      The rbCOD of the wastewater sample is calculated using the equation below to account for the sample and mixed liquor volumes and the fraction of rbCOD oxidized.

      i. Determine the rbCOD measured in the test from the oxygen consumed.

         O_A used = rbCOD - COD_{cells} = $(1 - Y_{H,COD})$rbCOD

$$\text{rbCOD} = \frac{O_A}{(1 - Y_{H,COD})}$$

$$Y_{H,COD} = 0.45 \frac{\text{g VSS}}{\text{g COD}} \left(1.42 \frac{\text{g COD}}{\text{g VSS}} \right) = \frac{0.64 \text{ g COD}_{\text{cells}}}{\text{g COD}}$$

$$\text{rbCOD} = \frac{16.0\text{ mg}}{(1.0 - 0.64)} = 44.44\text{ mg}$$

ii. Determine the rbCOD concentration in the sample

The sample volume for the rbCOD used was 0.50 L

$$\text{rbCOD concentration} = \frac{44.44\text{ mg}}{0.50\text{ L}} = 88.9\text{ mg/L}$$

PROBLEM 8-3

Problem Statement – see text, page 920

Solution (Wastewater 1)

1. Substract the treated effluent ffCOD from the primary effluent ffCOD.

   rbCOD = (90 – 30) mg/L = 60 mg/L

PROBLEM 8-4

Problem Statement – see text, page 920

Solution (Wastewater 1)

1. Determine the biodegradable COD (bCOD) concentration. The bCOD/BOD ratio is given as 1.6.

   bCOD = 1.6 (BOD) = 1.6 (200 mg/L) = 320 mg/L

2. Determine the slowly biodegradable COD (sbCOD). The sbCOD is defined as the bCOD minus the readily biodegradable COD (rbCOD).

   sbCOD = bCOD – rbCOD = (320 – 100) mg/L = 220 mg

3. Determine the nonbiodegradable COD (nbCOD).

   nbCOD = COD – bCOD = (500 – 320) mg/L = 180 mg/L

4. Determine the nonbiodegradable soluble COD (nbsCOD). The nonbiodegradable soluble COD is equal to the activated sludge system sCOD = 30 mg/L

5. Determine the nonbiodegradable volatile suspended solids (nbVSS) concentration.

   a. Determine the particulate nonbiodegradable COD (nbpCOD). The nbpCOD equals the nbCOD minus the nbsCOD.

      The nbPCOD equals the nonbiodegradable COD minus the nbsCOD nbpCOD = nbCOD – nbsCOD = (180 – 30) mg/L = 150 mg/L

b. Determine the nbVSS concentration.

From Eq. (8-8)

$$VSS_{COD} = \frac{TCOD - sCOD}{VSS} = \frac{[(500 - 160)\ mg/L]}{(200\ mg/L)} = 1.7\ mg\ COD/mg\ VSS$$

nbVSS = 150/1.7 = 88.2 mg/L

6. Determine the inert TSS (iTSS) concentration.

iTSS = TSS – VSS = 220 – 200 = 20 mg/L

PROBLEM 8-5

Problem Statement – see text, page 921

Solution (wastewater 1)

1. Determine the organic nitrogen for **Wastewater 1** using Eq. (8-16).

ON = TKN – NH_4-N

ON = (40 – 25) mg/L = 15 mg/L

2. Determine the nonbiodegradable particulate organic nitrogen (nbpON).

a. Calculate the organic nitrogen content of VSS using Eq. (8-10)

$$f_N = \frac{TKN - sON - (NH_4\text{-}N)}{VSS}$$

$$f_N = \frac{[(40 - 5.0 - 25)\,mg/L]}{(180\ mg/L)} = 0.056$$

b. Calculate nbVSS

nbVSS = VSS (nbVSS fraction)

nbVSS = 180 mg/L(0.40) = 72 mg/L

c. Determine nbpON using Eq. (8-11) and the results from part (a) and (b).

nbpON = f_N (nbVSS)

nbpON = 0.056 (72 mg/L) = 4.03 mg/L

3. Determine the biodegradable organic nitrogen (bON)

a. Calculate nbON using Eq. (8-18)

nbON = nbsON + nbpON

nbsON value is given, and nbpON was calculated in part 2

nbON = (1.0 + 4.03) mg/L = 5.03 mg/L

b. Calculate biodegradable organic nitrogen (bON) using Eq. (8-17)

bON = ON – nbON

bON = (15 – 5.03) mg/L = 9.97 mg/L

PROBLEM 8-6

Problem Statement – see text, page 921

Solution

1. Determine the aeration tank volume (m^3) for Influent BOD concentration of **120 mg/L**.

a. Determine the net waste sludge daily in kgVSS/d

From Figure 8-7, at SRT = 6 d, T = 10°C, the observed yield Y_{obs} = 0.7 kg VSS/kg BOD

Calculate $P_{X,VSS}$ using Eq. (8-19) in page 720

Assuming $S_o - S \approx S_o$ (S is usually small compared to S_o at SRT = 6 d)

$P_{X,VSS} = Y_{obs}\,Q\,(S_o - S) \approx Y_{obs}\,Q\,S_o$

$P_{X,VSS}$ = (0.7 kgVSS / kg BOD) (6000 m^3/d)(120 g/m^3 BOD)(1 kg/10^3 g)

= 504 kg/d

b. Calculate the aeration tank volume from Eq. (7-48) in Chap. 7

$$P_{X,VSS} = \frac{X_T V}{SRT}$$

$$V = \frac{P_{X,VSS}\,(SRT)}{X_T}$$

$$V = \frac{(504\ kg/d)(6\ d)(10^3\ g/kg)}{(2500\ g/m^3)} = 1210\ m^3$$

2. Determine the amount of sludge wasted daily in kg TSS/d using Eq. (7-48).

$$P_{X,VSS} = \frac{X_T V}{SRT}$$

$$P_{X,TSS} = \frac{(3000\ g/m^3)(1210\,m^3)(1\,kg/10^3 g)}{(6\,d)} = 605\ kg/d$$

3. Determine the tank volume and daily waste sludge for SRT = 12 d

   a. Determine the aeration tank volume. Calculate the amount of wasted sludge daily from Fig. 8-7, at SRT = 12 d and T = 10°C, the observed yield Y_{obs} = 0.6 kg VSS/kg BOD removed

   $P_{X,VSS} = Y_{obs}\ (Q)\ S_o$

   $P_{X,VSS}$ = (0.6 g VSS/g BOD)(6000 m^3/d) (120 g/m^3 BOD)(1 kg/10^3 g)

   = 432 kg/d

   Calculate the tank volume from Eq. (7-48)

   $$P_{X,VSS} = \frac{X_T V}{SRT}$$

   $$V = \frac{(432\ kg/d)(12\ d)(10^3\ g/kg)}{(2500\ g/m^3)} = 2074\ m^3$$

   b. Calculate the wasted sludge daily in TSS kg/d from Eq. (7-48).

   $$P_{X,VSS} = \frac{X_T V}{SRT}$$

   $$P_{X,TSS} = \frac{(3000\ g/m^3)(2074\,m^3)(1\,kg/10^3 g)}{(12\,d)} = 518.5\ kg/d$$

PROBLEM 8-7

Problem Statement – see text, page 921

Solution

1. Develop the wastewater characteristics needed for design

   Find bCOD using Eq. (8-13) in page 714

   bCOD = 1.6 (BOD)

   $bCOD_{inf}$ = 1.6 (150 mg/L) = 240 mg/L

   $bCOD_{eff}$ = 1.6 (2 mg/L) = 3.2 mg/L

2. Design an activated-sludge system for BOD removal only for **wastewater 1**

a. Determine biomass production using parts A and B of Eq. (8-20) in page 721.

$$P_{X,VSS} = \frac{Q\,Y_H(S_o - S)}{1 + b_H(SRT)} + \frac{(f_d)(b_H)QY_H(S_o - S)SRT}{1 + b_H(SRT)}$$

Define input data for above equation

Q = 10,000 m^3/d

Y_H = 0.4 g VSS/g bCOD

S_o = 240 mg/L

f_d = 0.15

b_H = 0.08

SRT = 6 d

S = 3.2 mg/L

$$P_{X,VSS} = \frac{(10{,}000\,m^3/d)(0.4)[(240 - 3.2)\,g/m^3](1 kg/10^3 g)}{[1 + (0.08\,d^{-1})(6\,d)]}$$

$$+ \frac{(0.15)(0.08)(10{,}000\,m^3/d)(0.4)(240 - 3.2)\,g/m^3(6\,d)(1 kg/10^3 g)}{[1 + (0.08\,d^{-1})(6\,d)]}$$

$$= (640\ kg/d) + (46.08\ kg/d)$$

$$= 686.08\ kg/d$$

b. Calculate the O_2 demand using Eq. (7-61) in Chap. 7.

$R_o = Q(S_o - S) - 1.42\,P_{X,bio}$

R_o = (10,000 m^3/d)[(240 – 3.2) g/m^3)](1 kg/10^3 g) – 1.42 (686.08 kg/d)

R_o = (2368 – 974.2) kg/d = 1393.8 kg/d

c. Determine the aeration tank OUR in mg/L•h

$$OUR = \frac{R_o}{V}$$

V = Q τ

Define input data for above equation

R_o= 1393.8 kg/d = 58.1 kg/h

Q = 10,000 m^3/d

$\tau = 4$ h

$$\text{OUR} = \frac{R_o}{Q\tau} = \frac{(158.1\ \text{kg/h})(10^6\ \text{mg/kg})}{(10{,}000\ \text{m}^3/\text{d})(1\ \text{d}/24\ \text{h})(4\ \text{h})(10^3\ \text{L/m}^3)}$$

OUR = 34.9 mg/L•h

d. Determine the aeration tank biomass concentration (mg/L) using Eq. (7-56) in Table 8-10

$$X_{VSS} = \frac{P_{X,VSS}(\text{SRT})}{V} = \frac{P_{X,VSS}(\text{SRT})}{Q\tau}$$

$$X_{bio} = \frac{(686.08\ \text{kg/d})(6\ \text{d})}{(10{,}000\ \text{m}^3/\text{d})(4\ \text{h})(1\text{d}/24\ \text{h})}$$

X_{bio} = 2.470 kg/m^3 = 2470 mg/L

PROBLEM 8-8

Problem Statement – see text, page 922

Solution

1. Develop the wastewater characteristics needed for design for **wastewater 1**.

   Determine bCOD using Eq. (8-13)

   bCOD = 1.6 (BOD)

   bCOD$_{inf}$ = 1.6 (150 mg/L) = 240 mg/L

   bCOD$_{eff}$ = 1.6 (2.0 mg/L) = 3.2 mg/L

2. Design an activated sludge system for BOD removal and nitrification

   a. Determine the aeration tank O$_2$ demand

   Calculate $P_{X,VSS}$ using Eq (8-20), parts A, B, and C

$$P_{X,VSS} = \frac{QY_H(S_o - S)(1\ \text{kg}/10^3\ \text{g})}{1 + b_H(\text{SRT})} + \frac{(f_d)(b_H)QY_H(S_o - S)\text{SRT}(1\text{kg}/10^3\ \text{g})}{1 + b_H(\text{SRT})} + \frac{QY_n(NO_x)(1\text{kg}/10^3\ \text{g})}{1 + b_n(\text{SRT})}$$

   b. Define data input for above equation

   Q = 10,000 m^3/d

   Y_H = 0.4 g VSS/g bCOD

S_o = 240 mg/L bCOD

S = 3.2 mg/L bCOD

b_H = 0.08 g VSS/gVSS•d

SRT = 15 d

f_d = 0.1 g VSS/g VSS

Y_n = 0.18 g VSS/g NH_4-N

b_n = 0.12

Assume all of the influent TKN is biodegradable

Assume 20 percent of the TKN is used for cell synthesis

NO_x = (100% – 20%)(TKN) – NH_4-N_{eff} = (0.80)(35) – 1.0 = 27.0 mg/L

c. Solve above equation

$$P_{X,VSS} = \frac{(10{,}000\ m^3/d)(0.4\ g/g)[(240-3.2)\ g/m^3](1\ kg/10^3 g)}{[1+(0.08\,d^{-1})(15\,d)]}$$

$$+\frac{(0.1\,g/g)(0.08\,d^{-1})(10{,}000\ m^3/d)(0.4\ g/g)[(240-3.2)\ g/m^3](15\,d)(1\,kg/10^3\,g)}{[1+(0.08\,d^{-1})(15\,d)]}$$

$$+\frac{(10{,}000\ m^3/d)(0.18)(27.0\ g/m^3)(1\,kg/10^3\,g)}{[1+(0.12\,d^{-1})(15\,d)]}$$

$P_{X,VSS}$ = (430.5 + 51.7 + 17.4) kg/d = 499.6 kg/d

Re-calculate NO_x using Eq (8-24)

NO_x = TKN – N_e – 0.12 $P_{X,bio}$ /Q

NO_x = 35 g/m^3 – 1.0 g/m^3 – 0.12(499.6 kg/d)(10^3 g/1 kg)10,000 m^3/d)

NO_x = (34.0 – 6.0) g/m^3 = 28.0 g/m^3

Re-calculate $P_{X,VSS}$ using NO_X = 28.0 mg/L

$P_{X,VSS}$ = (430.5 + 51.7 + 18.0) kg/d = 500.2 kg/d

Re-calculate NO_x = 35.0 – 1.0 – 6.0 g/m^3 = 28.0 mg/L

(NO_x = 28.0 g/m^3)

Calculate O_2 demand using Eq. (8-23)

R_o = Q (S_o – S) – 1.42 $P_{X,bio}$+ 4.57 Q (NO_X)

$P_{x,bio}$, (heterotrophs) = (430.5 + 51.7) kg/d = 482.2 kg/d

R_o = (10,000 m^3/d)[(240 – 3.2)g/m^3](1 kg/10^3g) – 1.42 (482.2 kg/d) + 4.57 (10,000 m^3/d)(28.0 g/m^3)(1 kg/10^3 g)

R_o = 2368 kg/d – 684.7 kg/d + 1279.6 kg/d = 2962.9 kg/d

R_o = 122.9 kg/h

b. Determine the OUR in mg/L • h

$$OUR = \frac{R_o}{Q\tau}$$

Define the input data for above equation

R_o = 123.5 kg/h

Q = 10,000 m^3/d

τ = 8 h

$$OUR = \frac{(123.5\ kg/h)(10^6 mg/kg)}{(10{,}000\,m^3/d)(1d/24h)(8h)(10^3\,L/m^3)}$$

OUR = 37.05 mg/L•h

c. Determine the tank biomass concentration (mg/L) using Eq. (7-56) in Table 8-10

$$X_{bio} = \frac{P_{X,VSS}(SRT)}{V} = \frac{P_{X,VSS}(SRT)}{Q\tau}$$

$$X_{bio} = \frac{(500.2\,kg/d)(15\,d)}{(10{,}000\,m^3/d)(8\,h)(1d/24\,h)}$$

X_{bio} = 2.251 kg/m^3 = 2251 mg/L

c. Determine the portion of the O_2 required that is for nitrification

$$f_n = \frac{R_{on}}{R_o} = \frac{(1279.6\ kg/d)}{(2962.9\ kg/d)} = 0.43$$

PROBLEM 8-9

Problem Statement – see text, page 922

Solution

1. Develop the wastewater characteristics needed for design

bCOD = 1.6 (BOD) [Eq. (8-13)]

$bCOD_{inf}$ = 1.6 (200 mg/L) = 320 mg/L

$bCOD_{eff}$ = 1.6(2 mg/L) = 3.2 mg/L

2. Determine sludge wasted daily using Eqs. (8-20) and (8-21)

$$\underset{(A)}{\frac{QY_H(S_o - S)(1\,kg/10^3 g)}{1 + b_H(SRT)}} + \underset{(B)}{\frac{(f_d)(b_H)QY_H(S_o - S)SRT(1\,kg/10^3 g)}{1 + b_H(SRT)}}$$

$$+ \underset{(C)}{\frac{QY_n(NO_X)(1\,kg/10^3 g)}{1 + (b_n)SRT}} + \underset{(D)}{Q(nbVSS)(1\,kg/10^3 g)}$$

a. Define the input data for above equation. For SRT = 10d:

$Q = 15{,}000\ m^3/d$

Y_H = 0.4 g VSS/g bCOD

S_o = 320 mg/L bCOD

S = 3.2 mg/L

b_H = 0.1 g VSS/gVSS•d

SRT = 10 d

f_d = 0.15 g VSS/g VSS

Y_n = 0.18 g VSS/g NH_4-N

Assume all of influent TKN is biodegradable

NO_x is assumed to be 80% of TKN: NO_x = (0.8)(35) = 28 mg/L

b_n = 0.12 g VSS/g VSS•d

For **Wastewater 1**, nbVSS = 100 mg/L

b. Determine $P_{X,VSS}$

$$P_{X,VSS} = \frac{(15{,}000\,m^3/d)(0.4\,g/g)[(320-3.2)\,g/m^3](1 kg/10^3 g)}{[1+(0.1\,g/g\cdot d)(10\,d)]} \qquad (A)$$

$$+\frac{(0.15\,g/g)(0.1 g/g)(15{,}000\,m^3/d)(0.4\,g/g)[(320-3.2)mg/L](10\,d)(1\,kg/10^3\,g)}{[1+(0.1\,g/g\cdot d)(10\,d)]} \qquad (B)$$

$$+\frac{(15{,}000\,m^3/d)(0.18\,g)(28\,g/m^3)(1 kg/10^3\,g)}{[1+(0.12\;g/g\cdot d)(10\,d)]} \qquad (C)$$

$$+(15{,}000\,m^3/d)(100\,g/m^3)(1 kg/10^3\,g) \qquad (D)$$

$P_{X,VSS}$ = (950.4 + 142.6 + 34.4 + 1500) kg/d = 2627.4 kg/d

$P_{X,Bio}$ = (950.4 + 142.6 + 34.4) kg/d = 1127.4 kg/d

3. Use the above $P_{X,VSS}$ to re-calculate NO_x

   $NO_x = TKN – N_e – 0.12\,P_{X,bio}/Q$

   $NO_x = (35 – 0.5)\,g/m^3 – [0.12(1127.4\,kg/d)/(15{,}000\,m^3/d)](10^3\,g/1\,kg)$

   $NO_x = 25.5\,g/m^3$

4. Re-calculate the VSS sludge production rate ($P_{x,vss}$) using $NO_X = 25.6\,g/m^3$

   $$(C) \qquad \frac{(15{,}000\,m^3/d)(0.18\,g)(25.5\,g/m^3)(1 kg/10^3\,g)}{[1+(0.12\;g/g\cdot d)(10\,d)]} = 31.3\text{ kg/d}$$

   $P_{X,VSS}$ = (950.4 + 142.6 + 31.3 + 1500) kg/d = 2624.3 kg/d

5. Determine sludge production rate in TSS using Eq (8-21).

   $$P_{X,TSS} = \frac{A}{0.85}+\frac{B}{0.85}+\frac{C}{0.85}+D$$

   $$P_{X,TSS} = \left(\frac{950.4}{0.85}+\frac{142.6}{0.85}+\frac{31.3}{0.85}+1500\right)\text{ kg TSS/d = 2822.7 kg TSS/d kg/d}$$

6. Determine biomass production rate using Eq (8-20), part A, B, and C.

   $P_{X,bio}$ = (950.4 + 142.6 + 31.3) kg/d = 1124.3 kg/d (note: it is close to the value in step 3, so further iteration for NO_x was not needed.)

7. Determine the TSS, VSS, and biomass production rates without accounting for cell debris production (B) and the resulting error.

   a. $P_{X,VSS}$ = A + C + D

      $P_{X,VSS}$ = (950.4 + 31.3 + 1500) kg/d = 2481.7 kg/d

$$\% \text{ Error} = \frac{(2624.3 - 2481.7)100}{2624.3} = 5.4\ \%$$

b. $P_{X,Bio} = A + C$

$P_{X,Bio} = (950.4 + 31.3)\text{ kg/d} = 981.7\text{ kg/d}$

$$\% \text{ Error} = \frac{(1124.3 - 981.7)100}{1124.3} = 12.7\ \%$$

c. $P_{X,TSS} = [(950.4 + 31.3)/0.85] + 1500 = 2654.9\text{ kg/d}$

$$\% \text{ Error} = \frac{(2822.7 - 2654.9)100}{2822.7} = 5.9\ \%$$

8. For 20 d SRT, repeat the above steps with SRT = 20 d instead of 10 d. The following table summarizes and compares the results.

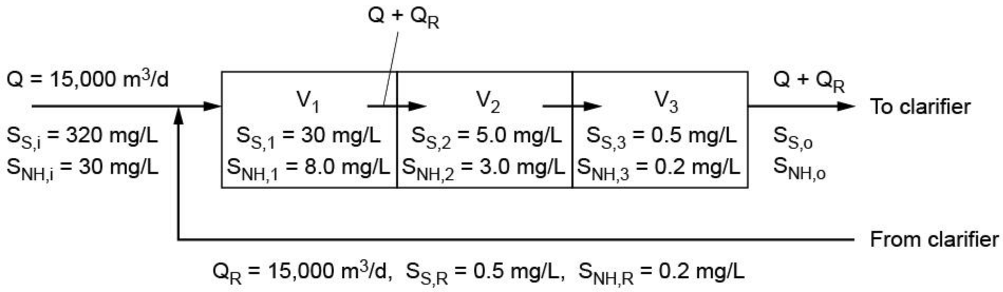
SRT, d	10		20	
$P_{X,VSS}$, kg/d	2624.3		2353.7	
$P_{X,Bio}$, kg/d	1124.3		853.7	
$P_{X,TSS}$, kg/d	2822.7		2504.4	
Without debris term		% Error		% Error
$P_{X,VSS}$, kg/d	2481.7	5.4	2163.6	8.1
$P_{X,Bio}$, kg/d	981.7	12.7	663.6	22.3
$P_{X,TSS}$, kg/d	2654.9	5.9	2280.7	8.9

PROBLEM 8-10

Problem Statement – see text, page 923

Solution – for wastewater #1

1. Sketch system and show information provided for 3-stage activated sludge system.



S_S = bCOD, X_H = biomass = 1500 mg/L

S_{NH} = NH_4-N

$V_1 = V_2 = V_3 = 2300\ m^3$

2. Determine the total oxygen transfer rate required for bCOD removal, nitrification, and endogenous decay using Eq. (8-25) in Table 8-10.

$$R_o = Q_1(1-Y_H)(S_{S,1}-S_{S,2}) + Q_1(4.57)(NO_2 - NO_1) + 1.42 b_H(X_H)V_2$$

Note: Y_H = g COD cell/g COD used

= (0.45 g VSS/g COD)(1.42 g COD/g VSS) = 0.639

$NO_2 - NO_1 = S_{NH,1} - S_{NH,2}$

a. Determine flow and concentration of bCOD and NH_4-N entering stage 1 from combining influent and recycle flow.

$Q_1 = Q + Q_R = 30{,}000\ m^3/d$

$Q(S_{S,i}) + Q_R(S_{SR}) = (Q + Q_R)(S_{S,o})$

$(15{,}000\ m^3/d)(320\ g/m^3) + (15{,}000\ m^3/d)(0.5\ g/m^3)$
$= (30{,}000\ m^3/d)(S_{S,o})$

$S_{S,o} = 160.25\ g/m^3$

$Q(S_{NH,i}) + Q_R(S_{NH,R}) = (Q + Q_R)(S_{NH,o})$

$(15{,}000\ m^3/d)(30\ g/m^3) + (15{,}000\ m^3/d)(0.2\ g/m^3)$
$= (30{,}000\ m^3/d)(S_{NH,o})$

$S_{NH,o} = 15.1\ g/m^3$

b. Determine the oxygen transfer rate for State 1, using Eq. (8-25). Q_1 = 30,000 m^3/d.

$$
\begin{aligned}
R_{o,1} &= (30{,}000\ \mathrm{m^3/d})(1-0.639)[(160.25-30.0)\ \mathrm{g/m^3}] \\
&\quad +(30{,}000\ \mathrm{m^3/d})(4.57)[(15.1-8.0)\ \mathrm{g/m^3}] \\
&\quad +1.42(0.10\ \mathrm{g/g{\bullet}d})(1500\ \mathrm{g/m^3})(2300\ \mathrm{m^3}) \\
&= 1{,}410{,}607.5\ \mathrm{g\,O_2/d} + 973{,}410\ \mathrm{g\,O_2/d} + 489{,}900\ \mathrm{g\,O_2/d} \\
&= (1{,}410{,}607.5\ \mathrm{g\,O_2/d})(1\ \mathrm{d}/24\ \mathrm{h})(1\ \mathrm{kg}/10^3\ \mathrm{g}) \\
&\quad +(973{,}410\ \mathrm{g\,O_2/d})(1\ \mathrm{d}/24\ \mathrm{h})(1\ \mathrm{kg}/10^3\ \mathrm{g}) \\
&\quad +(489{,}900\ \mathrm{g\,O_2/d})(1\ \mathrm{d}/24\ \mathrm{h})(1\ \mathrm{kg}/10^3\ \mathrm{g}) \\
&= 58.8\ \mathrm{kg\,O_2/h} + 40.6\ \mathrm{kg\,O_2/h} + 20.4\ \mathrm{kg\,O_2/h} \\
R_{o,1} &= 119.8\ \mathrm{kg\,O_2/h}
\end{aligned}
$$

c. Determine the oxygen transfer rate for Stage 2.

$$
\begin{aligned}
R_{o,2} &= (30{,}000\ \mathrm{m^3/d})(1-0.639)[(30.0-5.0)\ \mathrm{g/m^3}] \\
&\quad +(30{,}000\ \mathrm{m^3/d})(4.57)[(8.0-3.0)\ \mathrm{g/m^3}] \\
&\quad +1.42(0.10\ \mathrm{g/g{\bullet}d})(1500\ \mathrm{g/m^3})(2300\ \mathrm{m^3}) \\
&= 270{,}750\ \mathrm{g\,O_2/d} + 685{,}500\ \mathrm{g\,O_2/d} + 489{,}900\ \mathrm{g\,O_2/d} \\
&= (270{,}750\ \mathrm{g\,O_2/d})(1\ \mathrm{d}/24\ \mathrm{h})(1\ \mathrm{kg}/10^3\ \mathrm{g}) \\
&\quad +(685{,}500\ \mathrm{g\,O_2/d})(1\ \mathrm{d}/24\ \mathrm{h})(1\ \mathrm{kg}/10^3\ \mathrm{g}) \\
&\quad +(489{,}900\ \mathrm{g\,O_2/d})(1\ \mathrm{d}/24\ \mathrm{h})(1\ \mathrm{kg}/10^3\ \mathrm{g}) \\
&= 11.3\ \mathrm{kg\,O_2/h} + 28.6\ \mathrm{kg\,O_2/h} + 20.4\ \mathrm{kg\,O_2/h} \\
R_{o,2} &= 60.3\ \mathrm{kg\,O_2/h}
\end{aligned}
$$

d. Determine the oxygen transfer rate for Stage 3.

$$\begin{aligned}R_{o,3} &= (30{,}000\ \mathrm{m^3/d})(1-0.639)[(5.0-0.5)\ \mathrm{g/m^3}] \\ &\quad +(30{,}000\ \mathrm{m^3/d})(4.57)[(3.0-0.2)\ \mathrm{g/m^3}] \\ &\quad +1.42(0.10\ \mathrm{g/g{\bullet}d})(1500\ \mathrm{g/m^3})(2300\ \mathrm{m^3}) \\ &= 48{,}735\ \mathrm{g\,O_2/d} + 383{,}880\ \mathrm{g\,O_2/d} + 489{,}900\ \mathrm{g\,O_2/d} \\ &= (48{,}735\ \mathrm{g\,O_2/d})(1\ \mathrm{d}/24\ \mathrm{h})(1\ \mathrm{kg}/10^3\ \mathrm{g}) \\ &\quad +(383{,}880\ \mathrm{g\,O_2/d})(1\ \mathrm{d}/24\ \mathrm{h})(1\ \mathrm{kg}/10^3\ \mathrm{g}) \\ &\quad +(489{,}900\ \mathrm{g\,O_2/d})(1\ \mathrm{d}/24\ \mathrm{h})(1\ \mathrm{kg}/10^3\ \mathrm{g}) \\ &= 2.0\ \mathrm{kg\,O_2/h} + 16.0\ \mathrm{kg\,O_2/h} + 20.4\ \mathrm{kg\,O_2/h} \\ R_{o,3} &= 38.4\ \mathrm{kg\,O_2/h}\end{aligned}$$

e. Prepare a summary table.

Oxygen transfer rate (kg O_2/h)

Stage	bCOD removal	Nitrification	Endogenous	Total	% of total
1	58.8	40.6	20.4	119.8	55
2	11.3	28.6	20.4	60.3	28
3	2.0	16.0	20.4	38.4	17
Total	72.1	85.2	61.2	218.5	100

PROBLEM 8-11

Problem Statement – see text, pages 923-924

Solution

1. Determine the biomass production in kg/d using Eq (8-20), parts A and B, and assume the process is designed for BOD removal only for **wastewater 1.**

$$P_{X,bio} = \frac{QY_H(S_o - S)(1\ \mathrm{kg}/10^3\ \mathrm{g})}{1 + b_H(SRT)} + \frac{(f_d)(b_H)QY_H(S_o - S)SRT(1\ \mathrm{kg}/10^3\ \mathrm{g})}{1 + b_H(SRT)}$$

a. Define input data for above equation

Q = 3000 m^3/d

S_o = 2000 mg/L bCOD

S = 5 mg/L bCOD

Y_H = 0.4 g VSS/g COD

b_H = 0.1 g VSS/g VSS • d)

f_d = 0.1 g VSS/g VSS

SRT = 10 d

b. Solve for $P_{X,bio}$

$$P_{X,bio} = \frac{(3000\ m^3/d)(0.4\ g/g)[(2000-5)\ g/m^3](1\ kg/10^3 g)}{[1+(0.1 g/g{\bullet}d)(10\ d)]}$$

$$+\frac{(0.1\ g/g)(0.1\ g/g{\bullet}d)(3000\ m^3/d)(0.4\ g/g)[(2000-5)\ g/m^3](10\ d)(1\ kg/10^3\ g)}{[1+(0.1\ g/g{\bullet}d)(10\ d)]}$$

$P_{X,bio}$ = (1197 + 119.7) = 1316.7 kg/d

2. Determine the amount of N and P needed for biogrowth in kg/d

Assume 12 percent by weight of N will be required and assume P required is about 20 percent of N required (see page 686).

a. Determine the amount of N needed for biogrowth

N needed = ($P_{X,bio}$)(12%) = (1316.7 kg/d)(0.12) = 158 kg/d

b. Determine the amount of P needed for bio-growth

P needed = (N needed)(20%) = (158 kg/d)(0.2) = 31.6 kg/d

3. Determine the amount of N and P that must be added to the influent

a. Prepare a mass balance for N and P

N in the influent + N_{added} = N in biomass + N in effluent

Q (N_i) + Q (N_{added}) = $P_{X,bio}$ (12%) + Q (N_e)

$$N_{added} = \frac{P_{X,bio}(12\%)}{Q} + N_e - N_i \qquad \text{(i)}$$

P in the influent + P_{added} = P in biomass + P in effluent

Q (P_i) + Q (P_{added}) = $P_{X,bio}$ (12%)(20%) + Q(P_e)

$$P_{added} = \frac{P_{X,bio}(0.12)(0.20)}{Q} + P_e - P_i \qquad \text{(ii)}$$

b. Define input data for above equation (i) and (ii)

Q = 3000 m^3/d

$P_{X,bio}$ = 1316.7 kg/d from part 1

N_i = 20 mg/L NH_4-N	influent N
N_e = 0.1 mg/L NH_4-N	effluent N
P_i = 5 mg/L	influent P
P_e = 0.1 mg/L	effluent P

c. Solve Eq. (i).

N_{added} = (1316.7 kg/d)(0.12)/(3000 m^3/d)(10^3 g/1 kg) + 0.1 g/m^3 – 20 g/m^3

= (52.67 + 0.1 – 20) g/m^3= 32.77 g/m^3

N_{added} in kg/d = N_{added} (Q) = (32.77 g/m^3)(3000 m^3/d)(1 kg/10^3 g)

= 98.3 kg/d

d. Solve Eq. (ii).

P_{added} = (1376.7 kg/d)(0.12)(0.2) / (3000 m^3/d)(10^3 g/1 kg)

+ 0.1 g/m^3 – 5 g/m^3

P_{added} = (10.53 + 0.1 – 5) = 5.63 g/m^3

P_{added} in kg/d = P_{added} (Q) = (5.63 g/m^3)(3000 m^3/d)(1 kg/10^3 g)

= 16.9 kg/d

PROBLEM 8-12

Problem Statement – see text, page 924

Solution (Activated sludge system 1)

1. Determine the average daily waste sludge rate in m^3/d from the return activated sludge line for a 10 d SRT. Solve for Q_w in Eq. (8-27) in Table 8-10.

$$SRT = \frac{V(X)}{(Q - Q_w)X_e + Q_w X_R}$$

Rearranging:

$$Q_w = \frac{(VX/SRT) - Q_w X_e}{X_R - X_e}$$

From data in table,

$$Q_w = \frac{\left[\dfrac{(2000\ \text{m}^3)(3000\ \text{g/m}^3)}{10\ \text{d}}\right] - (4000\ \text{m}^3/\text{d})(10\ \text{g/m}^3)}{[(9000-10)\ \text{g/m}^3]}$$

$Q_w = 62.3\ \text{m}^3/\text{d}$

2. Determine the actual SRT when 1/10th of the aeration volume is wasted. In this case the wasting rate, Q_w, equals V/10 at a solids concentration = X. Substitute Q_w with V/10 into Eq. (8-27).

$$\text{SRT} = \frac{V(X)}{\left(Q - \dfrac{V}{10}\right)X_e + \left(\dfrac{V}{10}\right)X_R}$$

$$\text{SRT} = \frac{(2000\ \text{m}^3)(3000\ \text{g/m}^3)}{\left[(4000\ \text{m}^3/\text{d}) - \dfrac{(2000\ \text{m}^3/\text{d})}{10}\right](10\ \text{g/m}^3) + \left[\dfrac{(2000\ \text{m}^3/\text{d})}{10}\right](3000\ \text{g/m}^3)}$$

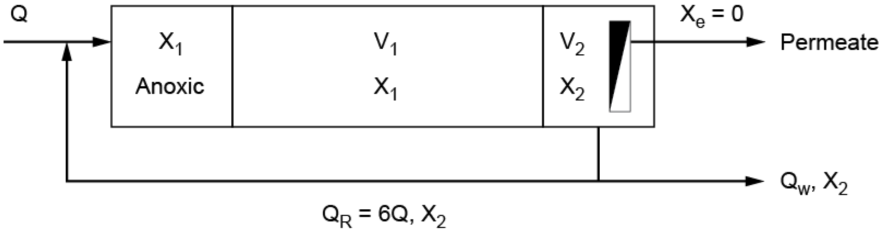
SRT = 9.4 d

PROBLEM 8-13

Problem Statement – see text, page 924

Solution

1. Provide a sketch of the membrane bioreactor and show problem information.



$V_1 = 0.75(V_T) = 0.75(4000\ \text{m}^3) = 3000\ \text{m}^3$

$V_2 = 0.25(V_T) = 0.25(4000\ \text{m}^3) = 1000\ \text{m}^3$

2. Define the aerobic SRT from Eq. (8-27) in Table 8-10 for the MBR process.

$$\mathrm{SRT} = \frac{V(X)}{(Q - Q_w)X_e + Q_w X_R}, \quad X_e = 0$$

$$\mathrm{SRT} = \frac{[V_1(X_1) + V_2(X_2)]}{Q_w(X_2)}$$

SRT = 10 d, X_2 = 12,000 mg/L

3. Determine X_1 by mass balance on volume, V_1.

$Q_R X_2 + Q(0) = (Q + Q_R)X_1$

$6Q(X_2) = (Q + 6Q)\, X_1$

$$X_1 = \left(\frac{6}{7}\right)X_2 = \left(\frac{6}{7}\right)(12{,}000\ \mathrm{mg/L})$$

$$X_1 = 10{,}285.7\ \mathrm{mg/L}$$

4. Solve for Q_w from Step 2.

$$Q_w X_2 = \frac{[V_1(X_1) + V_2(X_2)]}{\mathrm{SRT}}$$

$$Q_w = \frac{[V_1(X_1/X_2) + V_2]}{\mathrm{SRT}}$$

$$Q_w = \frac{(3000\ \mathrm{m^3})\left(\dfrac{10{,}285.7}{12{,}000}\right) + 1000\ \mathrm{m^3}}{10\ \mathrm{d}}$$

$$Q_w = 357.1\ \mathrm{m^3/d}$$

5. Alternative solution based on Q, Q_R, volumes from Step 3.

$$\frac{X_1}{X_2} = \frac{Q_R}{Q + Q_R} = \frac{(Q_R/Q)}{(1 + Q_R/Q)}$$

$R = Q_R/Q = 6.0$

$$\frac{X_1}{X_2} = \frac{R}{1 + R}$$

From Step 4,

$$Q_w = \frac{[V_1(X_1/X_2) + V_2]}{\mathrm{SRT}}$$

$$Q_w = \frac{\left[V_1\left(\frac{R}{1+R}\right)+V_2\right]}{SRT}$$

$$Q_w = \frac{\left[(3000\ m^3)\left(\frac{6}{1+6}\right)+1000\ m^3\right]}{10\ d}$$

$$Q_w = 357.1 m^3 / d$$

Note: The SRT can be controlled without any MLSS measurements as a function of recycle ratio and volumes.

PROBLEM 8-14

Problem Statement – see text, page 924

Solution

1. From discussion on page 729 and page 892, determine the SVI value using Eq. (8-83)

$$SVI = \frac{(\text{settled volume of sludge, mL/L})(10^3\ mg/1g)}{(\text{suspended solids, mg/L})} = mL/g$$

$$SVI = \frac{(840\ mL/2\ L)(10^3\ mg/1\ g)}{(3500\ mg/L)} = 120\ mL/g$$

PROBLEM 8-15

Problem Statement – see text, pages 924-925

Solution (for (1) heterotrophic bacteria under aerobic conditions)

1. Assume flow into 2nd stage equal influent flow, Q, plus return activated sludge flow Q_R.
2. Volume for 2nd stage equal V2 and heterotrophic bacteria concentration equal X_{Ha}.
3. Perform mass balance and use component stoichiometric terms for X_{Ha} shown in Table 8-13 with corresponding processes in Table 8-12.

a. Prepare mass balance

Rate of change = rate in – rate out + rate of production + rate of depletion

b. Express each term with stoichiometric terms

$$V_2\frac{dX_{H,2}}{dt}=(Q+Q_R)X_{H,1}-(Q+Q_R)X_{H,2}+R_4V_2+R_5V_2+R_9V_2$$

$$R_4=(1)\mu_H\left(\frac{S_{O_2}}{K_{O_2}+S_{O_2}}\right)\left(\frac{S_F}{K_F+S_F}\right)\left(\frac{S_F}{S_A+S_F}\right)(\text{Growth}_{\text{Lim}})(X_{H,2})$$

$$R_5=(1)\mu_H\left(\frac{S_{O_2}}{K_{O_2}+S_{O_2}}\right)\left(\frac{S_A}{K_A+S_A}\right)\left(\frac{S_A}{S_A+S_F}\right)(\text{Growth}_{\text{Lim}})(X_{H,2})$$

where:

$$(\text{Growth}_{\text{Lim}})=\left(\frac{S_{NH_4}}{K_{NH_4}+S_{NH_4}}\right)\left(\frac{S_{PO_4}}{K_{PO_4}+S_{PO_4}}\right)\left(\frac{S_{alk}}{K_{alk}+S_{alk}}\right)$$

$$R_9=(-1)b_HX_{H,2}$$

$$V_2\frac{dX_{H,2}}{dt}=(Q+Q_R)X_{H,1}-(Q+Q_R)X_{H,2}$$

$$+V_2\mu_H\left(\frac{S_{O_2}}{K_{O_2}+S_{O_2}}\right)\left(\frac{S_F}{K_F+S_F}\right)\left(\frac{S_F}{S_A+S_F}\right)\left(\frac{S_{NH_4}}{K_{NH_4}+S_{NH_4}}\right)\left(\frac{S_{PO_4}}{K_{PO_4}+S_{PO_4}}\right)\left(\frac{S_{alk}}{K_{alk}+S_{alk}}\right.$$

$$+V_2\mu_H\left(\frac{S_{O_2}}{K_{O_2}+S_{O_2}}\right)\left(\frac{S_A}{K_A+S_A}\right)\left(\frac{S_A}{S_A+S_F}\right)\left(\frac{S_{NH_4}}{K_{NH_4}+S_{NH_4}}\right)\left(\frac{S_{PO_4}}{K_{PO_4}+S_{PO_4}}\right)\left(\frac{S_{alk}}{K_{alk}+S_{al}}\right.$$

$$-V_2b_HX_{H,2}$$

PROBLEM 8-16

Problem Statement – see text, page 925

Solution

1. Determine the specific steps needed to investigate the cause of bulking sludge condition. The following steps should be taken to investigate possible causes of bulking sludge:

- View the mixed liquor under a microscope with phase contrast to determine if bulking is related to a filamentous growth population or perhaps to hydrous bulking due to a large polysaccharide growth around the cells. The latter can be determined by staining with India ink. If filamentous growth is present, further investigation can be done microscopically to identify the type of filament, which may lead to an understanding of the cause, such as low DO, sulfide, insufficient nutrients, or low F/M.
- Evaluate the wastewater characteristics. The characteristics of wastewater that may relate to bulking are the soluble BOD or rbCOD concentration, BOD/N/P ratio, pH, sulfides, and total dissolved solids. High influent sulfide concentrations may lead to thiothrix or beggiatoa growth (filamentous bacteria). A high soluble BOD fraction or high rbCOD concentration may encourage filamentous growth if there are no selective pressures in the system design to encourage uptake of most of the readily available soluble substrate by non-filamentous bacteria.
- Evaluate the system operation. What is the DO concentration in the aeration basin at various times of the day? Are there conditions that encourage low DO filaments? Operation with a DO concentration in the range of 0.5 mg/L and availability of rbCOD can encourage growth of low DO filamentous bacteria. It was stated that full nitrification was occurring so determine if significant denitrification is occurring in the secondary clarifier that affects the sludge blanket. Evidence of denitrification is the presence of rising gas bubbles in the clarifier and the presence of some floating sludge. Indications can also be found by observing the behavior of the sludge during an SVI test.

Note that the information given was that it is a complete-mix activated sludge process with full nitrification so DO is likely not a problem. If there is a significant rbCOD concentration in the wastewater influent, sufficient nutrients are present, sulfides are low, and the pH and total dissolved solids concentration are not abnormal, there is a good chance that the bulking is due to low F/M filamentous bacteria growth.

2. The possible short-term immediate actions that can be taken to reduce the effluent TSS concentration include the following and the choice depends on the initial investigation:
    - Add chlorine or hydrogen peroxide to the return sludge at a dose that will damage the filamentous bacteria extending from the floc but not damage the nitrifying bacteria in the floc. The addition of chlorine or hydrogen peroxide will be effective if bulking is caused by filamentous growth.
    - Add nutrients if needed
    - Chlorinate the influent if a high sulfide concentration is present
    - Control pH if needed
    - Increase the aeration DO concentration if needed.
    - Add alum to final clarifier to improve effluent TSS capture.
3. What selector type can be considered for bulking sludge control? The selector alternatives that can be considered for bulking sludge control include:
    - High F/M selector in series (usually up to 3 reactors)
    - Anaerobic selector
    - Anoxic selector

    Because nitrification is occurring, an anoxic selector, whether in a single stage or multiple stage (high F/M mode), is a logical choice. The design should evaluate the amount of rbCOD in the influent and the amount of nitrate produced in the system. For an anoxic selector sufficient nitrate must be provided to consume the rbCOD, and thus internal recycle to the anoxic selector may be needed to provide more nitrate in excess of that from the return activated sludge. If there is not sufficient nitrate, consideration should be given to a staged high F/M selector.

PROBLEM 8-17

Problem Statement – see text, page 925

Solution (Wastewater #1)

1. Develop the wastewater characteristics needed for design using the kinetic values in Table 8-14.

   a. Compute bCOD using Eq. (8-13) for **wastewater 1.**

      bCOD = 1.6 (BOD)

      bCOD = 1.6 (220) = 352 mg/L

   b. Compute kinetic coefficients for $T = 15^{o}C$ with Eq. (1-44) in Table 8-10

      $\mu_{max,H,15°C} = 6.0(1.07)^{15-20} = 4.3\ g/g \bullet d$

      $K_{s,15°C} = 8.0(1.0)^{15-20} = 8.0\ g/m^3$

      $b_{H,15°C} = 0.12(1.04)^{15-20} = 0.10\ g/g \bullet d$

      $\mu_{max,AOB,15°C} = 0.90(1.072)^{15-20} = 0.636\ g/g \bullet d$

      $K_{NH,15°C} = 0.50(1.0)^{15-20} = 0.50\ g\ NH_4\text{-}N/m^3$

      $b_{AOB,15°C} = 0.17(1.029)^{15-20} = 0.147\ g/g \bullet d$

2. Determine the effluent sbCOD and ammonia-N concentration as a function of SRT.

   a. Determine S as a function SRT using Eq. (7-46) where μ_m = Yk, and kinetic coefficients computed in step 1b.

      $Y_H = 0.45$ g VSS/g COD, $f_d = 0.15$ g VSS/g VSS

$$S = \frac{K_S[1+(b_H)SRT]}{SRT(\mu_m - b_H) - 1}$$

$$S = \frac{(8.0\,g/m^3)[1+(0.1g/g \bullet d)SRT]}{SRT[(4.3-0.1)g/g \bullet d]-1}$$

$$S = \frac{8(1+0.1SRT)}{4.2SRT-1}\,g/m^3$$

      At SRT = 3.0 d, $S = 0.90\ g/m^3$

      S as a function of SRT is summarized in table below.

b. Determine effluent NH_3-N (N_e) concentrations as a function of SRT by combining Eq. (7-94) and Eq. (7-98) in Table 10. Let S_o = DO.

$$\frac{1}{SRT} = \left(\frac{\mu_{max,AOB} S_{NH4}}{K_{NH4} + S_{NH4}}\right)\left(\frac{DO}{K_o + DO}\right) - b_{AOB}$$

Solving for S_{NH4} (let $S_{NH4} = N_e$):

$$N_e = \frac{K_{NH4}(1 + b_{AOB}SRT)}{[\mu_{max,AOB}\left(\frac{DO}{K_o + DO}\right) - b_{AOB}]SRT - 1}$$

$$N_e = \frac{0.50\ g/m^3\left[1 + (0.147\ g/g\text{-}d)SRT\right]}{SRT\left\{0.636\ g/g\text{-}d\left[\frac{(2.0\ g/m^3)}{(0.50\ g/m^3 + 2.0\ g/m^3)}\right] - 0.147\ g/g\text{-}d\right\} - 1}$$

At SRT = 3.0 days, $N_e = 8.62 g/m^3$

Table showing Effluent NH_3-N (N_e) and effluent sbCOD (S) concentration as a function of SRT:

SRT, d	Effl. sbCOD mg/L	Effl. NH_3-N mg/L	SRT, d	Effl. sbCOD mg/L	Effl. NH_3-N mg/L
3	0.90	8.62	12	0.36	0.42
4	0.71	1.79	13	0.34	0.39
5	0.60	1.08	14	0.33	0.38
6	0.53	0.81	15	0.32	0.36
7	0.48	0.66	16	0.31	0.35
8	0.44	0.58	17	0.31	0.34
9	0.41	0.52	18	0.75	0.24
10	0.39	0.47	19	0.73	0.23
11	0.37	0.44	20	0.72	0.22

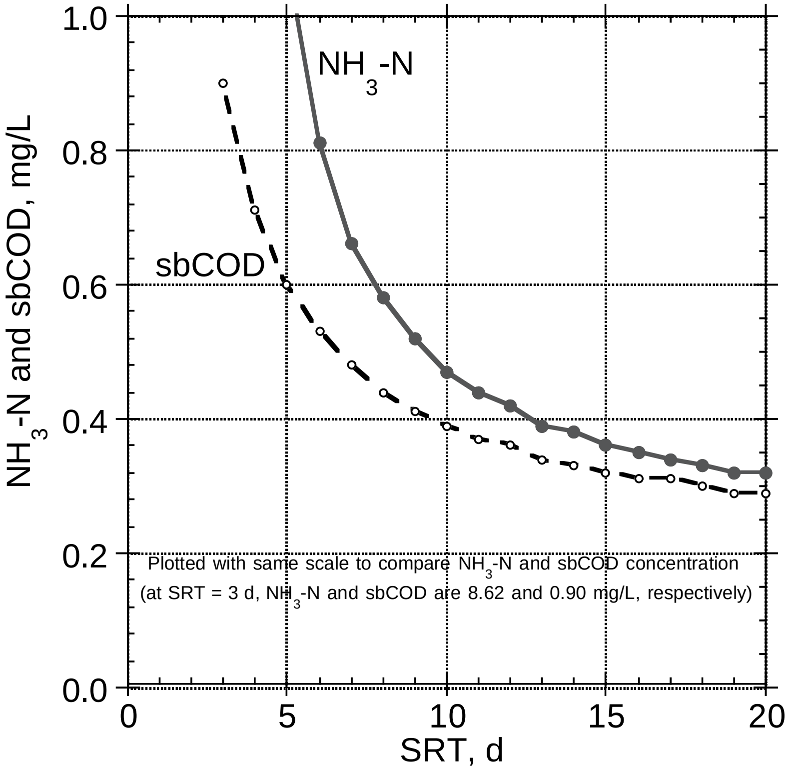


Figure 1. Effluent NH$_3$-N and sbCOD concentration vs SRT

3. Determine solids wasted as kg TSS/d as a function of SRT. At steady state solids wasted is equal to the solids production rate, which can be calculated using Eq. (8-20) and Eq. (8-21) in Table 8-10.

$$P_{X,TSS} = \frac{A}{0.85} + \frac{B}{0.85} + \frac{C}{0.85} + D + E$$

where E = $Q(TSS_o - VSS_o)$

a. Calculate the terms in Eq. 8-21; For first calculation assume $NO_X \approx$ 80% of influent TKN

i. Active biomass:

$$A = \frac{QY_H(S_o - S)(1\,kg/10^3\,g)}{[1 + (b_H)SRT]0.85}$$

$$= \frac{(20{,}000\,\mathrm{m^3/d})(0.45\text{ g VSS/g COD})(352 - S)(\text{g sbCOD/m}^3)(1\text{ kg}/10^3\text{g})}{[1 + (0.10\text{ g/g•d})(\text{SRT})]0.85}$$

At SRT = 3.0 d, A = 2869 kg TSS/d

ii. Cell debris:

$$B = \frac{(f_d)(b_H)(Q)(Y_H)(S - S_o)\text{SRT}(1\text{ kg}/10^3\text{g})}{[1 + b_H(\text{SRT})]0.85}$$

$$= \frac{(0.15\text{ g/g})(0.10\text{ g/g} \bullet \text{d})(20{,}000\,\mathrm{m^3/d})(0.45\text{ g VSS/g COD})(352 - S)(\text{g sbCOD/m}^3)\text{SRT}(1\text{ kg}}{[1 + (0.10\text{ g/g} \bullet \text{d})(\text{SRT})]0.85}$$

At SRT = 3.0 d, B= 127 kg TSS/d

iii. Nitrifying bacteria:

$$C = \frac{QY_n(NO_x)(1\text{ kg}/10^3\text{g})}{[1 + b_{AOB}(\text{SRT})]0.85}$$

Note Y_n = 0.20 g VSS/g NOx-N to account for growth of both AOB and NOB.

For first calculation assume NOx-N = 0.80(Influent TKN)

$$= \frac{(20{,}000\,\mathrm{m^3/d})(0.20\text{ g VSS/g NOx-N})(0.8)(40\text{ g/m}^3)(1\text{ kg}/10^3\text{g})}{[1 + (0.147\text{ g/g} \bullet \text{d})(\text{SRT})]0.85}$$

At SRT = 3.0 d, C= 52 kg TSS/d

iv. Nonbiodegradable VSS (VSS = TSS)

D = Q(nbVSS)(1 kg/10^3 g)

D = (20,000 $\mathrm{m^3}$/d)(100 g/$\mathrm{m^3}$)(1 kg/10^3 g) = 2000 kg VSS/d

v. Inert inorganic TSS

E = (20,000 $\mathrm{m^3}$/d)[(220 – 200) g/$\mathrm{m^3}$](1 kg/10^3 d) = 400 kg TSS/d

b. Iterate for NO_x-N value by calculating NO_x-N from $P_{X,bio}$, using Eq. (8-24), Table 8-10 and replacing the initial assume value.

$$\text{NOx-N} = \text{TKN} - 0.12\left(P_{X,bio}\right) - N_e$$

where $P_{X,bio}$ = VSS/d of active heterotrophs, debris, and nitrifiers

Solve for NO_x-N and change value inserted in Eq. C above to iterate

Insert A, B, C, D, and E into Eq. (8-21) to solve $P_{X,TSS}$ as a function of SRT. Using a spreadsheet program, the values of $P_{X,TSS}$ and $P_{X,bio,VSS}$ for SRTs ranging from 3 to 20 d are shown in the following table.

	As kg TSS/d, except $P_{x,bio}$ which is kg VSS/d						
SRT, d	A	B	C	D	E	$P_{X,TSS}$	$P_{x,bio}$
3	2869	127	52	2000	400	5448	2591
4	2667	158	68	2000	400	5293	2459
5	2492	184	68	2000	400	5144	2332
6	2338	208	65	2000	400	5010	2219
7	2202	228	63	2000	400	4892	2119
8	2081	246	58	2000	400	4785	2027
9	1972	263	57	2000	400	4691	1948
10	1874	277	53	2000	400	4605	1874
11	1786	291	52	2000	400	4528	1809
12	1705	303	49	2000	400	4457	1749
13	1632	314	47	2000	400	4392	1693
14	1564	324	46	2000	400	4334	1644
15	1502	333	44	2000	400	4279	1597
16	1444	342	42	2000	400	4228	1554
17	1391	350	42	2000	400	4183	1515
18	1342	357	41	2000	400	4140	1479
19	1296	364	40	2000	400	4100	1445
20	1253	371	38	2000	400	4062	1412

c. Determine tank volume V(m^3) and τ (h) as a function of SRT using Eq. (7-57) in Table 8-10.

$$(X_{TSS})(V) = (P_{X,TSS})SRT$$

$$V = \frac{(P_{X,TSS})SRT}{X_{TSS}}$$

$$V = \frac{(P_{X,TSS},\, kg/d)(SRT,\, d)}{(2500\, g/m^3)(1\, kg/10^3\, g)} = \frac{P_{X,TSS}(SRT)}{2.5}\, m^3$$

$$\tau = \frac{V}{Q}$$

$$\tau = \frac{\left[(P_{X,TSS})(SRT)\right](m^3)(24\ h/d)}{2.5(20{,}000\, m^3/d)} = 4.8 \times 10^{-4}\left[(P_{X,TSS})(SRT)\right]\ h$$

Using a spreadsheet program, compute the values of V and τ for SRTs ranging from 3 to 20 d as shown in the following table and plot below:

SRT d	Volume m^3	τ h	SRT d	Volume m^3	τ h
3	6538	7.8	12	21,394	25.7
4	8469	10.2	13	22,839	27.4
5	10,288	12.3	14	24,270	29.1
6	12,025	14.4	15	25,674	30.8
7	13,699	16.4	16	27,061	32.5
8	15,313	18.4	17	28,442	34.1
9	16,889	20.3	18	29,810	35.8
10	18,419	22.1	19	31,157	37.4
11	19,925	23.9	20	32,493	39.0

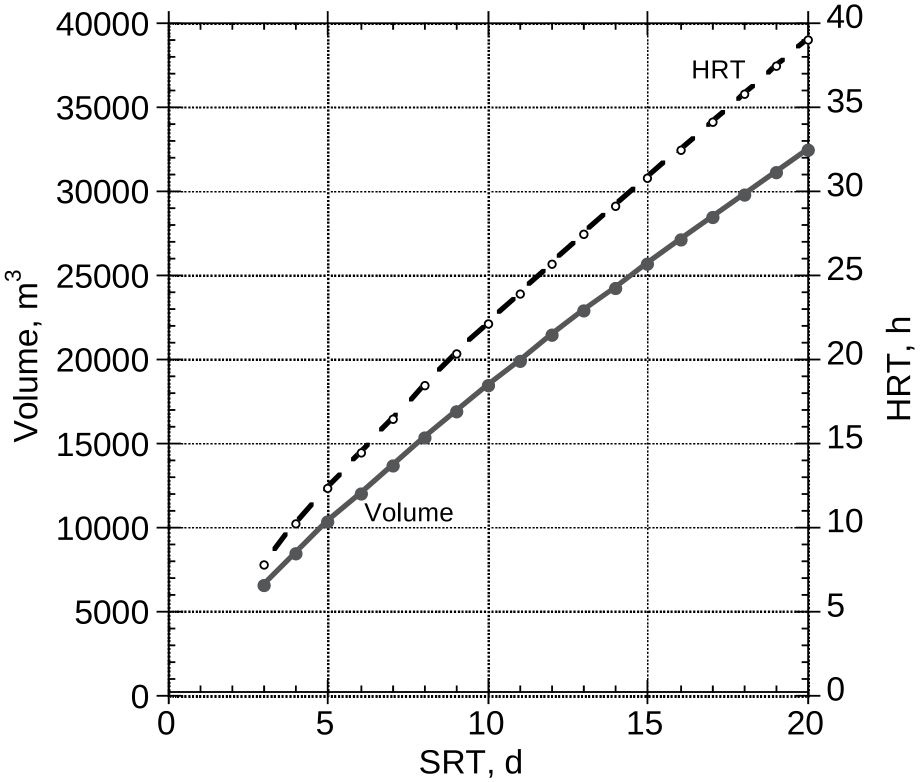


Figure 2. Plot of Volume and hydraulic retention time (HRT) versus SRT.

d. Determine observed yield as g TSS/g BOD and g TSS/g bCOD

Y_{obs} based on g TSS/g BOD

Observed yield = $P_{X,TSS}$/g BOD removed

$P_{X,TSS}$ was determined in Step 3a above.

BOD removed = Q (S_o – S), S is determined above as function of SRT

$$Y_{obs,\ TSS/BOD} = \frac{(P_{X,TSS},\ g\ TSS/d)}{(20{,}000\ m^3/d)(220 - S)g\ BOD/m^3}$$

$$Y_{obs,\ TSS/COD} = \left(Y_{obs,TSS/BOD}\right)\left(\frac{BOD}{1.6BOD}\right)$$

$$Y_{obs,\ TSS/COD} = \frac{\left(Y_{obs,TSS/BOD}\right)}{1.6}$$

Using a spreadsheet program, compute the values of Y_{obs} for SRTs ranging from 3 to 20 d as shown in the following table and plot.

SRT d	Y_{obs} gTSS/gBOD	Y_{obs} gTSS/gCOD	SRT d	Y_{obs} gTSS/gBOD	Y_{obs} gTSS/gCOD
3	1.24	0.78	12	1.01	0.63
4	1.20	0.75	13	1.00	0.62
5	1.17	0.73	14	0.99	0.62
6	1.14	0.71	15	0.97	0.61
7	1.11	0.70	16	0.96	0.60
8	1.09	0.68	17	0.95	0.59
9	1.07	0.67	18	0.94	0.59
10	1.05	0.66	19	0.93	0.58
11	1.03	0.64	20	0.92	0.58

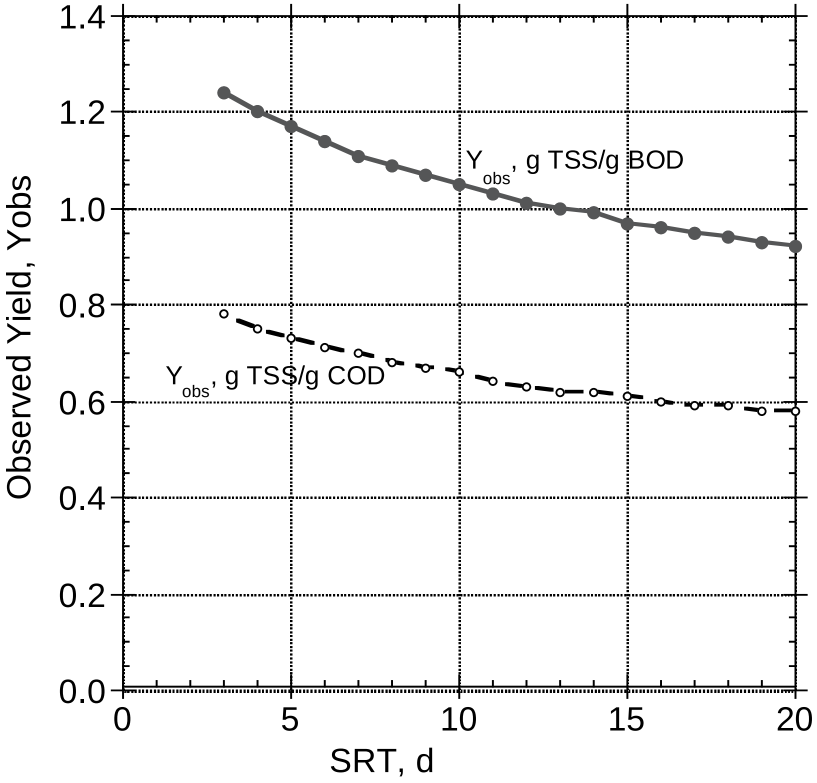


Figure 3. Observed yield vs SRT

e. Determine oxygen requirement in kg/d as a function of SRT

   i. Calculate NO_X using Eq. (8-24)

   $NO_x = TKN - N_e - 0.12\ P_{X,bio}/Q$

$P_{X,bio}$ is calculated as shown above from A, B, and C

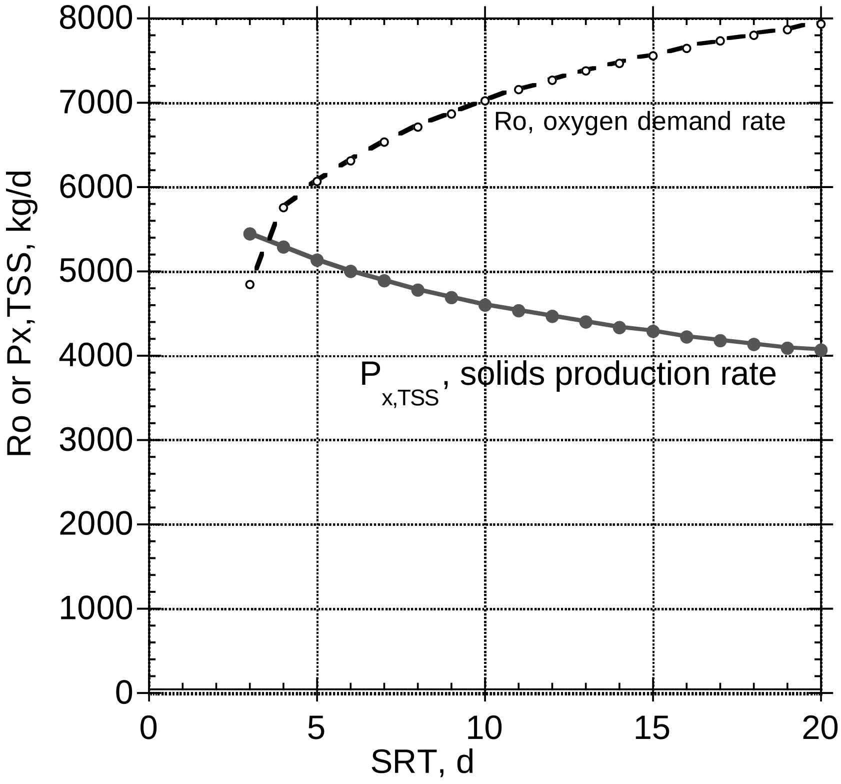
Using a spreadsheet program, compute the values of NO_X for SRTs ranging from 3 to 20 d as shown in the table following item ii. below.

ii. Calculate O_2 demand rate using Eq. (8-23).

$$R_o = Q(S_o - S) - 1.42P_{X,bio} + 4.57Q(NO_x\text{-N})$$

f. Using a spreadsheet program, compute the values of R_o for SRTs ranging from 3 to 20 d as shown in the following table and plot. The plot also includes the sludge production rate (kg TSS/d)

SRT d	NO_x-N mg/L	R_o kg/d	SRT d	NO_x-N mg/L	R_o kg/d
3	16	4853	12	29	7269
4	23	5760	13	29	7377
5	25	6076	14	30	7475
6	26	6323	15	30	7566
7	27	6531	16	30	7649
8	27	6714	17	31	7726
9	28	6875	18	31	7798
10	28	7020	19	31	7865
11	29	7150	20	31	7927



PROBLEM 8-18

Problem Statement – see text, page 925

Solution

The use of membranes for liquid-solids separation results in two important design changes compared to the single-tank activated sludge system in problem 8-17: (1) The aeration tank MLSS concentration is much higher with 12,000 mg/L (versus 2500 mg/L) in the membrane compartment and also a much higher MLSS concentration in the first compartment which will be determined here by a mass balance, and (2) the two-stage reactor configuration provides a greater BOD removal and ammonia oxidation efficiency due to removal at a higher concentration in the first compartment. Because the effluent soluble bCOD is already very low for the solution in problem 8-17, the 2-stage effluent concentration will not be calculated here. However, the effluent NH_4-N concentration is calculated in this solution to show the effect of staged kinetics.

Before proceeding with the solution, the effect of the higher MLSS concentration and two-stage reactor configuration are addressed for each process parameter required to be addressed in Problem 8-17.

(a) The solids wasted will be the same as in Problem 8-17 for a given SRT

(b) The aeration tank volume and τ will be lower for each SRT for the membrane system due to the higher average MLSS concentration

(c) The observed yields will be the same due to the same solids production rate at each SRT

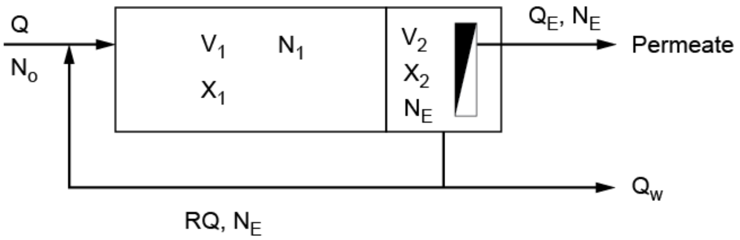
(d) The effluent soluble bCOD concentration will be lower for the two-stage membrane system but is not calculated here as it is already at a very low concentration in the Problem 8-17 solution

(e) The effluent NH_4-N concentration will be lower for the two-stage membrane system and is calculated here because of a greater interest to minimize effluent NH_4-N concentration for water quality concerns and as related to nitrogen removal processes

(f) The total oxygen demand will be increased by only a small amount due to slight increase in NH_4-N oxidized.

The following solution thus determines V, τ, effluent NH_4-N and Ro as a function of SRT.

1. Determine the MLSS concentration in compartment 1 and the total membrane aeration tank volume needed at each SRT.
   a. Perform a mass balance for MLSS (ignore waste solids flow) in V_1.



(N = NH_4-N concentration, V = volume, X = MLSS concentration, R = return activated sludge ratio)

$V_1 + V_2 = V$, $V_1 = 0.75V$, $V_2 = 0.25V$

(Solids in) = (Solids out)

$RQ(X_2) + Q(0) = (RQ + Q)X_1$

$$X_1 = \left(\frac{R}{R+1}\right)X_2 = \left(\frac{6}{6+1}\right)(12{,}000\ \text{mg/L})$$

$X_1 = 10, 286$ mg/L

2. Using the sludge production rate calculations for Problem 8-17 as a function of SRT, calculate the MBR compartment volumes and τ. The following is shown for SRT = 10d.

   a. Use Eq. (7-57) to calculate the aeration mass required.

      Mass = $(P_{X,TSS})$SRT

      At SRT = 10d, $P_{X,TSS}$ = 4369 kg/d

      Mass = $V_1X_1 + V_2X_2$ = (4369 kg/d)(10 d)

      $V_1X_1 + V_2X_2$ = 43,690 kg

   b. Solve for V_1 and V_2.

      $0.75VX_1 + 0.25VX_2$ = 43,690 kg

      $V(0.75X_1 + 0.25X_2)$ = 43,690 kg

$$V = \frac{43{,}690\ \text{kg}}{[0.75(10{,}286\ \text{g/m}^3) + 0.25(12{,}000\ \text{g/m}^3)](1\,\text{kg}/10^3\ \text{g})}$$

      $V = 4077.7\ \text{m}^3$

      $V_1 = 0.75(4077.7\ \text{m}^3) = 3058.3\ \text{m}^3$

      $V_2 = (0.25/0.75)(3058.3\ \text{m}^3) = 1019.4\ \text{m}^3$

   c. The hydraulic retention time, τ, for the MBR aeration tank of SRT = 10d:

$$\tau = \frac{V}{Q} = \frac{(4077.7\ \text{m}^3)(24\ \text{h/d})}{(20{,}000\ \text{m}^3/\text{d})} = 4.89\ \text{h}$$

      The MBR volume and τ as a function of SRT alongside the volumes for the activated sludge clarifier system are summarized in the following tables for comparison.

MBR and conventional activated sludge (CAS) volumes as a function of SRT

SRT d	Mass kg	MBR Volume m^3	CAS Volume m^3	SRT d	Mass kg	MBR Volume m^3	CAS Volume m^3
3.00	16,345	1525	6175	12.00	53,486	4992	20,338
4.00	21,173	1976	7980	13.00	57,097	5329	21,734
5.00	25,720	2400	9702	14.00	60,676	5663	23,110
6.00	30,062	2806	11,354	15.00	64,186	5991	24,469
7.00	34,247	3196	12,949	16.00	67,653	6314	25,813
8.00	38,282	3573	14,497	17.00	71,106	6636	27,143
9.00	42,222	3941	16,004	18.00	74,526	6956	28,461
10.00	46,049	4298	17,477	19.00	77,892	7270	29,769
11.00	49,812	4649	18,920	20.00	81,232	7582	31,066

MBR and conventional activated sludge (CAS) hydraulic retention time as a function of SRT

SRT d	MBR HRT h	CAS HRT h	SRT d	MBR HRT h	CAS HRT h
3	1.83	7.85	12	5.99	25.67
4	2.37	10.16	13	6.39	27.41
5	2.88	12.35	14	6.80	29.12
6	3.37	14.43	15	7.19	30.81
7	3.84	16.44	16	7.58	32.47
8	4.29	18.38	17	7.96	34.13
9	4.73	20.27	18	8.35	35.77
10	5.16	22.10	19	8.72	37.39
11	5.58	23.91	20	9.10	38.99

The tables illustrate the space reduction with an MBR.

3. Determine the effluent NH_4-N concentration in the first compartment of the MBR system.

   a. Perform a mass balance for NH_4-N in compartment 1 (refer to sketch).

$$V_1 \frac{dN_1}{dt} = QN_o + RQ(N_E) - (Q + RQ)N_1 = r_{NH4}(V_1)$$

Let N_o be the NH_4-N available after N is used for syntyesis for biomass growth,

$N_o = TKN - N_{syn}$

$$N_o = TKN - \frac{(P_{X,bio})(0.12\ g\,N/g\ VSS)}{Q} \qquad (8\text{-}18a)$$

$P_{X,bio}$ was determined in Problem 8-17 as a function of SRT.

At steady state:

$$QN_o + RQ(N_E) = (Q + RQ)N_1 = r_{NH4}(V_1)$$

r_{NH4} is determined with Eq. (7-101) in Table 8-10.

$$r_{NH4} = \left(\frac{\mu_{max,AOB}}{Y_{AOB}}\right)\left(\frac{N_1}{K_n + N_1}\right)\left(\frac{DO}{K_o + DO}\right)X_{AOB,1}$$

where, $N_1 = S_{NH4}$ in compartment 1.

Thus,

$$QN_o + RQ(N_E) = (Q + RQ)N_1 + \left(\frac{\mu_{max,AOB}}{Y_{AOB}}\right)\left(\frac{N_1}{K_n + N_1}\right)\left(\frac{DO}{K_o + DO}\right)X_{AOB,1}(V_1) \qquad (8\text{-}18b)$$

b. Provide equation for X_{AOB}. X_{AOB} is a function of SRT, amount of growth from NH_4-N oxidation, and compartment relative MLSS concentration. From Step 1a, the ratio of $X_{1,AOB} + X_{2,AOB}$ can be determined as proportional to the MLSS ratio.

$$\frac{X_{AOB,1}}{X_{AOB,2}} = \frac{10,286\ mg/L}{12,000\ mg/L} = 0.857$$

The mass of X_{AOB} produced per day is determined from Part C in Eq. (8-20)

$$P_{AOB,VSS} = \frac{Q(Y_{AOB})(NO_x)}{1 + b_{AOB}(SRT)}$$

where, $NO_x = N_o - N_E$

The mass of AOB in the system equals $(P_{AOB,VSS})$SRT as indicated by Eq. (7-56) in Table 8-10.

The AOB mass is divided between compartments 1 and 2, where:

$$X_{AOB,1}(V_1) + X_{AOB,2}(V_2) = P_{AOB,VSS}(SRT)$$

$$X_{AOB,1}(0.75V)+X_{AOB,2}(0.25V)=P_{AOB,VSS}(SRT)$$

$$X_{AOB,2}=\frac{X_{AOB,1}}{0.857}$$

$$X_{AOB,1}(0.75V)+\frac{X_{AOB,1}}{0.857}(0.25V)=P_{AOB,VSS}(SRT)$$

$$X_{AOB,1}(1.042V)=P_{AOB,VSS}(SRT)$$

$$=\frac{Q(Y_{AOB})(N_o-N_E)SRT}{1+b_{AOB}(SRT)}$$

$$X_{AOB,1}=\frac{Q(Y_{AOB})(N_o-N_E)SRT}{(1.042V)[1+b_{AOB}(SRT)]} \qquad (8\text{-}18c)$$

The equation coefficients at 15°C have been determined in Problem 8-17 and are summarized below.

$\mu_{max,AOB,15°C}$ = 0.90(1.072)$^{15-20}$ = 0.636 g/g • d

$K_{NH4,15°C}$ = 0.50(1.0)$^{15-20}$ = 0.50 g NH_4-N/m^3

$b_{AOB,15°C}$ = 0.17(1.029)$^{15-20}$ = 0.147 g/g • d

Y_{AOB} = 0.15 g VSS/g NH_4-N oxidized (Table 8-14)

K_o = 0.50 mg/L (Table 8-14)

4. Determine the effluent NH_4-N concentration for compartment 2 of the MBR system.

   a. Perform a mass balance for NH_4-N in compartment 2 (refer to sketch). Note that NH_4-N concentration is the same as the effluent concentration, N_E.

$$V_2\frac{dNE}{dt}=(Q+RQ)N_1-(Q+RQ)N_E-r_{NH4}(V_2)$$

$$r_{NH4}=\left(\frac{\mu_{max,AOB}}{Y_{AOB}}\right)\left(\frac{N_E}{K_n+N_E}\right)\left(\frac{DO}{K_o+DO}\right)X_{AOB,2}$$

   b. At steady state:

$$(Q+RQ)N_1=(Q+RQ)N_E$$

$$+\left(\frac{\mu_{max,AOB}}{Y_{AOB}}\right)\left(\frac{N_E}{K_n+N_E}\right)\left(\frac{DO}{K_o+DO}\right)X_{AOB,2}(V_2) \qquad (8\text{-}18d)$$

From Step 3b,

$$X_{AOB,1}(0.75V) + X_{AOB,2}(0.25V) = P_{AOB,VSS}(SRT)$$

$$X_{AOB,1} = 0.857X_{AOB,2}$$

$$0.857X_{AOB,2}(0.75V) + X_{AOB,2}(0.25V) = P_{AOB,VSS}(SRT)$$

$$X_{AOB,2}(0.893V) = P_{AOB,VSS}(SRT)$$

$$X_{AOB,2} = \frac{Q(Y_{AOB})(N_o - N_E)SRT}{0.893V[1 + b_{AOB}(SRT)]} \qquad (8\text{-}18e)$$

5. Solution approach.
    1. Select SRT
    2. Determine $P_{X1,bio}$ (obtain from Problem 8-17)
    3. Determine N_o (Eq. 8-18a in this solution)
    4. Assume N_E
    5. Determine $X_{AOB,1}$ (Eq. 8-18c in this solution)
    6. Solve for N_1 in Eq. (8-18d) in this solution. Excel solver provides convenient solution
    7. Determine $X_{AOB,2}$ (Eq. 8-18e in this solution)
    8. Solve for N_E in Eq. (8-18d) in this solution
    9. Compare N_E from Step 8 to N_E in Step 4. Reiterate as necessary until they agree

Example for SRT = 10d

Step 2. $P_{X1,bio}$ (from Problem 8-17) = 1874 kg VSS/d

Step 3. Determine N_o

$$N_o = TKN - \frac{(P_{X,bio})(0.12\ g\,N/g\ VSS)}{Q}$$

$$N_o = (40\ g/m^3) - \frac{(1874\ kg\ VSS/d)(0.12\ g\,N/g\ VSS)}{(20{,}000\ m^3/d)}$$

$$= 28.8\ g/m^3$$

Step 4. Assume N_E = 0.20 g/m^3

Step 5. Determine $X_{AOB,1}$

$$X_{AOB,1} = \frac{Q(Y_{AOB})(N_o - N_E)SRT}{(1.042V)[1 + b_{AOB}(SRT)]}$$

$$X_{AOB,1} = \frac{(20{,}000\ m^3/d)(0.15\ g\ VSS/g\ N)[(28.8 - 0.20)\ g/m^3](10\ d)}{(1.042)(4298\ m^3)[1 + (0.147\ g/g{\bullet}d)(10\ d)]}$$

$$= 77.6\ g/m^3$$

Step 6. Solve for N_1

$V_1 = 0.75V = 0.75(4298\ m^3) = 3223.5\ m^3$

$$QN_o + RQ(N_E) = (Q + RQ)N_1 + \left(\frac{\mu_{max,AOB}}{Y_{AOB}}\right)\left(\frac{N_1}{K_n + N_1}\right)\left(\frac{DO}{K_o + DO}\right)X_{AOB,1}(V_1)$$

$$(20{,}000\ m^3/d)(28.8\ g/m^3) + 6.0(20{,}000\ m^3/d)(0.20\ g/m^3)$$

$$= [(20{,}000\ m^3/d) + 6.0(20{,}000\ m^3/d)]N_1 + \left[\frac{(0.636\ g/g{\bullet}d)}{(0.15\ g\ VSS/g\ N)}\right]\left[\frac{N_1}{(0.50\ g/m^3) + N_1}\right]\left[\frac{2.0}{0.50 + 2.0}\right](77.6\ g/m^3)(3223.5\ m^3)$$

From solver, $N_1 = 1.2\ g/m^3$

Step 7. Determine $X_{AOB,2}$

$$X_{AOB,2} = \frac{Q(Y_{AOB})(N_o - N_E)SRT}{0.893V[1 + b_{AOB}(SRT)]}$$

$$X_{AOB,2} = \frac{(20{,}000\ m^3/d)(0.15\ g\ VSS/g\ N)[(28.8 - 0.20)\ g/m^3](10\ d)}{0.893(4298\ m^3)[1 + (0.147\ g/g{\bullet}d)(10\ d)]}$$

$$= 90.4\ g/m^3$$

Step 8. Solve for N_E

$$(Q + RQ)N_1 = (Q + RQ)N_E + \left(\frac{\mu_{max,AOB}}{Y_{AOB}}\right)\left(\frac{N_E}{K_n + N_E}\right)\left(\frac{DO}{K_o + DO}\right)X_{AOB,2}(V_2)$$

$V_2 = 0.25V = 0.25(4298\ m^3) = 1074.5\ m^3$

$$[(20{,}000\ \mathrm{m^3/d}) + 6.0(20{,}000\ \mathrm{m^3/d})](1.2\ \mathrm{g/m^3})$$
$$= [(20{,}000\ \mathrm{m^3/d}) + 6.0(20{,}000\ \mathrm{m^3/d})]N_E$$
$$+\left[\frac{(0.636\ \mathrm{g/g{\bullet}d})}{(0.15\ \mathrm{g\ VSS/g\ N})}\right]\left[\frac{N_E}{(0.50\ \mathrm{g/m^3}) + N_E}\right]\left[\frac{2.0}{0.50 + 2.0}\right](90.5\ \mathrm{g/m^3})(1074.5\ \mathrm{m^3})$$

From solver, $N_E = 0.09\ \mathrm{g/m^3}$

Reiteration results in N_1 = 0.68 mg/L and N_E = 0.08 mg/L

A summary of the first compartment and effluent NH_4-N concentrations is provided as a function of SRT and compared to the effluent NH_4-N concentration for the single tank CAS system in Problem 8-17.

Effluent NH_4-N concentrations from conventional activated sludge (CAS) process and from first compartment and effluent of MBR process

					MBR		CAS
SRT d	Px,bio kg VSS/d	No mg/L	$X_{AOB,1}$ mg/L	$X_{AOB,2}$ mg/L	N_1 mg/L	N_E mg/L	N_E mg/L
3	2591	24.5	94.1	109.8	1.86	0.50	8.62
4	2459	25.2	91.5	106.8	1.43	0.30	1.79
6	2219	26.7	86.8	101.3	1.00	0.16	0.81
8	2027	27.8	82.1	95.8	0.80	0.11	0.58
10	1874	28.8	77.8	90.7	0.68	0.08	0.47
12	1749	29.5	73.7	86.0	0.61	0.07	0.42
14	1644	30.1	70.0	81.7	0.56	0.06	0.38
16	1554	30.7	66.7	77.8	0.52	0.05	0.35
18	1479	31.1	63.5	74.1	0.50	0.05	0.33
20	1412	31.5	60.7	70.8	0.47	0.04	0.32

The two stage reactor provides a much lower effluent NH_4-N concentration at the same SRT.

PROBLEM 8-19

Problem Statement – see text, page 925

Solution (Wastewater 1)

Solution

1. Determine and summarize wastewater characteristics for **wastewater 1** after primary treatment and compute kinetic coefficients.

   a. Determine wastewater characteristics; values are summarized below.

Parameter	Unit	Calculation	Value
Flowrate	m^3/d		20,000
BOD	mg/L	(1 – 0.35) 220 mg/L	143
bCOD	mg/L	1.6 g/g (143 mg/L)	229
TSS	mg/L	(1 – 0.35) 220 mg/L	143
VSS	mg/L	(1 – 0.35) 200 mg/L	130
nbVSS	mg/L	(1 – 0.80) 100 mg/L	20
TKN	mg/L	(1 – 0.10) 40 mg/L	36
Temperature	°C		15

   b. Compute kinetic coefficients for T = 15°C with Eq. (1-44) in Table 8-10

$\mu_{max,H,15°C} = 6.0(1.07)^{15-20} = 4.3\ g/g \bullet d$

$K_{S,15°C} = 8.0(1.0)^{15-20} = 8.0\ g/m^3$

$b_{H,15°C} = 0.12(1.04)^{15-20} = 0.10\ g/g \bullet d$

$\mu_{max,AOB,15°C} = 0.90(1.072)^{15-20} = 0.636\ g/g \bullet d$

$K_{NH,15°C} = 0.50(1.0)^{15-20} = 0.50\ g\ NH_4\text{-}N/m^3$

$b_{AOB,15°C} = 0.17(1.029)^{15-20} = 0.147\ g/g \bullet d$

2. Determine the effluent sbCOD and ammonia-N concentration as a function of SRT.

   a. Determine S as a function SRT using Eq. (7-46) where $\mu_m = Yk$, and kinetic coefficients computed in step 1b.

$Y_H = 0.45$ g VSS/g COD, $f_d = 0.15$ g VSS/g VSS

$$S = \frac{K_S[1 + (b_H)SRT]}{SRT(\mu_m - b_H) - 1}$$

$$S = \frac{(8.0\,g/m^3)[1 + (0.1\,g/g \bullet d)SRT]}{SRT[(4.3 - 0.1)g/g \bullet d] - 1}$$

$$S = \frac{8(1+0.1SRT)}{4.2SRT-1} g/m^3$$

At SRT = 3.0 d, S = 0.90 g/m^3

S as a function of SRT is summarized in table below.

b. Determine effluent NH_4-N (N_e) concentrations as a function of SRT by combining Eq. (7-94) and Eq. (7-98) in Table 10. Let S_o = DO.

$$\frac{1}{SRT} = \left(\frac{\mu_{max,AOB}S_{NH4}}{K_{NH4}+S_{NH4}}\right)\left(\frac{DO}{K_o+DO}\right) - b_{AOB}$$

Solving for S_{NH4} (let S_{NH4} = N_e):

$$N_e = \frac{K_{NH4}(1+b_{AOB}SRT)}{[\mu_{max,AOB}\left(\frac{DO}{K_o+DO}\right) - b_{AOB}]SRT - 1}$$

$$N_e = \frac{0.50 \text{ g/m}^3\left[1 + (0.147 \text{ g/g-d})SRT\right]}{SRT\left\{0.636 \text{ g/g-d}\left[\frac{(2.0 \text{ g/m}^3)}{(0.50 \text{ g/m}^3 + 2.0 \text{ g/m}^3)}\right] - 0.147 \text{ g/g-d}\right\} -1}$$

At SRT = 3.0 days, N_e = 8.62g/m^3

Table showing Effluent NH_4-N (N_e) and effluent sbCOD (S) concentration as a function of SRT:

SRT d	Effl. sbCOD mg/L	Effl. NH_4-N mg/L	SRT d	Effl. sbCOD mg/L	Effl. NH_4-N mg/L
3	0.90	8.62	12	0.36	0.42
4	0.71	1.79	13	0.34	0.39
5	0.60	1.08	14	0.33	0.38
6	0.53	0.81	15	0.32	0.36
7	0.48	0.66	16	0.31	0.35
8	0.44	0.58	17	0.31	0.34
9	0.41	0.52	18	0.75	0.24
10	0.39	0.47	19	0.73	0.23
11	0.37	0.44	20	0.72	0.22

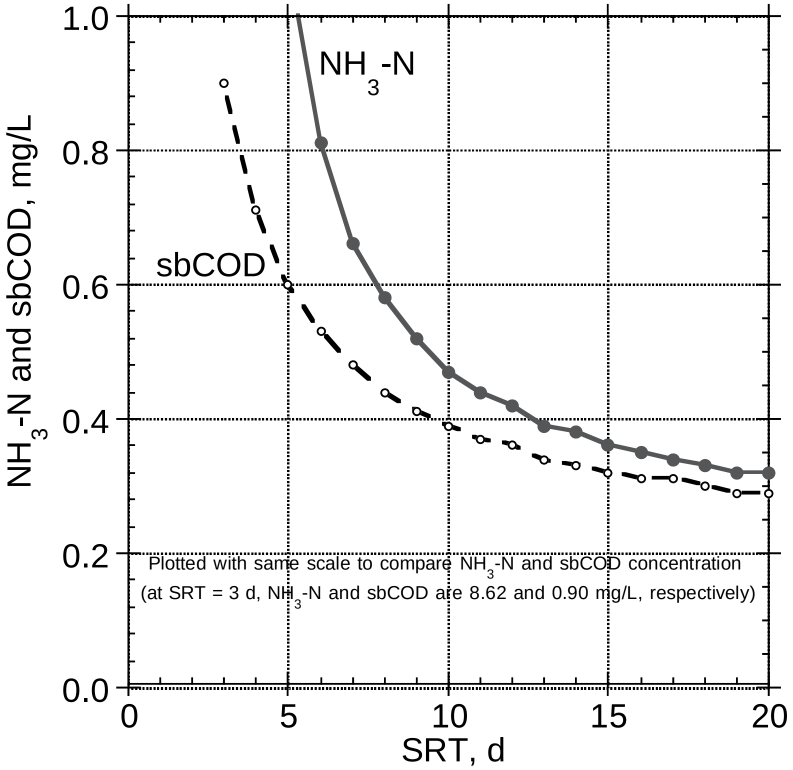


Figure 1. Effluent NH$_3$-N and sbCOD concentration vs SRT

3. Determine solids wasted as kg TSS/d as a function of SRT. At steady state solids wasted is equal to the solids production rate, which can be calculated using Eq. (8-20) and Eq. (8-21) in Table 8-10.

$$P_{X,TSS} = \frac{A}{0.85} + \frac{B}{0.85} + \frac{C}{0.85} + D + E$$

where E = Q(TSS$_o$ – VSS$_o$)

a. Calculate the terms in Eq. 8-21; For first calculation assume NO$_X$ ≈ 80% of influent TKN

i. Active biomass:

$$A = \frac{QY_H(S_o - S)(1\,kg/10^3\,g)}{[1 + b_H(SRT)]0.85}$$

$$= \frac{(20{,}000\,\text{m}^3/\text{d})(0.45\text{ g VSS/g COD})\left(229 - \text{S}\right)(\text{g sbCOD/m}^3)(1\text{ kg}/10^3\text{g})}{[1 + \left(0.10\text{ g/g} \bullet \text{d}\right)\text{SRT}]0.85}$$

At SRT = 3.0 d, S = 0.90 mg/L, A = 1862 kg TSS/d

ii. Cell debris:

$$\text{B} = \frac{(\text{f}_\text{d})(\text{b}_\text{H})(\text{Q})(\text{Y}_\text{H})(\text{S} - \text{S}_\text{o})\text{SRT}(1\text{ kg}/10^3\text{g})}{[1 + \text{b}_\text{H}(\text{SRT})]0.85}$$

$$= \frac{(0.15\text{ g/g})(0.10\text{ g/g} \bullet \text{d})(20{,}000\,\text{m}^3/\text{d})(0.45\text{ g VSS/g COD})\left(229 - \text{S}\right)(\text{g sbCOD/m}^3)\text{SRT}(1\text{ kg/10}}{[1 + \left(0.10\text{ g/g} \bullet \text{d}\right)(\text{SRT})]0.85}$$

At SRT = 3.0 d, S = 0.90 mg/L, B= 83 kg TSS/d

iii. Nitrifying bacteria:

$$\text{C} = \frac{\text{QY}_\text{n}(\text{NO}_\text{x})(1\text{ kg}/10^3\text{g})}{[1 + \text{b}_\text{AOB}(\text{SRT})]0.85}$$

Note Y_n = 0.20 g VSS/g NO_x-N to account for growth of both AOB and NOB.

For first calculation assume NOx-N = 0.80(Influent TKN)

$$= \frac{(20{,}000\,\text{m}^3/\text{d})(0.20\text{ g VSS/g NOx-N})(0.8)(36\text{ g/m}^3)(1\text{ kg}/10^3\text{g})}{[1 + (0.147\text{ g/g} \bullet \text{d})(\text{SRT})]0.85}$$

At SRT = 3.0 d, C= 94 kg TSS/d

iv. Nonbiodegradable VSS (VSS = TSS)

D = Q(nbVSS)(1 kg/10^3 g)

D = (20,000 m^3/d)(20 g/m^3)(1 kg/10^3 g) = 400 kg VSS/d

v. Inert inorganic TSS

E = (20,000 m^3/d)[(143 – 130) g/m^3](1 kg/10^3 d) = 260 kg TSS/d

b. Iterate for NO_x-N value by calculating NO_x-N from $P_{X,bio}$, using Eq. (8-24), Table 8-10 and replacing the initial assume value.

$$NO_x\text{-N} = TKN - 0.12(P_{x,bio}) - N_e$$

where $P_{X,bio}$ = VSS/d of active heterotrophs, debris, and nitrifiers

Solve for NO_x-N and change value inserted in Eq. C above to iterate

Insert A, B, C, D, and E into Eq. (8-21) to solve $P_{X,TSS}$ as a function of SRT. Using a spreadsheet program, the values of $P_{X,TSS}$ and $P_{X,bio,VSS}$ for SRTs ranging from 3 to 20 d are shown in the following table.

	As kg TSS/d, except $P_{x,bio}$ which is kg VSS/d							NOx-N
SRT, d	A	B	C	D	E	$P_{x,TSS}$	$P_{x,bio}$	mg/L
3	1862	83	55	400	260	2660	1700	17
4	1732	102	71	400	260	2565	1620	24
5	1618	120	70	400	260	2468	1537	26
6	1518	135	65	400	260	2378	1460	26
7	1430	148	63	400	260	2301	1395	27
8	1352	160	58	400	260	2230	1334	27
9	1281	171	57	400	260	2168	1282	28
10	1218	180	53	400	260	2111	1233	28
11	1160	189	50	400	260	2059	1189	28
12	1108	197	49	400	260	2014	1151	29
13	1060	204	47	400	260	1971	1114	29
14	1016	210	45	400	260	1931	1080	29
15	976	217	43	400	260	1895	1050	29
16	938	222	42	400	260	1863	1022	30
17	904	227	40	400	260	1831	996	30
18	872	232	39	400	260	1803	971	30
19	842	237	36	400	260	1774	947	30
20	814	241	36	400	260	1751	927	30

c. Determine tank volume $V(m^3)$ and τ (h) as a function of SRT using Eq. (7-57) in Table 8-10.

$(X_{TSS})(V) = (P_{X,TSS})SRT$

$$V = \frac{(P_{X,TSS})SRT}{X_{TSS}}$$

$$V = \frac{(P_{X,TSS},\ kg/d)(SRT,\ d)}{(2500\ g/m^3)(1\ kg/10^3\ g)} = \frac{P_{X,TSS}(SRT)}{2.5} m^3$$

$$\tau = \frac{V}{Q}$$

$$\tau = \frac{\left[(P_{X,TSS})(SRT)\right](m^3)(24\ h/d)}{2.5(20{,}000\ m^3/d)} = 4.8 \times 10^{-4}\left[(P_{X,TSS})(SRT)\right]\ h$$

Using a spreadsheet program, compute the values of V and τ for SRTs ranging from 3 to 20 d as shown in the following table and plot below:

SRT d	Volume m^3	HRT h	SRT d	Volume m^3	HRT h
3	3192	3.8	12	9666	11.6
4	4105	4.9	13	10,247	12.3
5	4937	5.9	14	10,814	13.0
6	5708	6.8	15	11,368	13.6
7	6442	7.7	16	11,920	14.3
8	7135	8.6	17	12,454	14.9
9	7806	9.4	18	12,978	15.6
10	8444	10.1	19	13,484	16.2
11	9060	10.9	20	14,004	16.8

Figure 2. Plot of Volume and hydraulic retention time (HRT) versus SRT.

d. Determine observed yield as g TSS/g BOD and g TSS/g bCOD

Y_{obs} based on g TSS/g BOD

Observed yield = $P_{X,TSS}$/g BOD removed

$P_{X,TSS}$ was determined in Step 3a above.

BOD removed = Q (S_o – S), S is determined above as function of SRT

$$Y_{\text{obs, TSS/BOD}} = \frac{(P_{X,TSS}\text{, g TSS/d})}{(20{,}000\ \text{m}^3/\text{d})(143-S)\ \text{g BOD}/\text{m}^3}$$

$$Y_{\text{obs, TSS/COD}} = \left(Y_{\text{obs,TSS/BOD}}\right)\left(\frac{\text{BOD}}{1.6\,\text{BOD}}\right)$$

$$Y_{\text{obs, TSS/COD}} = \frac{\left(Y_{\text{obs,TSS/BOD}}\right)}{1.6}$$

Using a spreadsheet program, compute the values of Y_{obs} for SRTs ranging from 3 to 20 d as shown in the following table and plot.

SRT d	Y_{obs} gTSS/gBOD	Y_{obs} gTSS/gCOD	SRT d	Y_{obs} gTSS/gBOD	Y_{obs} gTSS/gCOD
3	0.93	0.58	12	0.70	0.44
4	0.90	0.56	13	0.69	0.43
5	0.86	0.54	14	0.68	0.42
6	0.83	0.52	15	0.66	0.41
7	0.80	0.50	16	0.65	0.41
8	0.78	0.49	17	0.64	0.40
9	0.76	0.47	18	0.63	0.39
10	0.74	0.46	19	0.62	0.39
11	0.72	0.45	20	0.61	0.38

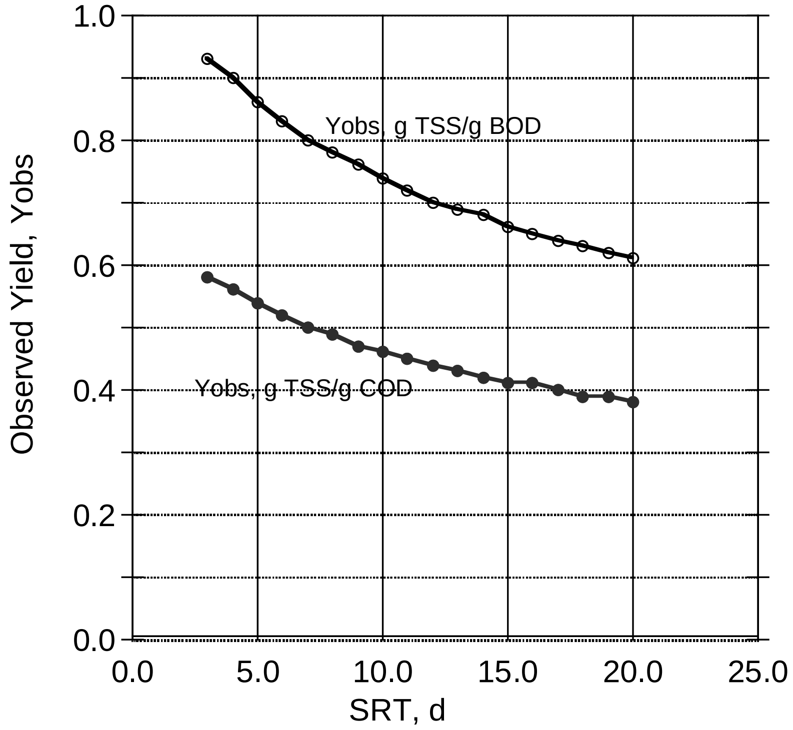


Figure 3. Observed yield vs SRT

e. Determine oxygen requirement in kg/d as a function of SRT

i. Calculate NO_X using Eq. (8-24)

$NO_x = TKN - N_e - 0.12\ P_{X,bio}/Q$

$P_{X,bio}$ is calculated as shown above from A, B, and C

Using a spreadsheet program, compute the values of NO_X for SRTs ranging from 3 to 20 d as shown in the table following item ii. below.

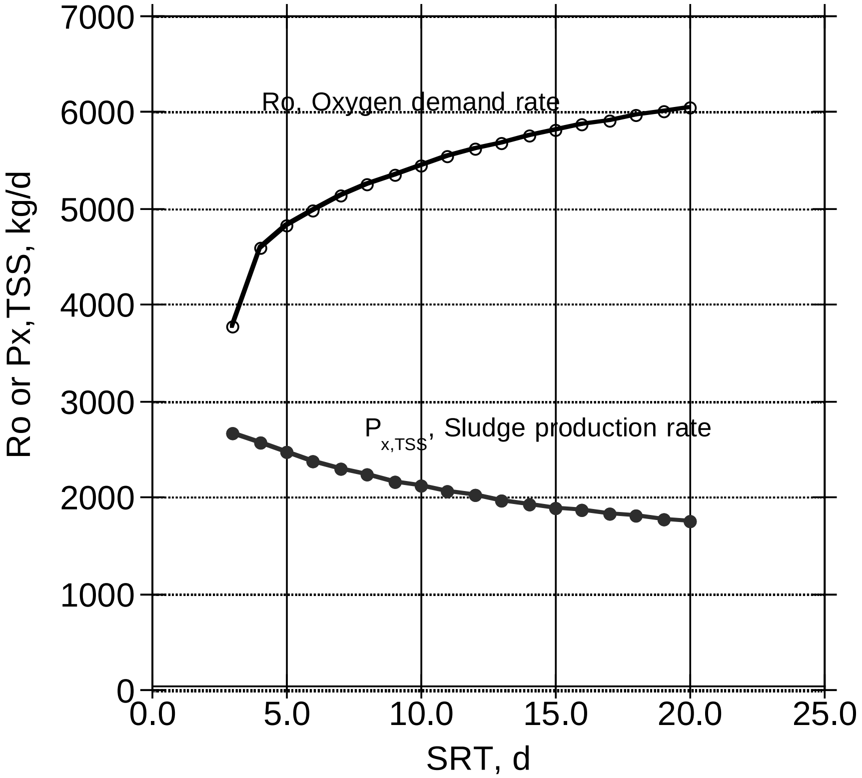
iii. Calculate O_2 demand rate using Eq. (8-23).

$R_o = Q(S_o - S) - 1.42P_{X,bio} + 4.57Q(NO_X\text{-}N)$

f. Using a spreadsheet program, compute the values of R_o for SRTs ranging from 3 to 20 d as shown in the following table and plot. The plot also includes the sludge production rate (kg TSS/d)

SRT	NOx-N	R_o	SRT	NOx-N	R_o

d	mg/L	kg/d	d	mg/L	kg/d
3	17	3781	12	29	5616
4	24	4587	13	29	5687
5	26	4815	14	29	5752
6	26	4986	15	29	5812
7	27	5126	16	30	5867
8	27	5249	17	30	5918
9	28	5356	18	30	5965
10	28	5452	19	30	6010
11	28	5538	20	30	6050



PROBLEM 8-20

Problem Statement – see text, page 925

Solution (for effluent NH_4-N = 1.0 mg/L)

1. Summary of operating conditions given for nitrification.

DO = 2.0 mg/L

Temperature = 10°C

Design safety factor = Peak/average TKN = 1.8

2. Establish basis for selecting SRT.
   a. The ammonia-oxidizing bacteria (AOB) specific growth rate is related to the SRT in a complete-mix activated sludge process as shown by Eq. (7-98) in Table 8-10.

$$\mathrm{SRT} = \frac{1}{\mu_{AOB}}$$

   b. The AOB specific growth rate is related to the ammonia-N and DO concentrations and kinetic coefficients as given by Eq. (7-94) in Table 8-10

$$\mu_{AOB} = \left(\frac{\mu_{max,AOB} S_{NH4}}{K_{NH4} + S_{NH4}}\right)\left(\frac{DO}{K_{o,AOB} + DO}\right) - b_{AOB}$$

Thus, the required SRT is related to the above factors by substitution for μ_{AOB}

$$\frac{1}{\mathrm{SRT}} = \left(\frac{\mu_{max,AOB} S_{NH4}}{K_{NH4} + S_{NH4}}\right)\left(\frac{DO}{K_o + DO}\right) - b_{AOB}$$

The design SRT is based on the selected safety factor (SF) value, and the SRT determined at the average design condition using Eq. (7-73) in Table 8-10.

Design SRT = SF (SRT)

3. Determine the kinetic coefficients. The coefficients for Eq. (7-94, 7-95) are obtained from Table 8-14. Use the temperature correction Eq. (1-44) shown in Table 8-10.

$$k_T = k_{20}(\theta)^{T-20}$$

Temperature = 10°C

$\mu_{max,AOB} = 0.90\ (1.072)^{10-20} = 0.449\ \mathrm{g/g \cdot d}$

$K_{NH4} = 0.50\ (1.0)^{10-20} = 0.50\ g/m^3$

$Y_n = 0.15$ g VSS/g Noxidized

$b_{AOB} = 0.17(1.029)^{10-20} = 0.128\ g/g \bullet d$

$K_o = 0.50\ g/m^3$

4. Determine the design SRT.

   a. Calculate μ_{AOB} for **an effluent NH_4-N concentration of 0.50 mg/L** and a DO concentration = 2.0 mg/L.

$$\mu_{AOB} = \left\{\frac{(0.449\ g/g\bullet d)(1.0\ g/m^3)}{[(0.50+1.0)\ g/m^3]}\right\}\left\{\frac{(2.0\ g/m^3)}{[(0.50+2.0)\ g/m^3]}\right\} - 0.128\ g/g\bullet d$$

$\mu_{AOB} = 0.111\ g/g \bullet d$

   b. Calculate the SRT.

$$SRT = \frac{1}{(0.111\ g/g{\cdot}d)} = 9.0\ d$$

   c. Determine the design SRT.

   Design SRT = 1.8 (9.0 d) = 16.2 d

PROBLEM 8-21

Problem Statement – see text, page 926

Solution

1. Determine the SRT using Eqs. (8-20), (8-21), and (7-57) in Table 8-10.

   a. Determine the total mass of solids **for τ = 8.3 h**

$$P_{X,TSS} = \frac{QY_H(S_o - S)}{[1+b_H(SRT)]0.85} + \frac{(f_d)(b_H)QY_H(S_o - S)SRT}{[1+b_H(SRT)]0.85} + \frac{QY_n(NO_X)}{[1+b_n(SRT)]0.85} + Q(nbVSS) + Q(TSS_o - VSS_o)$$

   Substituting $P_{X,TSS}$ in Eq. (7-57).

$$(X_{TSS})(V) = \frac{QY_H(S_o - S)SRT}{[1 + b_H(SRT)]0.85} + \frac{(f_d)(b_H)QY_H(S_o - S)(SRT)^2}{[1 + b_H(SRT)]0.85}$$
$$+ \frac{QY_n(NO_X)SRT}{[1 + b_n(SRT)]0.85} + Q(nbVSS)SRT + Q(TSS_o - VSS_o)SRT$$

b. Obtain input values for equation and solve for SRT

$$\tau = \frac{V}{Q} = \frac{8.3\ h}{(24\ h/d)} = 0.346\ d$$

$V = 0.346\ d\ (15{,}000\ m^3/d) = 5187.5\ m^3$

$S_o - S$ is given as 130 mg/L BOD removed

Convert to BOD to bCOD using Eq. (8-13)

$S_o - S = 1.6\ (130\ mg/L) = 208\ mg/L$

Assume $NO_X \sim 0.80\ (TKN) = 0.80\ (40) = 32\ mg/L$

(Note: Due to low yield of nitrifiers, the error with this assumption has only a small and insignificant effect on the SRT determination. An iterative process may also be used in which NO_X is calculated after the SRT is determined.)

c. Determine coefficients from Table 8-14 and adjust for temperature using Eq. (1-44) and the table μ values

$k_T = k_{20}(\theta)^{T-20}$

For heterotrophs:

$Y = 0.45$ gVSS/g bCOD

$f_d = 0.15$ g/g

$b_H = 0.12(1.04)^{10-20} = 0.081$ g/g•d

For nitrification:

$\mu_{max,AOB} = (0.90\ g/g{\bullet}d)\ (1.072)^{10-20} = 0.449$ g/g•d

k_{NH4} = (0.50 mg/L) $(1.0)^{10-20}$ = 0.50 g/m^3

b_{AOB} = (0.17 g/g•d) $(1.029)^{10-20}$ = 0.128 g/g•d

Y_n = 0.15 g VSS / g NH_4-N

K_o = 0.50 g/m^3

d. Summarize other design parameters to be used

X_{TSS} = 3000 g/m^3

nbVSS = 30 g/m^3

$TSS_o - VSS_o$ = (70 – 60) g/m^3 = 10 g/m^3

Q = 15,000 m^3/d

e. Substitute the above values and other given information into the equation developed in 1a.

$$(3000\ \mathrm{g/m^3})(5187.5\ \mathrm{m^3}) = \frac{(0.45\ \mathrm{g/g})(15{,}000\ \mathrm{m^3/d})(208\ \mathrm{g/m^3})(\mathrm{SRT})}{[1+(0.081\ \mathrm{g/g{\cdot}d})\mathrm{SRT}]0.85}$$

$$+\frac{(0.15\ \mathrm{g/g})(0.081\mathrm{g/g \bullet d})(15{,}000\mathrm{m^3/d})(0.45\ \mathrm{g/g})(208\ \mathrm{g/m^3})(\mathrm{SRT})^2}{[1+(0.081\mathrm{g/g \bullet d})\mathrm{SRT}]0.85}$$

$$+\frac{(0.15\ \mathrm{g/g})(15{,}000\mathrm{m^3/d})(32\ \mathrm{g/m^3})(\mathrm{SRT})}{[1+(0.128\ \mathrm{g/g \bullet d})\mathrm{SRT}]0.85}+(15{,}000\mathrm{m^3/d})(30\ \mathrm{g/m^3})(\mathrm{SRT})$$

$$+(15{,}000\mathrm{m^3/d})(30\ \mathrm{g/m^3})(\mathrm{SRT}) \quad +(15{,}000\mathrm{m^3/d})(10\ \mathrm{g/m^3})(\mathrm{SRT})$$

15,562,500 =

$$\frac{1{,}651{,}765(\mathrm{SRT})}{1+.081\mathrm{SRT}}+\frac{20{,}069(\mathrm{SRT})^2}{1+0.081\mathrm{SRT}}+\frac{84705(\mathrm{SRT})}{1+0.128\mathrm{SRT}}+450{,}000\,\mathrm{SRT}+150{,}000\,\mathrm{SRT}$$

f. Solve for SRT using spreadsheet – vary SRT until equation is solved or use Excel solver function:

SRT = 9.2 d

The SRT for nitrification by ammonia-oxidizing bacteria (AOB) for a complete-mix process is related to the specific growth rate of the nitrifying bacteria by Eq. (7-98) in Table 8-10.

$$\mathrm{SRT} = \frac{1}{\mu_{\mathrm{AOB}}}$$

$$\mu_{\mathrm{AOB}} = \frac{1}{\mathrm{SRT}} = \frac{1}{9.2\ \mathrm{d}} = 0.109\ \mathrm{g/g \bullet d}$$

g. Solve for effluent NH_4-N concentration. The value for μ_{AOB} is related to the kinetic coefficients, temperature, and DO and NH_4-N concentration as shown by Eq. (7-94) in Table 8-10. The DO is given as 2.0 mg/L.

$$\mu_{\mathrm{AOB}} = \left(\frac{\mu_{\mathrm{max,AOB}} S_{\mathrm{NH4}}}{K_{\mathrm{NH4}} + S_{\mathrm{NH4}}}\right)\left(\frac{\mathrm{DO}}{K_{\mathrm{o,AOB}} + \mathrm{DO}}\right) - b_{\mathrm{AOB}}$$

and thus:

$$\frac{1}{\mathrm{SRT}} = \left(\frac{\mu_{\mathrm{max,AOB}} S_{\mathrm{NH4}}}{K_{\mathrm{NH4}} + S_{\mathrm{NH4}}}\right)\left(\frac{\mathrm{DO}}{K_{\mathrm{o,AOB}} + \mathrm{DO}}\right) - b_{\mathrm{AOB}}$$

This is rearranged to solve for effluent NH_4-N concentration:

$$S_{\mathrm{NH4}} = \frac{K_{\mathrm{NH4}}(1 + b_{\mathrm{AOB}}\mathrm{SRT})}{[\mu_{\mathrm{max,AOB}}\left(\frac{\mathrm{DO}}{K_o + \mathrm{DO}}\right) - b_{\mathrm{AOB}}]\mathrm{SRT} - 1}$$

$$S_{\mathrm{NH4}} = \frac{(0.50\ \mathrm{g/m^3})[1 + (0.128\ \mathrm{g/g \bullet d})(9.2\ \mathrm{d})]}{\left\{(0.449\ \mathrm{g/g \bullet d})\left[\frac{2.0}{(0.5 + 2.0)}\right] - (0.128\mathrm{g/g \bullet d})\right\}(9.2) - 1}$$

$$S_{\mathrm{NH4}} = 0.97\ \mathrm{mg/L}$$

h. Determine the SRT needed to obtain an effluent NH4-N concentration of 1.0 mg/L and safety factor.

$$\frac{1}{\mathrm{SRT}}=\left(\frac{\mu_{\mathrm{max,AOB}}S_{\mathrm{NH4}}}{K_{\mathrm{NH4}}+S_{\mathrm{NH4}}}\right)\left(\frac{\mathrm{DO}}{K_{\mathrm{o,AOB}}+\mathrm{DO}}\right)-b_{\mathrm{AOB}}$$

$$\frac{1}{\mathrm{SRT}}=\left[\frac{(0.449\ \mathrm{g/g\bullet d})(1.0\ \mathrm{g/m^3})}{(0.50\ \mathrm{g/m^3})+(1.0\ \mathrm{g/m^3})}\right]\left[\frac{(2.0\ \mathrm{g/m^3})}{(0.50\ \mathrm{g/m^3})+(2.0\ \mathrm{g/m^3})}\right]-0.128\ \mathrm{g/g\bullet d}$$

$$\frac{1}{\mathrm{SRT}}=0.1115$$

SRT = 9.0

Safety factor = 9.2/9.0 = 1.02, (not significant)

PROBLEM 8-22

Problem Statement – see text, page 926

Solution (wastewater 1)

1. Determine the volume using Eqs. (7-57), (8-20), and (8-21) in Table 8-10.

   $(X_{TSS})V = P_{X,TSS}$ (SRT)

$$P_{X,TSS}=\frac{QY(S_o-S)}{[1+b_H(\mathrm{SRT})]0.85}+\frac{(f_d)(b_H)QY(S_o-S)\mathrm{SRT}}{[1+b_H(\mathrm{SRT})]0.85}$$
$$+\frac{QY_n(NO_X)}{[1+b_n(\mathrm{SRT})]0.85}+Q(\mathrm{nbVSS})+Q(\mathrm{TSS_o}-\mathrm{VSS_o})$$

2. Determine the value for S using Eq. (7-46) in Table 8-10 and **an SRT = 8 d**

$$S=\frac{K_s[1+b_H(\mathrm{SRT})]}{\mathrm{SRT}(Y_Hk-b_H)-1}$$

   From Eq. (7-16), Table 8-10, μ_{max} = Yk

   Substituting μ_{max} and values from problem statement:

$$S=\frac{(60\,\mathrm{g/m^3})[1+(0.08\,\mathrm{g/g\bullet d})(8\,\mathrm{d})]}{(8\,\mathrm{d})[(3.0\,\mathrm{g/g\bullet d})-(0.08\,\mathrm{g/g\bullet d})]-1}$$

   S = 4.4 g/m^3 bCOD

3. Solve for V. (Note: NO_x is insignificant per problem statement, NO_x =0)

The information given shows that it is a soluble wastewater, so nbVSS and $(TSS_o - VSS_o) = 0$.

$$V = \frac{(3000\,m^3/d)(0.40\,g/g)[(1800-4.4)\,g/m^3](8.0\,d)}{[1+(0.08\,g/g\bullet d)(8.0\,d)](0.85)(2500\,g/m^3)}$$

$$+\frac{(0.15\,g/g)(0.08\,g/g\bullet d)(0.40\,g/g)(3000\,m^3/d)[(1800-4.4)\,g/m^3](8.0\,d)^2}{[1+(0.08\,g/g\bullet d)(8.0\,d)](0.85)(2500\,g/m^3)}$$

$V = 4{,}946.3\ m^3 + 474.8\ m^3 = 5421.1\ m^3$

$$\tau = \frac{V}{Q} = \frac{5421.1\,m^3}{(3000\,m^3/d)} = 1.81\,d = 43.4\,h$$

4. Calculate the oxygen required using Eq. (8-23) in Table 8-10.

   $R_o = Q\,(S_o - S) - 1.42\,P_{X,bio}$

   Because nbVSS and $(TSS_o - VSS_o) = 0$, the solids are produced from only the biomass [components A and B in Eq. (8-20)]. Thus, the biomass production rate is equal to

   $_{PX,bio} = P_{X,VSS} = 0.85\,P_{X,TSS}$

   From Eq. (7-57): $P_{X,TSS} = \frac{(X_{TSS})V}{SRT}$

   Thus:

   $$P_{X,bio} = \frac{0.85(X_{TSS})V}{SRT} = \frac{0.85(2500\,g/m^3)(5421.1\ m^3)}{8.0\,d}$$

   $P_{X,bio} = 1{,}439{,}980\ g/d$

   $R_o = (3000\ m^3/d)[(1800 - 4.4)\ g/m^3] - [(1.42)(1{,}439{,}980\ g/d)](1\ kg/10^3\ g)$

   $R_o = 3{,}342\ kg/d$

5. Determine the sludge production using Eq. (7-57)

   $$P_{X,TSS} = \frac{(2500\,g/m^3)(5421.1 m^3)(1\,kg/10^3\,g)}{8.0\,d} = 1694\,kg/d$$

6. Calculate the soluble BOD concentration in the effluent from the problem statement of bCOD/BOD = 1.6.

   $$sBOD = \frac{(4.4\ mg/L)}{1.6} = 2.8\,mg/L$$

7. Determine the secondary clarifier diameter.
   a. Select secondary clarifier overflow rate and solids loading from Table 8-34. Use the midpoint for the air-activated sludge process. (Note: no peak loadings are given)

      Overflow rate = Q/A = 22 $m^3/m^2 \cdot d$

      Solids loading = SLR = 5.0 $kg/m^2 \cdot h$

      From Eq. (8-81), page 891

      $$SLR = \frac{(Q + Q_R)MLSS}{A}$$

   b. Calculate area per clarifier based on overflow rate assuming 2 clarifiers are used.

      $$A = \frac{(3000\ m^3/d)}{(22\ m^3/m^2{\cdot}d)} = 136.4\ m^2$$

      $$\text{Area/clarifier} = \frac{136.4\ m^2}{2} = 68.2\ m^2$$

   c. Calculate clarifier diameter

      $$A = \frac{\pi D^2}{4} = 68.2\ m^2$$

      D = 9.3, use D = 9 m

8. Check solids loading. (Assume recycle ratio = $Q/Q_R = 0.50$)

   $$SLR = \frac{(Q + Q_R)X}{A} = \frac{(Q + 0.5Q)X}{A} = 1.5\frac{Q}{A}X$$

   $$SLR = (1.5)(22\ m^3/m^2 \cdot d)(2500\ g/m^3)(1\ kg/10^3\ g)(1\ d/24\ h)$$

   $$= 3.4\ kg/m^2 \cdot h$$

   Solids loading rate is < 5.0 $kg/m^2 \cdot h$ and thus is acceptable.

9. Calculate the air flowrate
   a. The following information is provided to calculate the airflow rate for fine bubble aeration.

      R_o = 3342 kg/d = 139.3 kg/h (step 4)

      $\alpha = 0.45$

      F = 0.90

$\beta = 1.0$

Temperature = 15°C

Effective DO saturation depth = 2.5 m

Elevation = 300 m

Clean water O_2 transfer efficiency = 30%

Assume mixed liquor DO concentration = 2.0 mg/L

b. Convert the oxygen transfer rate to that required at clean water standard conditions using Eq. (5-70) as shown in Example 8-3.

$$\text{SOTR} = \frac{(\text{AOTR})C^*_{\infty,20}}{\left[(\beta)\left(\frac{P_b}{P_S}\right)\left(\frac{C^*_{S,T}}{C^*_{\infty,20}}\right)C^*_{\infty,20} - C\right]\alpha F(1.024)^{(T-20)}}$$

a. Determine effect of temperature and elevation on saturated DO concentration.

i. From Table E-1 (Appendix E), $C^*_{\infty,20}$ = 9.09 mg/L and C_{15} = 10.08 mg/L.

ii. Determine the relative pressure at elevation 300 m to correct the DO concentration for altitude

$$\frac{P_b}{P_s} = \exp\left[-\frac{gM(z_b - z_a)}{RT}\right]$$

$$= \exp\left\{-\frac{(9.81\,\text{m/s}^2)(28.97\text{ kg/kg-mole})[(300-0)\text{ m}]}{(8314\text{ kg}\bullet\text{m}^2/\text{s}^2\bullet\text{kg-mole}\bullet\text{K})[(273.15+15)\text{ K}]}\right\}$$

$$= 0.965$$

P_s = standard pressure at sea level, (760 mm)(10.33m)

b. Determine the effective saturated DO concentration at 20°C. The problem provides an effective saturation depth of 2.5 m.

The effective DO saturation at 20°C is thus:

$$C^*_{\infty 20} = \frac{9.09(10.33+2.5)\text{m}}{10.33\text{m}} = 9.09(1.24)\text{m}$$

$$C^*_{\infty 20} = 11.27\text{ mg/L}$$

c. Determine the effect of temperature

$$\frac{C^*_{s,T}}{C^*_{\infty,20}} = \frac{10.08}{9.09} = 1.109$$

d. Determine the SOTR

$$\text{SOTR} = \frac{(\text{AOTR})(11.27\ \text{mg/L})}{\{[(1.0)(0.965)(1.109)(11.27) - 2.0]\text{mg/L}\}(0.45)(0.90)(1.024)^{(15-20)}}$$

SOTR = 3.11(AOTR)

$$\text{SOTR} = 3.11(139.3\ \text{kg/h}) = 433.2\ \text{kg/h}$$

e. Determine the air flow rate

$$\text{Air flowrate, m}^3\text{/min} = \frac{(\text{SOTR kg/h})}{[(\text{E})(60\ \text{min/h})(\text{kg O}_2/\text{m}^3\ \text{air})]}$$

From Appendix B, the density of air at 15°C and standard pressure is:

$$\rho_a = \frac{\text{Pm}}{\text{RT}} = \frac{(1.01325 \times 10^5\ \text{N/m}^2)(28.97\ \text{g/mole air})}{(8314\ \text{N}\bullet\text{m/mole air}\bullet\text{K})[(273.15+15)\text{K}]}$$

$$\rho_a = 1.225\ \text{kg/m}^3$$

At 300 m elevation,

$$\rho_a = 0.965(1.225\ \text{kg/m}^3) = 1.182\ \text{kg/m}^3$$

The corresponding amount of oxygen at 23.18 percent by weight (Appendix B-2) is

$(0.2318\ \text{kg/kg})(1.182\ \text{kg/m}^3) = 0.274\ \text{kg O}_2/\text{m}^3\ \text{air}$

$$\text{Air flowrate} = \frac{(433.2\ \text{kg/h})}{(0.30)(60\ \text{min/h})(0.274\ \text{kg O}_2/\text{m}^3\ \text{air})}$$

Air flowrate = 87.8 m^3/min

PROBLEM 8-23

Problem Statement – see text, page 926

Solution (Wastewater 1)

1. Determine the volume is using Eqs. (8-20), (8-21), and (7-57) in Table 8-10.

$(X_{TSS})V = P_{X,TSS}\,(SRT)$

$$P_{X,TSS} = \frac{QY_H(S_o - S)}{[1 + b_H(SRT)]0.85} + \frac{(f_d)(b_H)QY_H(S_o - S)SRT}{[1 + b_H(SRT)]0.85}$$

$$+ \frac{QY_n(NO_x)}{[1 + b_n(SRT)]0.85} + Q(nbVSS) + Q(TSS_o - VSS_o)$$

Combine equations

$$(X_{TSS})\left(\frac{V}{Q}\right) = \frac{Y_H(S_o - S)SRT}{[1 + b_H(SRT)]0.85} + \frac{(f_d)(b_H)Y_H(S_o - S)SRT^2}{[1 + b_H(SRT)]0.85}$$

$$+ \frac{Y_n(NO_x)SRT}{[1+b_n(SRT)]0.85} + (nbVSS)SRT + (TSS_o - VSS_o)SRT$$

2. Define input for above equation **for wastewater 1**

Influent bCOD = 1.6 (BOD) = 1.6 (270 mg/L) = 432 mg/L

Assume $S_o - S \approx S_o$ = 432 mg/L

Assume NO_x ~ 0.80 (TKN) = 0.80(40 mg/L) = 32 mg/L

V/Q = 1 d

X_{TSS} = 3500 mg/L

3. Determine coefficients from Table 8-14 and adjust for temperature using Eq. (1-44) in Table 8-10.

$k_T = k_{20}(\theta)^{T-20}$

Y_H = 0.45 gVSS/g bCOD

f_d = 0.15 g/g

$b_H = 0.12(1.04)^{10-20} = 0.081$ g/g•d

$b_n = (0.17$ g/g-d$)\,(1.029)^{10-20} = 0.128$ g/g•d

Y_n = 0.20 g VSS/g NH_4-N (includes growth from ammonia and nitrite oxidation.

4. Substitute values in the step 1 equation

$$(3500\text{ g/m}^3)(1\text{ d}) = \frac{0.45\text{ g/g}(432\text{ g/m}^3)(SRT)}{[1 + (0.081\text{g/g•d})SRT]0.85} + \frac{(0.15\text{ g/g})(0.081\text{g/g•d})(0.45\text{ g/g})(432\text{ g/m}^3)(SRT)^2}{[1 + (0.081\text{g/g•d})SRT]0.85}$$

$$+\frac{0.20\,\text{g/g}(32\ \text{g/m}^3)(\text{SRT})}{[1+(0.128\,\text{g/g}\bullet\text{d})\text{SRT}]0.85}+130\,\text{g/m}^3(\text{SRT})+(250-240)\,\text{g/m}^3(\text{SRT})$$

5. Solve equation with a spreadsheet by selecting SRT value where left and right sides of equation are equal.

$$3500=\frac{260.47\ (\text{SRT})}{1+.081\ \text{SRT}}+\frac{3.16\ (\text{SRT})^2}{1+0.081\ \text{SRT}}+\frac{7.53\ (\text{SRT})}{1+0.128\ \text{SRT}}+130\ \text{SRT}+10\ \text{SRT}$$

SRT = 11.9 d

6. Determine the sludge production rate using Eq. (7-57)

$$P_{X,TSS}=\frac{(X_{TSS})(V)}{\text{SRT}}=\frac{(3500\,\text{g/m}^3)(4000\,\text{m}^3)(1\ \text{kg}/10^3\ \text{g})}{11.9\,\text{d}}$$

$P_{X,TSS}$ = 1176.5 kg/d

7. Calculate MLVSS using Eq. (8-20) to determine $P_{X,VSS}$ and $P_{X,VSS}$ / $P_{X,TSS}$ ratio.

MLVSS / MLSS = ($P_{X,VSS}$) / ($P_{X,TSS}$)

$$P_{X,VSS}=\frac{Q(Y_H)(S_o-S)(1\ \text{kg}/10^3\text{g})}{1+b_H(\text{SRT})}+\frac{f_d(b_H)QY_H(\text{So}-S)\text{SRT}(1\ \text{kg}/10^3\text{g})}{1+b_H(\text{SRT})}$$

$$+\frac{QY_n(NO_x)(1\ \text{kg}/10^3\text{g})}{1+b_n(\text{SRT})}+Q(\text{nbVSS})(1\ \text{kg}/10^3\ \text{g})$$

$$P_{X,VSS}=\frac{(4000\,\text{m}^3/\text{d})(0.45\,\text{g/g})(432\,\text{g/m}^3)(1\ \text{kg}/10^3\text{g})}{[1+(0.081\ \text{g/g}\bullet\text{d})11.9\ \text{d}]}$$

$$+\frac{(0.15\text{g/g})(0.081\text{g/g}\bullet\text{d})(4000\,\text{m}^3/\text{d})(0.45\,\text{g/g})(432\,\text{g/m}^3)(11.9\,\text{d})(1\ \text{kg}/10^3\text{g})}{[(1+(0.081\text{g/g}\bullet\text{d})(11.9\text{d})]}$$

$$+\frac{(4000\text{m}^3/\text{d})(0.20\,\text{g/g})(32\text{g/m}^3)(1\ \text{kg}/10^3\text{g})}{[1+(0.128\ \text{g/g}\bullet\text{d})(11.9\text{d})]}+(4000\,\text{m}^3/\text{d})(130\text{g/m}^3)(1\ \text{kg}/10^3\text{g})$$

$P_{X,VSS}$ = (395.9 + 57.2 + 10.2 + 520) kg/d = 983.3 kg/d

$$\text{MLVSS} = (3500\ \text{mg/L})\left[\frac{(983.3\ \text{kg/d})}{(1176.5\ \text{kg/d})}\right]=2925.2\ \text{mg/L}$$

8. Determine the rate of oxygen required using Eq. (8-23) in Table 8-10.

$R_o = Q(S_o - S) - 1.42\ P_{X,bio} + 4.57\ Q\ (NO_x)$

a. Calculate $P_{X,bio}$ from components A and B in Eq. (8-20)

$$P_{X,bio} = \frac{(4000\,m^3/d)(0.45\,g/g)(432\,g/m^3)(1\ kg/10^3 g)}{[1+(0.081 g/g•d)(11.9 d)]}$$

$$+\frac{(0.15\,g/g)(0.081 g/g•d)(4000\,m^3/d)(0.45\,g/g)(432\,g/m^3)(1\ kg/10^3 g)}{[1+(0.081 g/g•d)(11.9 d)]}$$

$$= 395.9\ kg/d + 57.2\ kg/d = 453.1\ kg/d$$

b. Calculate NO_x using Eq. (8-24) in Table 8-10.

$$NO_x = TKN - N_e - 0.12\ P_{X,bio}/Q$$

$$NO_x = (40 - 1.0)\ g/m^3 - \frac{0.12\ (453.1\ kg/d)(10^3 g/kg)}{(4000\,m^3/d)}$$

$$NO_x = 25.4\ g/m^3$$

Note: This is lower than the assumed value of 32 g/m^3. Recalculation using 25.4 g/m^3 results in the following values for the previously calculated parameters shown above.

Parameter	NOx 25.4 g/m^3	NOx 32.0 g/m^3
MLSS, mg/L	3500	3500
SRT, d	11.9	11.9
$P_{X,TSS}$, kg/d	1176.5	1176.5
$P_{X,VSS}$, kg/d	981.2	983.3
NOx-N, g/m^3	25.4	25.4

c. Calculate R_o

$$R_o = (4000\ m^3/d)\ (432\ g/m^3)\ (1\ kg/10^3\ g) - (1.42\ g/g)\ (453.1\ kg/d)$$
$$+ 4.57\ (4000\ m^3/d)\ (25.4\ g/m^3)(1\ kg/10^3\ g)$$

$$R_o = (1728.0 - 643.4 + 464.3)\ kg/d = 1548.9\ kg/d$$

$$AOTR = \frac{(1548.9\ kg/d)}{(24\ h/d)} = 64.54\ kg/h$$

9. Determine the aeration horsepower at 10°C by first converting the oxygen transfer rate to that required at clean water standard conditions using Eq. (5-70) and the values given in the problem statement. The value for the

fouling factor (F) is equal to 1.0 as fouling is not a factor for surface mechanical aerators.

$$\text{SOTR} = \frac{(\text{AOTR})C^*_{\infty,20}}{\left[(\beta)\left(\frac{P_b}{P_S}\right)\left(\frac{C^*_{S,T}}{C^*_{\infty,20}}\right)C^*_{\infty,20} - C\right]\alpha F(1.024)^{(T-20)}}$$

From Appendix E, Table E-1, $C_{s,20}$ = 9.09 mg/L

a. From Appendix B-4, determine the barometric pressure at 500 in elevation to use for a pressure correction.

$$\frac{P_b}{P_s} = \exp\left[-\frac{gM(z_b - z_a)}{RT}\right]$$

$$= \exp\left\{\frac{9.81\ \text{m/s}^2(28.97\,\text{kg/kg}-\text{mole})(500-0)\text{m}}{(8314\,\text{kg}\bullet\text{m}^2/\text{s}^2\bullet\text{kg}-\text{mole}\bullet\text{K})[(273.15+10)\text{K}]}\right\}$$

$$\frac{P_b}{P_s} = 0.941$$

b. From Appendix E, $C_{s,10°C}$ = 11.29 mg/L

$$\frac{C^*_{S,T}}{C^*_{\infty,20}} = \frac{11.29}{9.09} = 1.242$$

c. Calculate SOTR

$$\text{SOTR} = \frac{(65.54\ \text{kg/h})(9.09\ \text{mg/L})}{[(0.98)(0.941)(1.242)9.09 - 2.0](0.90)(1.024)^{(10\text{-}20)}}$$

$$= 103.3\ \text{kg/h}$$

d. Calculate the total aeration energy using clean water efficiency provided in problem statement.

$$\text{Installed energy} = \frac{(103.3\ \text{kg/h})}{(0.9\ \text{kg/kWh})} = 114.8\ \text{kW}$$

From Appendix A, Table A-1

$$\text{Horsepower} = \frac{114.8\ \text{kW}}{(0.746\,\text{kW/hp})} = 153.9$$

Note: For an actual aerator design application, these calculations should also be done at the high design temperature. At higher temperatures for the same SRT more oxygen will be consumed by the heterotrophic biomass and the aerator SOTR/AOTR calculation will be different.

10. Determine the SRT required for nitrification at the temperature given. Use Eq. (7-94) and Eq. (7-98) in Table 8-10 to calculate the specific growth rate of ammonia-oxidizing bacteria (AOB) in this complete-mix activated sludge system.

$$\mu_{AOB} = \left(\frac{\mu_{max,AOB} S_{NH4}}{K_{NH4} + S_{NH4}}\right)\left(\frac{DO}{K_{o,AOB} + DO}\right) - b_{AOB}$$

and thus:

$$\frac{1}{SRT} = \left(\frac{\mu_{max,AOB} S_{NH4}}{K_{NH4} + S_{NH4}}\right)\left(\frac{DO}{K_{o,AOB} + DO}\right) - b_{AOB}$$

a. Determine the design SRT using the safety factor (SF) based on Eq. (7-73) in Table 8-10:

Design SRT = SF (required SRT)

b. Determine nitrification kinetic coefficients at 10°C using values from Table 8-14. (based on ammonia oxidation)

$\mu_{max,AOB}$ = (0.90 g/g-d) $(1.072)^{10-20}$ = 0.449 g/g•d

k_{NH4} = (0.50 mg/L) $(1.0)^{10-20}$ = 0.50 g/m^3

b_{AOB} = (0.17 g/g-d) $(1.029)^{10-20}$ = 0.128 g/g•d

$K_{o,AOB}$ = 0.50 g/m^3

$$\frac{1}{SRT} = \left\{\frac{(0.449\ \text{g/g•d})(1.0\ \text{mg/L})}{[(0.50+1.0)\text{mg/L}]}\right\}\left\{\frac{(2.0\ \text{mg/L})}{[(0.50+2.0)\ \text{mg/L}]}\right\} - 0.128\ \text{g/g•d}$$

$$\frac{1}{SRT} = 0.111\ \text{d}^{-1}$$

$$SRT = \frac{1}{0.111\ \text{d}^{-1}} = 9.0\ \text{d}$$

Design SRT = 1.5(9.0 d) = 13.5 d

But the SRT is only 11.9 d, which gives a safety factor of 1.32.

For the 1.5 safety factor the SRT could be increased by increasing the MLSS concentration to approximately (1.5/1.32)(3500 mg/L) = 3980 mg/L, which may be possible if the secondary clarifiers have sufficient area. Otherwise the effluent NH_4-N concentration may be higher during peak loading.

11. Determine ratio of total volume to required nitrification volume at average load:

$$\frac{\text{Total volume}}{\text{Nitrification volume}} = \frac{11.9\,\text{d}}{9.0\,\text{d}} = 1.32$$

Note: By controlling DO concentration, a portion of the oxidation ditch channel volume can be at low to zero DO concentration to accomplish denitrification.

PROBLEM 8-24

Problem Statement – see text page 927

Solution

1. Determine fill time (t_F) by applying uniform flow assumption for 2 tanks and assuming idle time $t_I = 0$

   $T_C = t_F + t_A + t_S + t_D$

   for 2 Tanks

   $t_F = t_A + t_S + t_D = (2.0 + 1.0 + 0.5)\text{ h} = 3.5\text{ h}$

   Total cycle time, $T_c = (3.5 + 2.0 + 1.0 + 0.5)\text{ h} = 7.0\text{ h}$

2. Determine the total volume. The full volume is related to the feed volume per cycle and fraction of the tank volume removed (and filled) each cycle.

   Feed volume/cycle = flow rate (fill time)

$$= (4000\ \text{m}^3/\text{d})(1\ \text{d}/24\ \text{h})(3.5\ \text{h/fill}) = 583.3\ \text{m}^3$$

As given: $\frac{V_F}{V_T} = 0.20$

where V_F = fill volume and V_T = total volume

$$V_T = \frac{V_F}{0.20} = \frac{583.3\,\text{m}^3}{0.20} = 2916.7\ \text{m}^3$$

3. Determine the SRT using Eqs. (8-20), (8-21), and (7-57) in Table 8-10 and total volume of 2916.7 m^3 and flow of 2000 m^3/d per tank (4000 m^3/d for 2 tanks)

   $(X_{TSS})V = P_{X,TSS}\,(SRT)$

$$P_{X,TSS} = \frac{QY_H(S_o - S)}{[1+b_H(SRT)]0.85} + \frac{(f_d)(b_H)QY_H(S_o - S)SRT}{[1+b_H(SRT)]0.85}$$

$$+ \frac{QY_n(NO_X)}{[1+b_n(SRT)]0.85} + Q(nbVSS) + Q(TSS_o - VSS_o)$$

   Combine equations

$$(X_{TSS})\left(\frac{V}{Q}\right) = \frac{Y_H(S_o - S)SRT}{[1+b_H(SRT)](0.85)X} + \frac{(f_d)(b_H)Y_H(S_o - S)(SRT)^2}{[1+b_H(SRT)](0.85)X}$$

$$+ \frac{Y_n(NO_X)SRT}{[1+b_n(SRT)](0.85)X} + (nbVSS)SRT + (TSS_o - VSS_o)SRT$$

4. Define input for above equation **for wastewater A**

   Influent bCOD = 1.6 (BOD) = 1.6 (270 mg/L) = 432 mg/L

   Assume $S_o - S \approx S_o = 432$ mg/L

   Assume $NO_x \sim 0.80$ (TKN) = 0.80 (40) = 32 mg/L

   (Note: Nitrifier growth has very small effect on MLSS concentration compared to other factors)

5. Determine coefficients from Table 8-14 and adjust for temperature using Eq. (1-44) in Table 8-10.

   $k_T = k_{20}(\theta)^{T-20}$

   $Y_H = 0.45$ gVSS/g bCOD

f_d = 0.15 g/g

$b_H = 0.12(1.04)^{10\text{-}20} = 0.081$ g/g • d

Y_n = 0.20 g VSS/g NH_4-N (includes ammonia and nitrite oxidizers)

$b_n = 0.17(1.029)^{10\text{-}20} = 0.128$ g/g • d

6. Substitute values in the step 3 equation

$$(3500\ \mathrm{g/m^3})\left[\frac{2916.7\ \mathrm{m^3}}{(2000\ \mathrm{m^3/d})}\right] = \frac{0.45\,\mathrm{g/g}(432\,\mathrm{g/m^3})(\mathrm{SRT})}{[1+(0.081\mathrm{g/g \bullet d})\mathrm{SRT}]0.85}$$

$$+\frac{(0.15\,\mathrm{g/g})(0.081\mathrm{g/g \bullet d})(0.45\,\mathrm{g/g})(432\,\mathrm{g/m^3})(\mathrm{SRT})^2}{[1+(0.081\mathrm{g/g \bullet d})\mathrm{SRT}]0.85}$$

$$+\frac{0.20\,\mathrm{g/g}(32\ \mathrm{g/m^3})(\mathrm{SRT})}{[1+(0.128\,\mathrm{g/g \bullet d})\mathrm{SRT}]0.85} + 130\,\mathrm{g/m^3}(\mathrm{SRT}) + (250-240)\mathrm{g/m^3}(\mathrm{SRT})$$

7. Solve equation on spreadsheet by selecting SRT value where left and right sides of equation are equal, or use Excel solver function.

$$5104.2 = \frac{228.7(\mathrm{SRT})}{1+.081\mathrm{SRT}} + \frac{2.78(\mathrm{SRT})^2}{1+0.081\mathrm{SRT}} + \frac{7.53(\mathrm{SRT})}{1+0.128\,\mathrm{SRT}} + 130\,\mathrm{SRT} + 10\,\mathrm{SRT}$$

SRT = 20.5 d

8. Determine the decant pumping rate

$$Q_{decant} = \frac{\text{volume/fill}}{t_D} = \frac{583.3\ \mathrm{m^3}}{0.5\,\mathrm{h}\ (60\ \mathrm{m/h})} = 19.44\ \mathrm{m^3/min}$$

PROBLEM 8-25

Problem Statement – see text, page 927

Instructors Note: The approach used in example problem 8-3 can be followed to solve this problem. First, the biomass production rate ($P_{X,bio}$) is calculated and used to determine the nitrogen used for cell synthesis, so that the oxidizable nitrogen (NO_x) can be determined. Then the oxidizable N concentration at the beginning of the aeration period is calculated and the time necessary to reduce it to 0.5 mg/L NH_4-N is determined using the batch reaction Eq. (8-49). The time can be then compared to the actual aeration time.

Solution (Wastewater #1)

1. Determine $P_{X,bio}$ from the A, B, and C terms in Eq. (8-20)

$$P_{X,bio} = \frac{Q(Y_H)(S_o - S)}{1 + b_H(SRT)} + \frac{f_d(b_H)Q(Y_H)(S_o - S)SRT}{1 + b_H(SRT)} + \frac{QY_n(NO_x)}{1 + b_n(SRT)}$$

2. Define inputs for above equation **for wastewater #1**

Flowrate = 4800 m^3/d

Influent bCOD = 1.6BOD = 1.6(250 mg/L) = 400 mg/L

Assume $S_o - S \approx S_o$

Assume NO_x-N ~ 0.80(TKN) = 0.80(45 mg/L) = 36 mg/L

# of SBR tanks = 2

Volume per SBR Tank = 3000 m^3

$$\text{Flow/tank} = \frac{(4800\ m^3/d)}{2\ \text{tanks}} = 2400\ m^3/d\text{•tank}$$

SRT = 20 d

Aeration DO concentration = 2.0 mg/L

Fill volume fraction (V_F/V_T) per cycle = 0.20

Aeration Time per cycle = 2.0 h

Temperature = 15°C

3. Determine non-aerated time and fraction of aerobic time during cycle

Non-aerated time = fill + settle + decant times

Fill volume per cycle = $(V_F/V_T)(V_T) = 0.20(3000\ m^3) = 600\ m^3/\text{cycle}$

$$\text{Number of cycles per day per tank} = \frac{(2400\ m^3/\text{d-tank})}{(600\ m^3/\text{cycle})} = 4\ \text{cycles/d}$$

$$\text{Cycle time} = \frac{(24\ h/d)}{(4\ \text{cycles/d})} = 6\ h/\text{cycle}$$

From Example 8-5: $T_C = t_F + t_A + t_S + t_D$

$6.0\ h = t_F + 2.0\ h + t_S + t_D$

$t_F + t_S + t_D = 6.0 - 2.0 = 4.0\ h$

Fraction aerobic time = $\dfrac{t_A}{T_C} = \dfrac{2\ h}{6\ h} = 0.33$

4. Determine coefficients from Table 8-14 and adjust for temperature using Eq. (1-44) in Table 8-10, where T = 15°C

$k_T = k_{20}(\theta)^{T-20}$

$Y_H = 0.45$ g VSS/g bCOD

$f_d = 0.15$ g/g

$b_H = 0.12(1.04)^{(15-20)} = 0.0986$ g/g • d

$\mu_{max,AOB,15} = \mu_{max,AOB,20}(1.072)^{(15-20)} = 0.90(0.706) = 0.636$ g/g•d

$K_n = 0.50$ mg/L

$Y_n = 0.20$ g VSS/g NH_3-N (assumes minimal NO_2 at end of aeration)

Per Example 8-5 for weighted average b_n for nitrifiers

Aerobic $b_n = 0.17(1.029)^{(15-20)} = 0.147$ g/g•d

Anoxic $b_n = 0.07(1.029)^{(15-20)} = 0.061$ g/g•d

Weighted average $b_n = 0.147$ g/g•d$(t_A/T_C) + 0.061$ g/g•d$(1 - t_A/T_C)$

Weighted average $b_n = 0.147$ g/g•d(0.33) + 0.061 g/g•d(0.67) = 0.089 g/g•d

4. Determine $P_{X,bio}$

$$P_{X,bio} = \frac{(2400\,m^3/d)(0.45\,g/g)(400\,g/m^3)}{[1 + (0.0986\,g/g{\bullet}d)(20\,d)]}$$

$$+\frac{(0.15\,\text{g/g})(0.0986\,\text{g/g•d})(2400\,\text{m}^3\text{/d})(0.45\,\text{g/g})(400\,\text{g/m}^3)(20\,\text{d})}{[1+(0.0986\,\text{g/g•d})(20\text{d})]}$$

$$+\frac{(0.20\,\text{g/g})(2400\text{ m}^3\text{/d})(0.80)(45\,\text{g/m}^3)}{[1+(0.089\,\text{g/g•d})(20\,\text{d})]}$$

$P_{X,bio}$ = (145,357 + 42,997 + 6216) g/d = 194,570 g/d

5. Determine NO_x-N from Eq. (8-24), Table 8-10.

NO_x-N = TKN – N_e – 0.12 $P_{X,bio}$/Q

Assume N_e = 0.50 g/m^3

$$NO_x\text{-N} = 45.0\text{ g/m}^3 - 0.50\text{ g/m}^3 - \frac{0.12(194{,}570\text{ g/d})}{(2400\text{ m}^3\text{/d})}$$

NO_x-N = (45.0 – 0.50 – 9.73) g/m^3 = 34.8 g/m^3

Note: replace NO_x-N of [(0.8)(45) = 36] with 34.8 part C of $P_{x,bio}$. The iteration results in NO_x-N = 34.8.

6. Determine amount of oxidizable N available at start of aeration

NO_x-N available in feed = 34.8 g/m^3

NO_x added/cycle = V_F (NO_x)

NO_x added/cycle = (600 m^3/cycle)(34.8 g/m^3) = 20,880 g

NH_4-N remaining before fill = (V_T – V_F)(N_e)

Assumed N_e = 0.50 g/m^3

(V_T – V_F)(N_e)= (0.50 g/m^3)(3000 – 600) m^3 = 1200 g

Total oxidizable N = (20,880 + 1200) g = 22,080 g

$$\text{Initial concentration} = N_o = \frac{22{,}080\text{ g}}{3000\text{ m}^3} = 7.36\text{ g/m}^3$$

7. Solve for final NH_4-N concentration (N_t) at aeration time = 2.0 h

   a. Define equations needed

$$K_n \ln\frac{N_o}{N_t}+(N_o-N_t)=X_n\left(\frac{\mu_{nm}}{Y_n}\right)\left(\frac{DO}{K_o+DO}\right)t$$

where t = aeration time = 2.0 h

$$X_n = \frac{Q(Y_n)(NO_x\text{-}N)SRT}{[1+b_n(SRT)]V}$$

b. Apply coefficients from step 4 to determine AOB concentration.

$$X_n = \frac{(2400\,m^3/d)(0.15\,g/g)(34.8 g/m^3)(20\ d)}{[1+(0.089\,g/g{\bullet}d)(20\ d)](3000\,m^3)} = 30.0\ g/m^3$$

c. Solve for Nt for aeration time = 2.0 h (use solver on Excel)

$$K_n\ \ln\frac{N_o}{N_t} + (N_o - N_t) = X_n\left(\frac{\mu_{nm}}{Y_n}\right)\left(\frac{DO}{K_o + DO}\right) t$$

t = 2 h/(24 h/d) = 0.0833 d

$$(0.50\ g/m^3)\ \ln\left[\frac{(7.36\ g/m^3)}{N_t}\right] + (7.36\ g/m^3 - N_t) =$$

$$29.6\ g/m^3\left[\frac{(0.636\ g/g \bullet d)}{(0.15\ g/g)}\right]\left[\frac{(2.0\ g/m^3)}{(0.5\ g/m^3 + 2.0\ g/m^3)}\right] 0.0833\ d$$

N_t = 0.37 g/m^3

This value must be used in place of the assumed value of 0.50 g/m^3 and thus the previous calculations must be iterated on spreadsheet. At each interation the NO$_x$-N will change and thus must be adjusted before solving for Nt. By the 4th iteration the following was determined with an exact solution;

N_t = 0.30 mg/L

NO$_x$-N = 35.0 mg/L

X_n = 30.2 mg/L

PROBLEM 8-26

Problem Statement – see text, page 928

Solution

1. Determine the settled volume mixed liquor concentration with **SVI = 150** mL/g using Eq. (8-43).

$$X_R = \frac{1}{SVI}\frac{(10^3\ \text{mg/1 g})}{(1\,\text{L}/10^3\ \text{mL})} = \frac{10^6}{150\ \text{mL/g}} = 6666\ \text{mg/L}$$

2. Determine the fraction of the depth occupied by the settled mixed liquor.

   The depth fraction is equal to the settled volume divided by the total volume.

   $$\frac{V_S}{V_T} = \frac{X}{X_S} = \frac{(3500\ \text{mg/L})}{(6666\ \text{mg/L})} = 0.525\ = 0.525$$

3. Determine the settled, decant, andf fill depths.

   Settled mixed liquor depth = 0.525 (total depth) = 0.525 (5.5 m) = 2.9 m

   The allowable settled depth including the 0.6 m clear liquid = 0.6 m + 2.9 m = 3.5 m

   The decant depth = total depth – settled depth

   = (5.5 – 3.5) m = 2.0 m

   The fill depth = decant depth = 2.0 m

4. Determine the fill volume/total volume ratio

   The fill volume (V_F) to total volume (V_T) ratio is proportional to fill depth/total depth

   $$\frac{V_F}{V_T} = \frac{2.0\ \text{m}}{5.5\ \text{m}} = 0.36$$

PROBLEM 8-27

Problem Statement – see text, page 928

Solution

Design conditions and assumptions given in Example 8-6.

Solution

1. Determine the SRT value and the concentration of the nitrifying bacteria for a single-stage system, τ = 8 h = 0.33 d, **$N = 1.0\ g/m^3$**.

   a. Solve for the specific growth rate using Eq. (7–94) in Table 8–10.

$$\mu_{AOB} = \mu_{max,AOB,16}\left[\frac{S_{NH}}{S_{NH} + K_{NH}}\right]\left[\frac{S_o}{S_o + K_{o,AOB}}\right] - b_{AOB}$$

$$\mu_{AOB} = \left\{\frac{(0.681\,g/g \bullet d)(1.0\,g/m^3)}{[(0.50 + 1.0)\,g/m^3]}\right\}\left\{\frac{(2.0\,g/m^3)}{[(0.50 + 2.0)\,g/m^3]}\right\} - 0.151 = 0.212\ g/g \bullet d$$

b. Solve for SRT using Eq. (7–98) in Table 8-10.

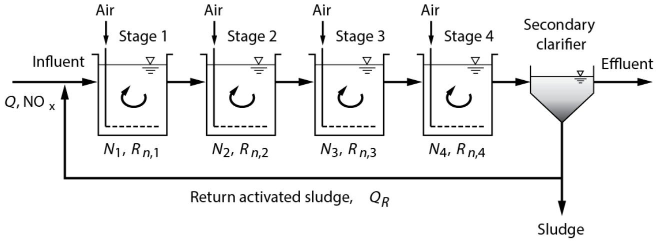
$$SRT = \frac{1}{\mu_{AOB}} = \frac{1}{(0.212\ g/g \bullet d)} = 4.72\ d$$

c. Solve for the concentration of nitrifying bacteria using a modified form of Eq. (7–42).

$$X_n = \frac{(SRT)Y_n(NO_x)}{\tau[1 + b_n(SRT)]}$$

$$= \frac{(4.72\ d)(0.15\ g/g)(30\ g/m^3)}{(0.33\ d)[1 + (0.151\,g/g \bullet d)(4.72\ d)]} = 37.5\ g/m^3$$

2. Perform nitrogen mass balances for a four-stage system shown on the following figure using equal volumes per stage. The total volume of the four-stage system is equal to the volume of the CMAS system, τ/stage = 0.333 d/4 = 0.0833 d/stage.



a. For Stage 1

Accumulation = in – out + generation

$$\frac{dN_1}{dt}V = Q(NO_x) + Q_R N_4 - (Q + Q_R)N_1 - R_{n,1}V$$

The rate expression for nitrification, derived from Eq. (7–101) in Table 8-10 includes a correction for the DO concentration, and is given by

$$r_{NH4} = \left[\frac{\mu_{max,AOB}}{Y_{AOB}}\right]\left[\frac{S_{NH4}}{S_{NH4} + K_{NH4}}\right]\left[\frac{S_o}{S_o + K_{o,AOB}}\right]X_{AOB}$$

where Q = wastewater flowrate, m^3/d

NO_x = amount of available influent NH_4-N oxidized, 30 g/m^3

Q_R = recycle flowrate from stage 4, m^3/d

$Q/Q_R = 0.50$

N_4 = NH_4-N concentration for stage 4, g/m^3

N_1 = NH_4-N concentration for stage 1, g/m^3

$R_{n,1}$ = nitrification rate for stage 1, $g/m^3 \cdot d$

X_n = nitrifying bacteria concentration, g/m^3

The nitrifying bacteria concentration is the same as that calculated for the CMAS system assuming that the same amount of NH_4-N is removed and the systems are at the same SRT.

At steady state $dN_1/dt = 0$, and

$$NO_x + Q_R / QN_4 - (1 + Q_R / Q) / N_1 - R_{n,1}V / Q = 0$$

$$NO_x + 0.5N_4 = 1.5N_1 + R_{n,1}(\tau)$$

where τ = 0.0833 d, detention time of stage 1

$NO_x = 30\ g/m^3$

b. For Stage 2, use the same procedure as Stage 1.

$$V\frac{dN_2}{dt} = (Q + Q_R)N_1 - (Q + Q_R)N_2 - R_{n,2}V$$

$$1.5N_1 = 1.5N_2 + R_{n,2}(\tau)$$

c. For Stage 3

$$1.5N_2 = 1.5N_3 + R_{n,3}(\tau)$$

d. For Stage 4

$$1.5N_3 = 1.5N_4 + R_{n,4}(\tau)$$

3. $R_{n,i(i=1-4)}$ is a function of the NH_4-N concentration (N) in each stage:

For stage 1,

$$R_{n,i}=\left[\frac{(0.681\,g/g\bullet d)}{(0.15\text{ g VSS/g NH}_4\text{-N})}\right]\left\{\frac{N_i}{[(0.50+N_i)\text{ g/m}^3]}\right\}\left\{\frac{(2.0\text{ g/m}^3)}{[(0.5+2.0)\text{ g/m}^3]}\right\}(37.5\text{ g/m}^3)$$

$$R_{n,i}=136.2\left[\frac{N_i}{[(0.50+N_i)\text{ g/m}^3]}\right],\text{where i = 1, 2, 3, or 4 for stages 1-4}$$

4. The above equations for the four stages are solved with a spreadsheet program starting with Stage 1 either by using Solver in the Excel software or by an iterative technique. In the iterative technique the value for N_4 is assumed and N_1 is calculated. Subsequently N_2, N_3 and N_4 are calculated. Using Solver, the following effluent NH_4-N concentrations are computed for each stage for a return sludge recycle ratio of 1.0. In addition a solutions is also shown for a return sludge recycle ratio of 6.0 as would be typical for an MBR system:

	NH_4-N concentration, g/m^3	
Stage	Recycle Ratio = 0.50	Recycle Ratio = 6.0
1	13.11	3.73
2	6.17	2.40
3	1.07	1.25
4	0.08	0.47

Comment

Based on the above results, the same effluent NH4-N concentration of 1.0 mg/L can be achieved with a little over 3 of the 4 stages for the aerobic staged nitrification system showing that staging reduces the aeration tank volume needed by about 25% compared to that required for a CMAS design at a recycle ratio of 0.50. At the higher recycle ratio the amount of volume reduction is not as much due to the greater dilution of the influent NH_4-N concentration with lower NH_4-N concentrations driving the nitrification reaction rates in the first two stages. Thus, a staged nitrification reactor is more efficient than a CMAS reactor design and compared to the CMAS the staged system can have a lower SRT and thus lower total volume. Or for the same SRT and volume, the staged system would produce a lower average effluent NH_4-N concentration. The above solution is also illustrative of the importance of the return activated sludge recycle ratio. The effluent NH_4-N concentration is higher for the MBR system, which has a higher recycle ratio. The effect of the higher recycle ratio is to dilute the influent NH_4-N concentration more so that the NH_4-N concentration is lower in the first stage. Because the nitrification rate is related to the NH_4-N concentration, the nitrification rate is lower and thus the effluent concentration is higher.

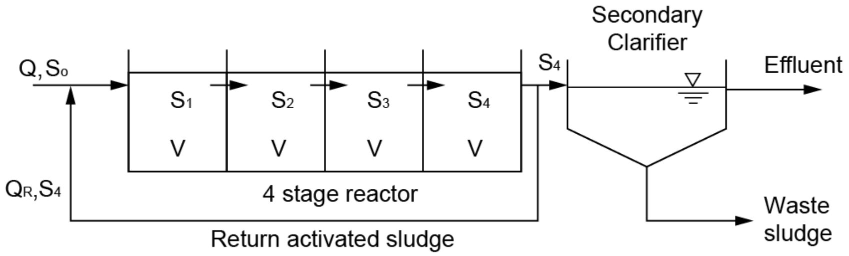
PROBLEM 8-28

Problem Statement – see text, page 928

Instructors Note: This problem is solved in a manner similar to that used for nitrification for the staged system in Example 8-6. A mass balance is performed at each stage using Eq. (7-12) in Table 8-10 for the substrate utilization rate, and the biomass concentration X is given. Changes in X in each stage is small relative to the stage concentration and can be ignored.

Solution

1. Develop a flow diagram



2. Prepare a mass balance; use Eq. (7-12) $r_{su} = \frac{kXS}{K_s + S}$

<u>Stage 1 mass balance</u>:

$$V\frac{dS_1}{dt} = QS_o + Q_RS_4 - (Q + Q_R)\,S_1 - Vr_{su,1}$$

at steady state, $\frac{dS_1}{dt}$ = 0, divide by Q, $Q_R/Q = R$

$$S_o + RS_4 - (1+R)\,S_1 - \frac{V}{Q}r_{su} = 0$$

Substitute r_{su}:

$$S_o + RS_4 - (1 + R)\,S_1 - \frac{V}{Q}\left(\frac{kXS_1}{K_s + S_1}\right) = 0$$

By assuming S_4, a value for S_1 can be calculated. S_4 is selected and an iterative spreadsheet solution is done until the S_4 calculated for Stage 4 equals the assumed S_4.

Stage 2:

$$V\frac{dS_2}{dt} = (Q + Q_R)S_1 - (Q + Q_R)\,S_2 - Vr_{su,2}$$

$$(1 + R)\,S_1 - (1 + R)\,S_2 - \frac{V}{Q}\left(\frac{kXS_2}{K_s + S_2}\right) = 0$$

Similarly:

Stage 3: $(1 + R)\,S_2 - (1 + R)\,S_3 - \frac{V}{Q}\left(\frac{kXS_3}{K_s + S_3}\right) = 0$

Stage 4: $(1 + R)\,S_3 - (1 + R)\,S_4 - \frac{V}{Q}\left(\frac{kXS_4}{K_s + S_4}\right) = 0$

3. Summarize the parameters to be used in the above equations.
   a. From table in Problem Statement for **wastewater 1**:

      $k = 1.2$ g COD/g VSS • d

      $K_s = 50\ g/m^3$
   b. Given values:

      $X = 1600\ g/m^3$

      $S_o = 300\ g/m^3$ BOD

      $= 1.6\ (300\ g/m^3) = 480\ g/m^3$ COD

      $$\frac{V}{Q} = \frac{240\ m^3}{(4000\ m^3/d)} = 0.06\ d$$

R = 0.5

4. Use a spreadsheet program to solve the equations.

   The spreadsheet solution is given in the following table

Stage	S, bCOD, mg/L
1	293.4
2	230.3
3	170.9
4	117.0

5. Determine the oxygen consumption rate. The oxygen consumption rate in each stage is related to oxygen consumed for substrate utilization, nitrification, and for endogenous decay as shown in Eq. (8-25). For this problem there is no nitrification. Thus, the oxygen demand is calculated as follows:

   Stage 1

$$R_{o,1} = [(QS_o + Q_RS_4) - (Q + Q_R)S_1](1 - Y_H) + 1.42b_HX(V_1)$$

Y_H = (0.35 g VSS/g COD)(1.42 g COD/g VSS) = 0.50 g COD/g COD

Q_R = RQ = 0.5(4000 m^3/d) = 2000 m^3/d

$$R_{o,1} = [(4000\ m^3/d)(480\ g/m^3) + (2000\ m^3/d)(117\ g/m^3)$$

$$-(6000\ m^3/d)(293.4\ g/m^3)][1 - (0.5\ g/g)]$$

$$+1.42(0.10\ g/g{\bullet}d)(1600\ g/m^3)(240\ m^3)$$

Two oxygen demand terms are shown; for substrate utilization rate (R_{os}) and for endogenous decay rate (R_{oe})

$R_{o,1} = R_{os} + R_{oe}$

$R_{o,1}$ = 198,129 g O_2/d + 54,528 g O_2/d

Stage 2

$$R_{o,2} = [(Q + Q_R)(S_1 - S_2)](1 - Y_H) + 1.42b_HX(V_2)$$

$$R_{o,2} = [(6000\ m^3/d)[(293.4 - 230.3)\ g/m^3][(1 - 0.5)\ g/g]$$

$$+1.42(0.10\ g/g{\bullet}d)(1600\ g/m^3)(240\ m^3)$$

$R_{o,2}$ = 190,432 g O_2/d + 54,528 g O_2/d

Similar calculations follow for Stages 3 and 4.

The oxygen demand for substrate utilization and endogenous decay is summarized for each stage.

Stage	S, bCOD, g/m^3	R_{os}, kg/d	R_{oe}, kg/d	O_2 Total, kg/d	Fraction of total
1	293.4	198.1	54.5	252.6	0.27
2	230.3	190.4	54.5	244.9	0.26
3	170.9	179.3	54.5	233.8	0.25
4	117.0	162.4	54.5	216.9	0.22
				948.2	1.00

Note: The oxygen demand per stage is similar as the substrate concentration is high relative to the half-velocity coefficient value, K_s, so that the reaction rate approaches zero order in each stage.

The solution for a higher value for k of 10.0 g COD/g VSS • d is shown in the following table.

Stage	S, bCOD, g/m^3	R_{os}, kg/d	R_{oe}, kg/d	O_2 Total, kg/d	Fraction of total
1	39.1	847.7	54.5	902.2	0.76
2	3.0	109.0	54.5	163.5	0.14
3	0.22	8.4	54.5	62.9	0.05
4	0.02	0.6	54.5	55.1	0.05
				1183.7	1.00

76% of oxygen required is in the first stage for this case with a higher specific substrate utilization rate coefficient value.

PROBLEM 8-29

Problem Statement – see text, page 928

Solution

The comparison is given in the following table.

Parameter	Processes			
	Complete-mix	Pure oxygen	Contact stabilization	Oxidation ditch
Effluent quality	Low BOD/TSS Good nitrification	Low BOD/TSS Nitrification not common due to low SRT and low pH	Higher BOD/TSS but less than 30 mg/L possible Little or no nitrification	Low BOD/TSS Good nitrification Some denitrification possible
Space requirements	Moderate	Low	Low but more than pure oxygen system	High
Complexity	Low	Most complex with covered system and O_2 supply	Low	Low
Energy requirements	Moderate	Higher than complete-mix system	Moderate to low	Highest
Operational requirements	Moderate	High	Moderate	Lowest
Ability to handle variable loads	Moderate	Low	Moderate	High

PROBLEM 8-30

Problem Statement – see text, page 928

Solution (wastewater #1)

1. Prepare a solids balance for each tank to determine the MLVSS concentration (ignore biomass or solids production – low relative to solids flow in/out). **Use parameters for wastewater #1.**

   Assume steady state: in = out.

   Pass 1:

$$Q_RX_R + Q_1(O) = (Q_1 + Q_R)\,X_1$$

$$X_1 = \frac{Q_RX_R}{Q_1+Q_R} = \frac{(2000\,m^3/d)(10{,}000\,g/m^3)}{[(800+2000)m^3/d]} = 7142.9\ g/m^3$$

   Pass 2

$$(Q_1 + Q_R)\,X_1 + Q_2(0) = (Q_1 + Q_2 + Q_R)\,X_2$$

$$X_2 = \frac{(Q_1 + Q_R)X_1}{Q_1 + Q_2 + Q_R} = \frac{[(800 + 2{,}000)\,m^3/d](7142.9\,g/m^3)}{[(800 + 1200 + 2000)\,m^3/d]} = 5000\ g/m^3$$

Pass 3

$(Q_1 + Q_2 + Q_R)\ X_2 + Q_3(0) = (Q_1 + Q_2 + Q_3 + Q_R)\ X_3$

$$X_3 = \frac{(Q_1 + Q_2 + Q_R)X_2}{Q_1 + Q_2 + Q_3 + Q_R} = \frac{[(800 + 1200 + 2{,}000)\,m^3/d](5000\,g/m^3)}{[(800 + 1200 + 1000 + 2000)\,m^3/d]}$$

X_3 = 4000 mg/L

Pass 4

Similarly,

$$X_4 = \frac{(Q_1 + Q_2 + Q_3 + Q_R)X_3}{Q_1 + Q_2 + Q_3 + Q_4 + Q_R} = \frac{[(800 + 1200 + 1000 + 2{,}000)\,m^3/d](4000\,mg/L)}{[(800 + 1{,}200 + 1000 + 1000 + 2000)\,m^3/d]}$$

X_4 = 3333 mg/L

Summary:

Tank #	MLVSS, mg/L
1	7143
2	5000
3	4000
4	3333

PROBLEM 8-31

Problem Statement – see text, page 929

Solution

1. Use Eq. (8-62) to determine the internal recycle ratio and recycle flow rate.

   $$IR = \frac{NO_x}{N_e} - 1.0 - R$$

2. Determine the effluent NO_3-N concentration (N_e) based on requirement of 85 percent N removal and given effluent NH_4-N = 1.0 mg/L. Assume effluent NO_2-N concentration ≈ 0.0 and ignore soluble organic nitrogen concentration (conservative design).

   N_e = (1 – 0.85) TKN – NH_4-N

   N_e = 0.15 (35 mg/L) – (1.0 mg/L) = 4.25 mg/L NO_3-N

3. Estimate sludge recycle ratio by simple mass balance around secondary clarifier (ignore sludge wasting) per Step 21 in Example 8-3.

$$R = \frac{X}{X_R - X} = \frac{(3500\,\text{mg/L})}{[(10{,}000 - 3{,}500)\,\text{mg/L}]} = 0.54$$

4. Determine NO_x using Eq. (8-24) in Table 8-10.

$NO_x = TKN - N_e - 0.12\ P_{X,bio}/Q$

$P_{X,bio}$ can be determined using Eq. (7-56), Table 8-10, and the information provided by using X_b in place of X_{vss}.

$X_b\ V = P_{X,bio}\ (SRT)$

$$P_{X,bio} = \frac{X_b V}{SRT} = \frac{(1620\,\text{g/m}^3)460\,\text{m}^3}{10\,\text{d}} = 74{,}520\ \text{g/d}$$

$$NO_x = 35.0\ \text{g/m}^3 - 1.0\ \text{g/m}^3 - \frac{(0.12\,\text{g/g})(74{,}520\,\text{g/d})}{(1000\,\text{m}^3/\text{d})} = 25.1\ \text{g/m}^3$$

5. Determine internal recycle rate (IR) using Eq. (8-62)

$$IR = \frac{25.1}{4.25} - 1.0 - 0.54 = 4.4$$

Internal recycle rate = IR (Q) = 4.4 (1000 m^3/d) = 4400 m^3/d

6. Determine the anoxic tank volume and τ for a single stage anoxic tank by the following steps:

- Determine the NO_3-N feed rate to the anoxic zone.
- Select an anoxic volume and use Eq. (8-52) to determine if the nitrate that can be removed is nearly equal to that determined above.
- Use the coefficients in Table 8-22 with Eq. (8-57) or Eq. (8-58) to obtain $SDNR_b$. Use E. (8-56) to obtain F/M_b.
- Use Eq. (8-60) to correct for $SDNR_b$ for recycle and θ value of 1.026 (page 808) to correct for temperature using Eq. (1-44). Use the final SDNR in Eq. (8-52) to determine if the nitrate removal is sufficient.

a. NO_3-N feed to anoxic zone:

$[(IR)\ Q + RQ]\ N_e = [4.4 + 0.54](1000\ \text{m}^3/\text{d})(4.25\ \text{g/m}^3) = 20{,}995\ \text{g/d}$

b. Determine anoxic volume. Use Eq. (8-52) (based on biomass)

$NO_r = V_{nox}$ (SDNR) ($MLVSS_{biomass}$)

Select anoxic volume, $\tau_{anoxic} = 2$ h

$V_{nox} = Q\tau_{anoxic} = (1000\ m^3/d)(2.0\ h)/(24 h/d) = 83.3\ m^3$

c. Determine SDNR **for wastewater 1**

Use Eq. (8-56) to compute F/M_b

$$F/M_b = \frac{QS_o}{X_b V_{nox}} = \frac{(1000\, m^3/d)(200\, g/m^3\, BOD)}{(1620\, g/m^3)(83.3\, m^3)} = 1.48\ g/g{\bullet}d$$

Compute rbCOD fraction and determine SDNR based on rbCOD fraction:

$$\text{rbCOD fraction} = \frac{(60\, g/m^3)}{(1.6\text{ g COD/g BOD})(200\, g/m^3\, BOD)} = 0.19$$

From Eq. (8-57) and Table 8-22,

$SDNR_b = 0.213 + 0.118[\ln(F/M_b)]$

$= 0.213 + 0.118[\ln(1.49)]$

$SDNR_b = 0.26$

Correct SDNR for internal recycle (Eq. 8-60) and temperature (Eq. 1-44)

$SDNR_{adj} = SDNR_{IR1} - 0.029 \ln (F/M_b) - 0.012$

$= 0.26 - 0.029 (\ln 1.48) - 0.012 = 0.236\ g/g \bullet d$

$SDNR_{15} = SDNR_{20} (1.026)^{15-20} = 0.236 (1.026)^{-5} = 0.21\ g/g \bullet d$

$NO_r = (83.3\ m^3)(0.21\ g/g \bullet d)(1620\ g/m^3) = 28{,}339\ g/d$

NO_x required = 20,995 g/d, so select lower τ_{anoxic}

Use a spreadsheet solution to recomputed values, as follows.

τ, h	V_{NO_x} m^3	F/M_b g/g • d	SDNR, g/g • d	$SDNR_{adj}$, g/g • d	$SDNR_T$, g/g • d	NO_r, g/d	Required NO_r, g/d
1.4	58.3	2.1	0.301	0.268	0.235	22,250	20,995

Thus, $\tau_{anoxic} = 1.4$ h is reasonable solution

7. Determine V_{NO_x} and τ for each stage of a 3 stage anoxic tank with equal volumes per stage.

The same procedure is used and NO_r is calculated for each stage.

Calculate the F/M_b for each stage as follows:

Stage	F/M_b
1	$\frac{QS_o}{X_b V_1}$
2	$\frac{QS_o}{X_b(V_1 + V_2)}$
3	$\frac{QS_o}{X_b(V_1 + V_2 + V_3)}$

The spreadsheet solution summary for three iterations is shown on the following table:

Parameter	Iteration		
	1	2	3
Flow, m^3/d	1000	1000	1000
BOD, mg/L	200	200	200
X_b, mg/L	1620	1620	1620
Temp, °C	15	15	15
rbCOD, mg/L	60	60	60
bCOD, mg/L	320	320	320
Fraction rbCOD	0.19	0.19	0.19
Required removal, g/d	20,995	20,995	20,995

Stage 1:			
Volume, m^3	19.4	13.9	16.7
HRT, min	28.0	20.0	24.0
F/M_b	6.3	8.9	7.4
$SDNR_b$ (graph)	0.43	0.47	0.45
$SDNR_{corr}$	0.37	0.40	0.38
$SDNR_T$	0.32	0.35	0.33

NO_3-N_r, g/d	10126	7826	9005
Stage 2			
Volume, m^3	19.4	13.9	16.7
HRT, min	28.0	20.0	24.0
F/M_b	3.2	4.4	3.7
$SDNR_b$ (graph)	0.35	0.39	0.37
SDNRcorr	0.30	0.33	0.32
$SDNR_T$	0.27	0.29	0.28
NO_3-N_r, g/d	8417	6605	7540
Stage 3			
Volume, m^3	19.4	13.9	16.7
HRT, min	28.0	20.0	24.0
F/M_b	2.1	4.4	3.7
$SDNR_b$ (graph)	0.30	0.39	0.37
SDNRcorr	0.27	0.33	0.32
$SDNR_T$	0.24	0.29	0.28
NO_3-N_r, g/d	7417	6605	7540
Total removal, g/d	25,962	21,036	24,087
Required removal	20,995	20,995	20,995

The first column solution is based on the same HRT of 1.4 h as used above for the single-stage anoxic zone. With 3 stages the removal capacity is about 24 percent higher. The total HRT used for 3 stages in the solution shown in the second column is 1.0 h. This lower HRT results in a NO_3-N removal rate that is similar to the single stage anoxic zone with an HRT of 1.4 h.

8. Determine the final alkalinity.

The final alkalinity (as $CaCO_3$) is determined based on 7.14 g alkalinity used/g NH_4-N oxidized and 3.57 g alkalinity produced/g NO_3-N reduced.

NO_x = 25.1 mg/L, final NO_3-N = 4.25 mg/L

$$\text{Final alkalinity} = (200\ \text{g/m}^3) - (7.14\ \text{g/g})(25.1\ \text{g/m}^3) + (3.57\ \text{g/g})(25.1 - 4.25)\ \text{g/m}^3$$

$$= 95.9\ \text{mg/L as } CaCO_3$$

9. Determine the oxygen required. The oxygen demand is calculated first for BOD removal and nitrification and then a credit is applied for the oxygen demand satisfied by BOD removal using nitrate in the anoxic zone before the aeration tank.

Using Eq. (8-24), Table 8-10,

$R_o = Q\,(S_o - S) - 1.42\,P_{X,bio} + 4.57\,Q\,(NO_x)$

$S_o - S \approx S_o = 320\ \text{g/m}^3$

$R_o = [1000\ \text{m}^3\text{/d}\ (320\ \text{g/m}^3) - 1.42\ (74{,}520\ \text{g/d})$

$\quad + 4.57\ (25.1\ \text{g/m}^3)\ (1000\ \text{m}^3\text{/d})]\ (1\ \text{kg}/10^3\ \text{g})$

$= (320 - 105.8 + 114.7)\ \text{kg/d} = 328.9\ \text{kg/d}$

Oxygen equivalent from denitrification

$$O_2 = 2.86\ \frac{\text{g } O_2}{\text{g } NO_x}\ [(25.1 - 4.25)\ \text{g/m}^3](1000\ \text{m}^3\text{/d})(1\ \text{kg}/10^3\ \text{g}) = 59.6\ \text{kg/d}$$

Net Oxygen required = (328.9 – 59.6) kg/d = 269.3 kg/d

Required oxygen for BOD removal/nitrification = 328.9 kg/d

Required oxygen with anoxic/aerobic process = 269.3 kg/d

$$\text{Energy savings} = \frac{[(328.9 - 269.3)\text{kg/d}]}{(328.9\ \text{kg/d})}\ (100\%) = 18.1\%$$

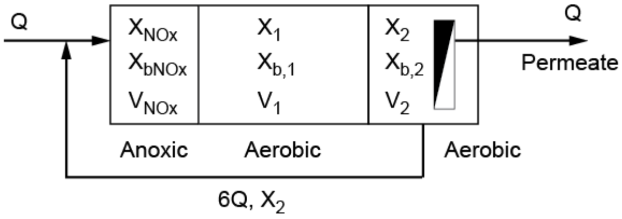
PROBLEM 8-32

Problem Statement – see text, page 929

Solution

The effect of using an anoxic/aerobic MBR compared to the activated sludge system in Problem 8-31 is that a higher MLSS concentration is used and thus a smaller volume is used for the same SRT of 10 days. In addition the recycle ratio is given for the MBR system, which results in a different effluent NO_3-N concentration. The MBR system anoxic tank volume is then a function of the NO_3-N removed and the higher biomass concentration.

1. Sketch of MBR system



Given:

X_2 = 10,000 mg/L

Membrane flux = 20 L/m^2•h

Membrane reactor volume = 0.025 m^3/m^2 (membrane area, m^2)

2. Determine MBR aerobic volumes.

a. Membrane area

$$\text{Area} = \text{Area} = \frac{Q}{\text{Flux}} = \frac{(1000\ \text{m}^3/\text{d})(10^3\ \text{L}/\text{m}^3)}{(20\ \text{L}/\text{m}^2{\bullet}\text{h})(24\ \text{h}/\text{d})} = 2083\ \text{m}^3$$

b. Membrane compartment volume, V_2

$V_2 = (0.025\ m^3/m^2)(2083\ m^2) = 52\ m^3$

c. Determine total volume and V_1

At same SRT, the mass of solids for $V_1 + V_2$ = mass of solids for aerobic system in Problem 8-31.

$V_1X_1 + V_2X_2 = (460\ m^3)(3500\ g\ TSS/m^3)$

$6Q(X_2) + Q(0) = 7QX_1$

$$X_1 = \frac{6}{7}(X_2) = \left(\frac{6}{7}\right)(10{,}000\ \text{g}/\text{m}^3) = 8571\ \text{g}/\text{m}^3$$

$V_1(8571) + V_2(10{,}000) = (460)(3500)$

$V_2 = 52\ m^3$

$V_1 = 127.2\ m^3$

The two stage nitrification system for the MBR will produce a lower effluent NH_4-N concentration than that for the single-stage aeration tank in Problem 8-31. However, because the volume for V_2 is small relative to V_1, the effluent NH_4-N will be only slightly lower. To simplify the problem, the same effluent NH_4-N concentration for Problem 8-31 will be used.

3. Determine $X_{b,NOX}$, $X_{b,1}$, and X_{bio} for MBR system.

   At same SRT of 10 d, the same ratio for X_b/X in Problem 8-31 can be used.

$$\frac{X_{b1,NOx}}{X_{NOx}} = \frac{X_{b,1}}{X_1} = \frac{X_{b,2}}{X_2} = \frac{(1620\ g/m^3)}{(3500\ g/m^3)} = 0.463$$

   Note $X_{NOX} = X_1$

   $X_{b,NOX} = X_{b,1} = 0.463(8571\ g/m^3) = 3968.4\ g/m^3$

   $X_{b,2} = 0.463(10{,}000\ g/m^3) = 4630\ g/m^3$

4. Determine the NO_3-N removed in the anoxic zone.

   a. Determine NO_x, using Eq. (8-24) in Table 8-10. This calculation will be the same as for Problem 8-31, but it is repeated here.

$$P_{X,bio} = \frac{V_1(X_{b,1}) + V_2(X_{b,2})}{SRT}$$

$$P_{X,bio} = \frac{(127.2\ m^3)(3968.4\ g/m^3) + (52\ m^3)(4630\ g/m^3)}{10\ d}$$

   $P_{X,bio} = 74{,}550\ g/d$

   $NO_x = TKN - N_e - 0.12P_{X,bio}/Q$

$$= 35\ g/m^3 - 1.0\ g/m^3 - \frac{0.12(74{,}550\ g/d)}{(1000\ m^3/d)}$$

   $NO_x = 25.1\ g/m^3$

   Assume all the NO_3-N in the recycle to the anoxic zone is removed.

   Mass balance on NO_x produced to obtain effluent NO_3-N concentration, NO_E.

   $NO_x(Q) = 6Q(NO_E) + Q(NO_E)$

   $25.1 = 6(NO_E) + 1(NO_E)$

   $NO_E = 3.6\ g/m^3$

   NO_3-N removed in anoxic zone = $6(1000\ m^3/d)(3.6\ g/m^3) = 21{,}600\ g/d$

5. Determine the anoxic tank volume and τ for a single stage anoxic tank by the following steps:

- Determine the NO_3-N feed rate to the anoxic zone.
- Select an anoxic volume and use Eq. (8-52) to determine if the nitrate that can be removed is nearly equal to that determined above.
- Use the coefficients in Table 8-22 with Eq. (8-57) or Eq. (8-58) to obtain $SDNR_b$. Use Eq. (8-56) to obtain F/M_b.
- Use Eq. (8-60) to correct for $SDNR_b$ for recycle and θ value of 1.026 (page 808) to correct for temperature using Eq. (1-44). Use the final SDNR in Eq. (8-52) to determine if the nitrate removal is sufficient.

a. NO_3-N feed to anoxic zone = 21,600 g/d

b. Determine anoxic volume. Use Eq. (8-52) (based on biomass)

$NO_r = V_{nox}$ (SDNR) ($MLVSS_{biomass}$)

The following has been determined by initial guess and then iteration.

Select anoxic volume, τ_{anoxic} = 0.55 h = 33 min

$V_{nox} = Q\tau_{anoxic} = (1000\ m^3/d)(0.55\ h)/(24 h/d) = 22.9\ m^3$

c. Determine SDNR **for wastewater 1**

Use Eq. (8-56) to compute F/M_b

$$F/M_b = \frac{QS_o}{X_b V_{nox}} = \frac{(1000\,m^3/d)(200\,g/m^3\,BOD)}{(3968\,g/m^3)(22.9\,m^3)} = 2.20\ g/g\text{•}d$$

Compute rbCOD fraction and determine SDNR based on rbCOD fraction:

$$\text{rbCOD fraction} = \frac{(60\,g/m^3)}{(1.6\text{ g COD/g BOD})(200\,g/m^3\,BOD)} = 0.19$$

From Eq. (8-57) and Table 8-22,

$SDNR_b = 0.213 + 0.118[\ln(F/M_b)]$

$= 0.213 + 0.118[\ln(2.2)]$

$SDNR_b = 0.306$

Correct SDNR for internal recycle (Eq. 8-60) and temperature (Eq. 1-44)

$SDNR_{adj} = SDNR_{IR1} - 0.029 \ln(F/M_b) - 0.012$

$= 0.306 - 0.029 (\ln 2.2) - 0.012 = 0.271\ g/g \bullet d$

$SDNR_{15} = SDNR_{20}\,(1.026)^{15-20} = 0.271\,(1.026)^{-5} = 0.238 \text{ g/g} \bullet \text{d}$

$NO_r = (22.9 \text{ m}^3)\,(0.238 \text{ g/g} \bullet \text{d})\,(3968 \text{ g/m}^3) = 21{,}626 \text{ g/d}$

10. Determine the final alkalinity.

The final alkalinity (as $CaCO_3$) is determined based on 7.14 g alkalinity used/g NH_4-N oxidized and 3.57 g alkalinity produced/g NO_3-N reduced.

NO_x = 25.1 mg/L, final NO_3-N = 3.6 mg/L

$$\text{Final alkalinity} = (200 \text{ g/m}^3) - (7.14 \text{ g/g})(25.1 \text{ g/m}^3) + (3.57 \text{ g/g})(25.1 - 3.6) \text{ g/m}^3$$

$$= 91.0 \text{ mg/L as } CaCO_3$$

11. Determine the oxygen required. The oxygen demand is calculated first for BOD removal and nitrification and then a credit is applied for the oxygen demand satisfied by BOD removal using nitrate in the anoxic zone before the aeration tank.

Using Eq. (8-24), Table 8-10,

$R_o = Q\,(S_o - S) - 1.42\,P_{X,bio} + 4.57\,Q\,(NO_x)$

$S_o - S \approx S_o = 320 \text{ g/m}^3$

$$R_o = [(1000 \text{ m}^3\text{/d})(320 \text{ g/m}^3) - 1.42\,(74{,}520 \text{ g/d}) + 4.57(25.1 \text{ g/m}^3)\,(1000 \text{ m}^3\text{/d})]\,(1 \text{ kg}/10^3 \text{ g})$$

$$= (320 - 105.8 + 114.7) \text{ kg/d} = 328.9 \text{ kg/d}$$

Oxygen equivalent from denitrification

$$O_2 = 2.86\,\frac{\text{g } O_2}{\text{g } NO_x}\,[(25.1 - 3.6) \text{ g/m}^3](1000 \text{ m}^3\text{/d})(1 \text{ kg}/10^3 \text{ g}) = 61.5 \text{ kg/d}$$

Net Oxygen required = (328.9 – 61.5) kg/d = 267.4 kg/d

Required oxygen for BOD removal/nitrification = 328.9 kg/d

Required oxygen with anoxic/aerobic process = 267.4 kg/d

$$\text{Energy savings} = \frac{[(328.9 - 267.4)\text{kg/d}]}{(328.9 \text{ kg/d})}\,(100\%) = 18.7\%$$

PROBLEM 8-33

Problem Statement – see text, page 929

Solution

1. Determine the anoxic and aerobic volumes. Based on the problem statement the anoxic volume is 10 percent of the total volume:

   $V_{NO_x} = 0.10\ (3600\ m^3) = 360\ m^3$

   Aerobic volume = $(3600 - 360)\ m^3 = 3240\ m^3$

2. Determine the effluent NH_4-N concentration. To determine the effluent NH_4-N concentration, the aerobic SRT must be first calculated, using Eqs. (7-57), (8-20) and (8-21) in Table 8-10.

   $(X_{TSS})V = P_{X,TSS}\ (SRT)$

   $$P_{X,TSS} = \frac{QY_H(S_o - S)}{[1 + b_H(SRT)]0.85} + \frac{(f_d)(b_H)QY_H(S_o - S)SRT}{[1 + b_H(SRT)]0.85}$$

   $$+ \frac{QY_n(NO_X)}{[1 + b_n(SRT)]0.85} + Q(nbVSS) + Q(TSS_o - VSS_o)$$

   Combine equations

   $$(X_{TSS})\left(\frac{V}{Q}\right) = \frac{Y(S_o - S)SRT}{[1 + b_H(SRT)](0.85)X} + \frac{(f_d)(b_H)Y_H(S_o - S)(SRT)^2}{[1 + b_H(SRT)](0.85)X}$$

   $$+ \frac{Y_n(NO_x)SRT}{[1 + b_n(SRT)](0.85)} + (nbVSS)SRT + (TSS_o - VSS_o)SRT$$

3. Define input for above equation

   Assume $S_o - S \approx S_o = 240$ mg/L

   Assume $NO_x \sim 0.80\ (TKN) = 0.80\ (40) = 32$ mg/L

   (Note: Nitrifier growth has very small effect on MLSS concentration compared to other factors)

4. Define coefficients from Table 8-14 at 10°C:

   $Y = 0.45$ gVSS / g bCOD

   $f_d = 0.15$ g/g

   $b_H = 0.12\ (1.04)^{10-20} = 0.081$ g/g • d

   $Y_n = 0.20$ g VSS / g NH_4-N (Includes NH_4-N and NO_2-N oxidizers)

   $b_n = 0.17\ (1.029)^{10-20} = 0.128$ g/g • d

5. Insert data and coefficients into equation

$$(3500\ \text{g/m}^3)\ (3240\ \text{m}^3) = \frac{(0.45\,\text{g/g})(8000\,\text{m}^3/\text{d})(240\,\text{g/m}^3)(\text{SRT})}{[1+(0.081\text{g/g•d})\text{SRT}]0.85}$$

$$+\frac{(0.15\,\text{g/g})(0.081\text{g/g•d})(8000\,\text{m}^3/\text{d})(0.45\,\text{g/g})(240\,\text{g/m}^3)(\text{SRT})^2}{[1+(0.081\text{g/g•d})\text{SRT}]0.85}$$

$$+\frac{(0.20\ \text{g/g})(8000\text{m}^3/\text{d})(32\ \text{g/m}^3)(\text{SRT})}{[1+(0.128\,\text{g/g•d})\text{SRT}]0.85}+(8000\,\text{m}^3/\text{d})(60\,\text{g/m}^3)(\text{SRT})$$

$$+\ (8000\,\text{m}^3/\text{d})[(80-70)\text{g/m}^3](\text{SRT})$$

6. Solve equation on spreadsheet by selecting SRT value where left and right side of equation are equal.

$$11{,}340{,}000\ \text{g} = \frac{1{,}106{,}470(\text{SRT})}{1+0.081\text{SRT}}+\frac{12{,}350(\text{SRT})^2}{1+0.081\text{SRT}}+\frac{60{,}235(\text{SRT})}{1+0.128\,\text{SRT}}$$

$$+\ 480{,}000\,\text{SRT}+80{,}000\,\text{SRT}$$

SRT = 9.2 d

7. Calculate effluent NH_4-N concentration.

Determine effluent NH_4-N (N_e) concentrations as a function of SRT by combining Eq. (7-94) and Eq. (7-98) in Table 10. Let S_o = DO.

$$\frac{1}{\text{SRT}}=\left(\frac{\mu_{\text{max,AOB}}S_{\text{NH4}}}{K_{\text{NH4}}+S_{\text{NH4}}}\right)\left(\frac{\text{DO}}{K_o+\text{DO}}\right)-b_{\text{AOB}}$$

The nitrification coefficients are obtained from Table 8-14. Use the temperature correction Eq. (1-44) shown in Table 8-10.

$$k_T = k_{20}(\theta)^{T-20}$$

Temperature = 10°C

$\mu_{\text{max,AOB}}$ = 0.90 $(1.072)^{10-20}$ = 0.449 g/g • d

K_{NH4} = 0.50 $(1.0)^{10-20}$ = 0.50 g/m^3

b_{AOB} = 0.17$(1.029)^{10-20}$ = 0.128 g/g • d

K_o = 0.50 g/m^3

Y_n = 0.15 g VSS/g NH_4-N oxidized

Solving for S_{NH4} (let S_{NH4} = N_e):

$$N_e = \frac{K_{NH4}[1+b_{AOB}(SRT)]}{\left[\mu_{max,AOB}\left(\dfrac{DO}{K_o+DO}\right)-b_{AOB}\right]SRT-1}$$

$$N_e = \frac{(0.50\ g/m^3)[1 + (0.128\ g/g{\bullet}d)(9.2\ d)]}{(9.2\ d)\left\{(0.449\ g/g{\bullet}d)\left[\dfrac{(2.0\ g/m^3)}{(0.50\ g/m^3) + (2.0\ g/m^3)}\right]-(0.128\ g/g{\bullet}d)\right\}-1}$$

At SRT = 9.2 d, $N_e = 0.97\ g/m^3$

8. Calculate effluent NO_3-N concentration. To determine the effluent NO_3-N concentration, the amount of NO_3-N produced (NO_x) in the aerobic zone and the amount of NO_3-N that can be removed in the anoxic zone must be determined. The difference is the NO_3-N in the effluent.

   a. To determine NO_x, use equation (8-24) in Table 8-10:

   $NO_x = TKN - N_e - 0.12\ P_{X,bio}/Q$

   $P_{X,bio}$ is determined from appropriate components of Eq. (8-15)

$$P_{X,bio} = \frac{Q(Y_H)(S_o-S)}{1+b_H(SRT)} + \frac{f_d(b_H)Q(Y_H)(S_o-S)SRT}{1+b_H(SRT)} + \frac{QY_n(NO_x)}{1+b_n(SRT)}$$

$$P_{X,bio} = \frac{(8000\,m^3/d)(0.45\,g/g)(240\,g/m^3)}{[1+0.081 g/g{\bullet}d(9.2\,d)]}$$

$$+ \frac{(0.15\,g/g)(0.081 g/g{\bullet}d)(8000\,m^3/d)(0.45\,g/g)(240\,g/m^3)(9.2\,d)}{[1+(0.081 g/g{\bullet}d)(9.2\,d)]}$$

$$+ \frac{(8000\,m^3/d)(0.15\,g/g)(32\,g/m^3)}{[1+0.128\,g/g{\bullet}d(9.2\,d)]}$$

   $P_{X{\cdot}bio}$ = (495,072 + 55,339 + 17,634) g/d = 568,045 g/d

$$NO_x = 40\ g/m^3 - 0.97\ g/m^3 - \frac{0.12(568{,}045\,g/d)}{(8000\,m^3/d)} = 30.5\ g/m^3$$

   b. To determine the nitrate removed in the anoxic zone use Eq. (8-52) (based on biomass)

   $NO_r = V_{nox}\,(SDNR)(MLVSS_{biomass})$

   The SDNR is a function of the anoxic zone F/M_b ratio.

Use Eq. (8-56) to compute F/M_b

$$F/M_b = \frac{QS_o}{X_b V_{nox}} \text{ Where } S_o = \text{BOD}$$

BOD = 240/1.6 = 150 g/m^3

c. Determine X_b using Eq. (8-20) in Table 8-10.

Assume $S_o - S \approx S_o$

$$X_b = \frac{QY_H(So - S)SRT}{[1 + (b_H)SRT]V} = \frac{(8000\,m^3/d)(0.45\,g/g)(240\,g/m^3)(9.2\,d)}{[(1 + 0.081 g/g \bullet d)(9.2\,d)](3240\,m^3)}$$

X_b = 1406 g/m^3

d. From Step 1 V_{nox} = 360 m^3

$$F/M_b = \frac{QS_o}{X_b V_{nox}} = \frac{(8000\ m^3/d)(150\ g/m^3\ BOD)}{(1406\ g/m^3)(360\ m^3)} = 2.37\ g/g \bullet d$$

9. Determine SDNR **for wastewater 1**

a. Compute rbCOD fraction and determine SDNR based on rbCOD fraction:

$$\text{rbCOD fraction} = \frac{(25\,g/m^3)}{(240\,g/m^3\,bCOD)} = 0.10$$

From Eq. (8-57) and coefficients in Table 8-22,

$SDNR_b = 0.186 + 0.078[\ln(F/M_b)]$

$= 0.186 + 0.078[\ln(2.37)]$

$SDNR_b = 0.253$

b. Correct SDNR for internal recycle (Eq. 8-60) (assume ratio = 3-4) and for temperature (Eq. 1-44)

$SDNR_{adj} = SDNR_{IR1} – 0.029 \ln (F/M_b) – 0.012$

$= 0.253 – 0.029 (\ln 2.37) – 0.012 = 0.216\ g/g \bullet d$

$SDNR_{10} = SDNR_{20} (1.026)^{10-20} = 0.216 (1.026)^{-10} = 0.167\ g/g \bullet d$

$NO_r = (360\ m^3) (0.167\ g/g \bullet d) (1406\ g/m^3) = 84{,}528\ g/d$

$$\text{Based on flow; } NO_3\text{-N removal} = \frac{(84{,}528\ g/d)}{(8000\ m^3/d)} = 10.6\ g/m^3$$

Effluent NO_3-N = NO_x – NO_3-N removal

$$= (30.5 – 10.6)\ g/m^3 = 19.9\ g/m^3$$

9. Determine the internal recycle ratio using Eq. (8-62)

$$IR = \frac{NO_x}{N_e} - 1.0 – R$$

$$IR = \frac{(30.5\ g/m^3)}{(19.9\ g/m^3)} – 1.0 – 0.5 = 0.03$$

An iteration is required as the nitrate that can be removed in the anoxic zone can be supplied by the recycle. Thus, there is no correction to the SDNR based on recycle.

10. Recalculate effluent NO_x-N concentration.

$SDNR_b = 0.253$

Correct SDNR for temperature only.

$SDNR_{10} = SDNR_{20}\ (1.026)^{10-20} = 0.253\ (1.026)^{-10} = 0.196\ g/g \bullet d$

$NO_r = (360\ m^3)\ (0.196\ g/g \bullet d)\ (1406\ g/m^3) = 99{,}207\ g/d$

Based on flow; NO_3-N removal = $\frac{(99{,}207\ g/d)}{(8000\ m^3/d)} = 12.4\ g/m^3$

Effluent NO_3-N = NO_x – NO_3-N removal

$$= (30.5 – 12.4)\ g/m^3 = 18.1\ g/m^3$$

$$IR = \frac{(30.5\ g/m^3)}{(18.1\ g/m^3)} – 1.0 – 0.5 = 0.18$$

So again no significant internal recycle is needed. In lieu of recycle, the RAS recycle rate can be increased slightly.

PROBLEM 8-34

Problem Statement – see text, page 930

Solution

Provide solution assuming steady state operating conditions with no safety factor for nitrification.

1. Determine the design effluent NH_4-N concentration. To determine the design effluent NH_4-N concentration, calculate the aerobic SRT using Eqs. (8-20), (8-21), and (7-57) in Table 8-10.

   Eq. 7-57. $(X_{TSS})V = P_{X,TSS}$ (SRT)

$$P_{X,TSS} = \frac{QY_H(S_o - S)}{[1 + b_H(SRT)]0.85} + \frac{(f_d)(b_H)QY_H(S_o - S)SRT}{[1 + b_H(SRT)]0.85} + \frac{QY_n(NO_X)}{[1 + b_n(SRT)]0.85} + Q(nbVSS) + Q(TSS_o - VSS_o)$$

   Substituting $P_{X,TSS}$ in Eq. (7-57).

$$(X_{TSS})(V) = \frac{QY_H(S_o - S)SRT}{[1 + b_H(SRT)]0.85} + \frac{(f_d)(b_H)QY_H(S_o - S)(SRT)^2}{[1 + b_H(SRT)]0.85} + \frac{QY_n(NO_X)SRT}{[1 + b_n(SRT)]0.85} + Q(nbVSS)SRT + Q(TSS_o - VSS_o)SRT$$

2. Define input for above equation for **wastewater 1**

   Influent bCOD = 1.6 (BOD) = 1.6 (250) = 400 mg/L

   Assume $S_o - S \approx S_o = 400$ mg/L

   Assume $NO_x \sim 0.80$ (TKN) = 0.80 (40) = 32 mg/L

   (Note: Nitrifier growth has very small effect on MLSS concentration compared to other factors)

3. Determine coefficients from Table 8-14 and adjust for temperature using Eq. (1-44) and the table θ values

   $k_T = k_{20}(\theta)^{T-20}$

   For heterotrophs:

   $Y = 0.45$ gVSS/g bCOD

   $f_d = 0.15$ g/g

   $b_H = 0.12(1.04)^{10-20} = 0.081$ g/g•d

   For nitrification:

   $\mu_{max,AOB} = (0.90\ \text{g/g•d})\ (1.072)^{10-20} = 0.449$ g/g•d

k_{NH4} = (0.50 mg/L) $(1.0)^{10-20}$ = 0.50 g/m^3

b_{AOB} = (0.17 g/g•d) $(1.029)^{10-20}$ = 0.128 g/g•d

Y_n = 0.20 g VSS / g NH_4-N (including both ammonia- and nitrite-oxidizers

Y_n = 0.15 g VSS / g NH_4-N for ammonia-oxidizers

K_o = 0.50 g/m^3

4. Determine the aerobic volume

   Aerobic volume = 0.50 (4600 m^3) = 2300 m^3

5. Insert data and coefficients into above equation. Assume a typical ditch detention time of 24 hours, so flow = 4600 m^3/d. Thus:

$$(3500\ \text{g/m}^3)\ (2300\ \text{m}^3) = \frac{(0.45\,\text{g/g})(4600\,\text{m}^3/\text{d})(400\,\text{g/m}^3)(\text{SRT})}{[1+(0.081\text{g/g•d})\text{SRT}]0.85}$$

$$+\ \frac{(0.15\,\text{g/g})(0.081\text{g/g•d})(4600\,\text{m}^3/\text{d})(0.45\,\text{g/g})(400\,\text{g/m}^3)(\text{SRT})^2}{[1+(0.081\text{g/g•d})\text{SRT}]0.85}$$

$$+\frac{(0.20\,\text{g/g})(4600\,\text{m}^3/\text{d})(32\,\text{g/m}^3)(\text{SRT})}{[1+(0.128\,\text{g/g•d})\text{SRT}]0.85}+(4600\,\text{m}^3/\text{d})(80\,\text{g/m}^3)(\text{SRT})$$

$$+\ (4600\,\text{m}^3/\text{d})[(220-210)\text{g/m}^3](\text{SRT})$$

6. Solve equation on spreadsheet by selecting SRT value where left and right side of equation are equal.

   8,050,000 g =

$$\frac{974{,}117(\text{SRT})}{1+.081\text{SRT}}+\frac{11{,}836(\text{SRT})^2}{1+0.081\text{SRT}}+\frac{34{,}635(\text{SRT})}{1+0.128\,\text{SRT}}+368{,}000\,\text{SRT}+46{,}000\,\text{SRT}$$

   SRT = 8.0 d

7. Determine effluent NH_4-N (N_e) concentrations as a function of SRT by combining Eq. (7-94) and Eq. (7-98) in Table 10. Let S_o = DO. Assume average DO concentration = 1.0 mg/L as it varies in the ditch from 0 to 2.0 mg/L.

$$\frac{1}{\text{SRT}}=\left(\frac{\mu_{\text{max,AOB}}S_{\text{NH4}}}{K_{\text{NH4}}+S_{\text{NH4}}}\right)\left(\frac{\text{DO}}{K_o+\text{DO}}\right)-b_{\text{AOB}}$$

Solving for S_{NH4} (let $S_{NH4} = N_e$):

$$N_e = \frac{K_{NH4}(1 + b_{AOB}SRT)}{\left[\mu_{max,AOB}\left(\frac{DO}{K_o + DO}\right) - b_{AOB}\right]SRT - 1}$$

$$N_e = \frac{(0.50\ g/m^3)\left[1 + (0.128\ g/g{\bullet}d)(8.0\ d)\right]}{\left\{(0.449\ g/g{\bullet}d)\left[\frac{(1.0\ g/m^3)}{(0.50\ g/m^3) + (1.0\ g/m^3)}\right] - (0.128\ g/g{\bullet}d)\right\}(8.0\ d) - 1}$$

$N_e = 2.7\ g/m^3$

8. Calculate nitrate removal. The amount of nitrate removed in the half of the ditch that is anoxic is calculated from Eq. (8-52) and Eqs. (8-66), (8-67), and (8-68).

   Eq. (8-52): $NO_r = V_{nox}(SDNR_b)(\text{MLVSS biomass})$

   Eq. (8-66): $SDNR_b = \frac{0.175\,A_N}{(Y_{net})SRT}$

   The total system SRT is used in Eq. (8-66) to reflect the endogenous decay activity of the mixed liquor for nitrate reduction. The same equation used above for the nitrification aerobic SRT calculation is used with the exception that the volume is 4600 m^3 instead of 2300 m^3:

   $$8{,}050{,}000\left(\frac{4600\,m^3}{2300\,m^3}\right) =$$

   $$\frac{974{,}117(SRT)}{1 + 0.081SRT} + \frac{11{,}836(SRT)^2}{1 + 0.081SRT} + \frac{34{,}635(SRT)}{1 + 0.128\,SRT} + 368{,}000\,SRT + 46{,}000\,SRT$$

   SRT = 17.7 d

   To obtain the $SDNR_b$ value A_n and Y_{net} values must be calculated for use in Eq. (8-66). A_n is calculated using Eq. (8-67).

   $$A_n = 1.0 - 1.42Y_H + \frac{1.42(b_H)(Y_H)SRT}{1 + (b_H)SRT}$$

A_n = 1.0 – 1.42 (0.45 g/g) + $\frac{1.42(0.081\text{g/g}\bullet\text{d})(0.45\,\text{g/g})17.7\,\text{d}}{[1+(0.081\text{g/g}\bullet\text{d})(17.7\,\text{d})]}$

A_n = 0.737 g O_2 / g bCOD

Y_{net} is calculated using Eq. (8-68).

$$Y_{net} = \frac{Y}{1+(b_H)SRT} = \frac{(0.45\,\text{g/g})}{[1+(0.081\text{g/g}\bullet\text{d})(17.7\,\text{d})]} = 0.185 \text{ g VSS / g bCOD}$$

$$\text{Then } SDNR_b = \frac{0.175\,A_N}{(Y_{net})SRT} = \frac{0.175(0.737\,\text{g/g})}{(0.185\,\text{g/g})(17.7\,\text{d})} = 0.039 \text{ g/g} \bullet \text{d}$$

V_{nox} = 2300 m^3 and

NO_r = (2300 m^3) (0.039 g/g • d) (X_b)

X_b is calculated using Eq. (8-20) in Table 8-10:

$$X_b = \frac{Q(Y_H)(S_o - S)SRT}{[1+(b_H)SRT]V} = \frac{(4600\,\text{m}^3/\text{d})(0.45\,\text{g/g})(400\,\text{g/m}^3)(17.7\,\text{d})}{[1+(0.081\,\text{g/g}\bullet\text{d})(17.7\,\text{d})](4600\,\text{m}^3)} = 1309$$

g/m^3

NO_r = (2300 m^3)(0.039 g/g • d)(1309 g/m^3) = 117,417 g/d

$$NO_3\text{-N removed, normalized to flow} = \frac{(117{,}417\,\text{g/d})}{(4600\,\text{m}^3/\text{d})} = 25.5 \text{ g/m}^3$$

The effluent NO_3-N equals the NO_3-N produced minus the NO_3-N reduced in the ditch anoxic volume. The NO_3-N produced (NO_x) is determined using Eq. (8-24) in Table 8-10:

NO_x = TKN – N_e – 0.12 $P_{X,bio}$/Q

$P_{X,bio}$ is determined from the appropriate components of Eqs. (8-20) and (8-21):

$$P_{X,bio} = \frac{QY_H(S_o - S)}{[1+b_H(SRT)]} + \frac{(f_d)(b_H)QY_H(S_o - S)SRT}{[1+b_H(SRT)]} + \frac{QY_n(NO_X)}{[1+b_n(SRT)]}$$

$$P_{X,bio} = \frac{(4600\,\text{m}^3/\text{d})(0.45\,\text{g/g})(400\,\text{g/m}^3)}{[1+(0.081\text{g/g}\bullet\text{d})(17.7\,\text{d})]}$$

$$+ \frac{(0.15\,\text{g/g})(0.081\text{g/g}\bullet\text{d})(4600\,\text{m}^3/\text{d})(0.45\,\text{g/g})(400\,\text{g/m}^3)(17.7\,\text{d})}{[1+(0.081\text{g/g}\bullet\text{d})(17.7\,\text{d})]}$$

$$+\ \frac{(4600\ \mathrm{m^3/d})(0.15\ \mathrm{g/g})(32\ \mathrm{g/m^3})}{[1+(0.128\ \mathrm{g/g\bullet d})(17.7\ \mathrm{d})]}$$

$P_{X,bio}$ = (340,222 + 73,166 + 6,761)g/d = 420,149 g/d

$$NO_x = 40\ \mathrm{g/m^3} - 2.7\ \mathrm{g/m^3} - \frac{(0.12\ \mathrm{g/g})(420{,}149\ \mathrm{g/d})}{(4600\ \mathrm{m^3/d})} = 26.3\ \mathrm{g/m^3}$$

Effluent NO_3-N = NO_x – NO_3-N removed = (26.3 – 25.5) g/m^3 = 0.80 g/m^3

PROBLEM 8-35

Problem Statement – see text, page 930

Solution

Instructors Note: For the SBR design, there is no mixing during the fill so that nitrate remaining after aeration, settling, and decanting will likely be consumed by the influent BOD during the non-aerated, anoxic fill period. The effluent NO_3-N concentration is then a function of how much nitrate is produced during each cycle and its dilution by the SBR tank volume.

1. Determine the nitrate produced in each cycle for **wastewater 1**. The NO_3-N produced each cycle is:

   V_F (NO_x), g/d

   where V_F is the fill volume (and effluent volume) per cycle. The NO_3-N produced is equal to the mass in the total volume, assuming that all the NO_3-N is reduced in the mixed un-aerated fill step.

   V_F (NO_x) = V_T (NO_e)

where, NO_e = reactor NO_3-N concentration before settling

$$\frac{V_F}{V_T}(NO_x) = 6\ \mathrm{mg/L}\ NO_3\text{-N}$$

Thus, the fill volume fraction, $\frac{V_F}{V_T}$, determines the effluent NO_3-N concentration.

An iterative solution is necessary and the procedure is as follows:

- Assume $NO_x = 0.80$ (TKN)
- Determine $\frac{V_F}{V_T}$
- Solve for V_F based on flow and cycle times and then calculate V_T
- From V_T and the assumed MLSS concentration, determine the SRT
- From the SRT, determine $P_{X,bio}$ and NO_x
- If NO_x is not equal or close to assumed NO_x, perform the calculation with another NO_x value
- With final solution SRT, determine the nitrifying bacteria concentration (X_N) and calculate the NH_4-N concentration at the end of the aeration period.

1. Compute NO_X; $NO_X = 0.80\,(45\text{ mg/L}) = 36\text{ mg/L}$

2. Determine $\frac{V_F}{V_T}$; $\frac{V_F}{V_T}(36\text{ mg/L}) = 6.0\text{ mg/L}$

$$\frac{V_F}{V_T} = \frac{(6.0\text{ mg/L})}{(36.0\text{ mg/L})} = \frac{1}{6} = 0.167$$

3. Determine the number of cycles/day and V_F by assuming uniform flow and the fill time (t_F) for one tank equals the sum of the aeration time (t_A), settle time (t_S), and decant time (t_D) for the second SBR tank.

$t_F = t_A + t_S + t_D$

T_C = cycle time = $t_F + t_A + t_S + t_D$

From information provided, $t_F = (2.0 + 1.0 + 0.5)\text{ h} = 3.5\text{ h}$

$T_C = 3.5\text{ h} + 3.5\text{ h} = 7.0\text{ h/cycle}$

Average number of cycle/d = $\frac{(24\,\text{h/d})}{(7.0\,\text{h/cycle})} = 3.43$ cycle/d

For 2 tanks, total number of cycle/d = 2 (3.43) = 6.86

$$V_F = \frac{(\text{flow/d})}{(\text{cycles/d})} = \frac{(5000\,\text{m}^3/\text{d})}{(6.86\,\text{cycles/d})} = 792.2\text{ m}^3\text{/cycle}$$

$$\frac{V_F}{V_T} = \frac{792.2\,m^3}{V_T} = 0.167$$

$$V_T = \frac{792.2\,m^3}{0.167} = 4374\ m^3$$

4. Determine the SRT using Eqs. (8-20), (8-21), and (7-57).

   a. From Eqs. (8-20) and (8-21)

$$P_{X,TSS} = \frac{QY_H(S_o - S)}{[1 + b_H(SRT)]0.85} + \frac{(f_d)(b_H)QY_H(S_o - S)SRT}{[1 + b_H(SRT)]0.85}$$

$$+ \frac{QY_n(NO_X)}{[1 + b_n(SRT)]0.85} + Q(nbVSS) + Q(TSS_o - VSS_o)$$

   Substituting $P_{X,TSS}$ in Eq. (7-57).

$$(X_{TSS})(V) = \frac{QY_H(S_o - S)SRT}{[1 + b_H(SRT)]0.85} + \frac{(f_d)(b_H)QY_H(S_o - S)(SRT)^2}{[1 + b_H(SRT)]0.85}$$

$$+ \frac{QY_n(NO_x)SRT}{[1 + (b_n)SRT]0.85} + Q(nbVSS)SRT + Q(TSS_o - VSS_o)SRT$$

   b. Define values for solution to above equation:

   Influent bCOD = 1.6 (BOD) = 1.6 (250) = 400 mg/L

   Assume $S_o - S \approx$ influent bCOD = 1.6(BOD) = 1.6(250 g/m^3)

   = 400 g/m^3

   Volume/tank = 4374 m^3

$$\text{Flow/tank} = \frac{(5000\,m^3/d)}{2} = 2500\ m^3/d$$

   c. Develop coefficients from Tables 8-14 at 12°C:

   Y = 0.45 g/g

   $K_n = 0.50(1.0)^{12-20} = 0.50\ g/m^3$

   $b_H = 0.12\ (1.04)^{12-20} = 0.088\ g/g \bullet d$

   Y_n = 0.20 g/g (including ammonia- and nitrite- oxidizers)

   $b_n = 0.17\ (1.029)^{12-20} = 0.135\ g/g \bullet d$

   $\mu_{max,AOB} = 0.90\ (1.072)^{12-20} = 0.516\ g/g \bullet d$

   $K_o = 0.50\ g/m^3$

d. Insert values and coefficients in equation developed in 4a and compute SRT.

$$(4000\ \text{g/m}^3)\ (4374\ \text{m}^3) = \frac{(0.45\,\text{g/g})(2500\,\text{m}^3/\text{d})(400\,\text{g/m}^3)(\text{SRT})}{[1+(0.088\,\text{g/g•d})\text{SRT}]0.85}$$

$$+\frac{(0.15\,\text{g/g})(0.088\,\text{g/g•d})(2500\,\text{m}^3/\text{d})(0.45\,\text{g/g})(400\,\text{g/m}^3)(\text{SRT})^2}{[1+(0.088\,\text{g/g•d})\text{SRT}]0.85}$$

$$+\ \frac{(0.20\,\text{g/g})(2500\,\text{m}^3/\text{d})(36\,\text{g/m}^3)(\text{SRT})}{[1+(0.135\,\text{g/g•d})\text{SRT}]0.85}+(2500\,\text{m}^3/\text{d})(120\,\text{g/m}^3)(\text{SRT})$$

$$+\ (2500\,\text{m}^3/\text{d})[(220-210)\text{g/m}^3](\text{SRT})$$

17,496,000 g =

$$\frac{529{,}411(\text{SRT})}{1+.088(\text{SRT})}+\frac{6988(\text{SRT})^2}{1+0.088(\text{SRT})}+\frac{21{,}176(\text{SRT})}{1+0.135(\text{SRT})}+300{,}000(\text{SRT})+25{,}000(\text{SRT})$$

SRT = 33.5 d

5. Determine $P_{X,bio}$ using appropriate components of Eq. (8-15)

$$P_{X,bio}=\frac{Q(Y_H)(S_o-S)}{1+b_H(\text{SRT})}+\frac{f_d(b_H)Q(Y_H)(S_o-S)\text{SRT}}{1+b_H(\text{SRT})}+\frac{QY_n(NO_x)}{1+b_n(\text{SRT})}$$

$$P_{X,bio}=\frac{(2500\,\text{m}^3/\text{d})(0.45\,\text{g/g})(400\,\text{g/m}^3)}{[1+(0.088\,\text{g/g•d})(33.5\,\text{d})]}$$

$$+\ \frac{(0.15\,\text{g/g})(0.088\,\text{g/g•d})(2500\,\text{m}^3/\text{d})(0.45\,\text{g/g})(400\,\text{g/m}^3)(33.5\,\text{d})}{[1+0.088\,\text{g/g•d}(33.5\,\text{d})]}$$

$$+\ \frac{(2500\,\text{m}^3/\text{d})(0.20\,\text{g/g})(36\,\text{g/m}^3)}{[1+0.135\,\text{g/g•d}(33.5\,\text{d})]}$$

$P_{X,bio}$ = (113,981 + 50,402 + 3259) g/d = 167,642 g/d

6. Determine NO_x using Eq. (8-24):

$NO_x = \text{TKN} - N_e - 0.12\ P_{X,bio}/Q$

Considering a long SRT, assume N_e = 0.5 mg/L NH_4-N

$$NO_x = 45.0\ \text{g/m}^3 - 0.5\ \text{g/m}^3 - \frac{0.12(167{,}642\,\text{g/d})}{(2500\,\text{m}^3/\text{d})}$$

NO_x = 36.5 g/m^3 (close to assumption of 36.0 mg/L; an additional iteration is not necessary)

7. Volume of each SBR tank = 4374 m^3
8. Compute the decant pumping rate. The decant pumping rate equals the fill volume divided by decant time:

$$Q_D = \frac{V_F}{t_D} = \frac{729.2\ \text{m}^3}{30\ \text{min}} = 24.3\,\text{m}^3/\text{min}$$

9. Compute the nitrification safety factor
   a. Compute the ammonia oxidizing bacteria concentration by using Eq. (7-42) in Table 8-10:

$$X_n = \frac{Q(Y_n)(NO_x)SRT}{[1+(b_n)SRT](V)}$$

Per Example 8-5, calculate weighted average nitrifier endogenous decay rate:

Aerobic b_n = 0.135 g/g•d

Anoxic b_n = (0.07 g/g•d)(1.029)$^{12-20}$ = 0.056 g/g•d

$$\text{Fraction of cycle aerobic} = \frac{t_A}{t_C} = \frac{2\ \text{h}}{7\ \text{h}} = 0.285$$

$$\text{Fraction of cycle anoxic} = (1-\frac{2\ \text{h}}{7\ \text{h}}) = 0.715$$

Average $b_{n,12°C}$ = 0.285(0.135) + 0.715(0.056)

= 0.078 g/g•d

$$X_n = \frac{(2500\,\text{m}^3/\text{d})(0.15\,\text{g/g})(36.5\,\text{g/m}^3)(33.5\,\text{d})}{[1+(0.078\,\text{g/g•d})(33.5\,\text{d})](4374\,\text{m}^3)}$$

X_n = 29.0 g/ m^3

   b. Solve for NH_4-N as a function of aeration time in the batch reaction using Eq. (8-53)

$$K_n \ln\left(\frac{N_o}{N_t}\right) + (N_o - N_t) = X_n\left(\frac{\mu_{max}}{Y_n}\right)\left(\frac{DO}{K_o + DO}\right) t$$

Assuming effluent NH_4-N = 0.50 mg/L, a mass balance on available NH_4-N after the fill is done to obtain N_o, the initial available NH_4-N concentration.

$(V_T – V_F)\ N_e + V_F\ (NO_x) = V_T\ (N_o)$

$$\left(1-\frac{V_F}{V_T}\right) N_e + \frac{V_F}{V_T}(NO_x) = N_o$$

$(1 - 0.167)\ (0.5\ g/m^3) + 0.167\ (36.5\ g/m^3) = N_o$

$N_o = 6.5\ g/m^3$

$$0.50 \ln\left(\frac{6.5}{N_t}\right) + (6.5 - N_t) = (29.0\,g/m^3)\left[\frac{(0.516\,g/g{\bullet}d)}{(0.15\,g/g)}\right] + \left[\frac{(2.0\,g/m^3)}{(0.5+2.0)\,g/m^3}\right] t$$

$$0.50 \ln\left(\frac{6.5}{N_t}\right) + (6.5 – N_t) = 79.8\ t$$

at $N_t = 1.0\ g/m^3$,

$0.94 + 5.5 = 79.8\ t$

t = 0.08 d = 1.92 h

Aeration time = 2.0 h

Thus, safety factor ≈ 1.0

PROBLEM 8-36

Problem Statement – see text, page 931

Solution

1. Using synthesis yield values given, determine exogenous carbon dose in mg COD/L to remove 5 mg/L NO_3-N for methanol, acetate, and ethanol. Use Eq. (8-69) to determine the carbon consumptive ratio C_R, g COD/g NO_3-N.

$$C_{R,NH3} = \frac{2.86}{1-1.42Y_H}$$

a. For methanol,

$$C_{R,NO3} = \frac{2.86}{1-1.42(0.25\text{ g VSS / g COD})}$$

C_R = 4.43 g COD/g NO_3-N

Dose = (4.43 g/g)(5.0 mg/L)

Dose = 22.2 mg/L methanol COD

b. For acetate,

$$C_{R,NO3} = \frac{2.86}{1-1.42(0.40\text{ g VSS / g COD})}$$

C_R = 6.62 g COD/g NO_3-N

Dose = (6.62 g/g)(5.0 mg/L)

Dose = 33.1 mg/L acetate COD

c. For ethanol,

$$C_{R,NO3} = \frac{2.86}{1-1.42(0.36\text{ g VSS / g COD})}$$

C_R = 5.85 g COD/g NO_3-N

Dose = (5.85 g/g)(5.0 mg/L)

Dose = 29.3 mg/L ethanol COD

2. Describe dose needed in terms of the substrate concentration, in g COD/g substrate.

a. Methanol

$$CH_3OH + 1.5O_2 \rightarrow CO_2 + 2H_2O$$

$$\frac{\text{g } O_2}{\text{g methanol}} = \frac{1.5(32\text{ g / mole})}{1.0(32\text{ g / mole})} = 1.5\text{ g COD / g methanol}$$

$$\text{Dose as methanol} = (22.2\text{ mg COD/L})\left[\frac{1}{(1.5\text{ g COD / g methanol})}\right]$$

= 14.8 mg/L methanol

b. Acetate

$$CH_3COOH + 2O_2 \rightarrow 2CO_2 + 2H_2O$$

$$\frac{\text{g } O_2}{\text{g acetate}} = \frac{2.0(32\text{ g / mole})}{1.0(60\text{ g / mole})} = 1.067\text{ g COD / g acetate}$$

$$\text{Dose as acetate} = (33.1\ \text{mg COD/L})\left[\frac{1}{(1.067\ \text{g COD/g acetate})}\right]$$

$$= 31.0\ \text{mg/L acetate}$$

c. Ethanol

$$CH_3CH_2OH + 3O_2 \rightarrow 2CO_2 + 3H_2O$$

$$\frac{\text{g }O_2}{\text{g ethanol}} = \frac{3.0(32\ \text{g/mole})}{1.0(46\ \text{g/mole})} = 2.09\ \text{g COD/g ethanol}$$

$$\text{Dose as ethanol} = (29.3\ \text{mg COD/L})\left[\frac{1}{(2.09\ \text{g COD/g ethanol})}\right]$$

$$= 14.0\ \text{mg/L ethanol}$$

3. Summary

Substrate dose to remove 5.0 mg/L NO_3-N

Substrate	mg COD/L	mg substrate/L
Methanol	22.2	14.8
Acetate	33.1	31.0
Ethanol	29.3	14.0

PROBLEM 8-37

Problem Statement – see text, page 931

Solution (Wastewater 1)

1. Determine the acetate consumptive ratio using Eq. (8-69).

$$C_{R,NO3} = \frac{2.86}{1 - 1.42(0.4\ \text{g VSS/g COD})} = 6.62\ \text{g COD/g}NO_3\text{-N}$$

2. Determine the amount of NO3-N reduced due to endogenous decay using Eq. (8-63).

$$R_{NO3} = \frac{1.42}{2.86}(b_{H,anox})(X_H)(V_{anox})$$

From Table 8-14, the endogenous decay rate at 15°C is

$$b_{H,15} = b_{H,20}(\theta)^{T-20} = 0.12(1.04)^{15-20} = 0.098\ \text{g/g}\bullet\text{d}$$

$$R_{NO3} = \frac{1.42}{2.86}(0.098\ g/g{\bullet}d)(1200\ g/m^3)(250\ m^3)$$

R_{NO3} = 14,597.2 g/d

Normalized to flow, $R_{NO3} = \dfrac{(14{,}597.2\ g/d)}{(5000\ m^3/d)} = 2.9\ g/m^3$

3. Determine the post anoxic tank acetate concentration using Eq. (8-70).

$$SDNR = \left(\frac{1-1.42Y_H}{2.86}\right)\left[\frac{\mu_{max}S_s}{Y_H(K_s+S_s)}\right]\left(\frac{S_{NO3}}{K_{NO3}+S_{NO3}}\right)\left(\frac{\eta X_H}{X_{VSS}}\right)$$

Determine the SDNR needed to remove the remaining NO_3-N after accounting for endogenous decay.

NO_3-N removal by acetate = (6.0 – 2.9 – 0.3) g/m^3

= 2.8 g/m^3

$$R_{NO3} = (2.8\ g/m^3)(5000\ m^3/d) = 14{,}000\ g/d$$

From Eq. (8-52),

R_{NO3} = SDNR(MLVSS)V

14,000 g/d = SDNR(3000 g/m^3)(250 m^3)

SDNR = 0.0187 g/g•d

Apply Eq. (8-70) and solve for the anoxic tank acetate concentration.

Determine $\mu_{max,15}$ with Eq. (1-44) in Table 8-10.

$$\mu_{max,15} = \mu_{max,20}\theta^{T-20} = (4.46\ g/g{\bullet}d)(1.21)^{15-20}$$

$\mu_{max,15}$ = 1.71 g/g•d

$$0.0187 = \left[\frac{1-1.42(0.40\ gVSS/gCOD)}{2.86}\right]\left[\frac{(1.71 g/g{\bullet}d)S_s}{(0.40\ gVSS/gCOD)(5.0+S_s)}\right]$$

$$\left\{\frac{(0.30\,g/m^3)}{[(0.10+0.30)\ g/m^3]}\right\}\left[\frac{0.80(1200\ g/m^3)}{(3000\ g/m^3)}\right]$$

Solve for S_s:

S_s = 0.69 g/m^3 acetate

As acetate COD,

$$CH_3COOH\ +\ 2O_2 \rightarrow 2CO_2 + 2H_2O$$

$$\frac{\text{g O}_2}{\text{g acetate}} = \frac{2.0(32\text{ g/mole})}{1.0(60\text{ g/mole})} = 1.067\text{ g COD/g acetate}$$

S_s = (0.69 g/m^3)(1.067 g COD/g acetate) = 0.74 g COD/m^3

4. Determine the carbon dose using Eq. (8-76).

$C_D = \text{SDNR}(X_{VSS})(V)C_{R,NO3} + Q(1+R)(S_s)$

C_D = (14,000 g/d)(6.62 g COD/g NO_3-N)

+ (5000 m^3/d)(1+0.5)(0.74 g COD/m^3)

C_D = 98,230 g COD/d = 98.23 kg COD/d

$$C_{D,acetate} = \frac{(98.23\text{ kg COD/d})}{(1.067\text{ g COD/g acetate})} = 92.1\text{ kg acetate/d}$$

Dose in mg/L

$$\text{Dose} = \frac{(98{,}230\text{ g COD/d})}{(5000\text{ m}^3\text{/d})} = 19.6\text{ g COD/m}^3$$

$$\text{Dose} = \frac{(19.60\text{ g COD/m}^3)}{(1.067\text{ g COD/g acetate})} = 18.4\text{ g acetate/m}^3$$

5. Determine the amount of NH_4-N released.

From Example 8-10, 0.06 g NH_4-N released/g VSS in endogenous decay.

$$\text{Increase in NH}_4\text{-N concentration} = \frac{(0.06\text{ g N/g VSS})(b_H)(X_H)V}{Q(1+R)}$$

$$= \frac{(0.06\text{ g N/g VSS})(0.098\text{ g/g}\bullet\text{d})(1200\text{ g VSS/m}^3)(250\text{ m}^3)}{(5000\text{ m}^3\text{/d})(1+0.50)}$$

= 0.20 g/m^3

PROBLEM 8-38

Problem Statement – see text, page 932

Solution (Wastewater 1)

1. Determine the Premoval by PAOs consuming rbCOD from the influent wastewater.
   a. rbCOD is first consumed for NO_3-N reduction. Assume return sludge recycle ratio = 0.50 mg/L.

NO_3-N available based on influent flow

$Q(NO_3\text{-N})_{available} = (NO_3\text{-N}_R)RQ$

$(NO_3\text{-N})_{available} = 5.0(0.5) = 2.5$ mg/L

From page 879 rbCOD consumption for NO_3-N reduction

$$= \frac{5.0 \text{ g rbCOD}}{\text{g NO}_3\text{-N}}(2.5 \text{ mg/L})$$

rbCOD consumption = 13.0 mg/L

rbCOD available for PAOs = 70 – 13 = 57 mg/L

b. Determine rbCOD/P ratio from Figure 8-38.

At VFA/rbCOD = 0.50, rbCOD/P = 10.0

$$\text{P removal by PAOs} = \frac{(57 \text{ mg rbCOD/L})}{(10.0 \text{ g rbCOD/g P})}$$

$$= 5.7 \text{ mg/L}$$

2. Determine P removal by biomass production. Assume 0.015 g P/g VSS from Example 8-13.

   Biomass growth = (0.30 g VSS/g BOD)(160 mg/L) = 48.0 mg/L VSS

   P removal by synthesis = (0.015 g P/g VSS)(48.0 mg/L) = 0.7 mg P/L

   Effluent soluble P = 7.0 – 0.7 – 5.7 = 0.6 mg/L

3. Determine the phosphorus content of the waste sludge

   Sludge production = (0.60 g TSS/g BOD)(160 g BOD/m^3)

   $= 96.0 \text{ g/m}^3$

   P removed = 7.0 – 0.60 = 6.4 g/m^3

   $$\text{g P/g sludge} = \frac{(6.4 \text{ g/m}^3)}{(96 \text{ g/m}^3)} = 0.067 \text{ g/g, P content of dry solids} = 6.7\%$$

4. Eliminate or reduce the amount of NO_3-N in the return sludge flow to the EBPR anaerobic contact zone. This could be done by incorporating the JHB or UCT process in the treatment process. The feasibility and preferred method would depend on the actual plant layout.

PROBLEM 8-39

Problem Statement – see text, page 932

Solution

1. Determine the change in effluent phosphorus content. The amount of nitrate fed to the anaerobic zone affects enhanced biological phosphorus removal efficiency due to rbCOD consumption by nitrate. Per page 879, 1.0 mg NO_3-N consumes 5.2 mg rbCOD.

   In the A^2O process, NO_3-N is fed to the anaerobic zone in the return activated sludge (RAS). Assuming no NO_3-N removal in the secondary clarifier, the NO_3-N concentration in RAS is equal to the effluent concentration. In this problem, the internal recycle for the A^2O process is to be decreased, which will increase the effluent and RAS NO_3-N concentration. Eq. (8-62) is used to determine changes in the effluent NO_3-N concentration as a function of the internal recycle ratio (IR).

   $$IR = \frac{NO_x}{N_e} - 1.0 - R$$

   Solve for NO_x for the present condition as this will not change with changes in recycle rates. Rearranging the equation:

   $NO_x = N_e\,(1 + R + IR)$

   $NO_x = 5.0\text{ mg/L}\,(1 + 0.50 + 3.0) = 22.5\text{ mg/L}$

   Determine N_e **for IR = 2.0 and R = 1.0**

   $$N_e = \frac{NO_x}{(1+R+IR)} = \frac{(22.5\text{ mg/L})}{(1+1.0+2.0)} = 5.63\text{ mg/L}$$

   The amount of nitrate fed to the anaerobic zone is equal to the RAS flow rate and NO_3-N concentration and is shown as follows:

   $$\text{g } NO_3\text{-N fed/d} = R\,Q\,N_e$$

   The rbCOD required in the influent flow for NO_3-N consumption is shown as follows:

   $$Q\,(rbCOD_{NO_3}) = \left(5.2\,\frac{\text{g rbCOD}}{\text{g } NO_3\text{-N}}\right) RQN_e$$

Thus, the rbCOD used in the influent flow for NO_3-N removal is:

$$\text{rbCOD}_{NO_3}\text{, mg/L} = 5.2\ R\ N_e$$

For the initial case, R = 0.5, N_e = 5.0 mg/L

$$\text{rbCOD}_{NO_3} = 5.2\ (0.5)\ (5.0\ \text{mg/L}) = 13.0\ \text{mg/L}$$

For the new recycle condition, R = 1.0, N_e= 5.63 mg/L

$$\text{rbCOD}_{NO_3} = 5.2\ (1.0)\ (5.63\ \text{mg/L}) = 29.3\ \text{mg/L}$$

Thus, the additional rbCOD consumed in the anaerobic zone = (29.3 – 13.0) mg/L = 16.3 mg/L

Assuming 10 g rbCOD / g P removal,

$$\text{the loss of P removal} = \frac{(16.3\ \text{mg/L})}{(10\ \text{g/g})} = 1.6\ \text{mg/L}$$

PROBLEM 8-40

Problem Statement – see text, page 932

Solution (Solids loading rate = 4.0 kg/m²•h)

1. Determine the influent flow rate given the return activated sludge recycle ratio, MLSS concentration, and clarifier number and diameter.
   a. Determine the clarifier average surface overflow rate (SOR) using Eq. (8-82).

      $\text{MLSS} = 3000\ \text{g/m}^3 = 3.0\ \text{kg/m}^3$

      $$\text{SLR} = \frac{(Q + RQ)\text{MLSS}}{A} = (1 + R)(\text{SOR})\text{MLSS}$$

      $$\text{SOR} = \frac{\text{SLR}}{(1 + R)\text{MLSS}} = \frac{(4.0\ \text{kg}/\text{m}^2\text{•h})}{(1 + 0.5)(3.0\ \text{kg}/\text{m}^3)}$$

      SOR = 0.88 m/h

      SOR = Q/A
   b. Determine the influent flowrate

      Q = A(SOR)

      Clarifier area = $(2)(\pi D^2/4)$

$= (2)(3.14/4)(20\ \text{m})^2$

$= 628\ \text{m}^2$

$Q = (628\ \text{m}^2)(0.88\ \text{m/h})(24\ \text{h/d})$

$Q = 13{,}263\ \text{m}^3/\text{d}$

2. Determine the return sludge MLSS concentration.

   Ideal mass balance on the clarifier:

   Solids in = Solids out

   Ignore effluent TSS and solids wasting

   $Q(1+R)\,X = RQ(X_R)$

   $$X_R = \frac{(1+R)X}{R} = \frac{1.5(3000\ \text{mg/L})}{0.5}$$

   $X_R = 9000\ \text{mg/L}$

PROBLEM 8-41

Problem Statement – see text, page 933

Solution

1. The effects are summarized in the following table.

Change in process or wastewater characteristics	Effect on effluent process concentration
SRT is increased	Effluent P decreases. Less phosphorus accumulating organism (PAO) bacteria biomass is produced due to lower yield at higher SRT
Influent rbCOD concentration increases	Effluent P decreases. Higher rbCOD provides more food for PAOs and thus more growth and P removal
Clarifier effluent suspended solids concentration increases	Effluent P increases. Effluent suspended solids contain P
Higher NO_3-N concentration in RAS	Effluent P increases. More NO_3-N is fed to the anaerobic zone, which means that rbCOD is consumed by NO_3-N with less available for PAOs.
Influent particulate BOD concentration increases	No change. Because the PAOs rely mainly on the availability of rbCOD fed to the anaerobic zone, changes in influent particulate BOD concentration have little or no effect on biological

P removed.

PROBLEM 8-42

Problem Statement – see text, page 933

Solution

Using the column test data a gravity flux curve is first developed by determining the initial interfacial settling from the data provided. Then the limiting solids flux can be determined graphically for each underflow MLSS concentration given. The underflow velocity (Q_R/A) is obtained as the negative slope of the underflow operating rate curve. The Q/A value is given for the problem, so the percent RAS recycle rate is:

$$\frac{(Q_R / A)100}{(Q / A)} = \text{percent RAS recycle rate}$$

1. Gravity flux curve from data

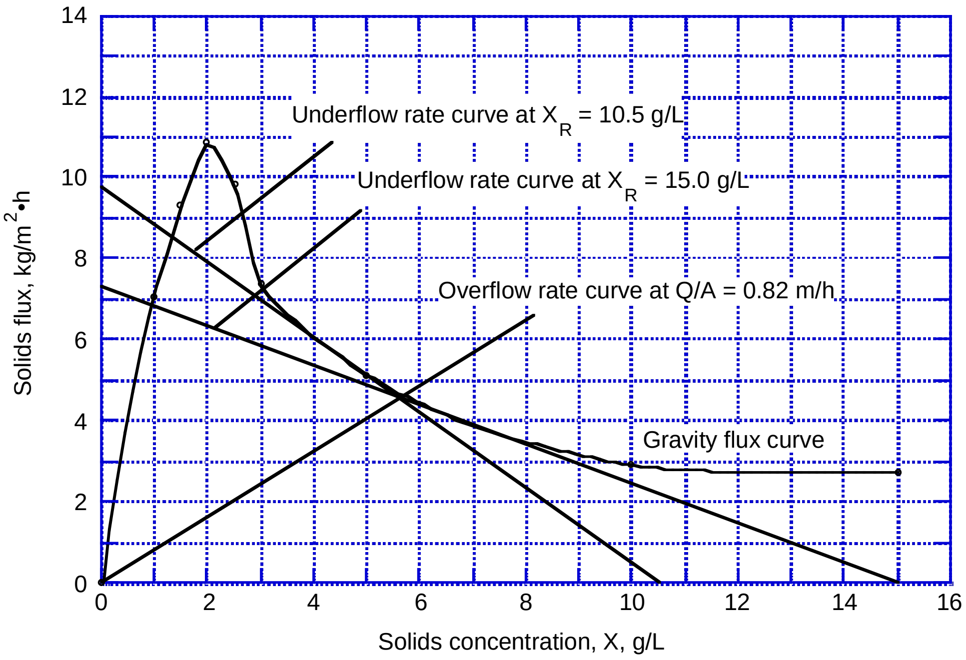
C_i, g/L	V_i, m/h	SF_g, kg/m^2•h
1.0	7.03	7.03
1.5	6.21	9.32
2.0	5.43	10.86
2.5	3.95	9.87
3.0	2.47	7.41
5.0	1.03	5.15
10.0	0.29	2.90
15.0	0.18	2.70

For C_i = 1 g/L,

$$V_i = \frac{117.1\,\text{cm}}{10\,\text{min}}\left(\frac{\text{m}}{100\,\text{cm}}\right)\frac{60\,\text{m}}{\text{h}} = 7.03\ \text{m/h}$$

$$SF_g = C_i V_i = \left(\frac{1\text{g}}{\text{L}}\right)(7.03\,\text{m/h})\left(\frac{10^3\,\text{L}}{\text{m}^3}\right)\left(\frac{1.0\ \text{kg}}{10^3\ \text{g}}\right) = 7.03\ \text{kg/m}^2 \bullet \text{h}$$

2. Plot solids flux graph with X_R = 10,500 mg/L and 15,000 mg/L. Compute percent recycle for a clarifier overflow rate of 0.82 m/h.



a. At X_R = 10,500 mg/L

SF$_L$ = 9.8 kg/m^2•h

$$\frac{Q_R}{A} = \frac{(9.8\,kg/m^2 \bullet h)}{(10.5\,g/L)} = 0.93\ m/h$$

$$\text{Percent recycle} = \frac{[0.93\,m/h(100)]}{(0.82\,m/h)} = 114$$

b. At X_R = 15,000 mg/L

SF$_L$ = 7.0 kg/m^2•h

$$\frac{Q_R}{A} = \frac{(7.0\,kg/m^2 \bullet h)}{(15.0\,g/L)} = 0.47\ m/h$$

$$\text{Percent recycle} = \frac{(0.47\ m/h)(100)}{(0.82\ m/h)} = 57$$

PROBLEM 8-43

Problem Statement – see text, page 933

Solution

1. First calculate the solids flux due to gravity thickening using equation given for V_i

$$SF_g = V_i C_i = \left[X_i V_o(e^{-kX_i})\right]\left(\frac{1.0\,d}{24\,h}\right)$$

$k = 0.4004$ L/g

$V_o = 172$ m/d

X_i = MLSS, g/L

$SF_g = \text{kg/m}^2\bullet\text{h}$

a. The solids flux is summarized as follows and graphed as shown:

X_i, g/L	SF_g, kg/m^2•h	X_i, g/L	SF_g, kg/m^2•h
1.0	4.80	8.0	2.34
2.0	6.44	9.0	1.76
3.0	6.48	10.0	1.31
4.0	5.79	12.0	0.71
5.0	4.85	14.0	0.37
6.0	3.90	16.0	0.19
7.0	3.05	18.0	0.10

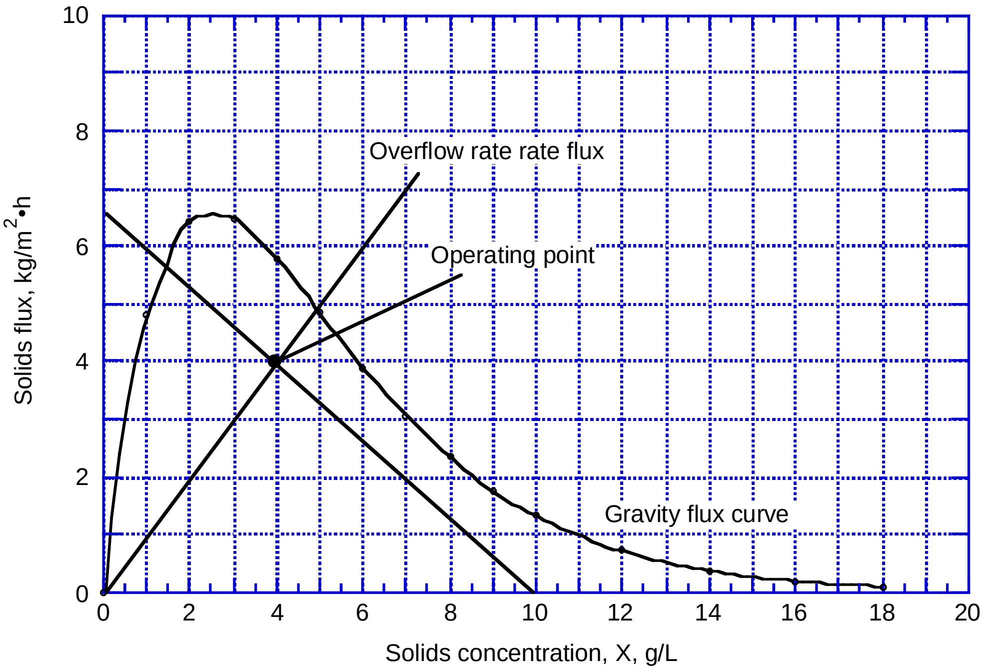
b. The overflow rate operating flux line = $\frac{Q}{A}(X_i)$

$Q/A = 1$ m/h

Shown on graph, at $X_i = 5$ g/L, the overflow rate operating flux

= 5 kg/m^2•h

c. Underflow concentration, $\mathbf{X_R = 10}$ **g/L**



The underflow line is drawn by starting at 10 g/L on the X-axis and intersecting the operating state point.

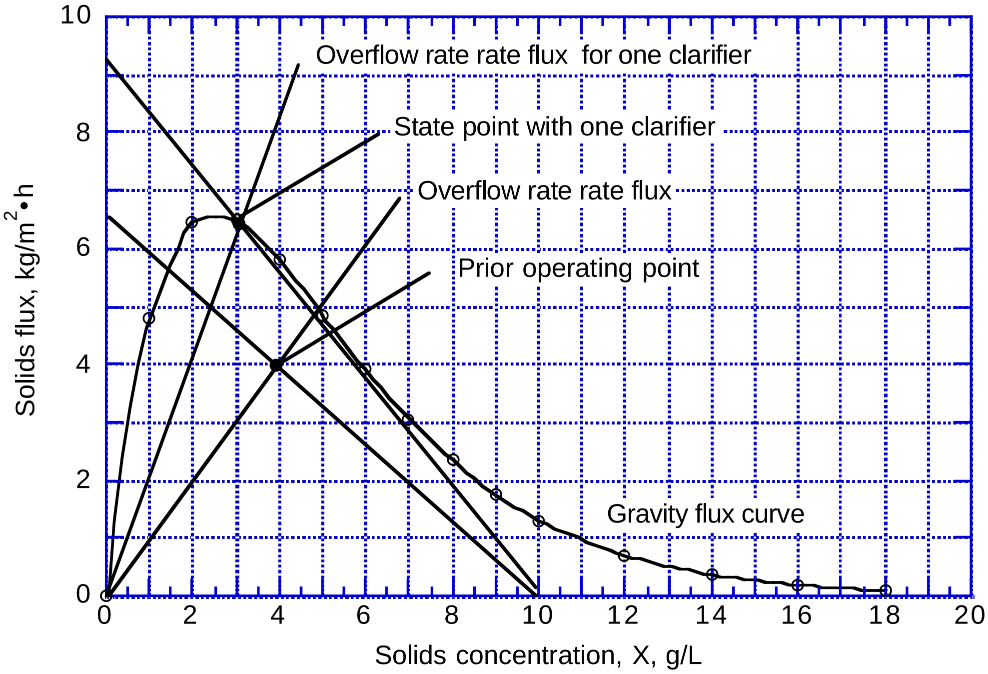
The solids flux rate is determined from the y-axis intercept and is 6.5 kg/m^2•h.

The value for Q_R/A is the negative slope:

$$Q_R/A = \frac{(6.5\,kg/m^2 \bullet h)}{(10\,g/L)} = 0.65\ m/h$$

$$\text{Recycle ratio} = \frac{Q_R}{Q} = \frac{(Q_R/A)}{(Q/A)} = \frac{(0.65\ m/h)}{(1.0\ m/h)} = 0.65$$

d. With only one clarifier in operation the overflow rate is doubled and Q/A = 2 m/h. The new overflow rate operating flux line is shown on the graph. The recycle flux line is drawn so that it is just below the gravity flux curve and thus does not exceed the solids flux limitation. A new graph is shown below.



The maximum MLSS concentration is 3000 mg/L and the solids flux is 9.3 kg/m^2•h. The recycle overflow rate is:

$$\frac{Q_R}{A} = \frac{(9.3\,\mathrm{kg/m^2 \bullet h})}{(10\ \mathrm{g/L})} = 0.93\,\mathrm{m/h}$$

$$\text{The recycle ratio} = \frac{(0.93\ \mathrm{m/h})}{(2.0\ \mathrm{m/h})} = 0.47$$

PROBLEM 8-44

Problem Statement – see text, page 934

Solution (MBR MLSS = 10,000 mg/L)

1. The SRTs and MLSS concentrations are given for the two cases. The flow that can be treated is related to sludge production, $P_{X,TSS}$. $P_{X,TSS}$ is related to the SRT and MLSS by Eq. (7-57) in Table 8-10.

$$\frac{(X_{TSS})(V)}{SRT} = P_{X,TSS}$$

The solids production $P_{X,TSS}$ is obtained using Eq. (8-20) and (8-21) in Table 8-10.

$$P_{X,TSS} = \frac{Q\,Y_H(S_o - S)}{[1+(b_H)\,SRT]0.85} + \frac{(f_d)(b_H)Q\,Y_H(S_o - S)SRT}{[1+(b_H)SRT]0.85}$$

$$+ \frac{QY_n(NO_X)}{[1+(b_n)\,SRT]0.85} + Q(nbVSS) + Q(TSS_o - VSS_o)$$

For the 6 d SRT operation,

$$P_{X,TSS} = \frac{(2500\,g/m^3)(4600\,m^3)}{6\,d} = 1{,}916{,}667 \text{ g/d}$$

As the temperature is not given the above equation, the relationship for $P_{X,TSS}$ must be used with the flow rate at the 6-d SRT condition to determine b_H, which will be the same value for the 12-d SRT membrane reactor application. The following coefficients are used in the equation.

Y_H = 0.45 gVSS / g bCOD

f_d = 0.15 g VSS/g VSS

Y_n = 0.20 g VSS / g NH_4-N

Use b_n at 20°C as error in this case for low solids production nitrification has small effect:

b_n = 0.17 g VSS/g VSS•d

Thus:

$$1{,}916{,}667 \text{ g/d} = \frac{0.45 g/g(15{,}000\,m^3/d)(240\,g/m^3)}{[1+(b_H, g/g\bullet d)(6\,d)]0.85}$$

$$+\frac{(0.15\,g/g)(b_H)(15{,}000\,m^3/d)(0.45\,g/g)(240\,g/m^3)(6\,d)}{[1+(b_H, g/g\bullet d)(6\,d)]0.85}$$

$$+\frac{0.20\,g/g(15{,}000\,m^3/d)(28\,g/m^3)}{[1+(0.17\,g/g\bullet d)(6\,d)]0.85} + (15{,}000\,m^3/d)(35\,g/m^3)$$

$$+ (15{,}000\,m^3/d)(80 - 68)g/m^3$$

$$1{,}916{,}667 = \frac{1{,}905{,}882}{[1+b_H(6\,d)]} + \frac{1{,}715{,}292(b_H)}{[1+b_H(6\,d)]} + 753{,}922$$

Use a spreadsheet to solve for b_H.

b_H = 0.14 g/g•d

2. For the membrane reactor, SRT = 12 d

MLSS = 10,000 mg/L, and V also = 4600 m^3

$$P_{X,TSS} = \frac{XV}{SRT} = \frac{(10{,}000\,g/m^3)(4600\,m^3)}{12\,d} = 3{,}833{,}333 \text{ g/d}$$

Use equation for $P_{X,TSS}$ and solve for Q with same input values as for the 6 d SRT application.

$$3{,}833{,}333 \text{ g/d} = \frac{Q(0.45\,g/g)(240\,g/m^3)}{[1+(0.14\,g/g\bullet d)(12\,d)]0.85}$$

$$+\frac{(0.15\,g/g)(0.14\,g/g\bullet d)(Q)(0.45\,g/g)(240\,g/m^3)12\,d}{[1+(0.14\,g/g\bullet d)(12\,d)]0.85}$$

$$+\frac{(Q)(0.20\,g/g)(28\,g/m^3)}{[1+(0.17\,g/g\bullet d)(12\,d)]0.85} + (Q)(35\,g/m^3) + Q(80-68)\,g/m^3$$

Q = 35,320 m^3/d

Thus, the MLSS concentration was increased by a factor of 4 and the SRT and flowrate were increased by factors of 2 and 2.3, respectively.

3. The volumetric BOD loading (L_{org}) and F/M ratio are calculated using Eq. (7-69) and (7-62), respectively in Table 8-10.

$$L_{org} = \frac{(Q)(S_o)}{V}$$

$$F/M = \frac{QS_o}{VX}$$

SRT = 6 d

$$L_{org} = \frac{(15000\,m^3/d)(150\,g/m^3)(1\,kg/10^3\,g)}{4600\,m^3} = 0.49 \text{ kg BOD}/m^3\bullet d$$

$$F/M = \frac{(15{,}000\,m^3/d)(150\,g/m^3)}{(4600\,m^3)(2500\,g/m^3)} = 0.20\,gBOD/gMLSS \bullet d$$

SRT = 12 d with membrane

$$L_{org} = \frac{(35{,}320\,m^3/d)(150\,g/m^3)(1\,kg/10^3\,g)}{4600\,m^3} = 1.15\ kg\,BOD/m^3 \bullet d$$

$$F/M = \frac{(35{,}320\,m^3/d)(150\,g/m^3)}{(4600\,m^3)(10{,}000\,g/m^3)} = 0.11\,g\,BOD/g\,MLSS \bullet d$$

4. The flowrate divided by the allowable membrane flux of 900 L/m^2•d determines the membrane surface area:

$$Area = \frac{(35{,}320\,m^3/d)}{(20.0\,L/m^2 \bullet h)(1.0\ m^3/10^3\,L)(24\ h/d)} = 73{,}583\ m^2$$

9

ATTACHED GROWTH AND COMBINED BIOLOGICAL TREATMENT PROCESSES

Instructors Note: In many of the problems where constituent concentrations are used, the units mg/L and g/m^3 are used interchangeably to facilitate computations without introducing additional conversion factors.

In the first print of the textbook, Eq. (9-15) should to be corrected to

$$\frac{S_e}{S_i} = \exp\left(\frac{-kD}{q^n}\right)$$

PROBLEM 9-1

Problem Statement – see text, page 1046

Solution

1. Determine effluent concentration at 20°C for **an average flowrate of 390 m^3/h**.

   a. Determine k_{20} for design conditions using Eq. (9-20).

$$k_2 = k_1\left(\frac{D_1}{D_2}\right)^{0.5}\left(\frac{S_1}{S_2}\right)^{0.5}$$

$$= 0.210\left(\frac{6.1}{6.1}\right)^{0.5}\left(\frac{150}{150}\right)^{0.5} = 0.210(\mathrm{L/s})^{0.5}/\mathrm{m}^2$$

   b. Determine the hydraulic application rate.

   q = Q/A

   where Q = (390 m^3/h) (10^3 L/1 m^3) (1 h/3600 s) = 108.3 L/s

   A = πD^2/4 = [(π/4)(20^2)] = 314.2 m^2

   q = (108.3 L/s)/(314.2 m^2) = 0.345 L/m^2 • s

   c. Determine effluent concentration using Eq. (9-15).

$$\frac{S_e}{S_i} = \exp\left(\frac{-kD}{q^n}\right)$$

$$S_e = S_i e^{-k\,D/q^n}$$

$$= (150\ \mathrm{mg/L})[e^{-(0.210)(6.1)/0.345^{0.5}}] = 16.9\ \mathrm{mg/L}$$

d. Determine percent BOD removal

$$\%\ \text{removal} = \frac{[(150 - 16.9)\ \mathrm{mg/L}]}{(150\ \mathrm{mg/L})}(100\%) = 88.7$$

2. Determine effluent concentration at 15°C.

   a. Correct k_2 for design conditions using Eq. (9-16).

$$k_T = k_{20}(1.035)^{(T-20)}$$

$$k_{15} = 0.210\,(1.035)^{(15-20)} = 0.177$$

   b. the hydraulic application rate is the same as in Step 1b.

   $q = 0.345\ \mathrm{L/m^2 \cdot s}$

   c. Determine effluent concentration using Eq. (9-15).

$$S_e = S_i e^{-k\,D/q^n}$$

$$= (150\ \mathrm{mg/L})\ e^{-(0.177)(6.1)/0.345^{0.5}} = 23.9$$

   d. Determine percent BOD removal

$$\%\ \text{removal} = \frac{[(150\ \text{-}\ 23.9)\ \mathrm{mg/L}]}{(150\ \mathrm{mg/L})}(100\%) = 84.1$$

3. In comparing BOD removal, the removal rate is reduced at the lower temperature (88.7 vs. 84.1 %).

PROBLEM 9-2

Problem Statement – see text, page 1046

Solution

1. Determine the operating and flushing dose rates for an influent BOD concentration of 600 mg/L.

   a. Determine the volume of each filter.

$$V = \left(\frac{\pi\ D^2}{4}\right)h = \left[\frac{\pi\ (15)^2}{4}\right]6 = 1060.3\ m^3$$

b. Determine BOD loading for each filter (two filters operating in parallel)

BOD loading = QS_o/V

= [(2120/2) m^3/d](600 g/m^3)(1 kg/10^3 g)/(1060.3 m^3)

= 0.60 kg/m^3•d

c. Determine the estimated operating and flushing dosing rates.

From Table 9-3 (page 959) the estimated dosing rates are:

Operating rate = 75 mm/pass

Flushing rate = 125 mm/pass

2. Determine the distributor speed using Eq. (9-1)

$$DR = \frac{(1+R)\,q\,(10^3\ mm\,/\,1\,m)}{(N_A)(n)(60\ min/\,1\,h)}$$

a. Calculate the hydraulic application rate, q

q = Q/A

Where Q = 2120/2 = 1060 m^3/d

A = $\pi D^2/4 = (\pi/4)(15)^2$ = 176.7 m^2

q = [(1060 m^3/d)/(176.7 m^2)](1 d/24 h)(10^3 L/1 m^3)(1 h/3600 s)

= 0.069 L/m^2 • s

b. Determine the recirculation rate and recirculation ratio. Use a minimum hydraulic application rate of 0.5 L/m^2•s (as in Example 9-3 in page 975).

Determine the recirculation ratio.

$q + q_r$ = 0. 5 L/m^2•s

q_r = 0.5 – 0.069 = 0.431 L/m^2•s

Determine the recirculation ratio

$R = q_r/q$ = 0.431/0.069 = 6.24

c. Calculate the distributor speed for the flushing rate.

$$n = \frac{(1+R)\,q\,(1000\text{ mm/min})}{(N_A)(DR)(60\text{ min/h})} =$$

$$\frac{(1+6.24)\,(0.069\text{ L/m}^2\bullet\text{s})(1\text{ m}^3/10^3\text{ L})(10^3\text{ mm}/1\text{ m})}{(2)(125\text{ mm/pass})}$$

$$= 0.002\text{ rev/sec}$$

$$\frac{1}{n} = \frac{1}{(0.002\text{ rev/s})}\left(\frac{1\text{ min}}{60\text{ s}}\right) = 8.33\text{ min/rev}$$

3. Calculate the pumping rate to each filter.

   Pumping rate = $(q + q_r)A = (0.5\text{ L/m}^2 \bullet \text{s})(176.7\text{ m}^2)$

   $= 88.35\text{ L/s} = (88.35\text{ L/s})(1\text{ m}^3/10^3\text{ L})(3600\text{ s}/1\text{ h}) = 318\text{ m}^3\text{/h}$

PROBLEM 9-3

Problem Statement – see text, page 1046

Solution (4 m packing depth)

The correct solution for the trickling filter in textbook **EXAMPLE 9-3** is presented first.

1. Determine k_{20} for the design conditions using Eq. (9-20)

$$k_2 = k_1\left(\frac{D_1}{D_2}\right)^{0.5}\left(\frac{S_1}{S_2}\right)^{0.5}$$

   a. Solve for k_2

      From Table 9-6, k = 0.210 $(\text{L/s})^{0.5}/\text{m}^2$ [Note: k = kA_s in Eq. (9-19)]

      Trickling filter depth = 6.1 m

$$=0.210\left(\frac{6.1}{6.1}\right)^{0.5}\left(\frac{150}{125}\right)^{0.5} = 0.230(\text{L/s})^{0.5}/\text{m}^2$$

   b. Correct k_2 for temperature effect using Eq. (9-16)

      i. $k_T = k_{20}\,(1.035)^{T-20}$

      ii. $k_{14} = 0.230(1.035)^{14-20} = 0.187\ (\text{L/s})^{0.5}/\text{m}^2$

2. Determine the hydraulic loading rate and the filter area, volume, and diameter

   a. Using Eq. (9-19) with $k_T = (kA_s)\theta^{T\text{-}20} = 0.187\ (L/s)^{0.5}/m^2$ determine the hydraulic loading rate

   $$S_e = \frac{S_o}{(R+1)\exp\left\{\dfrac{k_T D}{[q\,(R+1)]^n}\right\} - R}$$

   Rearrange to get following:

   $$\left[q(1+R)\right] = \left\{\frac{k_T D}{\ln\left[\dfrac{S_o + RS_e}{S_e(1+R)}\right]}\right\}^{1/n}$$

   $$\left[q(1+1)\right] = \left\{\frac{(0.187\ L/m^2{\bullet}s)(6.1\,m)}{\ln\left[\dfrac{(125\ g/m^3)+(1)(20\ g/m^3)}{(20\ g/m^3)(1+1)}\right]}\right\}^2$$

   $q = 0.392\ L/m^2{\bullet}s$

   b. Determine the tower area

   $Q = 15{,}140\ m^3/d = 175.2\ L/s$

   Filter area = $Q/q = 175.2/0.0.392 = 446.9\ m^2$

   c. Determine the packing volume

   Packing volume = $(446.9\ m^2)\ (6.1\ m) = 2726\ m^3$

   d. Determine the tower diameter

   Area/tower = $446.9\ m^2/2 = 223.5\ m^2$

   Diameter = 16.9 m each

   Two towers each with a diameter of 17 m

3. Determine the pumping rate

   $q + q_r = (1+R)q = (1+1)0.392\ L/m^2{\bullet}s = 0.784\ L/m^2{\bullet}s$

   Total pumping rate = $(0.784\ L/m^2{\bullet}s)(\ 446.9\ m^2)$

   $= 350.4\ L/s = 1{,}261\ m^3/h$

4. Determine flushing and normal dose rate using the data given in Table 9-3.

   a. Determine BOD loading

BOD loading = Q S_o/V

$$= \frac{(15{,}140\ m^3/d)(125\ mg/L)(1\ kg/10^3 g)}{2726\ m^3}$$

$= 0.69\ kg/m^3 \bullet d$

b. Determine the dosing rates

From Table 9-3, the estimated flushing and operation dose rates are:

i. Flushing dose = 150 mm/pass

ii. Operating dose = 75 mm/pass

5. Determine the distributor speed using Eq. (9-1).

a. For normal operation:

$$n = \frac{(1+R)\,q\,(1000\ mm/min)}{(N_A)(DR)(60\ min/h)}, \text{where } q = m^3/m^2 \bullet h$$

$$q = \left(0.392\ L/m^2 \bullet s\right)\left(\frac{3600\ s}{h}\right)\left(\frac{1\ m^3}{10^3\ L}\right) = 1.4\ m^3/m^2 \bullet h$$

R = 1.0

$$n = \frac{(1+1)(1.4)(1000)}{(2)(75)(60)} = 0.31 rev/min \ \ (i.e.\ 3.2\ min/rev)$$

b. For flushing operation:

$$n = \frac{(1+1)(1.4)(1000)}{(2)(150)(60)} = 0.16\ rev/min \ \ (i.e.\ 6.25\ min/rev)$$

For 4.0 m packing depth

1. Determine k_{20} for the design conditions and a **packing depth of 4.0 m** using Eq. (9-20)

a. From Table 9-6, k = 0.210 $(L/s)^{0.5}/m^2$

b. For a 4.0 m tower

$$k_2 = k_1\left(\frac{D_1}{D_2}\right)^{0.5}\left(\frac{S_1}{S_2}\right)^{0.5}$$

$$= 0.210\left(\frac{6.1}{4.0}\right)^{0.5}\left(\frac{150}{125}\right)^{0.5} = 0.284\ (L/s)^{0.5}/m^2$$

c. Correct k_2 for temperature effect using Eq. (9-16)

$k_T = k_{20}\,(1.035)^{T-20}$

$k_{14} = 0.284(1.035)^{14-20} = 0.231$

2. Determine the hydraulic loading rate and the filter area, volume, and diameter

   a. Using Eq. (9-19) with $k_T = (kA_S)\theta^{T-20} = 0.231\ (L/s)^{0.5}/m^2$ determine the hydraulic loading rate

   $$S_e = \frac{S_o}{(R+1)\exp\left\{\dfrac{k_T D}{[q\,(R+1)]^n}\right\} - R}$$

   Rearrange to get following:

   $$\left[q(1+R)\right] = \left\{\frac{k_T D}{\ln\left[\dfrac{S_o+RS_e}{S_e(1+R)}\right]}\right\}^{1/n}$$

   $$\left[q(1+1)\right] = \left\{\frac{(0.231\,L/m^2{\bullet}s)(4.0\ m)}{\ln\left[\dfrac{(125\ g/m^3) + (1)(20\ g/m^3)}{(20\ g/m^3)(1+1)}\right]}\right\}^2$$

   $q = 0.257\ L/m^2{\bullet}s$

   b. Determine the tower area

   $Q = 15{,}140\ m^3/d = 175.2\ L/s$

   Filter area = Q/q = 175.2/0.257 = 681.7 m^2

   c. Determine the packing volume

   Packing volume = (681.7 m^2) (4.0 m) = 2727 m^3

   d. Determine the tower diameter

   Area/tower = 681.7 m^2/2 = 340.9 m^2

   Diameter = 20.8 m each

   Two towers each with a diameter of 21 m

3. Determine volumetric BOD loading rate.

   BOD loading = $Q\,S_o/V$

$$= \frac{(15{,}140\ \mathrm{m^3/d})(125\ \mathrm{g/m^3})(1\ \mathrm{kg}/10^3\ \mathrm{g})}{2727\ \mathrm{m^3}}$$

$$= 0.69\ \mathrm{kg/m^3 \cdot d}$$

The following table compares the two designs. For the same treatment removal efficiency the two systems have similar packing volume. At the greater depth a smaller diameter trickling filter with a high hydraulic loading rate is used

Comparison of design at two packing depths.

		Value	
Parameter	Unit	Design 1	Design 2
Packing depth	m	6.1	4.0
Packing volume	m^3	2726	2727
Hydraulic loading rate	$L/m^2 \cdot s$	0.392	0.257
Volumetric BOD loading	$kg/m^3 \cdot d$	0.69	0.69

PROBLEM 9-4

Problem Statement – see text, page 1047

Solution (for test data collected at 12°C)

1. Determine the treatability coefficient in Eq. (9-15) by the least squares approach as summarized in the table below. The value for k is determined using Excel Solver function which selects a k that minimizes the sum of the square of the error between the observed S_e/S_i and the calculated S_e/S_i using the selected k value in Eq. (9-15).

$$\frac{S_e}{S_i} = \exp\left(\frac{-kD}{q^n}\right)$$

The values for D and n are given.

D = 6.1 m n = 0.5

Example calculation for the first data point (6 m^3/d, 88% BOD removal) using the k value determined by least squares method shown in the table below:

At 88% removal $S_e/S_i = [1.0 - (88/100)] = 0.12$

Calculated S_e/S_i using solution k value and flowrate

q = Q/A, where Q = 6 m^3/d and $A = \pi D^2/4 = (\pi/4)(1^2) = 0.785\ m^2$

$q = 6\ m^3/d / 0.785\ m^2 = 7.64\ m^3/m^2 \bullet d = 0.0885\ L/m^2 \bullet s$

$$\frac{S_e}{S_i} = \exp\left[\frac{-0.103\,(6.1)}{0.0885^{0.5}}\right] = 0.12$$

Flowrate, m^3/d	q $L/m^2 \bullet s$	Removal eff., %	Observed Se/Si	Predicted Se/Si	error	$error^2$
6	0.0885	88	0.12	0.12	0.00	0.000001
12	0.1769	82	0.18	0.22	-0.04	0.002013
18	0.2654	67	0.33	0.30	0.03	0.001176
24	0.3539	63	0.37	0.35	0.02	0.000478
48	0.7077	54	0.46	0.47	-0.01	0.000202
					Sum	0.003871

For least squares solution using solver k = 0.103 $(L/s)^{0.5}\ m^2$ for the test temperature of 12°C.

2. Compute k_{20} using Eq. (9-16) and the k_{12} value determined above.

$$k_T = k_{20}(1.035)^{(T-20)}$$

$$0.103 = k_{20}\,(1.035)^{(12-20)}$$

$$k_{20} = 0.136\ (L/s)^{0.5}\ m^2$$

3. If the data collection was at 18 or 24°C, the k_{20} values are 0.110 and 0.09 $(L/s)^{0.5}\ m^2$ respectively.

PROBLEM 9-5

Problem Statement – see text, page 1047

Instructors Note: For this problem, an effluent BOD of 20 mg/L is used. Sizing of the clarifiers and tower trickling filters is based on two units each.

Solution

1. Determine primary clarifier diameter for **wastewater #1**.

   From Table 5-19 in Chap. 5 (page 394), use an overflow rate (OR) at average flow of 40 $m^3/m^2 \cdot d$.

   Clarifier surface area = Q/OR = (10,000 m^3/d)/(40 $m^3/m^2 \cdot d$) = 250 m^2

   Use two clarifiers, A = 250 m^2/2 = 125 m^2 each

   $$D = \sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4(125)}{\pi}} = 12.6\,m$$

   Use two 13 m diameter clarifiers.

2. Determine k_{20} for the design conditions using Eq. (9-20).

   a. From Table 9-6, k = 0.210 $(L/s)^{0.5}/m^2$

   b. Influent to tower S_i = (270 mg/L) (0.7) = 189 mg/L

   c. For 6.1 m tower

   $$k_2 = k_1\left(\frac{D_1}{D_2}\right)^{0.5}\left(\frac{S_1}{S_2}\right)^{0.5}$$

   $$= 0.210\left(\frac{6.1}{6.1}\right)^{0.5}\left(\frac{150}{189}\right)^{0.5} = 0.187\ (L/s)^{0.5}/m^2$$

   d. Correct k_2 for temperature effect using Eq. (9-20)

   $k_T = k_{20}\,(1.035)^{T-20}$

   $k_{15} = 0.187(1.035)^{15-20} = 0.157$

3. Solve for the hydraulic application rate and calculate area and volume using Eq. (9-15)

$$\frac{S_e}{S_i} = \exp\left(\frac{-kD}{q^n}\right)$$

$$q = \{kD / [\ln(S_i / S_e)]\}^{1/n}$$

$q = [0.157(6.1)/\ln(189/20)]^2$

$q = 0.1818\ L/m^2 \cdot s$

$Q = 10{,}000\ m^3/d = (10{,}000\ m^3/d)(1\ d/24\ h)(1\ h/3600\ s) = 115.7\ L/s$

Filter tower area = $Q/q = (115.7\ L/s)/(0.1818\ L/m^2{\cdot}s) = 636.4\ m^2$

Packing volume = $(636.4\ m^2)(6.1\ m) = 3882\ m^3$

Tower diameter, use two towers

Area/tower = $636.4\ m^2/2 = 318.2\ m^2$

Diameter = 20.1 m each

Two towers each with a diameter of 20 m

4. Recirculation rate

Minimum wetting rate required = $0.5\ L/m^2{\cdot}s$

$q + q_r = 0.5\ L/m^2{\cdot}s$

$q = 0.1818\ L/m^2{\cdot}s$ (round to 0.2)

$q_r = 0.5 - 0.2 = 0.3\ L/m^2{\cdot}s$

$R = q_r/q = 0.3/0.2 = 1.5$

5. Total pumping rate

$q + q_r = 0.5\ L/m^2{\cdot}s$

Total pumping rate = $(0.5\ L/m^2{\cdot}s)(636.4\ m^2) = 318\ L/s$

Total pumping rate = $(318\ L/s)(60\ s/min)(60\ min/h)(1\ m^3/10^3\ L) = 1145\ m^3/h$

6. Determine flushing and normal dose rate using the data given in Table 9-3.

BOD loading = $Q\ S_o/V$

$$= \frac{(10{,}000\ m^3/d)(189\ g/m^3)(1\ kg/10^3\ g)}{3882\ m^3}$$

$= 0.49\ kg/m^3{\cdot}d$

From Table 9-3, the estimated flushing and operation dose rates are:

Flushing dose = 120 mm/pass

Operating dose = 90 mm/pass

7. Determine diameter of secondary clarifier

From Fig. 9-12, select a 4 m sidewater depth clarifier with an overflow rate at average flow of 1.1 m/h ($m^3/m^2 \bullet h$)

Clarifier surface area = Q/OR = ($10{,}000\ m^3/d$)(1 d/24 h)/($1.1\ m^3/m^2 \bullet h$)

$= 379\ m^2$

Use two clarifiers, $A = 379\ m^2/2 = 189.5\ m^2$ each

$$D = \sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4(189.5)}{\pi}} = 15.5\,m$$

Use two 16 m diameter clarifiers.

PROBLEM 9-6

Problem Statement – see text, page 1047-1048

Solution (Use the NRC equation for rock trickling filters that can be found in the 4th edition of the Metcalf and Eddy Wastewater Engineering textbook or other references)

1. Compute BOD loading to filters for **wastewater #1**.

BOD = 220 mg/L x 0.65 = 143 mg/L

2. Compute E_1 and E_2.

$$\text{Overall efficiency} = \frac{[(143-20)\,mg/L]}{(143\,mg/L)}(100) = 86.0\%$$

$E_1 + E_2(1 - E_1) = 0.86$

Assume $E_1 = E_2$,

$2E_1 - E_1^2 = 1 - (1 - E_1)^2 = 0.86$

$E_1 = E_2 = 0.626 = 62.6\%$

3. Compute the recirculation factor using Eq. (9-12), 4th edition.

Use R = 2.

$$F = \frac{1+R}{(1+R/10)^2} = \frac{1+2}{(1.2)^2} = 2.08$$

4. Compute the BOD loading for the first filter.

W_1 = (5000 m^3/d) (143 g/m^3) (1 kg/10^3g) = 715 kg BOD/d

5. Compute the volume for the first stage using Eq. (9-11), 4th edition.

$$E_1 = \frac{100}{1+0.04432\sqrt{\frac{W_1}{VF}}}$$

$$62.6 = \frac{100}{1+0.4432\sqrt{\frac{715}{V(2.08)}}}$$

V = 189 m^3

6. Compute the diameter of the first filter.

$$A = \frac{V}{D} = \frac{189\ m^3}{1.5\ m} = 126.1\,m^2$$

D = 12.7 m

7. Compute the BOD loading for the second-stage filter.

$W_2 = (1 - E_1)\ W_1$ = 0.374(715 kg BOD/d) = 267 kg BOD/d

8. Compute the packing volume of the second-stage filter using Eq. (9-13), 4th edition.

$$E_2 = \frac{100}{1+\frac{0.4432}{1-E_1}\sqrt{\frac{W_2}{VF}}}$$

$$62.6 = \frac{100}{1+\frac{0.4432}{1-0.626}\sqrt{\frac{267}{V(2.08)}}}$$

V = 505 m^3

9. Compute the diameter of the second filter.

$$A = \frac{V}{D} = \frac{505\,m^3}{1.5\,m} = 336.6\ m^2$$

D = 20.7 m

PROBLEM 9-7

Problem Statement – see text, page 1048

Solution

1. Compute the required oxygen supply using Eq. (9-4) for wastewater with a **primary effluent BOD concentration of 100 mg/L**.

$$R_o = (20\ \text{kg/kg})(0.80e^{-9L_B} + 1.2e^{-0.17L_B})(\text{PF})$$

   a. Summarize data input to equation

   BOD to filter = (7600 m^3/d) (100 g/m^3) (1 kg/10^3 g) = 760 kg/d

   Volume of filter = (π/4)(18 m)^2(6.1 m) = 1552.3 m^3

   L_B = (760 kg/d)/1552.3 m^3 = 0.490 kg BOD/m^3 • d

   PF = 1.5

   b. Compute R_o

$$R_o = (20\ \text{kg/kg})(0.80e^{-9(0.490)} + 1.2e^{-0.17(0.490)})(1.5)$$

   = 33.41 kg O_2 /kg BOD applied

   c. Compute oxygen supplied in kg/h.

   O_2 supplied = (33.41 kg O_2 /kg BOD)(760 kg BOD/d)(1 d/24 h)

   =1058 kg/h

2. Determine the airflow rate at warmest temperature (23°C).

   a. Compute airflow at 20°C using Eq. (9-6).

$$AR_{20} = \frac{(R_o)(Q)(S_o)(3.58\ m^3/\text{kg}\ O_2)}{(10^3\ \text{g/kg})(1440\ \text{min/d})}$$

$$AR_{20} = \frac{(33.41\ \text{kg/kg})(7600\ m^3/\text{d})(100\ \text{g}/m^3)(3.58\ m^3/\text{kg}\ O_2)}{(10^3\ \text{g/1kg})(1440\ \text{min/d})}$$

   = 63.1 m^3/min

b. Compute airflow at 23°C assuming the treatment plant is located near sea level using Eq. (9-7).

$$AR_T = AR_{20}\left(\frac{273.15 + T_A}{273.15}\right)\left(\frac{760}{P_o}\right)$$

$$AR_T = 63.1\left(\frac{273.15+23}{273.15}\right)\left(\frac{760}{760}\right) = 68.4\ \text{m}^3/\text{min}$$

c. Correct airflow for temperature above 20°C using Eq. (9-8).

$$AR_{T,>20} = AR_T\left(1+\frac{T_A-20}{100}\right)$$

$$AR_{T,>20} = 68.4\left(1+\frac{23-20}{100}\right) = 70.5\ \text{m}^3/\text{min}$$

2. Compute airflow pressure drop across packing.

a. Compute tower resistance term N_p using Eq. (9-10).

$$N_p = 10.33(D)e^{(1.36\text{x}10^{-5})(L/A)}$$

From Table C-1 in Appendix C, density of water at 18 °C = 998.6 kg/m^3

L = (7600 m^3/d) (1 d/24 h) (998.6 kg/m^3) = (316.7 m^3/h) (998.6 kg/m^3) = 316,223 kg/h

$$A = \frac{\pi\ D^2}{4} = \frac{\pi\ (18)^2}{4} = 254\ \text{m}^2$$

$$N_p = 10.33(6.1)e^{(1.36\text{x}10^{-5})(316{,}223/254)} = 64.1$$

b. Compute the pressure drop through the packing using Eq. (9-9).

$$\Delta P = N_p\left(\frac{v^2}{2g}\right)$$

v = airflow rate/filter area = (70.5 m^3/min)(1 min/60 s)/ 254 m^2

= 0.005 m/s

$$\Delta P = 64.1\left[\frac{(0.005\,m/s)^2}{2(9.81m/s^2)}\right] = 8.16\,x\,10^{-5}m$$

c. Compute total pressure drop through filter

$$\Delta P_T = 8.16\,x\,10^{-5}\,m + 1.5\left(\frac{v^2}{2g}\right)$$

$$\Delta P_T = 8.16\,x\,10^{-5}\,m + 1.5\left[\frac{(0.005\,m/s)^2}{2(9.81m/s^2)}\right]$$

$= (8.16 \text{ x } 10^{-5} + 0.18 \text{ x } 10^{-5})$ m $= 8.34 \text{ x } 10^{-5}$ m

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PROBLEM 9-8

Problem Statement – see text, page 1048

Solution

1. Compute the BOD loading for a wastewater with a concentration of 150 mg/L.

   BOD loading = (11,200 m^3/d)(150 g/m^3)(1 kg/10^3 g) = 1680 kg/d

   $$\text{Surface area of filter} = A = 2\left(\frac{\pi\,D^2}{4}\right) = 2\left[\frac{\pi\,(20)^2}{4}\right] = 628\ m^2$$

   BOD surface loading = (1680 kg/d)/628 m^2 = 2.68 kg/m^2 • d

2. Determine the nitrogen removal efficiency by estimating the effluent NH_4-N concentration using Eq. (9-23).

   $$NH_4\text{-}N_e = 20.81(BOD_L)^{1.03}(NH_4\text{-}N_L)^{1.52}(Iv)^{-0.36}(T)^{-0.12}$$

   a. Determine the media surface area.

      Media volume = A(D)

      = (628 m^2)(6.1 m) = 3830.8 m^3

      Surface area = (3830.8 m^3)(100 m^2/m^3) = 383.080 m^2

   b. Determine specific loading rates for Eq. (9-23) terms.

$$BOD_L = \frac{(11{,}200\ m^3/d)(150\ g\ BOD/m^3)}{383{,}080\ m^2} = 4.386\ g\ BOD/m^2 \bullet d$$

$$NH_4\text{-}N_L = \frac{(11{,}200\ m^3/d)(24\ g\ TKN/m^3)}{383{,}080\ m^2} = 0.70\ g\ N/m^2 \bullet d$$

$$Iv = \frac{(11{,}200\ m^3/d)(10^3\ L/1\ m^3)}{383{,}080\ m^2} = 29.2\ L/m^2 \bullet d$$

c. Determine the effluent NH_4-N concentration and removal efficiency.

$$NH_4\text{-}N_e = 20.81(4.386)^{1.03}(0.70)^{1.52}(29.2)^{-0.36}(18)^{-0.12} = 11.6\ mg/L$$

$$\text{Nitrogen removal efficiency} = \frac{(100)[(24-11.6)\ mg/L]}{(24\ mg/L)}$$

$$= 51.7\%$$

PROBLEM 9-9

Problem Statement – see text, page 1048

Solution

Design input from Example 8-3.

Flow = 22,700 m^3/d

BOD = 140 mg/L

TKN = 35 mg/L

Temperature = 12°C

A. BOD Removal

1. Determine the trickling filter hydraulic loading rate and the area and volume needed using Eq. (9-19).

$$S_e = \frac{S_o}{(R+1)\exp\left\{\dfrac{k_T D}{[q\,(R+1)]^n}\right\} - R}$$

a. Determine K_T,

From Table 9-6, k = 0.210 $(L/s)^{0.5}/m^2$ at 20°C. [Note: k = kA_s in Eq. (9-19)]

Trickling filter depth = 6.1 m

$$=0.210\left(\frac{6.1}{6.1}\right)^{0.5}\left(\frac{150}{140}\right)^{0.5}=0.217(L/s)^{0.5}/m^2$$

b. Correct k_2 for temperature effect using Eq. (9-16)

i. $k_T = k_{20}(1.035)^{T-20}$

ii. $k_{12} = 0.217(1.035)^{12-20} = 0.165\,(L/s)^{0.5}/m^2$

Rearrange Eq. (9-19) to solve for q.

$$\left[q(1+R)\right]=\left\{\frac{k_TD}{\ln\left[\dfrac{S_o+RS_e}{S_e(1+R)}\right]}\right\}^{1/n}$$

$$\left[q(1+0.5)\right] = \left\{\frac{(0.165\ L/m^2\bullet s)(6.1\ m)}{\ln\left[\dfrac{(140\ g/m^3)+(0.5)(25\ g/m^3)}{(25\ g/m^3)(1+0.5)}\right]}\right\}^2$$

$q = 0.343\ L/m^2\bullet s$

c. Determine the tower area

$Q = 22{,}700\ m^3/d = 262.7\ L/s$

Filter area = $Q/q = 262.7/0.343 = 765.9\ m^2$

d. Determine the packing volume

Packing volume = $(765.9\ m^2)(6.1\ m) = 4672\ m^3$

e. Determine the tower diameter

Area/tower = $765.9\ m^2/2 = 383\ m^2$

Diameter = 22 m each

2. Determine the pumping rate and pumping energy needed.

$Q_p = (1+R)Q = (1 + 0.5)(22{,}700\ m^3/d) = 34{,}050\ m^3/d$

Pumping energy =

$$\frac{1.58\ kW}{(1000\ m^3/d)}(34{,}050\ m^3/d)=53.8\ kW$$

$$\text{kWh/d} = (24\text{ h/d})53.8\text{ kW} = 1291.2\text{ kWh/d}$$

$$\text{kWh/mo} = (1291.2\text{ kWh/d})(30\text{ d/mo}) = 38{,}736\text{ kWh/mo}$$

3. Determine the trickling filter clarifier area.

From Fig. 9-12, select a 4 m sidewater depth clarifier with an overflow rate at average flow of 1.1 m/h ($m^3/m^2 \cdot h$)

Clarifier surface area = Q/OR = (22,700 m^3/d)(1 d/24 h)/1.1 $m^3/m^2 \cdot h$

= 860 m^2

Use two clarifiers, A = 860 m^2/2 = 430 m^2 each

$$D = \sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4(430)}{\pi}} = 23.4\text{ m}$$

B. **Combined BOD removal and nitrification**

1. Determine the trickling filter area using Eq. (9-23)

$$NH_4\text{-}N_e = 20.81(BOD_L)^{1.03}(NH_4\text{-}N_L)^{1.52}(Iv)^{-0.36}(T)^{-0.12}$$

NH_4-N_e = 1.0 mg/L

$$BOD_L\left(\frac{\text{g BOD}}{m^2 \bullet d}\right) = \left[\frac{Q(S_o)}{V(a)}\right]$$

where,

V = trickling filter volume = (A)(d) = A(6.1 m)

a = specific area of media = 100 m^2/m^3

$$BOD_L = \frac{(22{,}700\text{ m}^3\text{/d})(140\text{ g/m}^3)}{A(6.1\text{ m})(100\text{ m}^2\text{/m}^3)} = \frac{5209.8}{A}$$

$$NH_4\text{-}N_L\left(\frac{\text{g N}}{m^2 \bullet d}\right) = \left[\frac{Q(N)}{V(a)}\right]$$

where,

N = (35 – 8) g/m^3 = 27 g/m^3

$$NH_4\text{-}N_L = \frac{(22{,}700\text{ m}^3\text{ / d})(27\text{ g / m}^3)}{A(6.1\text{ m})(100\text{ m}^2\text{ / m}^3)} = \frac{1004.8}{A}$$

$$\text{lv}\left(\frac{\text{L}}{\text{m}^2\bullet\text{d}}\right)=\frac{\text{Q}}{\text{V(a)}}=\frac{(22{,}700\ \text{m}^3/\text{d})(10^3\ \text{L}/1\,\text{m}^3)}{\text{A}(6.1\,\text{m})(100\ \text{m}^2/\text{m}^3)}=\frac{37{,}213.1}{\text{A}}$$

$$1.0=20.81\left(\frac{5209.8}{\text{A}}\right)^{1.03}\left(\frac{1004.8}{\text{A}}\right)^{1.52}\left(\frac{37{,}213.1}{\text{A}}\right)^{-0.36}(12)^{-0.12}$$

A = 4198 m^2

Area = 4198 m^2

Assume 4 filter, $\pi D^2/4$ = Area

Diameter for each filter $=\sqrt{\frac{4(\text{A})}{\pi}}$

$=\sqrt{\frac{4(4198/4)}{\pi}}$

= 36.6 m

Media volume = 4198 m^2 (6.1 m) = 25,608 m^3

2. Determine the pumping rate and pumping energy needed.

 a. Determine the hydraulic application rate based on the effluent flow.

$$\text{G}=\frac{\text{Q}}{\text{A}}=\frac{(22{,}700\ \text{m}^3/\text{d})(\text{d}/24\ \text{h})(\text{h}/3600\ \text{s})(10^3\ \text{L}/1\,\text{m}^3)}{4198\ \text{m}^2}$$

$$=0.063\ \text{L/m}^2\bullet\text{s}$$

Minimum q = 0.50 L/m^2•s

Recycle rate = (0.50 – 0.063) L/m^2•s = 0.437 L/m^2•s

Recycle ratio $=\frac{0.437}{0.063}=6.9$

Q_p = (1 + R)Q = (1 + 6.9)(22,700 m^3/d) = 179,330 m^3/d

 b. Determine the pumping energy.

Pumping energy =

$$\frac{1.58\ \text{kW}}{(1000\ \text{m}^3/\text{d})}\left(179{,}330\ \text{m}^3/\text{d}\right)=283.3\ \text{kW}$$

$$\text{kWh/d}=\left(24\ \text{h/d}\right)283.3\ \text{kW}=6800\ \text{kWh/d}$$

$$\text{kWh/mo}=(6800\ \text{kWh/d})(30\,\text{d/mo})=204{,}000\ \text{kWh/mo}$$

3. The trickling filter clarifier area is the same as in the BOD removal only application as shown in Step A3 above.

   Area = 860 m^2

   BOD removal only and BOD and nitrification design information is found in Example 8-3. These results are included in the summary comparison tables below.

Summary Table (BOD removal only)

Parameter	Unit	Trickling filter	Activated sludge
Aeration volume	m^3		4446
Aeration depth	m		5.0
Media volume	m^3	4672	
Media deph	m	6.1	
Aerobic tank area	m^2		889
Trickling filter area	m^2	766	
Clarifier area	m^2	860	946
Total area	m^2	1626	1835
Pumping rate	m^3/d	34,050	
Pumping energy	$kW/10^3\ m^3/d$	1.5	
Air supply rate	m^3/min		60.5
Aeration energy	$kW/m^3{\bullet}min$		1.8
Monthly energy	kWh/mo	38,736	78,408

Note: Activated sludge monthly energy = (60.5)(1.8)(24)(30) = 78,408 kWh.

Summary Table (combined BOD and nitrification)

Parameter	Unit	Trickling filter	Activated sludge
Aeration volume	m^3		13,418
Aeration depth	m		5.0
Media volume	m^3	25,608	
Media deph	m	6.1	
Aerobic tank area	m^2		2684
Trickling filter area	m^2	4198	
Clarifier area	m^2	860	946
Total area	m^2	5058	3630
Pumping rate	m^3/d	179,330	
Pumping energy	$kW/10^3\ m^3/d$	1.5	
Air supply rate	m^3/min		115.5

Aeration energy	kW/m^3•min		1.8
Monthly energy	kWh/mo	204,000	149,700

Note: Activated sludge monthly energy = (115.5)(1.8)(24)(30) = 149,700 kWh.

PROBLEM 9-10

Problem Statement – see text, page 1048

Solution

1. The advantages and disadvantages of tower trickling filters with plastic packing as compared to activated sludge treatment are summarized in the following table (see also page 953-954).

Advantages	Disadvantages
Less energy required for treatment	Poorer effluent quality in terms of BOD and TSS concentrations
Simpler operation with no issues of mixed liquor inventory control and sludge wasting	Greater sensitivity to lower temperatures resulting in lower removals of BOD and TSS
No problems with sludge bulking in secondary clarifiers	Odor production especially in overloaded filters
Better sludge thickening properties Less equipment maintenance needs	Pumping stations are usually required for filter feed and recirculation
Better recovery from shock toxic loads	Solids sloughing needs to be controlled Not able to nitrify to as low an effluent ammonia-N concentration as with activated sludge
Less susceptible to upset caused by shock organic loads	Not compatible with biological nitrogen removal and enhanced biological phosphorus removal.

PROBLEM 9-11

Problem Statement – see text, page 1049

Solution (Influent flowrate is 37,000 m^3/d)

Input and Assumptions

$J_{N,max}$ value =1.8 g/m^2•d

$J_{N,max}$ value is decreased by 0.10/m after the NH_4-N concentration decreased to 6.0 g/m^3 per Example 9-5.

K_N = 1.5 g/m^3

Temperature > 10°C

Trickling filter diameter = 20 m

Packing depth = 5 m

Influent NH_4-N = 20 mg/L

Solution with No Recycle:

(a) R=0 and q ≥ 1.0 $L/m^2 \cdot s$

1. Determine the hydraulic application rate, q, in units of $m^3/m^2 \cdot d$ for use in Eq. (9-29).

   Trickling filter area $= \frac{\pi D^2}{4} = \frac{\pi (20\text{ m})^2}{4} =$ 117.83 $m^3/m^2 \cdot d$ = 1.36 $L/m^2 \cdot s$

2. Solve for depth N in Eq. (9-29), where N_o is 20.0 g/m3 and Z is 5.0 m. Because no recirculation is used, the NH_4-N concentration at the top of the tower is 20.0 g/m^3. $J_{N,\,max} = 1.8\ g/m^2 \bullet d$

$$(N_o - N) + K_N \ln\left(\frac{N_o}{N}\right) = \frac{Z a J_{N,max}}{q}$$

$$[(20.0 - N) g/m^3] + (1.5\ g/m^3) \ln\left(\frac{20.0}{N}\right) = \frac{(5\text{ m})(138\ m^2/m^3)(1.8\ g/m^2 \bullet d)}{(117.8\ m^3/m^2 \bullet d)}$$

   N = 10.44 mg/L

Solution with recycle

(b) R = 1.0,

1. Determine the total hydraulic application rate.

   q = (1+R)117.83 $m^3/m^2 \cdot d$ = (2)117.83 $m^3/m^2 \cdot d$ = 235.7 $m^3/m^2 \cdot d$

2. Determine the NH_4-N concentration at the top of the tower due to influent dilution by the recycle using Eq. (9-30).

   Assume effluent NH_4-N = 10.4 g/m^3.

$$N_o = \frac{N_{sec} + RN}{1 + R} = \frac{20.0\ g/m^3 + (1.0)(10.4\ g/m^3)}{1.0 + 1.0} = 15.2\ g/m^3$$

3. Solve for N in Eq. (9-29), where N_o is 15.2 g/m^3 and Z is 5.0 m.

$$[(15.2-\text{N})\ \text{g/m}^3]+(1.5\ \text{g/m}^3)\ \ln\left(\frac{15.2}{\text{N}}\right)=\frac{(5\ \text{m})(138\ \text{m}^2/\text{m}^3)(1.8\ \text{g/m}^2\bullet\text{d})}{(235.7\ \text{m}^3/\text{m}^2\bullet\text{d})}$$

N = 10.49 mg/L

4. Repeat the above for N = 10.49 mg/L.

$$\text{N}_\text{o}=\frac{\text{N}_\text{sec}+\text{RN}}{1+\text{R}}=\frac{(20.0\ \text{g/m}^3)+(1.0)(10.49\ \text{g/m}^3)}{1.0+1.0}=15.25\ \text{g/m}^3$$

Solve for N in Eq. (9-29), where N_o is 15.25 g/m^3 and Z is 5.0 m.

$$[(15.25-\text{N})\ \text{g/m}^3]+(1.5\ \text{g/m}^3)\ \ln\left(\frac{15.25}{\text{N}}\right)=\frac{(5\ \text{m})(138\ \text{m}^2/\text{m}^3)(1.8\ \text{g/m}^2\bullet\text{d})}{(235.7\ \text{m}^3/\text{m}^2\bullet\text{d})}$$

N = 10.53 mg/L

5. Repeat the above and solve for N.

N = 10.56 mg/L

Comment

The system with recycle had a slightly higher effluent NH_4-N concentration due to the lower NH_4-N concentration at the top of the tower which resulted in a slightly lower nitrification rate.

6. No effluent suspended solids removal is necessary because the biomass yield from nitrification is small. With a synthesis yield of 0.20 g VSS/g N oxidized (Table 8-14), the VSS production for the removal of 10 mg/L NH_4-N would be less than 2.0 mg/L with consideration for endogenous decay.

PROBLEM 9-12

Problem Statement – see text, page 1049

Solution - Part A, 40 percent BOD removal in trickling filter

1. Determine the trickling filter size for 40 percent BOD removal and **a BOD of 400 mg/L** (S_e = 240 mg/L).

a. Correct the removal rate coefficient for temperature effect using Eq. (9-16).

$k_T = k_{20}\,(1.035)^{(T-20)}$

$k_{12} = 0.18\,(1.035)^{(12-20)} = 0.137$

b. Normalize the removal rate coefficient for the design conditions using Eq. (9-20).

For a 6.1 m tower

$$k_{12} = k_1\left(\frac{D_1}{D_2}\right)^{0.5}\left(\frac{S_1}{S_2}\right)^{0.5}$$

$$= 0.137\left(\frac{6.1}{6.1}\right)^{0.5}\left(\frac{150}{400}\right)^{0.5} = 0.0839(\mathrm{L/s})^{0.5}/\mathrm{m}^2$$

c. Solve for the hydraulic application rate and calculate area and volume of each tower using Eq. (9-15).

$$\frac{S_e}{S_i} = \exp\left(\frac{-kD}{q^n}\right)$$

$$q = \{kD/[\ln(S_i/S_e)]\}^{1/n}$$

$q = [0.0839(6.1)/\ln(400/240)]^2 = 1.004$

$q = 1.004\ \mathrm{L/m^2\cdot s}$

$Q = 8000\ \mathrm{m^3/d} = (8000\ \mathrm{m^3/d})\,(10^3\ \mathrm{L/1\ m^3})\,(1\ \mathrm{d/86400\ s}) = 92.6\ \mathrm{L/s}$

Filter area = Q/q = $(92.6\ \mathrm{L/s})/(1.004\ \mathrm{L/m^2\cdot s}) = 92.2\ \mathrm{m^2}$

Packing volume = $(92.2\ \mathrm{m^2})\,(6.1\ \mathrm{m}) = 562.4\ \mathrm{m^3}$

Tower diameter

Area/tower = $92.2\ \mathrm{m^2}/2 = 46.1\ \mathrm{m^2}$

$$D = \sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4(46.1)}{\pi}} = 7.7\,\mathrm{m}$$

Use two towers each with a diameter of 8 m

2. Determine the amount of soluble BOD in the effluent from the trickling filter.

sBOD = 0.5 (BOD) = 0.5 (240 mg/L) = 120 mg/L

3. Determine the oxygen demand satisfied in the trickling filter.

a. Determine the organic loading rate using a modified version of Eq. (7-69) in Chap. 7 (page 607).

$$L_{org} = \frac{q S_i}{D(10^3 \text{ g}/1 \text{ kg})}$$

$$L_{org} = \frac{(1.004 \text{ L}/\text{m}^2 \cdot \text{s})(1 \text{ m}^3/10^3 \text{ L})(86400 \text{ s}/1 \text{ d})(400 \text{ g}/\text{m}^3)}{(6.1 \text{ m})(10^3 \text{ g}/1 \text{ kg})}$$

$$= 5.69 \text{ kg BOD}/\text{m}^3 \cdot \text{d}$$

b. Determine the SRT from Fig. 9-15.

SRT = 1.25 d

c. Determine biomass produced using Eq. (7-42).

$$X = \frac{Y(S_o - S)}{1 + b(\text{SRT})}$$

$$X_{TF} = \frac{[0.6(400 - 240) \text{ g}/\text{m}^3]}{[1 + (0.12 \text{ g}/\text{g} \cdot \text{d})(1.25 \text{ d})]} = 83.5 \text{ g/m}^3 \text{ (mg/L)}$$

For short SRT values, cell debris (Sec. 8-3 in Chap. 8) is negligible and is not included here.

Determine the oxygen satisfied in trickling filter with a COD balance

O_2 used = $\text{UBOD}_{IN} - \text{UBOD}_{OUT} - 1.42X$

= [1.6 (400 – 240) mg/L)] – 1.42 (83.5 mg/L)

Oxygen used in trickling filter = 137.4 mg/L

4. Determine biomass produced in the aeration tank

Approximate BOD removed = 240 mg/L, SRT = 5 d

Biomass due to oxidation of organic matter

$$X_{AT} = \frac{0.6(240 \text{ g}/\text{m}^3)}{[1 + (0.12 \text{ g}/\text{g} \cdot \text{d})(5 \text{ d})]} = 90 \text{ g}/\text{m}^3$$

Trickling filter biomass remaining after endogenous decay in the activated sludge tank.

$$X_{TF,\text{decay}} = \frac{(83.5 \text{ g}/\text{m}^3)}{[1 + (0.12 \text{ g}/\text{g} \cdot \text{d})(5 \text{ d})]} = 52.2 \text{ g}/\text{m}^3$$

Total biomass produced and fed to the aeration tank = (90 + 52.2) g/m^3

= 142.2 g/m^3

5. Determine oxygen demand in the aeration tank in mg/L and kg O_2/d

   Total oxygen consumed = 1.6 (400) – 1.42 (142.2) = 438.1 g/m^3

   Activated sludge oxygen demand = total demand - TF demand

   = 438.1 – 137.4 = 300.7 g/m^3 (mg/L)

   kg O_2/d = 300.7 g/m^3 (8000 m^3/d) (1 kg/10^3g) = 2406 kg/d

6. Determine the amount of solids wasted per day (TSS). Assume biomass VSS/TSS = 0.85

   a. Determine the inert inorganic solids

      Inert solids = TSS – VSS = (65 – 55) mg/L = 10 mg/L

   b. Determine the total solids wasted per day expressed in mg/L

      Total solids = biomass + inert inorganics + nbVSS

      $$\text{Biomass} = \frac{(142.2\ \text{g VSS}/\text{m}^3)}{(0.85\ \text{g VSS}/\text{g TSS})} = 167.3\ \text{g TSS}/\text{m}^3$$

      Inert organics = 10 g/m^3

      nbVSS = 22 g/m^3

      Total solids = (167.3 + 10 + 22) = 199.3 g TSS/m^3

   c. Determine the total solids wasted per day expressed in kg TSS/d

      P_X = (199.3 g/m^3) (8000 m^3/d) (1 kg/10^3g)

      = 1594 kg TSS/d solids wasted

7. Determine the aeration tank volume and the corresponding hydraulic detention time

   a. Determine the aeration tank volume using Eq. (7-57)

      $$(X_{TSS})(V) = P_{X,TSS}(SRT)$$

      $$V = \frac{P_X(SRT)}{X} = \frac{(1594\ \text{kg}/\text{d})(5\ \text{d})(10^3\ \text{g}/1\ \text{kg})}{(3000\ \text{g}/\text{m}^3)} = 2657\ \text{m}^3$$

   b. Determine the hydraulic detention time in the aeration tank

      $$\tau = \frac{(2657\ \text{m}^3)(24\ \text{h}/1\ \text{d})}{(8000\ \text{m}^3/\text{d})} = 8.0\ \text{h}$$

Solution - Part B, 80 percent BOD removal in trickling filter

1. Determine the trickling filter size for 80 percent BOD removal and **a BOD of 400 mg/L.** (S_e = 80 mg/L).

   a. k_{12} is the same as computed in Part A, 1b.

   b. Solve for the hydraulic application rate and calculate area and volume of each tower using Eq. (9-15)

   $$\frac{S_e}{S_i} = \exp\left(\frac{-kD}{q^n}\right)$$

   $$q = \{kD/[\ln(S_i/S_e)]\}^{1/n}$$

   $q = [0.0839(6.1)/\ln (400/80)]^2$

   $q = 0.101\ \text{L/m}^2\bullet\text{s}$

   $Q = 8000\ \text{m}^3\text{/d} = (8000\ \text{m}^3\text{/d})\ (10^3\ \text{L/1 m}^3)\ (1\ \text{d/86400 s}) = 92.6\ \text{L/s}$

   Filter area = Q/q = 92.6/0.101 = 916.8 m^2

   Packing volume = (916.8 m^2) (6.1 m) = 5592 m^3

   Tower diameter

   Area/tower = 916.8 m^2/2 = 458.4 m^2

   $$D = \sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4(458.4)}{\pi}} = 24.1\text{m}$$

   Diameter = 24.1 m

   Use two towers each with a diameter of 24 m

2. Determine the amount of soluble BOD in the effluent from the trickling filter.

   sBOD = 0.5 (BOD) = 0.5 (80 mg/L) = 40 mg/L

3. Determine the oxygen demand satisfied in the trickling filter

   a. Determine the organic loading rate using a modified version of Eq. (7-69)

   $$L_{org} = \frac{q S_i}{D(10^3\ \text{g/kg})}$$

$$L_{org} = \frac{(0.101\,m^3/m^2{\cdot}d)(1\,m^3/10^3\,L)(86400\,s/1\,d)(400\,g/m^3)}{(6.1\,m)(10^3\,g/kg)}$$

$$= 0.57\,kg\,BOD/m^3{\bullet}d$$

b. Determine the SRT from Fig. 9-15

SRT = 4 d

c. Determine biomass produced using Eq. (7-42).

$$X = \frac{Y\,(S_o - S)}{1 + b(SRT)}$$

$$X_{TF} = \frac{[0.6(400-80)\,g/m^3]}{[1+(0.12\,g/g{\cdot}d)(4\,d)]} = 129.8\,g/m^3 \text{ (mg/L)}$$

Assume cell debris is negligible.

d. Determine the oxygen satisfied in trickling filter with a COD balance

O_2 used = $UBOD_{IN} - UBOD_{OUT} - 1.42X$

= [1.6 (400 – 80) mg/L)] – 1.42 (129.8 mg/L)

Oxygen used in trickling filter = 327.7 mg/L

4. Determine biomass produced in the aeration tank

Approximate BOD removed = 80 mg/L, SRT = 5 d

Biomass due to oxidation of organic matter

$$X_{AT} = \frac{0.6(80\,g/m^3)}{[1+(0.12\,g/g\bullet d)(5\,d)]} = 30\,g/m^3 \text{ biomass}$$

Trickling filter biomass remaining after endogenous decay

$$X_{TF,\,decay} = \frac{(129.8\,g/m^3)}{[1+(0.12\,g/g\bullet d)(5\,d)]} = 81.1\,g/m^3$$

Total biomass produced and fed to the aeration tank = (30 + 81.1) g/m^3

= 111.1 g/m^3

5. Determine oxygen demand in the aeration tank in mg/L and kg O_2/d

Total oxygen consumed = 1.6 (400) – 1.42 (111.1) = 482.2 g/m^3

Activated sludge oxygen demand = total demand – TF demand

= 482.2 – 327.7 = 154.5 mg/L

kg O_2/d = 154.5 g/m^3 (8000 m^3/d) (1 kg/10^{3}g) = 1236 kg/d

6. Determine the amount of solids wasted per day (TSS). Assume biomass VSS/TSS = 0.85

   a. Determine the inert inorganic solids

      Inert solids = TSS – VSS = (65 – 55) mg/L = 10 mg/L

   b. Determine the total solids wasted per day expressed in mg/L

      Total solids = biomass + inert inorganics + nbVSS

$$\text{Biomass} = \frac{(111.1\text{ g VSS/m}^3)}{(0.85\text{ g VSS/g TSS})} = 130.7\text{ g TSS/m}^3$$

      Inert organics = 10 g/m^3

      nbVSS = 22 g/m^3

      Total solids = (130.7 + 10 + 22) = 162.7 g TSS/m^3

   c. Determine the total solids wasted per day expressed in kg TSS/d

      P_X = (162.7 g/m^3) (8000 m^3/d) (1 kg/10^{3}g)

      = 1302 kg/d solids wasted

7. Determine the aeration tank volume and the corresponding hydraulic detention time

   a. Determine the aeration tank volume using Eq. (7-57)

$$(X_{TSS})(V) = P_{X,TSS}(SRT)$$

$$V = \frac{P_X(SRT)}{X} = \frac{(1302\text{ kg/d})(5\text{ d})(10^3\text{ g/kg})}{(3000\text{ g/m}^3)} = 2170\text{ m}^3$$

   b. Determine the hydraulic detention time in the aeration tank

$$\tau = \frac{(2170\text{ m}^3)(24\text{ h/d})}{(8000\text{ m}^3\text{/d})} = 6.5\text{ h}$$

Solution - Part C, Summarize and compare the alternative designs

1. Summarize design data

Design Parameter	Unit	Design A	Design B
Trickling filter diameter	m	8	24
Trickling filter packing volume	m^3	562	5592
Hydraulic application rate	L/m^2 • s	1.004	0.101

O_2 required in aeration tank	kg/d	2406	1236
Solids wasted	kg/d	1594	1302
Volume of aeration tank	m^3	2657	2170
Hydraulic retention time in aeration tank	h	8.0	6.5

2. Selection of design preference.

A definitive selection cannot be made unless a life cycle cost estimate is made to assess capital, aeration and pumping energy costs, and waste sludge handling costs. There would be significant differences in capital cost of the facilities with Design B requiring almost 10 times the packing media volume as for Design A, but only a about a 20 percent reduction in the aeration tank volume. The activated sludge aeration energy costs would be lower for Design B as the oxygen demand is about 1/2 of that needed for Design A. However, the trickling filter feed pumping energy would be higher in Design B due to the need for recycle in the nitrification system to maintain a minimum hydraulic application rate of about 0.50 $L/m^2 \cdot s$. The solids handling costs is lower for Design B with about 20 percent less sludge production. Design B would require much more land area than Design A.

Design B would have greater operational stability as it would better handle load variations.

PROBLEM 9-13

Problem Statement – see text, page 1049-1050

1. A listing of the potential impacts of converting an activated sludge process to a TF/AS facility follows based on the fact that the trickling filter application with 60 percent BOD removal is in a roughing performance mode.

Category	Impact
Hydraulics	Construction of a trickling filter following the primary tanks and before the aeration tanks will require installation of a filter feed pumping station. Construction of a recirculation line from the filter

	effluent to the filter feed pumping station will also be required
Site requirements	Space is needed for the construction of the trickling filters. As computed below, space will be needed for two trickling filters approximately 14 m each in diameter and their related pumping equipment.
Operating considerations	Installation of an additional process, trickling filters, will have some advantages and disadvantages. Advantages include (1) reducing loading variations on the activated sludge process that will improve treatment performance and (2) reducing the aeration requirements. Disadvantages include the need to maintain the additional process and its ancillary equipment and materials (pumps, valves, filter medium).
Flow capacity	There will a small or no change in the treatment capacity. All of the trickling filter effluent goes to the activated sludge process so that the sludge production is still a function of the wastewater feed BOD and TSS. The sludge production will be reduced by a nominal amount due to the longer SRT from the combined trickling filter and activated sludge solids holding time. Thus the volume needed in the activated sludge process will be reduced. However, if the final secondary clarifier size is the limiting factor there will be no reduction in treatment capacity.
Solids production	If the system is operated at the same influent flowrate and SRT used for the activated sludge process alone, the solids production will be slightly less due to oxidation of material in the trickling filter.
Oxygen requirements	Because of the BOD removal in the trickling filter the required oxygen transfer rate in the activated sludge process will be decreased.
Energy requirements	As stated in the text, one of the advantages of combined aerobic processes is the low energy requirement for partial BOD removal. The energy requirements for pumping to the trickling filter should be less than the energy required in the activated sludge process for an equivalent BOD removal. Because complete nitrification is required, the oxygen requirements will be higher than that required for BOD removal only, but the energy requirements for the TF/AS process will be less than that for the AS process alone.
Settling characteristics	Because the trickling filter acts as a biological selector, the settleability of the solids from the combined treatment system should be improved over the activated sludge process alone. Having a better settling sludge can lead to an increased capacity for the secondary clarifiers if they were limited by solids loading.
Effluent quality	The effluent NH_4-N concentration will be the same as the same SRT is used for the activated sludge system with or without the trickling filter. However, because of the slightly lower sludge production rate the SRT could be increased while maintaining the same aeration tank MLSS concentration. In that case the effluent NH_4-N concentration would be decreased. The effluent BOD would be decreased because a lower clarifier effluent TSS concentration may be expected due to the improved solids settling characteristics.

PROBLEM 9-14

Problem Statement – see text, page 1050

Solution (Influent BOD = 1200 mg/L)

Instructors Note: Corrections to problem statement – $k_{20°C}$ = 0.075 $(L/s)^{0.5}/m^2$ is to be corrected to $k_{20°C}$ As = 0.175 $(L/s)^{0.5}/m^2$, the trickling filter hydraulic application rate of 0.10 m^3/m^2•min is 0.015 m^3/m^2•min, the winter MLSS concentration is 4000 mg/L and the pilot plant trickling filter media depth is 6.1 m. Use the same biomass yield and decay coefficients for the trickling filter and activated sludge units.

Solution for Winter Condition (Temperature = 5°C and activated sludge SRT = 15 days)

1. Determine the trickling filter size and media volume
    a. Determine the area and media volume

$$\text{Area} = \frac{Q}{q} = \frac{20{,}000\ m^3/d}{\left(0.015\ m^3/m^2-\text{min}\right)\left(1440\ \text{min}/d\right)} = 925.9\ m^2$$

$$\text{Diameter} = \sqrt{\frac{4\,A}{\pi}} = \sqrt{\frac{4\,(925.9)}{\pi}} = 34.3\,\text{m}$$

    b. 2 trickling filters would likely be used

    Packing volume = (depth)(A) = (6.1 m)(925.9 m^2) = 5648 m^3

2. Determine the amount of soluble BOD removed in the trickling filter using Eq. (9-19) and Eq. (8-26). Note Eq. (9-19) is based on an effluent settled BOD. Assume a settled effluent TSS concentration of 30 mg/L.

$$S_e = \frac{S_o}{(R+1)\exp\left(\frac{k_{20}\,A_s\,D\,\theta^{T-20}}{[q\,(R+1)]^n}\right) - R} \tag{9-19}$$

$$q = \frac{0.015\ m^3}{m^2\text{•min}}\left(\frac{10^3\ L}{1\,m^3}\right)\left(\frac{1\,\text{min}}{60\ s}\right) = 0.25\ \frac{L}{m^2\text{•s}}$$

From Example 9-3 the minimum wetting rate = 0.50 L/m^2•s

Recycle is thus required to add additional flow of 0.25 L/m^2•s and thus R = 0.25/0.25 = 1.0

$$S_e = \frac{(1200\ \mathrm{g\,BOD/m^3})}{(1+1)\exp\left\{\dfrac{(0.175(\mathrm{L/s})^{0.5}/\mathrm{m^2})(6.1\ \mathrm{m})1.035^{5\text{-}20}}{[(0.25\ \mathrm{L/m^2})\bullet \mathrm{s}(1+1)]^{0.5}}\right\}-1} = 305.8\ \mathrm{g\ BOD/m^3}$$

Determine the soluble BOD from Eq. (8-26)

$$\mathrm{BOD_e} = \mathrm{sBOD_e} + \frac{0.60\ \mathrm{g\ BOD}}{\mathrm{g\ UBOD}}\left(\frac{1.42\ \mathrm{g\ UBOD}}{\mathrm{g\ VSS}}\right)\left(\frac{0.85\ \mathrm{g\ VSS}}{\mathrm{g\ TSS}}\right)\left(\frac{30\ \mathrm{g\ TSS}}{\mathrm{m^3}}\right)$$

$$305.8\ \mathrm{g/m^3} = \mathrm{sBOD_e} + 21.7\ \mathrm{g/m^3},\ \mathrm{sBOD_e} = 284.1\ \mathrm{g/m^3}$$

sBOD removal = (1200 – 284.1) = 915.9 g/m^3

3. Determine the biomass produced in the trickling filter and concentration in flow to the activated sludge tank.
   a. Determine the organic loading rate using Eq. (7-69) in Chap. 7 (page 607).

$$L_{org} = \frac{QS_o}{V(10^3\ \mathrm{g/1\ kg})} = \frac{(20{,}000\ \mathrm{m^3/d})(1200\ \mathrm{g/m^3})}{5648\ \mathrm{m^3}(10^3\ \mathrm{g/1\ kg})} = 4.25\ \mathrm{kg/m^3\bullet d}$$

   b. Determine the SRT from Fig. 9-15.

      Estimate SRT = 1.0 d

   c. Determine biomass produced in trickling filter using Eq. (7-42).

$$X = \frac{Y(S_o - S)}{1 + b(\mathrm{SRT})}$$

From Eq. (1-44), Table 8-10, page 743, $K_T = K_{20}\theta^{(T\text{-}20)}$

$$b_5 = b_{20}\theta^{(T\text{-}20)} = 0.12\ \mathrm{g/g\bullet d}(1.035)^{(5\text{-}20)} = 0.072\ \mathrm{gVSS/gVSS\bullet d}$$

$$X_{TF,VSS} = \frac{[(0.6\ \mathrm{gVSS/g\,BOD})(915.9)\ \mathrm{g/m^3}]}{[1 + 0.072\ \mathrm{g/g}\circ\mathrm{d}(1.0\ \mathrm{d})]} = 512.6\ \mathrm{g\ VSS/m^3}$$

For short SRT values, cell debris (Sec. 8-3 in Chap. 8) is negligible and is not included here.

4. Determine biomass produced in the aeration tank
   a. Determine the effluent soluble BOD from Eq. (7-46) shown in Table 8-10, page 743.

$$S_e = \frac{K_s[1+b_H(SRT)]}{SRT(Y_H k\text{-}b_H)-1}$$

At 5°C, $k_5 = k_{20}(1.035)^{(5\text{-}20)} = (6.0\ \text{g BOD / gVSS})(1.035)^{-15}$

$$k_5 = 3.58\ \text{gBOD/gVSS}$$

$$S_e = \frac{(90\ \text{g/m}^3)[1+(0.072\,\text{g/g•d})(15\ \text{d})]}{15\ \text{d}\left[(0.60\ \text{g/g})(3.58\,\text{g/g•d})-(0.072\ \text{g/g•d})\right]-1} = 6.2\ \text{gBOD/m}^3$$

   b. Soluble BOD removed in activated sludge = 284.1 – 6.2 = 277.9 g BOD/m^3

   Activated sludge biomass due to oxidation of organic matter

$$X_{AS} = \frac{(0.6\ \text{gVSS/gBODr})(277.9\ \text{g BOD/m}^3)}{[1+(0.072\ \text{g/g•d})(15.0\,\text{d})]} = 80.2\ \text{g VSS/m}^3$$

5. Determine the sludge production rate in the activated sludge.
   a. Determine net biomass production from trickling filter and activated sludge

   Trickling filter biomass remaining after endogenous decay in the activated sludge tank.

$$X_{TF,\ decay} = \frac{(512.6\ \text{g VSS/m}^3)}{[1+(0.072\,\text{g/g·d})(15.0\ \text{d})]} = 246.4\ \text{gVSS/m}^3$$

   Net biomass produced in the aeration tank =

   = (246.4 + 80.2) gVSS/m^3 = 326.6 g VSS/m^3

   b. Determine net amount of solids amount of solids wasted per day (TSS) from the activated sludge system using Eq. (8-21) in Table 8-10. (Cell debris term ignored, no nitrification of ammonia, and there was no influent nbVSS)

$$P_{X,TSS} = \frac{P_{X,Bio}}{0.85} + Q\left(TSS_o - VSS_o\right)$$

$$P_{X,TSS} = \frac{(20{,}000\ m^3/d)(326.6\ gVSS/m^3)}{(0.85\ gVSS/\ gTSS)}$$

$$+(20{,}000\ m^3/d)(100 - 0)\ gTSS/m^3 = 9{,}684{,}706\ gTSS/d$$

The total solids wasted per day expressed in kg/d = 9685 kgTSS/d

6. Determine the aeration tank volume and the corresponding hydraulic retention time

   a. Determine the aeration tank volume using Eq. (7-57) in Table 8-10.

$$(X_{TSS})(V) = P_{X,TSS}(SRT)$$

$$V = \frac{P_{X,TSS}(SRT)}{X_{TSS}} = \frac{(9685\ kg/d)(15.0\ d)(10^3\ g/kg)}{(4000\ g/m^3)} = 36{,}319\ m^3$$

   b. Determine the hydraulic retention time in the aeration tank

$$\tau = \frac{(36{,}319\ m^3)(24\ h/d)}{(20{,}000\ m^3/d)} = 43.6\ h$$

   c. The activated sludge recycle ratio may range from 0.50 to 1.0.

7. Determine the amount of nitrogen and phosphorus that must be added daily in kg/d

   a. Nitrogen needed for net biomass growth.

      From $C_5H_7NO_2$ (page 723) the biomass contains 0.12 g N/g VSS

      Nitrogen needed = (0.12 g/g)(326.6 gVSS/m^3) = 39.2 g N/m^3

      Nitrogen addition = 39.2 g N/m^3 – 10.0 g N/m^3 = 29.2g N/m^3

      Nitrogen addition in kg/d = (20,000 m^3/d)(29.2 g/m^3)(1 kg/10^3 g)

      = 584 kg N/d

   b. Phosphorus needed for net biomass growth.

      From Example 8-13, assume content of biomass = 1.5%

      Phosphorus needed = (0.015 g/g)(326.6 gVSS/m^3) = 4.9 g P/m^3

      Phosphorus addition = 4.9 g P/m^3 – 4.0 g P/m^3 = 0.9 g P/m^3

Phosphorus addition in kg/d = $(20{,}000\ \text{m}^3/\text{d})(0.9\ \text{g/m}^3)(1\ \text{kg}/10^3\ \text{g})$

= 18 kg P/d

Solution for Summer Condition (Temperature = 26°C and activated sludge SRT = 5 days)

1. Determine the trickling filter size and media volume

   a. Determine the area and media volume

$$\text{Area} = \frac{Q}{q} = \frac{(20{,}000\ \text{m}^3/\text{d})}{(0.015\ \text{m}^3/\text{m}^2-\text{min})(1440\,\text{min/d})} = 925.9\ \text{m}^2$$

$$\text{Diameter} = \sqrt{\frac{4\,A}{\pi}} = \sqrt{\frac{4\,(925.9)}{\pi}} = 34.3\ \text{m}$$

2 trickling filters would likely be used

Packing volume = (depth)(A) = $(6.1\ \text{m})(925.9\ \text{m}^2) = 5648\ \text{m}^3$

2. Determine the amount of soluble BOD removed in the trickling filter using Eq. (9-19) and Eq. (8-26). Note Eq. (9-19) is based on an effluent settled BOD. Assume a settled effluent TSS concentration of 30 mg/L.

$$S_e = \frac{S_o}{(R+1)\exp\left(\dfrac{k_{20}\,A_s\,D\,\theta^{T-20}}{[q\,(R+1)]^n}\right) - R} \tag{9-19}$$

$$q = \frac{0.015\ \text{m}^3}{\text{m}^2\bullet\text{min}}\left(\frac{10^3\ \text{L}}{1\,\text{m}^3}\right)\left(\frac{1\,\text{min}}{60\ \text{s}}\right) = 0.25\ \frac{\text{L}}{\text{m}^2\bullet\text{s}}$$

From Example 9-3 the minimum wetting rate = 0.50 L/m^2-s

Recycle is thus required to add additional flow of 0.25 L/m^2-s and thus R = 0.25/0.25 = 1.0

$$S_e = \frac{(1200\ \text{g BOD}/\text{m}^3)}{(1+1)\exp\left\{\dfrac{(0.175(\text{L/s})^{0.5}/\text{m}^2)(6.1\ \text{m})\,1.035^{26-20}}{[(0.25\ \text{L}/\text{m}^2)\bullet \text{s}(1+1)]^{0.5}}\right\} - 1} = 101.8\ \text{g BOD/m}^3$$

Determine the soluble BOD from Eq. (8-26)

$$BOD_e = sBOD_e + \frac{0.60\text{ g BOD}}{\text{g UBOD}}\left(\frac{1.42\text{ g UBOD}}{\text{g VSS}}\right)\left(\frac{0.85\text{ g VSS}}{\text{g TSS}}\right)\left(\frac{30\text{ g TSS}}{m^3}\right)$$

$101.8\text{ g/m}^3 = sBOD_e + 21.7\text{ g/m}^3$, $sBOD_e = 80.1\text{ g/m}^3$

sBOD removal = (1200 – 80.1) = 1119.9 g/m^3

3. Determine the biomass produced in the trickling filter and concentration in flow to the activated sludge tank.

   a. Determine the organic loading rate using Eq. (7-69) in Chap. 7 (page 607).

$$L_{org} = \frac{QS_o}{V(10^3\text{ g/1 kg})} = \frac{(20{,}000\text{ m}^3\text{/d})(1200\text{ g/m}^3)}{5648\text{ m}^3(10^3\text{ g/1 kg})} = 4.25\text{ kg/m}^3\text{•d}$$

   b. Determine the SRT from Fig. 9-15.

   Estimate SRT = 1.0 d

   c. Determine biomass produced in trickling filter using Eq. (7-42).

$$X = \frac{Y(S_o - S)}{1 + b(SRT)}$$

   From Eq. (1-44), Table 8-10, page 743, $K_T = K_{20}\theta^{(T-20)}$

$$b_5 = b_{20}\theta^{(T-20)} = 0.12\text{ g/g•d}\left(1.035\right)^{(26-20)} = 0.148\text{ gVSS/gVSS•d}$$

$$X_{TF,VSS} = \frac{[\left(0.6\text{ gVSS/gBOD}\right)(1119.9)\text{g/m}^3]}{[1 + (0.148\text{ g/g•d})(1.0\text{ d})]} = 585.3\text{ g VSS/m}^3$$

   For short SRT values, cell debris (Sec. 8-3 in Chap. 8) is negligible and is not included here.

4. Determine biomass produced in the aeration tank

   a. Determine the effluent soluble BOD from Eq. (7-46) shown in Table 8-10, page 743.

$$S_e = \frac{K_s[1 + b_H\left(SRT\right)]}{SRT\left(Y_H k - b_H\right) - 1}$$

   At 5°C, $k_5 = k_{20}1.035^{(26-20)} = 6.0\text{ gBOD/gVSS}\left(1.035\right)^6$

$$k_{26} = 7.38\ \text{gBOD/gVSS}$$

$$S_e = \frac{(90\ \text{g/m}^3)[1+(0.148\ \text{g/g}\bullet\text{d})(5\ \text{d})]}{5\ \text{d}\left[(0.60\ \text{g/g})(7.38\ \text{g/g}\bullet\text{d})\ -(0.148\ \text{g/g}\bullet\text{d})\right]-1} = 7.7\ \text{g BOD/m}^3$$

b. Soluble BOD removed in activated sludge

$= 80.1 - 7.7 = 72.4\ \text{g BOD/m}^3$

c. Activated sludge biomass due to oxidation of organic matter

$$X_{AS} = \frac{(0.6\ \text{gVSS/gBODr})(72.4\ \text{g BOD/m}^3)}{[1+(0.148\ \text{g/g}\bullet\text{d})(5.0\ \text{d})]} = 25.0\ \text{g VSS/m}^3$$

5. Determine the sludge production rate in the activated sludge.

a. Determine net biomass production from trickling filter and activated sludge

Trickling filter biomass remaining after endogenous decay in the activated sludge tank.

$$X_{\text{TF, decay}} = \frac{(585.3\ \text{g VSS/m}^3)}{[1+(0.148\ \text{g/g}\bullet\text{d})(5.0\ \text{d})]} = 336.4\ \text{gVSS/m}^3$$

b. Net biomass production rate in the aeration tank =

$= (25.0 + 336.4)\ \text{gVSS/m}^3 = 361.4\ \text{g VSS/m}^3$

c. Determine net amount of solids amount of solids wasted per day (TSS) from the activated sludge system using Eq. (8-21) in Table 8-10. (Cell debris term ignored, no nitrification of ammonia, and there was no influent nbVSS)

$$P_{X,TSS} = \frac{P_{X,Bio}}{0.85} + Q(TSS_o - VSS_o)$$

$$P_{X,TSS} = \frac{(20{,}000\ \text{m}^3/\text{d})(361.4\ \text{gVSS/m}^3)}{(0.85\ \text{gVSS/gTSS})}$$

$$+(20{,}000\ \text{m}^3/\text{d})[(100-0)\ \text{gTSS/m}^3] = 10{,}503{,}529\ \text{gTSS/d}$$

The total solids wasted per day expressed in kg/d = 10,504 kgTSS/d

6. Determine the aeration tank MLSS concentration. The aeration tank volume was determined from the winter longer-SRT, cold temperature condition.

a. Determine the MLSS concentration using Eq. (7-57) in Table 8-10.

$$(X_{TSS})(V) = P_{X,TSS}(SRT)$$

$$V = \frac{P_{X,TSS}(SRT)}{X_{TSS}} = \frac{(10{,}504\text{ kg/d})(5.0\text{ d})(10^3\text{ g/kg})}{(X_{TSS},\text{ g/m}^3)} = 36{,}319\text{ m}^3$$

X_{TSS} = 1446 g/m^3

b. The hydraulic retention time in the aeration tank is the same assuming same average influent flowrate.

$$\tau = \frac{(36{,}319\text{ m}^3)(24\text{ h/d})}{(20{,}000\text{ m}^3/\text{d})} = 43.6\text{ h}$$

7. Determine the amount of nitrogen and phosphorus that must be added daily in kg/d

a. Nitrogen needed for net biomass growth.

From $C_5H_7NO_2$ (page 723) the biomass contains 0.12 g N/g VSS

Nitrogen needed = 0.12 g/g(361.4 gVSS/m^3) = 43.4 g N/m^3

Nitrogen addition = 43.4 g N/m^3 – 10.0 g N/m^3 = 33.4 g N/m^3

Nitrogen addition in kg/d = (20,000 m^3/d)(33.4 g/m^3)(1 kg/10^3 g)

= 668 kg N/d

b. Phosphorus needed for net biomass growth.

From Example 8-13, assume content of biomass = 1.5%

Phosphorus needed = 0.015 g/g(361.4 gVSS/m^3) = 5.4 g P/m^3

Phosphorus addition = 5.4 g P/m^3 – 4.0 g P/m^3 = 1.4 g P/m^3

Phosphorus addition in kg/d = (20,000 m^3/d)(1.4 g/m^3)(1 kg/10^3 g)

= 28 kg P/d

Solution Summary Table (TF-trickling filter, AS-activated sludge)

Parameter	Units	Winter, 5°C	Summer, 26°C
AS SRT	d	15	5
AS HRT	h	43.6	43.6
AS MLSS	mg/L	4000	1446
TF recycle ratio		1.0	1.0
TF effluent sBOD	mg/L	284.1	80.1

AS effluent sBOD	mg/L	6.2	7.7
Daily sludge wasting	kg TSS/d	9685	10,505
Nitrogen addition	kg/d	584	668
Phosphorus addition	kg/d	18	28

PROBLEM 9-15

Problem Statement – see text, page 1050

Solution (DO concentration = 3.0 mg/L)

The procedure is identical to that used in Example 9-7 to produce and effluent NH_3-N concentration below 0.70 mg/L but with a DO concentration of 3.0 mg/L instead of 4.0 mg/L.

The same following steps are used: the media fill volume percent is assumed for 2/3rd of the aeration tank volume, the average percent fill volume and fill fraction is calculated (V_m/V), the suspended growth SRT is calculated within the MLSS concentration constraint of 3,000 mg/L, the amount of ammonia oxidized is determined and then equations are solved for the media nitrifier biomass density, the nitrifier concentration in the suspended growth and the bulk liquid ammonia-N concentration. From a plot of effluent NH_3-N versus V_m/V, the desired fill volume fraction is determined.

At a DO of 3.0 mg/L the maximum DO limited nitrification flux is 0.88 g $N/m^2 \cdot d$ from Figure 9-25 and it is DO limited at NH_3-N concentration at 0.80 mg/L or more.

Solution (calculation shown for maximum fill volume percent):

1. Assume a media fill volume percent in 2/3rds of tank = maximum at 60 percent. Average fill volume percent = 2/3(60) = 40 percent. $V_M/V = 0.40$
2. Determine the kinetic coefficients at 12°C.

   $b_{H,12} = (0.12)[1.04^{(12-20)}] = 0.088 \text{ g/g} \cdot \text{d}$

   $\mu_{max,12} = (0.90)[1.072^{(12-20)}] = 0.516 \text{ g/g} \cdot \text{d}$

   $b_{n,12} = (0.17)[1.029^{(12-20)}] = 0.135 \text{ g/g} \cdot \text{d}$

3. Determine the influent bCOD concentration

   bCOD = 1.6(140 g BOD/m^3) = 224.0 g/m^3

4. Determine the suspended growth SRT using Eq. (9-50) and MLSS = 3000 g/m^3 (for simplicity ignore cell debris and nitrifier growth sludge production)

   From Eqs (8-20 and 8-21) in Table 8-10 on page 743:

$$P_{X,TSS} = \frac{QY_HS_o}{[1+b_H(SRT)]0.85} + Q(nbVSS) + Q(TSS - VSS)$$

From Eq (7-57) in Table 8-10 on page 743:

$$X_{TSS}(V) = P_{X,TSS}(SRT), \text{ where } V = (1 - V_M / V)(V)$$

$$\text{and } X = 3000 \text{ mg/L} = \frac{P_{X,TSS}(SRT)}{(1 - V_M / V)(V)}$$

Substituting for $P_{X,TSS}$:

$$3000 = \frac{QY_HS_o(SRT)}{[1+b_H(SRT)]0.85(1 - V_M/V)V} + \frac{Q(nbVSS)(SRT)}{(1 - V_M/V)V}$$

$$+ \frac{Q(TSS - VSS)(SRT)}{(1 - V_M/V)V}$$

And substituting τ = V/Q:

$$3000 = \frac{Y_HS_o(SRT)}{[1+b_H(SRT)]0.85(1 - V_M/V)\tau} + \frac{(nbVSS)(SRT)}{(1 - V_M/V)\tau}$$

$$+ \frac{(TSS - VSS)(SRT)}{(1 - V_M/V)\tau}$$

For V_M/V = 0.40 and other inputs from Example 9-7:

$$3000 = \frac{(0.45 \text{ gVSS/gbCOD})(224 \text{ gbCOD/m}^3)(SRT)}{[1+0.088 \text{ g/g}\bullet\text{d}(SRT)]0.85(1 - 0.40)0.233\text{d}} + \frac{(25 \text{ gVSS/m}^3)(SRT)}{(1 - 0.40)0.233\text{d}}$$

$$+ \frac{(10 \text{ gTSS/m}^3)(SRT)}{(1 - 0.40)0.233\text{d}}$$

$$3000 = \frac{848.27(SRT)}{[1+0.088(SRT)]} + 178.83SRT + 74.53SRT$$

Activated sludge SRT = 3.29 d

$$X_H = \frac{(0.45 \text{ gVSS/gbCOD})(224 \text{ gbCOD/m}^3)(3.29 \text{ d})}{[1+(0.088 \text{ g/g}\bullet\text{d})(SRT)](1 - 0.40)0.233\text{d}} = 1840 \text{ gVSS/m}^3$$

5. Determine N available for nitrification (N_o) from Eq. (8-24) in Table 8-10 on page 743.

$$N_o = TKN - \frac{0.12P_{X,bio}}{Q}$$

$$N_o = TKN - \frac{0.12Y_H S_o}{[1+b_H(SRT)]}$$

$$N_o = 35.0 - \frac{(0.12)(0.45\ gVSS/gCOD)(224\ gbCOD/m^3)}{[1+(0.088\ g/g\bullet d)(3.29\ d)]} = 25.6\ g/m^3$$

6. Assume the bulk liquid N concentration is below the critical value and use the left side of Eq. (9-43) to calculate X_{BF}.

$$X_{BF} = \frac{Y_n\left(\frac{N}{k_{n,BF}+N}\right)J_{N,max}}{b_n+\left(\frac{1}{SRT_{BF}}\right)}$$

$$= \frac{(0.15\ g\ VSS/g\ N_{oxidized})\left[\frac{N}{(2.2\ g/m^3)+N}\right](3.3\ g\ N/m^2\bullet d)}{(0.135\ g/g\bullet d)+\left(\frac{1}{6.0\ d}\right)}$$

7. Calculate the bulk liquid AOB concentration from Eq. (9-46).

$$X_n = \frac{SS_A(\frac{V_m}{V})(\frac{X_{BF}}{SRT_{BF}})}{b_n(1-\frac{V_m}{V})+\frac{1}{SRT_{AS}}(1-\frac{V_m}{V})-(\frac{\mu_{max}N}{K_n+N})(\frac{DO}{K_o+DO})(1-\frac{V_m}{V})}$$

$$= \frac{(500\ m^2/m^3)(0.40)(X_{BF}/6\ d)}{(0.135\ g/g\bullet d)(1-0.40)+(\frac{1}{3.34\ d})(1-0.40)-\left\{\frac{(0.516\ g/g\bullet d)N(3.0\ g/m^3)(1-0.40)}{[(0.50\ g/m^3)+N][(0.50\ g/m^3)+(3.0\ g/m^3)]}\right\}}$$

8. Put in known values for Eq. (9-48).

$$N_o = N + \left[\frac{(\mu_{max} / Y_n)N}{K_n + N}\right]\left(\frac{DO}{K_o + DO}\right)X_n(\tau) + \left(\frac{N}{K_{n,BF} + N}\right)J_{N,max}\left(\frac{V_m}{V}\right)(SS_A)(\tau) - 0.12b_H X_H\left(1 - \frac{V_m}{V}\right)(\tau)$$

$$25.6\ g/m^3 = N + \frac{[(0.516\ g/g\bullet d)/(0.15\ g\ VSS/g\ N)](N)(3.0\ g/m^3)X_n(0.233\ d)}{[(0.50\ g/m^3) + N][(0.50\ g/m^3) + (3.0\ g/m^3)]} + \frac{(N)(3.3\ g\ N/m^2\bullet d)(0.40)(500\ m^2/m^3)(0.233\ d)}{[(2.2\ g/m^3) + N]} - 0.12(0.088\ g/g\bullet d)(1840\ g/m^3)(0.60)(0.233\ d)$$

9. For steps 6, 7, and 8, there are three unknowns (X_{BF}, X_n, and N) and three equations. These equations can be solved on an excel spreadsheet using a solver function. The result is:

X_n = 21.5 g/m^3

X_{BF} = 0.24 g/m^2

N= 0.39 g/m^3

The fraction of the amount of NH_3-N nitrified that occurred in the biofilm = 0.79

The bulk liquid N concentration is below the critical value of 0.80 g/m^3 so the appropriate equations were selected.

10. The spreadsheet calculations were repeated for different V_M/V values to determine the fraction that resulted in an effluent NH_3-N concentration of 0.70 mg/L. At this concentration the biofilm nitrification flux was not DO limited.

		Average Fill Volume Fraction		
Parameter	Unit	0.27	0.30	0.40
SRT_{AS}	d	4.2	4.0	3.29
X_{BF}	g/m^2	0.38	0.33	0.24
X_n	g/m^3	18.0	19.1	21.5
N	g/m^3	0.67	0.56	0.39
Fraction of N oxidized in biofilm	-	0.77	0.77	0.78

11. Determine the amount of media to add.

The average fill volume fraction for the aeration tank is 0.27. The fill fraction in the aeration tank portion with media is (0.27)(3/2) = 0.405, as two-thirds of the aeration tank will have the media. The aeration tank volume is 6940 m^3 as given and thus the bulk volume of the amount of media needed is 0.405(6940 m^3) = 2810 m^3.

PROBLEM 9-16

Problem Statement – see text, page 1050

Solution

Compare the advantages and disadvantages for selecting one of the following processes for a small flow decentralized wastewater treatment facility with limited land space and close to a residential area to produce a nitrified effluent: (a) activated sludge with conventional clarification, (b) membrane bioreactor and (c) moving bed bioreactor process.

Criteria	Activated sludge with a clarifier	Membrane bioreactor (MBR)	Moving bed bioreactor (MBBR)
Less space	Most space	Least space- major advantage	Medium in space The need for a clarifier requires more space than MBR
Less operator attention	More operator issues with sludge settling characteristics and potential for settling issues in gravity clarifier. Less advantageous than MBR and MBBR	Easy to operate with almost all suspended solids removal by membrane. Membrane fouling control required with chemical cleaning. Advantage similar to that for MBBR	Easiest to operate, no issues with sludge settling and recycle and solids wasting. Screens need to be checked. Advantage similar to that for MBR
Less energy	Least energy	Highest energy	Medium for energy
Ability to house/aesthetics	More involved for housing. Not as good as that for MBR and MBBR	Easiest to house. This is commonly done for small systems. Very advantageous for this application	Can be housed but not as easy as for MBR

Treatment reliability	Complete nitrification has been proven but risk is related to sludge settling issues and changes that may occur	Very reliable for maintaining good treatment and nitrification	Should be very reliable. Not as well demonstrated for small systems as MBR
Capital Cost	Least expensive	Most expensive	Medium in cost
System simplicity	Medium complexity	Most complex with regard to equipment	Least complex with regard to equipment.

The least preferred is the conventional activated sludge system with clarifier due to higher operational concerns and reliability. The MBR is the most reliable in treatment but has a higher capital and energy cost. In addition it is more complex with the membrane fouling equipment. The MBBR is a better choice if all factors are of equal weight. It could be housed but with more cost but is simple to operate and has less energy than MBR. For the treatment level needed the MBBR is the selected process.

PROBLEM 9-17

Problem Statement – see text, page 1051

Design conditions:

1. Use same primary effluent wastewater characteristics as for Example 9-8
2. Single stage BOD removal followed by single stage nitrification
3. Effluent NH_4-N concentration goal = 0.70 mg/L
4. DO = 2.0 mg/L in BOD removal zone and 4.0 mg/L in nitrification zone
5. Carrier media fill fraction = 50 percent
6. Effective SRT for BOD biofilm = 4.0 d
7. Effective SRT for nitrifying biofilm = 8.0 d

Determine media and tank volumes, sludge production rate and oxygen utilization rate.

Solution:

1. Determine plastic media volume needed and tank volume for BOD removal reactor.

   a. Applied BOD flux (Example 9-8) $= \dfrac{(4.0\ \text{g/m}^2{\bullet}\text{d})}{0.90} = 4.44\ \text{gBOD/m}^2{\bullet}\text{d}$

   b. BOD loading = $(30{,}000\text{m}^3/\text{d})(140\ \text{g/m}^3) = 4{,}200{,}000$ g BOD/d

   c. Media area = $\dfrac{(4{,}200{,}000\ \text{gBOD/d})}{(4.44\ \text{gBOD/m}^2{\bullet}\text{d})} = 945{,}946\ \text{m}^2$

   d. Media volume = $\dfrac{945{,}946\ \text{m}^2}{(500\ \text{m}^2/\text{m}^3)} = 1892\ \text{m}^3$

   e. Tank volume at 50 percent fill fraction = $\dfrac{1892\ \text{m}^3}{0.50\ \text{m}^3/\text{m}^3} = 3784\ \text{m}^3$

   f. Hydraulic retention time, $\tau = V/Q = \dfrac{3784\ \text{m}^3}{30{,}000\ \text{m}^3}\left(\dfrac{24\text{h}}{\text{d}}\right) = 3.03\ \text{h}$

2. Determine available NH_4-N for nitrification after nitrogen consumption for heterotrophic bacteria synthesis from BOD removal using Eq. (8-20), Table 8-10.

$$P_{x,bio} = \frac{Q(Y_H)(BOD)}{1 + b_H(SRT)} + \frac{f_d(b_H)Q(Y_H)(BOD)SRT}{1 + b_H(SRT)}$$

$$\frac{P_{x,bio}}{Q} = \frac{(Y_H)(BOD)[1 + f_d(b_H)SRT]}{1 + b_H(SRT)}$$

$$b_{H,12} = b_{H,20}(1.04)^{(12\text{-}20)} = (0.12\ \text{g/g}{\bullet}\text{d})(1.04)^{(12\text{-}20)} = 0.087\ \text{g/g}{\bullet}\text{d}$$

$$Y_H = 0.45\frac{\text{gVSS}}{\text{gbCOD}}\left(\frac{1.6\ \text{g bCOD}}{\text{gBOD}}\right) = 0.72\,\text{gVSS/gBOD}$$

$$\frac{P_{x,bio}}{Q} = \frac{(0.72\ \text{gVSS/gBOD})(140\ \text{g/m}^3)[1 + 0.15(0.087\ \text{g/g}{\bullet}\text{d})6\text{d}]}{[1 + 0.15(0.087\ \text{g/g}{\bullet}\text{d})6\text{d}]} = 71.4\ \text{gVSS/m}^3$$

Ammonia available for nitrification (Eq. 8-25, Table 8-10):

$$NH_o = TKN - \left(\frac{0.12\text{ g N}}{\text{g biomass}}\right)\frac{P_{x,bio}}{Q}$$

$$NH_o = 35.0\text{ g N/m}^3 - 0.12(71.4\text{ gVSS/m}^3) = 26.4\text{ gN/m}^3$$

3. Determine media volume and tank volume for nitrification reactor

   a. Determine nitrification flux in nitrification reactor under ammonia limited conditions from Eq. (9-52) and adjust to 12°C.

$$J_{N,15} = \left(\frac{N}{2.2\text{ g/m}^3 + N}\right)(3.3\text{ g N/m}^2\bullet\text{d})$$

$$= \left[\frac{(0.70\text{ g/m}^3)}{(2.2\text{g/m}^3) + (0.70\text{g/m}^3)}\right](3.3\text{ g N/m}^2\bullet\text{d}) = 0.797\text{ N/m}^2\bullet\text{d}$$

$$J_{N,12} = (0.797\text{ g N/m}^2\bullet\text{d})(1.098)^{(12-15)} = 0.60\text{ gN/m}^2\bullet\text{d}$$

   b. Media area = $\frac{(26.4\text{ g N/m}^3)(30{,}000\text{ m}^3\text{/d})}{(0.60\text{ g N/m}^2\bullet\text{d})} = 1{,}320{,}000\text{ m}^2$

   c. Media volume = $\frac{1{,}320{,}000\text{ m}^2}{500\text{ m}^2/\text{m}^3} = 2640\text{ m}^3$

   d. Tank volume at 50 percent fill fraction = $\frac{2640\text{ m}^3}{(0.50\text{ m}^3/\text{m}^3)} = 5280\text{ m}^3$

   e. Hydraulic retention time, $\tau = V/Q = \frac{5280\text{ m}^3}{30{,}000\text{ m}^3}\left(\frac{24\text{h}}{\text{d}}\right) = 4.22\text{ h}$

4. Summary of media and tank volumes.

   Example 9-8

Reactor	Function	DO, mg/L	Media volume, m^3	Tank volume, m^3	T, h
1	BOD removal	2.0	525	1050	0.8
2	BOD removal	3.0	473	1050	0.8
3	Nitrification	4.0	1030	1720	1.4
4	Nitrification	4.0	1030	1720	1.4
	Total		3058	5540	4.4

Problem 9-17

Reactor	Function	DO, mg/L	Media volume, m^3	Tank volume, m^3	T, h
1	BOD removal	2.0	1892	3784	3.0
2	Nitrification	4.0	2640	5280	4.2
	Total		4532	9064	7.2

The use of only a single BOD and single nitrification tank increases the media volume for BOD removal and nitrification by 90% for BOD removal and 28% for nitrification. The volume and hydraulic retention times also increase by these percentages.

5. Determine the daily sludge production rate in kgTSS/d using Eqs. (8-20) and (8-21) and the yield and decay coefficients in Table 8-14.

$$\underset{(A)}{\frac{QY_H(S_o-S)(1\,kg/10^3 g)}{1+b_H(SRT)(0.85)}}+\underset{(B)}{\frac{(f_d)(b_H)QY_H(S_o-S)SRT(1\,kg/10^3 g)}{1+b_H(SRT)(0.85)}}$$

$$+\underset{(C)}{\frac{QY_n(NO_X)(1\,kg/10^3 g)}{1+(b_n)SRT(0.85)}}+\underset{(D)}{Q(nbVSS)(1 kg/10^3 g)}+\underset{(E)}{Q(TSS-VSS)(1 kg/10^3 g)}$$

a. Define the input data for above equation.

For BOD removal, SRT = 4d:

Q = 30,000 m^3/d

Y_H = 0.45 g VSS/g bCOD

$S_o - S \sim S_o = 1.6(140) = 224$ mg/L bCOD

$b_H = (0.12\ g\ VSS/gVSS•d)(1.04)^{12-20} = 0.088$ g/g•d

f_d = 0.15 g VSS/g VSS

For nitrification, SRT = 8 d

Y_n = 0.20 g VSS/g NH_4-N (accounting for both type of nitrifiers)

$b_n = (0.17\ g\ VSS/g\ VSS•d)(1.029)^{12-20} = 0.135$g/g•d

Wastewater characteristics

$Q = 30{,}000\ m^3/d$

$nbVSS = 25\ g/m^3$

$TSS–VSS = 10\ g/m^3$

b. Determine $P_{X,VSS}$

$$P_{X,TSS} = \frac{(30{,}000\,m^3/d)(0.45\,g/g)[(224)\,g/m^3](1kg/10^3 g)}{[1+(0.088\ g/g{\bullet}d)(4\,d)](0.85)} \quad (A)$$

$$+\frac{(0.15\,g/g)(0.088\,g/g{\bullet}d)(30{,}000\,m^3/d)(0.45\,g/g)[(224)mg/L](4\,d)(1\,kg/10^3 g)}{[1+(0.088\ g/g{\bullet}d)(4\,d)](0.85)} \quad (B)$$

$$+\frac{(30{,}000\,m^3/d)(0.20\,g)(26.4-0.7\,g/m^3)(1kg/10^3 g)}{[1+(0.135\ g/g{\bullet}d)(8\,d)](0.85)} \quad (C)$$

$$+(30{,}000\,m^3/d)(25\,g/m^3)(1kg/10^3 g) \quad (D)$$

$$+(30{,}000\,m^3/d)(10\,g/m^3)(1kg/10^3 g) \quad (E)$$

$P_{X,TSS}$ = (2631.4 + 138.9 + 87.2 + 750 + 300) kg/d = 3907.5 kg/d

$P_{X,Bio}$ = (2631.4 + 138.9) kg/d = 2770.3 kg/d

6. Determine the total oxygen required using Eq. (8-23), Table 8-10.

For BOD removal: $R_O = Q(S_o\text{-}S) – 1.42\ P_{X,Bio}$

For Nitrification: $R_O = 4.57Q(NOx)$

a. Determine total oxygen required for BOD removal

$R_{O,BOD} = (30{,}000\ m^3/d)(224\ g\ COD/m^3) – 1.42(2770.3\ kg/d)(10^3 g/kg)$

$R_{O,BOD} = 2{,}786{,}174\ g\ O_2/d = 2786\ kg\ O_2/d$

b. Determine the oxygen required for nitrification

$R_{O,nitrif.} = (4.57g\ O_2/g\ NOx)(30{,}000\ m^3/d)[(26.4 – 0.7)\ gN/m^3]$

$= 3{,}523{,}470\ g\ O_2/d = 3524\ kg\ O_2/d$

7. Estimate the oxygen required in each MBBR stage.

a. Stage 1

Assume 90% of BOD is removed in stage 1 and no nitrification

$R_{O,1} = 0.90(2786\ kg\ O_2/d) = 2507.4\ kg/d$

b. Stage 2

$R_{O,2} = 0.10(2786\ kg\ O_2/d) + 3524\ kgO_2/d = 3802.6\ kg/d$

PROBLEM 9-18

Problem Statement – see text, page 1051

Solution

1. Determine the media volume and tank volume required for the nitrification reactors in Example 9-8 for nitrification tank DO = 3.0 mg/L instead of 4.0 mg/L. Note that this does not change the design of the BOD removal tanks preceding the nitrification tanks. From Example 9-8 the ammonia-N available for nitrification is 26.4 gN/m^3.
   a. From Fig. 9-25 the nitrification flux at DO limited condition for DO = 3.0 mg/L is 0.88 $gN/m^2 \bullet d$ at 15°C and the critical NH_4-N concentration for DO limitation is 0.80 g/m^3, so the nitrification rate for the first nitrification reactor will be DO limited.
   b. adjust DO limited flux for temperature

$$J_{N,12} = (0.88\,gN/m^2 \bullet d)(1.058)^{(12-15)} = 0.743\ gN/m^2 \bullet d$$

   c. Determine nitrification flux in 2nd nitrification reactor under ammonia limited conditions at NH_4-N = 0.70 mg/L from Eq. (9-52)

$$J_{N,15} = \left[\frac{N}{(2.2 g/m^3 + N)}\right](3.3\,g\,N/m^2 \bullet d)$$

$$= \left[\frac{(0.70\ g/m^3)}{(2.2\ g/m^3) + (0.70\ g/m^3)}\right](3.3\,g\,N/m^2 \bullet d) = 0.797\,g\,N/m^2 \bullet d$$

$$J_{N,12} = (0.797\,gN/m^2 \bullet d)(1.098)^{(12-15)} = 0.60\ gN/m^2 \bullet d$$

   d. Design the two tanks with equal media area; thus will have same volume as they have the same fill volume fraction.

$$\text{Media area} = \frac{(g\ N\ removed/d)}{flux\ (g\ N/m^2 \bullet d)}$$

Reactor 3

$$\text{Media area} = A_3 = \frac{[(26.4 - X)\,\text{gN/m}^3](30{,}000\ \text{m}^3/\text{d})}{(0.743\ \text{gN/m}^2\bullet\text{d})},$$

where X = NH_4-N concentration in reactor

Reactor 4

$$\text{Media area} = A_4 = \frac{[(X - 0.70)\ \text{gN/m}^3](30{,}000\ \text{m}^3/\text{d})}{(0.60\ \text{gN/m}^2\bullet\text{d})},$$

$A_3 = A_4$

$$\frac{[(26.4 - X)\,\text{gN/m}^3](30{,}000\ \text{m}^3/\text{d})}{(0.743\ \text{gN/m}^2\bullet\text{d})} = \frac{[(X - 0.70)\ \text{gN/m}^3](30{,}000\ \text{m}^3/\text{d})}{(0.60\ \text{gN/m}^2\bullet\text{d})}$$

solve for X; X = 12.18 gN/m^3

Media area for each tank =

$$\frac{[(26.4 - 12.18)\ \text{gN/m}^3](30{,}000\ \text{m}^3/\text{d})}{\left(0.743\ \text{g N/m}^2 \bullet \text{d}\right)} = 574{,}158\ \text{m}^2$$

e. Media volume = $\dfrac{574{,}158\ \text{m}^2}{(500\ \text{m}^2/\text{m}^3)} = 1148\ \text{m}^3$

f. Nitrification reactors tank volume at 60 percent packing fill fraction

$$= \frac{1148\ \text{m}^3}{(0.60\ \text{m}^3/\text{m}^3)} = 1913\ \text{m}^3$$

g. Hydraulic retention time, $\tau = V/Q = \dfrac{1913\ \text{m}^3}{30{,}000\ \text{m}^3}\left(\dfrac{24\text{h}}{\text{d}}\right) = 1.53\text{h}$

h. Compare the effect of the DO concentration.

By decreasing the DO concentration from 4.0 to 3.0 mg/L, the media volume per each of the nitrification reactors was increased by ($1148\ \text{m}^3 - 1030\ \text{m}^3$) = $118\ \text{m}^3$ or 11.5 percent. The reactor tank volume and hydraulic retention time increases by the same amount at the 60 percent packing fill fraction.

2. Determine the effect on the design if the packing volume fill fraction in Example 9-8 is increased from 60 percent to 65 percent.

a. Determine the effect on the tank volume. Note that this does not change the media area required. Thus the tank volume and hydraulic retention time decrease by:

$$\frac{(65-60)100}{65}=7.7\%$$

PROBLEM 9-19

Problem Statement – see text, page 1051

Solution

The same wastewater characteristics and operating conditions for Example 9-8 are used with the only difference being that the temperature is 18°C instead of 12°C.

1. Determine plastic media volume needed and tank volume for 1st reactor.

   a. Determine the applied flux for BOD removal for the first two reactors at the higher temperature. Assume a similar temperature correction factor as used for the trickling filter fixed film biological degradation, Eq. (9-16), page 973

   $$k_T = k_{20}(1.035)^{T-20}$$

   Thus, $k_{12} = k_{20}(1.035)^{12-20}$ and $k_{18} = k_{20}(1.035)^{18-20}$

   By equating K_{20} for the two temperatures,

   $$k_{18} = k_{12}(1.035)^{6} = 1.23k_{12}$$

   1st reactor BOD removal flux = 1.23(12 g/m^2-d) = 14.8 g/m^2•d
   2nd reactor BOD removal flux = 1.23(4 g/m^2-d) = 4.9 g/m^2•d

$$\text{Applied BOD flux} = \frac{\text{BOD removal flux}}{(\%\text{ BOD removal}/100)} = \frac{(14.8\ \text{g/m}^2\bullet\text{d})}{0.75} = 19.7\ \text{g BOD/m}^2\bullet\text{d}$$

   b. Media area:

$$= \frac{\text{BOD application rate}}{\text{Applied BOD flux}} = \frac{(30{,}000\ \text{m}^3/\text{d})(140.0\ \text{g BOD}/\text{m}^3)}{(19.7.0\ \text{g BOD/m}^2{\bullet}\text{d})} = 213{,}198\ \text{m}^2$$

c. Media volume = $\frac{213{,}198\ \text{m}^2}{500\ \text{m}^2/\text{m}^3} = 426\ \text{m}^3$

d. First reactor tank volume = $\frac{426\ \text{m}^3}{(0.50\ \text{m}^3/\text{m}^3)}$ = $852\ \text{m}^3$

e. Hydraulic retention time, $\tau = V/Q = \frac{852\ \text{m}^3}{30{,}000\ \text{m}^3}\left(\frac{24\text{h}}{\text{d}}\right) = 0.68\text{h}$

2. Determine plastic media volume needed and tank volume for 2nd reactor.

a. Applied BOD flux $= \frac{4.9\ \text{g}/\text{m}^2{\bullet}\text{d}}{0.90} = 5.4\ \text{gBOD/m}^2{\bullet}\text{d}$

b. Media area: BOD remaining to 2nd reactor

$= 0.25(30{,}000\text{m}^3/\text{d})(140\ \text{g/m}^3) = 1{,}050{,}000\ \text{g BOD/d}$

$$= \frac{(1{,}050{,}000\ \text{g BOD}/\text{d})}{(5.4\ \text{g BOD/m}^2{\bullet}\text{d})} = 194{,}444\ \text{m}^2$$

c. Media volume = $\frac{194{,}444\ \text{m}^2}{(500\ \text{m}^2/\text{m}^3)} = 389\ \text{m}^3$

d. Second reactor tank volume = $\frac{389\ \text{m}^3}{(0.50\ \text{m}^3/\text{m}^3)}$ = $778\ \text{m}^3$

Use same volume as first reactor = $852\ \text{m}^3$

e. Hydraulic retention time, $\tau = V/Q = \frac{852\ \text{m}^3}{30{,}000\ \text{m}^3}\left(\frac{24\text{h}}{\text{d}}\right) = 0.68\text{h}$

3. Determine available NH4-N for nitrification after nitrogen consumption for heterotrophic bacteria synthesis from BOD removal using Eq. (8-20), Table 8-10.

$$P_{x,\text{bio}} = \frac{Q(Y_H)(\text{BOD})}{(1+b_H\text{SRT})} + \frac{f_d(b_H)Q(Y_H)(\text{BOD})\text{SRT}}{(1+b_H\text{SRT})}$$

$$\frac{P_{x,bio}}{Q} = \frac{(Y_H)(BOD)\left(1+f_d(b_H)SRT\right)}{(1+b_H SRT)}$$

$$b_{H,12} = b_{H,20}(1.04)^{(12\text{-}20)} = (0.12\text{ g/g}\bullet\text{d})(1.04)^{(12\text{-}20)} = 0.087\text{ g/g}\bullet\text{d}$$

$$Y_H = 0.45\frac{\text{gVSS}}{\text{g bCOD}}\left(\frac{1.6\text{g bCOD}}{\text{gBOD}}\right) = 0.72\text{gVSS/g BOD}$$

$$\frac{P_{x,bio}}{Q} = \frac{(0.72\text{ gVSS/g BOD})(140\text{ g/m}^3)[1+0.15(0.087\text{g/g}\bullet\text{d})6\text{d}]}{[1+0.15(0.087\text{g/g}\bullet\text{d})6\text{d}]} = 71.4\text{ gVSS/m}^3$$

Ammonia available for nitrification (Eq. 8-25, Table 8-10):

$$NH_o = TKN - \left(\frac{0.12\text{ gN}}{\text{g biomass}}\right)\frac{P_{x,bio}}{Q}$$

$$NH_o = 35.0\text{ g N/m}^3 - 0.12(71.4\text{gVSS/m}^3) = 26.4\text{g N/m}^3$$

4. Determine media volume and tank volume for nitrification reactors
   a. Adjust DO limited flux for temperature

      $$J_{N,12} = (1.07\text{ gN/m}^2\bullet\text{d})(1.058)^{(18\text{-}15)} = 1.27\text{ gN/m}^2\bullet\text{d}$$

   b. Determine nitrification flux in 2nd nitrification reactor under ammonia limited conditions from Eq. (9-52)

      $$J_{N,15} = \left[\frac{N}{(2.2\text{ g/m}^3+N)}\right](3.3\text{ gN/m}^2\bullet\text{d})$$

      $$= \left[\frac{(0.70\text{ g/m}^3)}{(2.2\text{ g/m}^3+0.70\text{ g/m}^3)}\right](3.3\text{ g N/m}^2\bullet\text{d}) = 0.797\text{ g N/m}^2\bullet\text{d}$$

      $$J_{N,12} = (0.797\text{ gN/m}^2\bullet\text{d})(1.098)^{(18-15)} = 1.06\text{ gN/m}^2\bullet\text{d}$$

   c. Design the two tanks with equal media area; thus will have same volume as they have the same fill volume fraction.

      $$\text{Media area} = \frac{(\text{g N removed/d})}{\text{flux (g N/m}^2\bullet\text{d)}}$$

Reactor 3

$$\text{Media area} = A_3 = \frac{[(26.4 - X)\,\text{gN/m}^3](30{,}000\ \text{m}^3/\text{d})}{(1.27\ \text{gN/m}^2{\bullet}\text{d})},$$

where X = NH_4-N concentration in reactor

Reactor 4

$$\text{Media area} = A_4 = \frac{[(X - 0.70)\,\text{gN/m}^3](30{,}000\ \text{m}^3/\text{d})}{(1.06\ \text{gN/m}^2{\bullet}\text{d})},$$

$A_3 = A_4$

$$\frac{[(26.4 - X)\,\text{gN/m}^3](30{,}000\ \text{m}^3/\text{d})}{(1.27\ \text{gN/m}^2{\bullet}\text{d})} = \frac{[(X - 0.70)\,\text{gN/m}^3](30{,}000\ \text{m}^3/\text{d})}{(1.06\ \text{gN/m}^2{\bullet}\text{d})}$$

solve for X; X = 12.39 gN/m^3

Media area for each tank

$$= \frac{[(12.39 - 0.70)\ \text{gN/m}^3](30{,}000\ \text{m}^3/\text{d})}{(1.06\ \text{gN/m}^2{\bullet}\text{d})} = 330{,}850\ \text{m}^2$$

d. Media volume = $\dfrac{330{,}850\ \text{m}^2}{(500\ \text{m}^2/\text{m}^3)} = 662\ \text{m}^3$

e. Nitrification reactors tank volume = $\dfrac{662\ \text{m}^3}{(0.60\ \text{m}^3/\text{m}^3)} = 1103\ \text{m}^3$

f. Hydraulic retention time, $\tau = V/Q = \dfrac{1103\ \text{m}^3}{30{,}000\ \text{m}^3}\left(\dfrac{24\text{h}}{\text{d}}\right) = 0.88\text{h}$

5. Comparison of the media volume at 12°C and 18°C

Reactor	Function	12°C, m^3	18°C, m^3
1	BOD removal	525	426
2	BOD removal	473	389
3	Nitrification	1030	662
4	Nitrification	1030	662
	Total	3058	2139

Comparison of the tank volume at 12°C and 18°C

Reactor	Function	12°C, m^3	18°C, m^3
1	BOD removal	1050	850
2	BOD removal	1050	850
3	Nitrification	1720	1100
4	Nitrification	1720	1100
	Total	5540	3900

Operation at 18°C requires about 30% less volume than operation at 12°C.

PROBLEM 9-20

Problem Statement – see text, page 1051

Solution

Problem Inputs

Wastewater characteristics are the same as for Example 9-8 and the soluble BOD concentration is 80 mg/L.

Summary of influent wastewater characteristics

Design parameter	Unit	Design value
Average flow	m^3/d	30,000
BOD	g/m^3	140
Soluble BOD	g/m^3	80
TKN	g/m^3	35
Nonbiodegradable VSS	g/m^3	25
TSS	g/m^3	70
VSS	g/m^3	60
Minimum design temperature	°C	12.0

Other assumptions and inputs

1. Effluent BOD ≤ 20 mg/L
2. Media depth = 2 m

3. Hydraulic application rate = 6.0 m/h
4. Use 4 cells and 1 standby
5. BOD loading = 3.5 kg BOD/m^3•d
6. Actual oxygen transfer efficiency = 6.0 percent
7. Fraction of influent VSS destroyed = 0.25
8. Backwash water flush rate is 40 m/h for 15 min/d

1. Determine the BAF volume and dimensions.

   a. Determine the volume

$$\text{Volume} = \frac{\text{BOD applied}}{\text{Design BOD loading}}$$

$$= \frac{(30{,}000\ \text{m}^3/\text{d})(140\ \text{g/m}^3)(1\ \text{kg}/10^3\ \text{g})}{(3.5\ \text{kgBOD/m}^3\text{•d})}$$

$$\text{Volume} = 1200\ \text{m}^3$$

   b. Determine the area per cell and dimensions

$$\text{Area based on organic loading} = \frac{1200\ \text{m}^3}{2\ \text{m}} = 600\ \text{m}^2$$

Area based on hydraulic application rate (HAR):

$$\text{HAR} = \frac{Q}{A}$$

$$\frac{6\ \text{m}}{\text{h}} = \frac{(30{,}000\ \text{m}^3/\text{d})}{A(24\ \text{h/d})},\ A = 208.3\ \text{m}^2$$

Thus BOD loading and media depth control the area.

Use Area = 600 m^2

$$\text{Area / cell} = \frac{600\ \text{m}^2}{4\ \text{cells}} = 150\ \text{m}^2/\text{cell}$$

Assuming square configuration, L = W

$L^2 = 150\ m^2$

L = 12.25 m

4 cells + 1 standby at 12.25 m × 12.25 m × 2 m

Add underdrain and freeboard depth per specific manufacturer's design details.

c. Determine the equivalent hydraulic retention time based on empty bed contact volume

$$\text{Equivalent HRT} = \frac{(1200\ \text{m}^3)(24\ \text{h/d})}{(30{,}000\ \text{m}^3/\text{d})} = 0.96\ \text{h}$$

2. Determine the oxygen required and air supply rate to each cell.

a. Determine the oxygenation rate required from Eq. (9-51).

$$\text{OR} = 0.82\frac{\text{sBOD}_o}{\text{TBOD}_o} + \frac{1.6(\text{BF}_{\text{VSS}})\text{X}_o}{\text{TBOD}_o}$$

$$\text{OR} = 0.82\left[\frac{(80\ \text{g/m}^3)}{(140\ \text{g/m}^3)}\right] + \frac{1.6(0.25)(60\ \text{g/m}^3)}{(140\ \text{g/m}^3)}$$

$$= 0.64\ \text{gO}_2/\text{g BOD applied}$$

Oxygenation rate required

$$= (0.64\ \text{gO}_2/\text{gBOD applied})(30{,}000\ \text{m}^3/\text{d})(140\ \text{gBOD/m}^3)$$

$$= 2{,}699{,}000\ \text{gO}_2/\text{d}$$

$$= 2688\ \text{kgO}_2/\text{d}$$

b. Determine the air supply rate in m^3/min per treatment unit at standard conditions of 20°C and 1.0 atm.

i. The oxygenation rate per unit

$$\frac{(2688\ \text{kgO}_2/\text{d})}{4\ \text{unit}(1440\ \text{min/d})} = 0.46\ \text{kgO}_2/\text{min}\bullet\text{unit}$$

ii. The density of air at standard conditions is 1.204 kg/m^3 per Appendix B-3

iii. The fraction by weight of oxygen in air is 0.2318 per Appendix B-2

iv. The oxygen content of the air at standard condition

$$= 0.231\frac{\text{g O}_2}{\text{g air}}(1.204\ \text{kg/m}^3)$$

$$= 0.279\ \text{kgO}_2/\text{m}^3\ \text{air}$$

v. Air flow rate at 100% efficiency

$$= \frac{(0.46 \text{ kg O}_2/\text{min})}{(0.279 \text{ kg O}_2/\text{m}^3 \text{ air})}$$

$$= 1.65 \text{ m}^3/\text{min•unit}$$

vi. Air flow rate at 6% efficiency

$$= \frac{(1.65 \text{ m}^3/\text{min•unit})}{0.06} = 27.5 \text{ m}^3/\text{min•unit}$$

vii. Total air flow rate = 4(27.5) = 110 m^3/min

3. Determine the sludge production rate using Eq. (9-52).

$$P_{X,VSS} = [0.60(sBOD_o) + (1 - BF_{VSS})(X_o)]Q$$

$$P_{X,VSS} = [0.60(80 \text{ g/m}^3) + (1 - 0.25)(60 \text{ g/m}^3)](30{,}000 \text{ m}^3/\text{d})$$

$$= [\quad (\text{biomass}) \quad + \quad (\text{remaining VSS}) \quad](30{,}000 \text{ m}^3/\text{d})$$

$$P_{X,VSS} = 0.60(80 \text{ g/m}^3)(30{,}000 \text{ m}^3/\text{d}) + (1 - 0.25)(60 \text{ g/m}^3)(30{,}000 \text{ m}^3/\text{d})$$

$$= 1{,}440{,}000 \text{ g/d} + 1{,}350{,}000 \text{ g/d}$$

Biomass is about 85 percent volatile

$$P_{X,TSS} = \frac{(1{,}440{,}000 \text{ g/d})}{(0.85 \text{ g VSS/g TSS})} + 1{,}350{,}000 \text{ g/d} + [(70 - 60) \text{ g TSS/m}^3](30{,}000 \text{ m}^3/\text{d})$$

$$P_{X,TSS} = 3{,}344{,}117 \text{ g TSS/d} = 3344 \text{ kg TSS/d}$$

4. Determine the amount of backwash water used daily per unit.

$$\text{Backwash volume/d•unit} = \frac{40 \text{ m}}{\text{h}}(150 \text{ m}^2/\text{unit})\left(\frac{1 \text{ h}}{60 \text{ min}}\right)\left(\frac{15 \text{ min}}{\text{d}}\right)$$

$$= 1500 \text{ m}^3/\text{d•unit}$$

Total backwash volume = (4 units)(1500 m^3/d•unit) = 6000 m^3/d

5. Determine the backwash water TSS concentration.

Daily solids production = 3,344,112 g TSS/d

Assume effluent TSS = 10 mg/L

Daily solids loss in effluent = (10 g/m^3)(30,000 m^3/d) = 300,000 g/d

Solids removed daily in backwash water

= (3,344,117 – 300,000) g TSS/d = 3,044,117 g TSS/d

$$\text{TSS concentration} = \frac{(3{,}044{,}117\ \text{g TSS/d})}{(6000\ \text{m}^3/\text{d})} = 507\ \text{mg/L}$$

6. Prepare a summary table.

Parameter	Unit	Value
Media volume	m^3	1200
Total area	m^2	600
# active units	-	4
Area/unit	m^2/unit	150
Length and width	m	12.25 × 12.25
Equivalent HRT	h	0.96
Oxygen required	kg/d	2688
Total air application rate	m^3/min	110
Air application rate /unit	m^3/min	27.5
Sludge production rate	kg TSS/d	3344
Total backwash water	m^3/d	6000
Backwash water /unit	m^3/d	1500
Backwash water TSS concentration	mg/L	507

PROBLEM 9-21

Problem Statement – see text, page 1051

Solution (Effluent NO_3-N concentration = 2.0 mg/L)

Wastewater characteristics

Item	Unit	Value
Flowrate	m^3/d	5000
TSS	g/m^3	15
NO_3-N	g/m^3	30
Temperature	°C	18

Assumptions in problem statement:

1. Synthesis yield with methanol = 0.25 g VSS/g CODr
2. The half-order nitrate removal kinetic coefficient = 0.30 mg/L•min
3. Effluent TSS concentration = 5.0 mg/L

Solution

1. Determine the denitrification filter media volume.

   a. Determine filter size based on nitrogen loading (NL). Apply Eq. (9-59):

$$NL = \frac{-0.5K\left(1.44NO_o\right)}{(NO_e)^{0.5} - (NO_o)^{0.5}}$$

$$NL = \frac{-0.5(0.30\ g/m^3 \bullet min)(1.44)(30.0\ g/m^3)}{(2.0\ g/m^3)^{0.5} - (30.0\ g/m^3)^{0.5}} = 1.60\ kg\ NO_3\text{-N/m}^3 \bullet d$$

$$NO_3\text{-N applied} = (30.0\ g/m^3)(5000\ m^3/d)(1\ kg/10^3\ g)$$

$$= 150\ kg/d$$

$$Volume = \frac{(150\ kg/d)}{(1.60\ kg/m^3 \bullet d)} = 93.75\ m^3$$

$$Area = V / D = 93.75\ m^3/1.6m$$

$$= 58.6\ m^2$$

   b. Determine filter size based on filtration hydraulic loading bases.

Hydraulic application rate = 4m/h

Flowrate = 5000 m^3/d = 208.33 m^3/h

$$\text{Filter area} = (208.33\ m^3/h)/(4\ m/h)$$

$$= 52.1\ m^2$$

Thus, the filter size is controlled by the nitrogen loading; Area = 58.6 m^2.

2. Determine filter dimensions assuming square tanks.

   a. Assume 5 filters installed with 1 filter used as standby so that loading is only increased by about 30% when one filter is taken out for backwashing.

$$Area / filter = \frac{58.6\ m^2}{4} = 14.65\ m^2$$

Use a square configuration.

Filter bed dimensions = 3.83 × 3.83 × 1.6 m

(check supplier standard modules)

3. Determine the methanol dose

   a. Nitrate removal = (30.0 g/m^3 - 2.0 g/m^3)(5000 m^3/d) = 140 kg/d

   b. Calculate methanol dose from Eq. (8-69)

$$C_{R,NO3}=\frac{2.86}{1-1.42\left(Y_H\right)}=\frac{2.86}{1-1.42\left(0.25\,\text{gVSS}/\text{gCOD}\right)}$$

$$= 4.43\ \text{g methanol COD}/\text{g NO}_3\text{-N}$$

$$\text{Methanol dose} = \frac{(4.43\ \text{g methanol COD/ g NO}_3\text{-N})}{(1.5\ \text{g COD/g methanol})} = 2.95\ \text{g methanol/g NO}_3\text{-N}$$

Methanol = (2.95 kg/kg)(140 kg/d) = 413 kg/d

Provisions for an additional amount to be added to consume DO and NO_2-N in the influent should be made.

4. Determine the amount of solids produced.

Solids = filtered solids + biomass production

Effluent TSS = 5 g/m^3

$$\text{Filtered solids} = [(15-5)\ \text{g/m}^3](5000\ \text{m}^3\text{/d})(1\ \text{kg/}10^3\text{g})$$

$$= 50\ \text{kg/d}$$

Biomass production: based on 0.25 gVSS/g methanol

Biomass produced =

$$P_{X,bio} = \frac{\left(\dfrac{0.25\ \text{g VSS}}{\text{g COD}}\right)\left(\dfrac{1.5\ \text{g COD}}{\text{g CH}_3\text{OH}}\right)\left(413\ \text{kg CH}_3\text{OH/d}\right)}{(0.85\ \text{g VSS/g TSS})} = 182.2\ \text{kgTSS/d}$$

Total solids produced in filter = 50 kgTSS/d + 182.2 kgTSS/d = 232.2 kgTSS/d

These solids will be removed daily by backwashing the filters.

PROBLEM 9-22

Problem Statement – see text, page 1052

Solution

1. Determine the effect of using glycerol on the effluent NO_3-N concentration due to the higher half-order nitrate removal kinetics with glycerol.
   a. Apply Eq. (9-59) using the nitrogen load (NL) resulting from the filter volume determined in Example 9-9. Use the higher value for K with glycerol and calculate the effect on the effluent NO_3-N (NO_e) concentration.

$$NL = \frac{-0.5\,K\left(1.44\,NO_o\right)}{(NO_e)^{0.5} - (NO_o)^{0.5}}$$

The resulting nitrogen loading for Example 9-9:

$$NL = \frac{Q\left(NO_o\right)}{A\left(D\right)} = \frac{(8000\text{ m}^3/\text{d})(25\text{ g/m}^3)(1\text{ kg}/10^3\text{ g})}{(83.3\text{ m}^2)(2.0\text{ m})} = 1.2\text{ kg }NO_3\text{-N/m}^3{\bullet}\text{d}$$

   b. NL if NO_e = 0 mg/L

$$NL = \frac{-0.5(0.40\text{ g/m}^3{\bullet}\text{min})(1.44)(25.0\text{ g/m}^3)}{(0.0\text{ g/m}^3)^{0.5} - (25.0\text{ g/m}^3)^{0.5}} = 1.44\text{ kg/m}^3{\bullet}\text{d}$$

Using the design equation with glycerol kinetics the allowable NO_3-N loading can be higher than the design loading of 1.2 kg NO_3-N/m^3•d in Example 9-9. Thus, the higher kinetics using glycerol will reduce the NO_3-N concentration to its minimal value where the NO_3-N concentration is rate limiting, likely < 0.20 mg/L.

2. Determine the carbon dose requirement for using glycerol given that the synthesis yield is 0.36 g VSS/g CODr.
   a. From Example 9-9: Nitrate removal = (25.0 g/m^3 – 1.0 g/m^3)(8000 m^3/d)

= 192 kg/d

b. Calculate glycerol dose from Eq. (8-69)

$$C_{R,NO3} = \frac{2.86}{1\text{-}1.42(Y_H)} = \frac{2.86}{1-1.42\left(0.36\ \text{gVSS}/\text{gCOD}\right)}$$

$= 5.85$ g glycerol COD/g NO_3-N

add 10% for DO and NO_2-N in influent

Glycerol dose = $(1.1)5.85 = 6.44$ g glycerol COD/g NO_3-N

Glycerol COD dose = (6.44 kg/kg)(192 kg/d) = 1236.5 kg glycerol COD/d

c. Determine COD of glycerol and determine dose as glycerol.

$C_3H_8O_3 + 3.5O_2 = 3CO_2 + 4H_2O$

MW of $C_3H_8O_3 = 92$

$$\frac{\text{g COD}}{\text{g glycerol}} = \frac{3.5(32)}{92} = 1.217 \text{ gCOD/g glycerol}$$

Carbon dose as glycerol = 1236.5 kg COD/1.217 kg COD/kg glycerol

Glycerol dose = 1016 kg glycerol/d

3. Calculate the solids production rate using glycerol

Solids = filtered solids + biomass production

Use effluent TSS = 5 mg/L (g/m^3)(given value)

$$\text{Filter solids} = [(20-5)\ \text{g/m}^3](8000\ \text{m}^3/\text{d})(1\ \text{kg}/10^3\text{g})$$

$$= 120\ \text{kg/d}$$

Biomass production: based on 0.36 gVSS/g methanol COD (given)

Biomass produced =

$$P_{X,bio} = \frac{\left(\frac{0.36\ \text{g VSS}}{\text{g COD}}\right)(1236.5\ \text{kg glycerol COD/d})}{(0.85\ \text{g VSS/g TSS})} = 523.7\ \text{kgTSS/d}$$

Total solids = 120 kgTSS/d + 523.7 kgTSS/d = 643.7 kgTSS/d

Denite filter volume = (83.3 m^2)(2 m) = 166.6 m^3

Solids storage/24h

$$= \left(\frac{643.7 \text{ kg TSS}}{\text{d}} \right) \left(\frac{\text{filters}}{166.6 \text{ m}^3} \right) = 3.9 \text{ kg TSS/m}^3$$

This amount of solids storage exceeds the typical accumulation capacity given on page 1034 and thus the filters would have to be backwashed more than once per day.

10

ANAEROBIC SUSPENDED AND ATTACHED GROWTH BIOLOGICAL TREATMENT PROCESSES

PROBLEM 10-1

Problem Statement – see text, page 1109

Solution

1. Define the conditions that determine the anaerobic reactor pH.

   It is safe to assume that the pH is below 8.0 and by referring to Fig. F-1 in Appendix F (page 1927) all of the alkalinity must be present as bicarbonate (HCO_3^-). The corresponding carbonate equilibrium relationship is defined by Eq. (10-3):

$$\frac{[H^+][HCO_3^-]}{[H_2CO_3^*]} = K_{a1}$$

   The value of first acid dissociation constant K_{a1} at 30°C is 4.677 x 10^{-7} mole/L. Rearrange Eq. (10-3) to solve for $[H^+]$.

$$[H^+] = \frac{K_{a1}[H_2CO_3^*]}{[HCO_3^-]}$$

2. Determine the carbonic acid concentration

   a. Determine the concentration of H_2CO_3 using Eq. (2-46) in Chap. 2.

$$x_{H_2CO_3} = \frac{P_T}{H} p_g$$

   Determine the value of the Henry's constant in atm at 30°C using Eq. (2-48) as indicated in Example 10-1.

$$\log_{10} H = \frac{-A}{T} + B$$

   From Table 2-7, the values of A and B are 1012.40 and 6.606, respectively.

$$\log_{10} H = \frac{-A}{T} + B = \frac{-1012.40}{273.15 + 30} + 6.606 = 3.27$$

$$H = 10^{3.27} = 1862.1 \text{ atm}$$

Note that the value given in Table F-1 of Appendix F is 1847, which is within 1 percent.

$$x_{H_2CO_3} = \frac{P_T}{H} p_g = \frac{(1 \text{ atm})(0.35)}{1862.1 \text{ atm}} = 1.88 \text{ x } 10^{-4}$$

Because one liter of water contains 55.6 mole [1000 g/(18 g/mole)], the mole fraction of H_2CO_3 is equal to:

$$x_{H_2CO_3} = \frac{\text{mole gas } (n_g)}{\text{mole gas } (n_g) + \text{mole water } (n_w)}$$

$$1.88 \text{ x } 10^{-4} = \frac{[H_2CO_3]}{[H_2CO_3] + (55.6 \text{ mole/L})}$$

Because the number of moles of dissolved gas in a liter of water is much less than the number of moles of water,

$$[H_2CO_3] \approx (1.88 \text{ x } 10^{-4})(55.6 \text{ mole/L}) \approx 10.45 \text{ x } 10^{-3} \text{ mole/L}$$

3. Solve for pH.

$$[H^+] = \frac{K_{a1}[H_2CO_3^*]}{[HCO_3^-]} = \frac{\left(4.677 \text{ x } 10^{-7} \text{ moles/L}\right)\left(10.45 \text{ x } 10^{-3} \text{ moles/L}\right)}{[HCO_3^-]}$$

a. Determine moles/L of HCO_3 for alkalinity = 2200 mg/L as $CaCO_3$

meq/L of alkalinity = (2200 mg/L)/(50 mg/meq) = 44 meq/L

Because valence of HCO3 equal 1, the meq/L = moles/L

Thus moles/L of HCO_3 = 44.0 x 10^{-3}

b. Determine the H^+ concentration and pH.

$$[H^+] = \frac{K_{a1}[H_2CO_3^*]}{[HCO_3^-]} = \frac{\left(4.677 \text{ x } 10^{-7} \text{ moles/L}\right)\left(10.45 \text{ x } 10^{-3} \text{ moles/L}\right)}{\left(44.0 \text{ x } 10^{-3} \text{ moles/L}\right)}$$

$$[H^+] = 1.11 \text{ x } 10^{-7} \text{ moles/L}$$

$$pH = -Log[H^+] = -Log\left(1.11 \text{ x } 10^{-7} \text{ moles/L}\right) = 7.0 - 0.05$$

$$pH = 6.95$$

PROBLEM 10-2

Problem Statement – see text, page 1109-1110

Solution: Part A Anaerobic Process

4. Determine the alkalinity required to maintain the pH of the anaerobic process at a value of 7.0, and the corresponding cost.

    a. Determine the concentration of H_2CO_3 using Eq. (2-46) in Chap. 2.

    $$x_{H_2CO_3} = \frac{P_T}{H} p_g$$

    Determine the value of the Henry's constant in atm at 35°C using Eq. (2-48) as shown in Example 10-1.

    $$\log_{10} H = \frac{-A}{T} + B$$

    From Table 2-7, the values of A and B are 1012.40 and 6.606, respectively.

    $$\log_{10} H = \frac{-A}{T} + B = \frac{-1012.40}{273.15 + 35} + 6.606 = 3.32$$

    $$H = 10^{3.32} = 2092 \text{ atm}$$

    $$x_{H_2CO_3} = \frac{P_T}{H} p_g = \frac{(1 \text{ atm})(0.35)}{2092 \text{ atm}} = 1.67 \text{ x } 10^{-4}$$

    Because one liter of water contains 55.6 mole [1000 g/(18 g/mole)], the mole fraction of H_2CO_3 is equal to:

$$x_{H_2CO_3} = \frac{\text{mole gas}\,(n_g)}{\text{mole gas}\,(n_g) + \text{mole water}\,(n_w)}$$

$$1.67 \text{ x } 10^{-4} = \frac{[H_2CO_3]}{[H_2CO_3] + (55.6 \text{ mole/L})}$$

Because the number of moles of dissolved gas in a liter of water is much less than the number of moles of water,

$$[H_2CO_3] \approx (1.67 \text{ x } 10^{-4})(55.6 \text{ mole/L}) \approx 9.29 \text{ x } 10^{-3} \text{ mole/L}$$

b. Determine the concentration of HCO_3^- required to maintain the pH at a value of 7.0 using Eq. (10-3).

$$\frac{[H^+][HCO_3^-]}{[H_2CO_3]} = K_{a1}$$

where, $K_{a1} = 4.85 \text{ x } 10^{-7}$ (Table F-2) and $H^+ = 10^{-7}$ mole/L

$$[HCO_3^-] = \frac{(4.85 \text{x} 10^{-7})(9.29 \text{ x } 10^{-3} \text{ mole/L})}{(10^{-7} \text{ mole/L})}$$

= 0.045 mole/L

HCO_3^- = 0.045 mole/L (61 g/mole) (10^3 mg/1g) = 2745 mg/L

c. Determine the amount of alkalinity required per day

Equivalents of $HCO_3^- = \frac{(2.745 \text{ g/L})}{(61 \text{ g/eq})} = 0.045 \text{ eq/L}$

1 eq. $CaCO_3 = \frac{\text{m.w.}}{2} = \frac{(100 \text{ g/mole})}{2} = 50 \text{ g } CaCO_3/\text{eq}$

Alkalinity as $CaCO_3$ = (0.045 eq/L) (50 g/eq) 10^3 mg/g

= 2250 mg/L as $CaCO_3$

Alkalinity needed = (2250 – 200) mg/L

= 2050 mg/L as $CaCO_3$

Daily alkalinity addition = (2050 g/m^3) (4000 m^3/d) (1 kg/10^3 g)

= 8200 kg $CaCO_3$/d

Alkalinity addition as HCO_3:

$$= \frac{(8200\ \text{kg CaCO}_3/\text{d})(61\ \text{g HCO}_3/\text{eq})}{(50\ \text{g CaCO}_3)} = 10{,}004\ \text{kg HCO}_3/\text{d}$$

d. Determine the daily cost for the needed alkalinity.

Alkalinity cost = (10,004 kg/d)($0.90/kg) = $9004/d

2. Determine the amount of energy, and the corresponding cost, required to raise the temperature of the sludge from 20 to 35°C using a specific heat value of 4200 J/kg•°C (see inside of back cover). Heat transfer efficiency = 80 percent (given).

a. Energy required

$q = [(4000\ \text{m}^3/\text{d})\ (10^3\ \text{kg/m}^3)\ [(35 - 20)°\text{C}]\ (4200\ \text{J/kg}\bullet°\text{C})]/0.80$

$= 31.5 \times 10^{10}\ \text{J/d}$

b. Cost of the required energy at $0.08/kWh (given)

1.0 kWh = 3.6 MJ (Table A-2)

$$\text{Cost} = \frac{(31.5 \times 10^{10}\ \text{J/d})(\$0.08/\text{kWh})}{(3.6 \times 10^6\ \text{J/kWh})} = \$6776/\text{d}$$

3. Determine the amount of methane produced per day at a COD concentration of **10,000** mg/L and the corresponding value of the methane.

a. Gas production. Ignoring biomass production, the methane production at 35°C = 0.40 m^3/kg COD removed. The methane production rate at a COD removal efficiency 95 percent (given) is:

$= (0.40\ \text{m}^3/\text{kg})\ (10{,}000\ \text{g COD/m}^3)\ (4000\ \text{m}^3/\text{d})\ (1.0\ \text{kg}/10^3\ \text{g})(0.95)$

$= 15{,}200\ \text{m}^3/\text{d}$

At 0°C, the methane volume is:

$$\text{Volume, } 0°\text{C} = \frac{(15{,}200\ \text{m}^3/\text{d})(273.25)}{(273.15 + 35)} = 13{,}473.6\ \text{m}^3/\text{d}$$

Energy content of methane at standard conditions = 38,846 kJ/m^3

(Example problem 10-2)

b. Energy value produced

$= (13{,}473.6\ \text{m}^3/\text{d})(38{,}846\ \text{kJ/m}^3) = 523.4 \times 10^6\ \text{kJ/d}$

c. Value of methane.

$= (523.4 \times 10^6\ \text{kJ/d})(\$5/10^6\ \text{kJ}) = \$2{,}615/\text{d}$

d. Use of digester gas for heating water. To reduce the cost of electrical energy for heating the water, the energy contained in the digested gas will be used instead.

Energy required to heat water (from Step 2a) = 31.5×10^{10} J/d
Energy available to heat water (Step 3b, above) = 52.34×10^{10} J/d
Fraction of methane produced needed to heat the digester:

$$= \frac{(31.5 \times 10^{10}\ \text{J/d})}{(52.34 \times 10^{10}\ \text{J/d})} = 0.60$$

Excess methane at Std. conditons = $(1 - 0.60)(13{,}473.6\ \text{m}^3/\text{d})$
$= 5389.4\ \text{m}^3/\text{d}$
Value of excess methane =
$(5389.4\ \text{m}^3/\text{d})(38{,}846\ \text{kJ/m}^3)(\$5/10^6\ \text{kJ}) = \$1046/\text{d}$

Solution: Part B Aerobic Process

4. Determine the oxygen required to treat the waste, and the corresponding energy cost.

a. O_2 required

$= (10{,}000\ \text{g COD/m}^3)\ (4000\ \text{m}^3/\text{d})\ (1.0\ \text{kg}/10^3\ \text{g})(0.99)(1.2\ \text{g/g}\ O_2)$

$= 47{,}520\ \text{kg}\ O_2/\text{d}$

b. Cost of aeration

$$= \frac{(47{,}520\ \text{kg}\ O_2/\text{d})(\$0.08/\text{kWh})}{(1.2\ \text{kg}\ O_2/\text{kWh})} = \$3168/\text{d}$$

5. Determine the daily net sludge production, and the corresponding processing cost.

a. Sludge production

$= (10{,}000\ \text{g COD/m}^3)(4000\ \text{m}^3/\text{d})\ (1.0\ \text{kg}/10^3\ \text{g})(0.3\ \text{g TSS/g COD})$

$= 12{,}000\ \text{kg TSS/d}$

b. Cost of sludge processing

= (12,000 kg TSS/d)($0.10/kg TSS) = $1200/d

Solution: Comparison of Anaerobic and Aerobic Process

6. Prepare a summary table to compare the anaerobic and aerobic processes.

	Treatment process cost, $/d		
Item	Anaerobic without internal use of digester gas	Anaerobic with internal use digester gas	Aerobic
Required alkalinity	< 9,004 >	< 9004 >	
Raise temperature	< 6,776 >	0	
Methane produced	2,615	1,046	
Net cost	< 13,165 >	< 7,958 >	
Aeration			< 3,168 >
Sludge processing			< 1,200 >
Net cost			< 4,368 >

Comment

In this problem, the importance of the organic concentration, alkalinity cost, and temperature of the wastewater is illustrated. The economic benefit of using of digester gas for heating is also illustrated. The need to add alkalinity is a major negative cost for the anaerobic process in this case.

PROBLEM 10-3

Problem Statement - See text, page 11110

Solution (flowrate of 1000 m^3/d)

1. Determine the amount of substrate degradation that will occur.

$$C_{50}H_{75}O_{20}N_5S \text{ removed} = (0.95)(4000 \text{ mg/L}) = 3800 \text{ mg/L}$$

2. Write a balanced equation for substrate degradation using Eq. (10-4).

$$C_{50}H_{75}O_{20}N_5S + \left(50 - \frac{75}{4} + \frac{20}{2} + \frac{3(5)}{4} + \frac{1}{2}\right)H_2O \rightarrow$$

$$\left(\frac{50}{2} + \frac{75}{8} + \frac{20}{4} + \frac{3(5)}{8} + \frac{1}{4}\right)CH_4$$

$$+ \left(\frac{50}{2} - \frac{75}{8} + \frac{20}{4} + \frac{3(5)}{8} + \frac{1}{4}\right)CO_2$$

$$+ (5)NH_3 + (1)H_2S$$

$$C_{50}H_{75}O_{20}N_5S + 45.5H_2O \rightarrow 41.5CH_4 + 22.75CO_2 + 5NH_3 + 1H_2S$$

3. Write the pertinent reaction for the formation of alkalinity as the substrate is degraded using Eq. (10-5).

$$C_{50}H_{75}O_{20}N_5S + 45.5H_2O \rightarrow 41.5CH_4 + 22.75CO_2 + 5NH_3 + 1H_2S$$

$$+ \quad 5(NH_3 + H_2O + CO_2) \rightarrow 5NH_4^+ + 5HCO_3^-)$$

$$C_{50}H_{75}O_{20}N_5S + 50.5H_2O \rightarrow 41.5CH_4 + 17.75CO_2 + 5NH_4^+ + 1H_2S + 5HCO_3^-$$

The amount of alkalinity (expressed as $CaCO_3$) produced per g/L of substrate degraded is 250/1097 = 0.23 g/L as $CaCO_3$.

4. Determine the amount of alkalinity produced per day for an average flowrate of **1000 m³/d**.

$$\text{Alk prod.} = \left(\frac{3.8\text{ g}}{\text{L}}\right)\left(\frac{0.23\text{ g/L}}{\text{g/L}}\right)\left(\frac{10^3\text{ L}}{\text{m}^3}\right)\left(\frac{10^3\text{ m}^3}{\text{d}}\right)\left(\frac{1\text{ kg}}{10^3\text{ g}}\right)$$

$$= 874\text{ kg/d as }CaCO_3$$

Summary of results for various flowrates

Flowrate, m³/d	Alkalinity produced, kg/d as $CaCO_3$
1000	874
2000	1748
3000	2622

5. Determine the approximate mole fraction of CO_2, CH_4, and H_2S in the gas phase using Eqs. (10-6), (10-7), and (10-8), respectively.

$$f_{CO_2} = \frac{4(50) - 75 + 2(20) - 5(5) + 2(1)}{8(50 - 5 + 1)} = 0.386$$

$$f_{CH_4} = \frac{4(50) + 75 - 2(20) - 5(5) - 2(1)}{8(50 - 5 + 1)} = 0.565$$

$$f_{H_2S} = \frac{1}{8(50 - 5 + 1)} = 0.003$$

PROBLEM 10-4

Problem Statement - See text, page 1110

Instructors Note: The discussion in the text that accompanies Eq. (10-16) and the data presented in Fig. 10-7 are not correct. The percent H_2S should be on the right axis and the HS^- on the left axis. Thus, at a pH of 7, about 40% of the H_2S present is gaseous H_2S.

Solution

1. Determine the amount of COD that will be used for sulfate reduction at 98 percent degradation.

$$\text{COD used} = 0.98\left(\frac{0.89 \text{ mg COD}}{\text{mg sulfate}}\right)\left(\frac{500 \text{ mg sulfate}}{\text{L}}\right) = 436 \text{ mg COD/L}$$

2. For the influent COD value of **4000 mg/L**, compute the amount of methane gas that will be generated (a) with and (b) without the presence of sulfate.

   a. Determine the amount of methane produced accounting for the COD removed by sulfate reduction. The COD remaining after sulfate reduction and considering the 95 percent COD degradation is

$$\text{COD remaining} = 0.95(4000 \text{ mg/L}) - 436 \text{ mg/L} = 3364 \text{ mg/L}$$

$$\text{Methane produced} = \left(\frac{3.364 \text{ g COD}}{\text{L}}\right)\left(\frac{0.40 \text{ L } CH_4}{\text{g COD}}\right) = 1.35 \text{ L } CH_4/\text{L}$$

At the flowrate of 2000 m3/d, the total amount of methane produced per day is

$$\text{Methane produced} = \left(\frac{1.35\ \text{m}^3\ \text{CH}_4}{\text{m}^3}\right)\left(\frac{2000\ \text{m}^3}{\text{d}}\right) = 2691\,\text{m}^3/\text{d}$$

b. Determine the amount of methane produced without accounting for the COD removed by sulfate reduction. The COD remaining assuming 95 percent COD degradation is

$$\text{COD remaining} = 0.95(4000\ \text{mg/L}) = 3800\ \text{mg/L}$$

$$\text{Methane produced} = \left(\frac{3.8\ \text{g COD}}{\text{L}}\right)\left(\frac{0.40\ \text{L CH}_4}{\text{g COD}}\right) = 1.52\ \text{L CH}_4/\text{L}$$

At the flowrate of 2000 m3/d, the total amount of methane produced per day is

$$\text{Methane produced} = \left(\frac{1.52\ \text{m}^3\ \text{CH}_4}{\text{m}^3}\right)\left(\frac{2000\ \text{m}^3}{\text{d}}\right) = 3{,}040\ \text{m}^3/\text{d}$$

3. Compute the amount of H_2S in the gas phase at a reactor pH value of 7.0.

a. Determine the total amount of H_2S produced (hydrogen sulfide gas and hydrogen sulfide ion) from sulfate reduction.

$$\text{H}_2\text{S prod.} = \left(\frac{0.4\ \text{m}^3\ \text{H}_2\text{S}}{\text{kg COD}}\right)\left(\frac{0.436\ \text{kg COD}}{\text{m}^3}\right)\left(\frac{2000\ \text{m}^3}{\text{d}}\right) = 349\ \text{m}^3/\text{d}$$

b. Compute the percent of H_2S in the gas phase at pH 7 and 35°C.

For a reactor temperature of 35°C, the acid equilibrium constant for H_2S, K_{a1}, must be interpolated between the temperatures of 30 and 40°C, as given in Table 10-11. Plotting the K_{a1} values on log-paper as a function of temperature results in a value of 1.88 for K_{a1} at 35°C. The percent H_2S is then determined using Eq. (10-16).

$$H_2S,\ \% = \frac{100}{1 + K_{a1}/\left[H^+\right]}\quad \frac{100}{1 + \left(1.88 \text{ x } 10^{-7}\right)/\left[10^{-7}\right]} = 35\%$$

c. Determine the total amount of H_2S in the gas phase produced in the reactor.

H_2S gas produced = 349 m^3/d x 0.35 = 122 m^3/d

4. Summary of values for all influent COD concentrations

		Influent COD		
Item	Unit	4000	6000	8000
COD remaining after sulfate reduction	mg/L	3364	5264	7164
Methane produced accounting sulfate reduction	m^3/d	2691	4211	5731
Methane produced without accounting for sulfate reduction	m^3/d	3040	4560	6080

PROBLEM 10-5

Problem Statement - See text, page 1110

Solution

1. Summarize the possible causes and mechanisms for a decrease in the methane gas production rate.

Cause	Mechanism
Nutrient limitation	The concentration of nitrogen, phosphorus, or sulfur may be insufficient to support anaerobic biomass growth.
Micronutrient limitation	Trace metals, such as iron, cobalt, nickel, and zinc, may be not present or bioavailable.
Alkalinity limitation	Because of the high concentration of dissolved CO_2, alkalinity is needed to buffer the pH in an anaerobic reactor. Alkalinity will need to be added if the wastewater does not contain sufficient alkalinity to maintain a neutral pH.
Ammonia toxicity	High concentrations of ammonia (toxicity threshold of 100 mg/L as NH_3-N), are inhibitory to methanogenic activity. Proteins and amino acids may be degraded to produce ammonium
Sulfide toxicity	High concentrations (50 to 250 mg/L) of H_2S has been shown to decrease methanogenic activity.
General toxicity	The presence of other toxic or inhibitory substances in wastewater may reduce methanogenic reaction rates.

PROBLEM 10-6

Problem Statement - See text, page 1110-1111

Instructors Note: Students should be instructed to assume a value for the percent COD removal. For the following example a value of 90 percent was selected.

Solution (wastewater 1):

1. For a degradable COD concentration of **4000 mg/L** and a temperature of **25°C**, determine the SRT.

   At 90 percent COD removal the effluent COD is:

   = (1.0 – 0.9) (4000 mg/L) = 400 mg/L

   The given effluent TSS concentration is 120 mg/L.

   Effluent COD from TSS = (120 mg/L) 1.8 g COD/g TSS = 216 mg/L

   Allowable effluent soluble COD = (400 – 216) mg/L = 184 mg/L

   Rearranging Eq. (7-70) and substituting kY = μ [Eq. (7-16)]:

   $$\text{SRT} = \left[\frac{\mu_m S_o}{K_s + S_e} - b\right]^{-1}$$

   Use kinetic coefficients from Table 10-13,

   μ_m = 0.20 g/g•d

   K_S = 120 mg/L

   b = 0.03 g/g•d

   $$\text{SRT} = \left\{\frac{(0.20\ \text{g/g}\cdot\text{d})(184\ \text{g/m}^3)}{[(120 + 184)\ \text{g/m}^3]} - 0.03\ \text{g/g}\cdot\text{d}\right\}^{-1}$$

   SRT = 11.0 d

   Use a factor of safety of 1.5

   Design SRT = 1.5 (11.0) = 16.5 d

2. Determine the amount of sludge that will need to be wasted daily

   Use Eq. (8-21) in Table 8-10 to determine solids production:

$$P_{X,TSS} = \frac{Q\,Y(S_o - S)}{[1 + b(SRT)](0.85)} + \frac{f_d(b)Q\,Y(S_o - S)SRT}{(1 + bSRT)(0.85)} + Q(nbVSS)$$

$S_o - S$ = degradable COD = 4000 mg/L – 184 mg/L = 3816 mg/L

Use coefficients from Table 10-13 and assume $f_d = 0.15$

Y = 0.08 g VSS/g COD

b = 0.03 g/g•d

$$P_{X,TSS} = \frac{(2000\ \text{m}^3/\text{d})(0.08\ \text{g VSS/g COD})(3816\ \text{mg COD/L})}{[1 + 0.03\ \text{g/g}\cdot\text{d}\ (16.5\ \text{d})](0.85)} +$$

$$\frac{0.15\ \text{g/g}(0.03\ \text{g/g}\cdot\text{d})(2000\ \text{m}^3/\text{d})(0.08\ \text{g/g})(3816\ \text{mg/L})(16.5\ \text{d})}{[1 + 0.03(16.5\ \text{d})](0.85)} + 0\ \text{g/d}$$

= 480,472 g/d + 35,675 g/d + 0 g/d

$P_{X,TSS}$ = 516,147 g/d = 516.1 kg/d

3. Determine reactor volume and τ

   a. Determine the volume using Eq. (7-57)

   $$\text{Volume} = \frac{(P_{X,TSS})(SRT)}{MLSS}$$

   Assume MLSS = 5000 g/m^3

   $$\text{Volume} = \frac{(516{,}147\ \text{g/d})(16.5\ \text{d})}{(5{,}000\ \text{g/m}^3)} = 1703\ \text{m}^3$$

   b. Determine the hydraulic detention time, τ

   $$\tau = \frac{V}{Q} = \frac{1703\ \text{m}^3}{(2000\ \text{m}^3/\text{d})} = 0.85\ \text{d}$$

4. Determine the methane gas production rate

   Assume 0.4 m^3 gas/kg COD at 35°C

   At 25°C gas production rate = $(0.4)\dfrac{(273.15 + 25)}{(273.15 + 35)} = 0.39\ \text{m}^3/\text{kg COD}$

   Amount of COD removed in waste sludge

$$= \frac{(516{,}147\ \text{gTSS/d})(0.85\ \text{gVSS/gTSS})(1.42\ \text{gCOD/gVSS})}{(2000\ \text{m}^3/\text{d})}$$

$$= 312\ \text{gCOD/m}^3$$

The methane gas production

= (0.39 m^3/kg) (3816 – 312 g COD/m^3) (2000 m^3/d) (1.0 kg/10^3 g)

= 2733 m^3/d

5. Determine the methane gas production rate

$$\text{Methane production} = \frac{(2733\ \text{m}^3\ \text{CH}_4/\text{d})}{(0.65\ \text{m}^3\ \text{CH}_4/\text{m}^3\ \text{gas})} = 4{,}205\ \text{m}^3/\text{d}$$

6. Determine nutrient requirements

Biomass production = $P_{X,TSS}$ = 516,547 g TSS/d

N = 12%, P = 2% of VSS

N required = (516,547)(0.12)(0.85) = 52,787 g/d

P required = (516,547)(0.02)(0.85) = 8,781 g/d

Repeat the solution for 35°C

For a degradable COD concentration of **4000 mg/L** and a temperature of **35°C**, determine the SRT.

At 90 percent COD removal the effluent COD is:

= (1.0 – 0.9) (4000 mg/L) = 400 mg/L

The given effluent TSS concentration is 120 mg/L.

Effluent COD from TSS = (120 mg/L) 1.8 g COD/g TSS = 216 mg/L

Allowable effluent soluble COD = (400 – 216) mg/L = 184 mg/L

Rearranging Eq. (7-70) and substituting kY = μ [Eq. (7-16)]:

$$\text{SRT} = \left[\frac{\mu_m S_o}{K_s + S_e} - b\right]^{-1}$$

Use kinetic coefficients from Table 10-13,

μ_m = 0.35 g/g•d

K_S = 120 mg/L

b = 0.03 g/g•d

$$\mathrm{SRT} = \left\{ \frac{(0.35\ \mathrm{g/g \cdot d})(184\ \mathrm{g/m^3})}{[(120\ +\ 184)\ \mathrm{g/m^3}]}\ -\ 0.03\ \mathrm{g/g \cdot d} \right\}^{-1}$$

SRT = 5.5 d

Use a factor of safety of 1.5

Design SRT = 1.5 (5.5) = 8.3 d

2. Determine the amount of sludge that will need to be wasted daily

Use Eq. (8-21) in Table 8-10 to determine solids production:

$$P_{X,TSS} = \frac{Q\,Y(S_o - S)}{[1 + b(SRT)](0.85)} + \frac{f_d(b)\,Q\,Y(S_o - S)SRT}{(1 + bSRT)(0.85)} + Q(\mathrm{nbVSS})$$

S_o – S = degradable COD = 4000 mg/L – 184 mg/L = 3816 mg/L

Use coefficients from Table 10-13 and assume f_d = 0.15

Y = 0.08 g VSS/g COD

b = 0.03 g/g•d

$$P_{X,TSS} = \frac{(2000\ \mathrm{m^3/d})(0.08\ \mathrm{g\ VSS/g\ COD})(3816\ \mathrm{mg\ COD/L})}{[1\ +\ 0.03\ \mathrm{g/g \cdot d}\ (8.3\ \mathrm{d})](0.85)}\ +$$

$$\frac{0.15\ \mathrm{g/g}(0.03\ \mathrm{g/g \cdot d})(2000\ \mathrm{m^3/d})(0.08\ \mathrm{g/g})(3816\ \mathrm{mg/L})(8.3\ \mathrm{d})}{[1 + 0.03(8.3\ \mathrm{d})](0.85)}\ +\ 0\ \mathrm{g/d}$$

= 575,104 g/d + 21,480 g/d + 0 g/d

$P_{X,TSS}$ = 596,584 g/d = 596.6 kg/d

3. Determine reactor volume and τ

a. Determine the volume using Eq. (7-57)

$$\mathrm{Volume} = \frac{(P_{X,TSS})(SRT)}{MLSS}$$

Assume MLSS = 5000 g/m^3

$$\text{Volume} = \frac{(596{,}584\ \text{g/d})(8.3\ \text{d})}{(5{,}000\ \text{g/m}^3)} = 990\ \text{m}^3$$

b. Determine the hydraulic detention time, τ

$$\tau = \frac{V}{Q} = \frac{990\ \text{m}^3}{(2000\ \text{m}^3/\text{d})} = 0.50\ \text{d}$$

4. Determine the methane gas production rate

Assume 0.4 m^3 gas/kg COD at 35°C

Amount of COD removed in waste sludge =

$$= \frac{(596{,}584\ \text{gTSS/d})(0.85\ \text{gVSS/gTSS})(1.42\ \text{gCOD/gVSS})}{(2000\ \text{m}^3/\text{d})} = 360\ \text{gCOD/m}^3$$

The methane gas production =

= $(0.40\ \text{m}^3/\text{kg})\ (3816 - 360\ \text{g COD/m}^3)\ (2000\ \text{m}^3/\text{d})\ (1.0\ \text{kg}/10^3\ \text{g})$

= 2765 m^3/d

5. Determine the methane gas production rate

$$\text{Methane production} = \frac{(2765\ \text{m}^3\ \text{CH}_4/\text{d})}{(0.65\ \text{m}^3\ \text{CH}_4/\text{m}^3\ \text{gas})} = 4254\ \text{m}^3/\text{d}$$

6. Determine nutrient requirements

Biomass production = $P_{X,TSS}$ = 596,584 gTSS/d

N = 12%, P = 2% of VSS

N required = (596,584)(0.12)(0.85) = 60,851 g/d

P required = (596,584)(0.02)(0.85) = 10,142 g/d

Summary

The solutions for 25 and 35°C for wastewater 1 is summarized in the following table.

Parameter	Unit	25°C	35°C
Design SRT	d	16.5	8.3

Reactor volume	m^3	1703	990
Detention time, τ	d	0.85	0.50
CH_4 production rate	m^3/d	2733	2765
Total gas production rate	m^3/d	4205	4254
Solids to be wasted	kg/d	516	597
Nitrogen requirements	kg/d	52.6	60.8
Phosphorus requirements	kg/d	8.8	10.1

PROBLEM 10-7

Problem Statement - See text, page 1111

Solution:

1. It is stated in the problem that 95 percent of the influent soluble COD is degraded at a 30 d SRT and an **effluent VSS concentration = 100 mg/L**. Thus, effluent $S = 0.05\ S_o$ and $S_o - S = 0.95\ S_o$.

2. Using Eq. (8-20) in Table 8-10 for biomass solids production, the yield and decay coefficients in Table 10-10, assuming $f_d = 0.15$ g/g and $S = 0.95\ S_o$, the influent concentration S_o is calculated as follows.

$$P_{X,VSS} = \frac{QY(S_o - S)}{1+b(SRT)} + \frac{f_d(b)QY(S_o - S)SRT}{1+b(SRT)}$$

$$\frac{P_{X,VSS}}{Q} = X_e = \frac{Y(0.95\ S_o)}{1+b(SRT)} + \frac{f_d(b)Y(0.95\ S_o)SRT}{1+b(SRT)}$$

$$100\ g/m^3 = \frac{(0.08\ g/g)(0.95\ S_o)}{[1+(0.03\ g/g \bullet d)(30\ d)]}$$

$$+\frac{(0.15\ g/g)(0.03\ g/g \bullet d))(0.08\ g/g)[(0.95\ S_o)g/m^3](30d)}{[1+(0.03\ g/g \bullet d)(30\ d]}$$

$100 = 0.04S_o + 0.0054S_o$

$S = 2203\ g/m^3$

3. The solution for effluent VSS concentrations of 100, 150, and 200 mg/L are summarized in the following table.

Effluent VSS, mg/L	Influent sCOD, mg/L
100	2203
150	3304
200	4405

PROBLEM 10-8

Problem Statement - See text, page 1111-1112

Solution (Wastewater 1):

1. Define the wastewater components and amount of COD removed.

   Particulate COD = 0.40 (6000 g/m^3) = 2400 g/m^3

   Particulate COD degraded = 0.60 (2400 g/m^3) = 1440 g/m^3

   Soluble COD = 0.60 (6000 g/m^3) = 3600 g/m^3

   Soluble COD degraded = 0.97 (3600 g/m^3) = 3492 g/m^3

   Total amount of COD degraded = 1440 + 3492 = 4932 g/m^3

   Non degraded particulate COD = 0.40 (2400 g/m^3) = 960 g/m^3

   $$\text{Non degraded VSS} = \frac{(960\ \text{gCOD}/\text{m}^3)}{(1.8\ \text{gCOD}/\text{g VSS})} = 533.33\ \text{g}/\text{m}^3$$

2. Determine the reactor process volume.

   a. Determine the reactor volume based on the maximum upflow velocity Eq. (10-18) and Eq. (10-19)

   $$A = \frac{Q}{\nu} = \frac{(500\ \text{m}^3/\text{d})}{(0.50\ \text{m/h})(24\ \text{h/d})} = 41.67\ \text{m}^2$$

   $$V_\nu = A(H) = 41.67\ \text{m}^2(8\ \text{m}) = 333.3\ \text{m}^3$$

   b. Determine the reactor volume based on the organic loading rate.

   From Eq. (10-20)

   $$V_{OLR} = \frac{Q\,S_0}{OLR} = \frac{(500\ \text{m}^3/\text{d})(6.0\ \text{kg COD/m}^3)}{(6.0\ \text{kg COD/m}^3 \cdot \text{d})} = 500\ \text{m}^3$$

The organic loading rate controls the reactor volume design.

3. Determine the process hydraulic retention time.

$$\frac{V}{Q} = \frac{500\ m^3}{(500\ m^3/d)} = 1.0\ d$$

4. Determine the reactor dimensions.

a. Reactor Area $= \frac{V}{H} = \frac{500\ m^3}{8\ m} = 62.5\ m^2$

$$\frac{\pi D}{4} = 62.5\ m^2,\ D = 8.92\ m$$

b. Total reactor height

H_T = process hgt + clear zone hgt + separator hgt (see Example 10-3)

H_T = 8 m + 0.5 m + 2.5 m = 11 m

Reactor dimensions = 8.92 m dia. $\times 11\,m$ height

5. Determine the reactor SRT.

a. From Eq. (7-56), $(X)V = P_X SRT$

b. From Eq. (8-20),

$$P_X = \frac{Q(Y_H)(S_o - S)}{1 + b_H(SRT)} + \frac{f_d b_H(Q)(Y_H)(S_o - S)(SRT)}{1 + b(SRT)} + (nbVSS)Q$$

c. Substituting Eq. (8-20) into Eq. (7-56),

$$X_{VSS}(V) = \frac{Q(Y_H)(S_o - S)(SRT)[1 + f_d b_H(SRT)]}{1 + b_H(SRT)} + (nbVSS)Q(SRT)$$

From Step 1, $S_o - S = 4932\ g\ COD/m^3$

From Table 10-13,

Y_H = 0.08 g VSS/g COD

b_H = 0.03 g VSS/g VSS•d

$$\left(50{,}000\text{ g VSS/m}^3\right)\left(500\text{ m}^3\right) =$$

$$\frac{\left(500\text{ m}^3\text{/d}\right)\left(0.08\text{ g VSS/g COD}\right)\left(4932\text{ g COD/m}^3\right)\left(\text{SRT}\right)\left(1 + 0.15\left(0.03\text{ g/g•d}\right)\text{SRT}\right)}{1 + (0.03\text{ g/g•d})\left(\text{SRT}\right)}$$

$$+\ 533.3\text{ g VSS/m}^3\left(500\text{ m}^3\text{/d}\right)\text{SRT}$$

Solving: SRT = 71.5 d

6. Determine the daily sludge production rate from Eq. (7-56).

$$P_{X,\ VSS} = \frac{X_{VSS}\left(V\right)}{SRT}$$

$$= \frac{\left(50{,}000\text{ g VSS/m}^3\right)\left(500\text{ m}^3\right)\left(1\text{ kg/10}^3\text{ g}\right)}{71.5\text{ d}}$$

$$P_{X,\ VSS} = 349.65\text{ kg VSS/d}$$

7. Determine the excess sludge daily waste volume.

$$P_{X,\ VSS} = Q\left(X_e\right) + \left(X\right)Q_W$$

$$Q_W = \frac{P_{X,\ VSS} - Q\left(X_e\right)}{X}$$

$$= \frac{(349{,}650\text{ g VSS/d}) - \left(500\text{ m}^3\text{/d}\right)\left(200\text{ g VSS/m}^3\right)}{(50{,}000\text{ g VSS/m}^3)}$$

$$Q_W = 5.0\text{ m}^3\text{/d}$$

8. Determine the methane gas production rate by COD balance.

COD removal = methane COD + biomass COD

$$P_{X,\ bio} = P_{X,\ VSS} - \text{nbVSS}\left(Q\right)$$

$$P_{X,\ bio} = 349{,}650\text{ g VSS/d} - 533.3\text{ g VSS/m}^3\left(500\text{ m}^3\text{/d}\right)$$

$$P_{X,\ bio} = 349{,}650\text{ g VSS/d} - 266{,}650\text{ g VSS/d}$$

$$= 83{,}000\text{ g VSS/d}$$

Methane COD = COD removed - biomass COD

CH_4 COD/d

$= 500\ m^3/d\left(4932\ g\ COD/m^3\right) - 1.42\ g\ COD/g\ VSS\left(83{,}000\ g\ VSS/d\right)$

$= (2{,}466{,}000 - 117{,}860)\ g\ COD/d$

CH_4 COD = 2,348,140 g CH_4 COD/d

At standard conditions, methane production rate =

$\left(2{,}348{,}140\ g\ CH_4\ COD/d\right)\left(0.35\ L\ CH_4/g\ COD\right)\left(m^3/10^3\ L\right)$

= 821.8 m^3 CH_4/d at 0°C

Methane production rate at 30°C =

$$\left(821.8\ m^3\ CH_4/d\right)\left[\frac{\left(273.15 + 30\right)°C}{273.15°C}\right] = 912\ m^3\ CH_4/d$$

8. Determine the total gas production rate; Percent methane = (100 – 35)% = 65%

$$\text{Total gas production rate} = \frac{(912\ m^3\ CH_4/d)}{(0.65\ m^3\ CH_4/m^3\ gas)} = 1403\ m^3\ gas/d$$

9. Energy content of methane production

$$\text{Energy} = \left(38{,}846\ kJ/m^3\right)\left(821.8\ m^3\ CH_4/d\right) = 31.9 \times 10^6\ kJ/d$$

10. Determine alkalinity requirements.

Assume pH = 7.0

From Table 10-7 at pH = 7.0, T = 30°C,

percent CO_2 = 35%, alkalinity = 2465 g/m^3 as $CaCO_3$

Influent alkalinity = 300 g/m^3 as $CaCO_3$

$$\text{Alkalinity needed} = \left(2465 - 300\right) g/m^3\ \text{as}\ CaCO_3$$

$$= 2165\ g/m^3\ \text{as}\ CaCO_3$$

$$\text{Alkalinity in kg/d} = \left(2165\ g/m^3\right)\left(500\ m^3/d\right)\left(\frac{1\ kg}{10^3\ g}\right)$$

$$= 1083\ kg/d$$

Summary of Results

Parameter	Unit	Value
Reactor process volume	m^3	500.0
Reactor total height	m	11.0
Reactor diameter	m	8.92
Hydraulic retention time	d	1.0
SRT	d	71.5
Excess waste sludge	m^3/d	5.0
Total gas production rate	m^3/d	1403
Methane production rate	m^3/d	912
Energy production rate	kJ/d	31.9×10^6
Alkalinity needed as $CaCO_3$	kg/d	1083

PROBLEM 10-9

Problem Statement - See text, page 1112

Solution (Wastewater 1):

1. Determine the reactor dimensions.

   a. Determine the reactor volume based on upflow velocity, Eq. (10-18) and Eq. (10-19).

   Upflow velocity = 0.7 m/h from Table 10-17.

   $$A = \frac{Q}{\nu} = \frac{(3000\ m^3/d)}{(0.70\ m/h)(24\ h/d)} = 178.6\ m^2$$

   Use reactor height = 5m from Table 10-17.

   $V = A(H) = 178.6\ m^2\ (5\ m) = 892\ m^3$

   $$\text{Hydraulic retention time} = \frac{892.9\ m^3}{(3000\ m^3/d)} = 0.3\ d = 7.1\ h$$

   b. Determine the organic loading rate.

   $$OLR = \frac{QS_o}{V} = \frac{(3000\ m^3/d)(450\ g\ COD/m^3)}{892.9\ m^3} = 1.51\ kg\ COD/m^3{\bullet}d$$

   From Fig. 10-10, this is an acceptable organic loading rate at 25°C.

   c. Determine reactor dimensions

   i. Reactor diameter

$$\frac{\pi D^2}{4} = 178.6\ \text{m}^2,\ D = 15.1\ \text{m}$$

ii. Reactor height

Assume per Example 10-3: Clear zone height = 0.5 m and gas-solids separator = 2.5 m.

Height = 5 m + 0.5 m + 2.5 m = 8.0 m

Reactor dimension = 15.1 m dia x 8.0 m height

2. Effluent BOD and TSS from UASB reactor. From p1091, effluent TSS concentration may range from 50 to 150 mg/L. At 85 percent VSS/TSS and 0.5 g BOD/gVSS, the effluent particulate BOD may range from 21 to 63 mg/L. The effluent soluble BOD is mainly from volatile fatty acids (VFA). VFA concentration from UASB reports may range from 20 to 50 mg/L at long SRT and thus the soluble BOD may range from

$$\left(1.07\ \frac{\text{g COD}}{\text{g acetate}}\right)\left(\frac{1\text{g BOD}}{1.6\ \text{g COD}}\right)(20-50)$$

$$= 13\ \text{to}\ 40\ \text{mg/L}$$

Thus the total effluent BOD may range from 34 to 100 mg/L.

3. Post UASB treatment to obtain a secondary treatment effluent quality.
   The challenge is treating what could be a relatively weak wastewater with a possibility of a significant VSS concentration as dispersed solids. Conventional activated sludge process may have limited success due to the limitations on developing a flocculent suspension to capture the dispersed solids. A biological aerated filter (Sec. 9-6) or moving bed bioreactor (MBBR, Sec. 9-5) with chemical addition before the clarifier would be the better choice.

4. Based on review of the literature, alkalinity is typically not limited as alkalinity is produced and the high hydraulic throughput rate minimizes dissolved CO_2 concentrations.

PROBLEM 10-10

Problem Statement - See text, page 1112

Solution

1. Determine the reactor volume and dimensions.
   a. A COD loading rate of 5 kg COD/m^3•d is given.
   b. Determine the reactor volume.

   $$\text{Reactor volume} = \frac{(4 \text{ kg COD/m}^3)(1000 \text{ m}^3\text{/d})}{(5 \text{ kg COD/m}^3 \cdot \text{d})} = 800 \text{ m}^3$$

   c. Determine the reactor area given reaction depth of 4 m.

   Area = 800 m^3/4 m = 200 m^2

   Assume 3 reactors in parallel to limit area needed for flow distribution,

   Area each = 66.7 m^2 = $\pi D^2/4$

   Diameter = $[(4)(66.7 \text{ m}^2) / 3.14]^{0.5}$ = 9.2 m

   Assume at least 1 m above media for freeboard and gas collection

   3 reactors at 9.2 m dia x 5.0 m height

2. Determine the methane gas production rate ignoring COD in biomass production.
   a. Determine the biological COD consumption rate at 90 percent removal.

   COD consumption rate = (1000 m^3/d)(4000 g/m^3)(0.9) = 3,600,000 g/d

   b. Determine the methane production rate.

   Methane production at 35°C = 0.40 CH_4 L/g COD

   Methano production rate = (0.40 CH_4 L/g COD)(3,600,000 g COD/d)

   = 1,440,000 L/d

   = 1440 m^3/d

3. Determine the effluent TSS concentration using Eq. (8-20).

$$P_{X,TSS} = \frac{Q\,Y(S_o - S)}{[1 + b(SRT)](0.85)} + \frac{f_d(b)Q\,Y(S_o - S)SRT}{[1 + b(SRT)](0.85)} + Q(nbTSS)$$

Assume nbTSS = 0

$$P_{X,TSS} = \frac{(1000 \text{ m}^3/\text{d})(0.08 \text{ g VSS/g COD})(3600 \text{ mg COD/L})}{[1 + 0.03 \text{ g/g}\cdot\text{d}\ (30 \text{ d})](0.85)} +$$

$$\frac{(0.15 \text{ g/g})(0.03 \text{ g/g}\cdot\text{d})(1000 \text{ m}^3/\text{d})(0.08 \text{ g/g})(3600 \text{ mg/L})(30 \text{ d})}{[1 + 0.03(30 \text{ d})](0.85)} + 0 \text{ g/d}$$

$P_{X,TSS}$ = 202,402 g/d

Effluent TSS = (202,402 g/d) / (1000 m^3/d) = 202 mg/L

Effluent VSS = 0.85(202 mg/L) = 171.7 mg/L

4. Determine methane production rate when accounting for COD in biomass produced.

   a. COD conversion rate to biomass =

      (1000 m^3/d)(171.7 g VSS/m^3)(1.42 g COD/g VSS) = 243,814 g/d

   b. COD consumption rate (step 2a) = 3,600,000 g/d

   c. Determine the methane production rate.

      Methane production rate = (0.40 L/d)[(3,600,000 – 243,8140) g COD/d]

      = 1,342,594 L/d

      = 1343 m^3/d

PROBLEM 10-11

Problem Statement - See text, page 1112

Problem Analysis

Process	Compatibility with high concentrations of COD and nbVSS	Potential impact of influent solids
UASB	The UASB process is compatible with high COD wastewaters, specific loading rate dependant on temperature	Influent solids can inhibit the formation of dense, granulated sludge. A prefermentation step may be helpful.
Anaerobic fluidized-bed reactor	High biomass concentration allows fluidized bed reactor to operate at high organic loading	Best suited for highly soluble wastewaters, does not capture solids well
Anaerobic baffled reactor	Lower COD loadings than some of the other processes, will result in a larger reactor.	Solids may inhibit the formation of sludge granules
Upflow packed-bed reactor	Compatible with high COD loadings, however, better suited for wastewaters with low suspended solids concentrations	Solids will eventually accumulate in the packing and cause clogging and flow short circuiting
Downflow attached growth reactor	Compatible with high COD loadings. Packing with high void volume recommended.	If high void volume packing used, solids less likely to cause clogging problems
Anaerobic covered lagoon	Low COD loading rate results in a large area needed for this process.	Solids not expected to be a problem.

PROBLEM 10-12

Problem Statement - See text, page 1113

The instructor should suggest reference sources for the students. Journal articles from Bioresource Technology, Journal of Bioscience and Bioengineering, Separation and Purification Technology, and Biomass and Bioenergy would be appropriate sources.

PROBLEM 10-13

Problem Statement - See text, page 1113

The instructor should suggest reference sources for the students. Journal articles from Bioresource Technology, Water Science and Technology, Biomass and Bioenergy and Water Environment Research would be appropriate sources.

11

SEPARATION PROCESSES FOR REMOVAL OF RESIDUAL CONSTITUENTS

PROBLEM 11-1

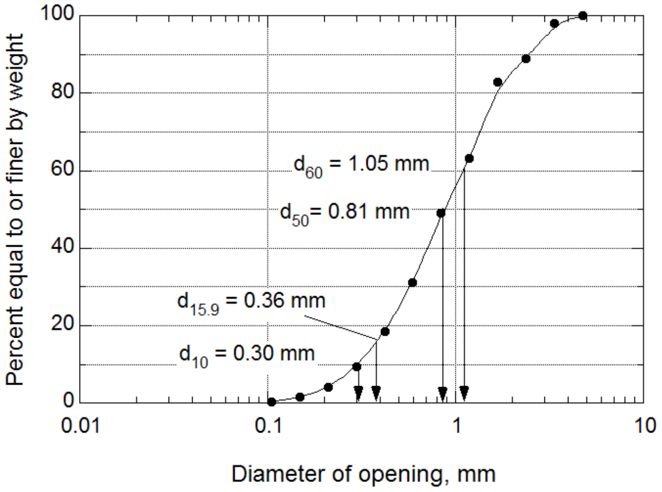
Problem Statement - See text, page 1278

Instructors Note: Before assigning this problem, the use of arithmetic and logarithmic probability paper should be discussed. The graphical determination of the geometric mean and standard deviation is discussed in the Section 3-3. As an aid in solving this problem, the procedure used to determine the useable sand from a stock sand is given on the following page. In addition, the students can be referred to the section on filtration in Fair and Geyer (1954) or Fair et al. (1968).

Solution

Part a

1. Plot the cumulative weight passing values for **sample 1** versus the corresponding sieve size opening on arithmetic and logarithmic probability paper. The geometric mean size (M_g) corresponds to the value at d_{50} and the geometric standard deviation (s_g) is equal to the $d_{84.1}/M_g$ or $M_g/d_{15.9}$. The effective size is equal to the value at d_{10} and the uniformity coefficient is d_{60}/d_{10}.



Modifying Stock Sand To Produce Desired Filter Sand

Sand obtained from river bottoms or from coastal areas will generally not be suitable for use as a filter sand unless modified by removing the material that is too coarse or too fine. The material that is too coarse is generally removed by sieving. The material that is too fine is removed using a sand washer in which the material that is too fine is carried out with the wash water. Fine material can also be removed after the sand is placed in the filter by backwashing. To determine the amount of usable sand the following terms are defined.

p_1 = percent of stock sand that is smaller than the desired effective size (i.e. d_{10})

p_2 = percent of stock sand that is smaller than the desired 60 percentile size (i.e. d_{60})

Because the difference between the d_{60} and d_{10} sizes represents 50 percent of useable filter sand, the percent of stock sand that is useable is:

p_3 = percent of stock sand that is useable

$= 2(p_2 – p_1)$

Because 10 percent of the useable sand will be below the d_{10} size, the percent below which the stock sand is too fine is:

p_4 = percent below which the stock sand is too fine

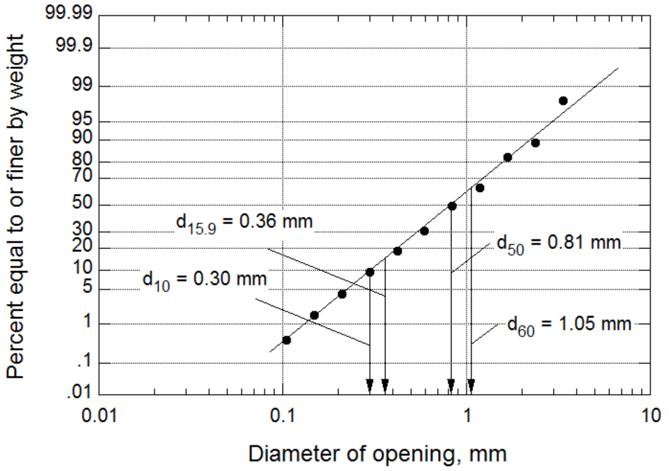
$= p_1 – 0.1\ p_3 = p_1 – 0.2\ (p_2 – p_1)$

The percent of the sand that has been accounted for is equal to $p_3 + p_4$, of which p_3 is useable and p_4 is too fine. Thus, the percent of the sand that is too coarse is given is by

p_5 = percent of stock sand that is too coarse

$= p_3 + p_4 = p_1 – 1.8\ (p_2 – p_1)$

Adapted from: Fair, G. M., and J. C. Geyer (1954) *Water Supply and Waste-Water Disposal*, John Wiley & Sons, Inc., New York.

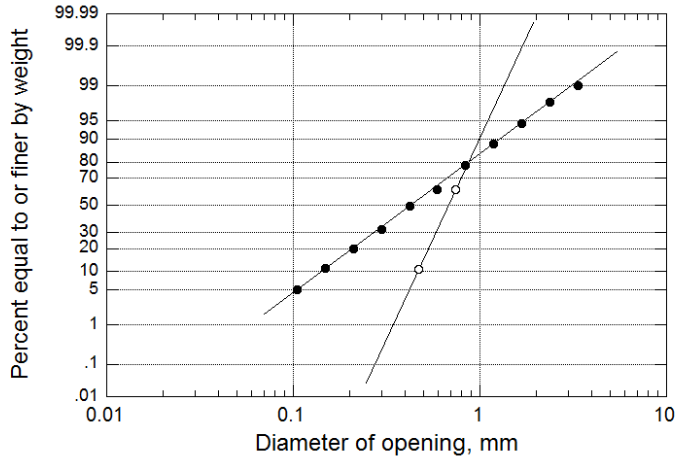


Summary of results for Problem 1, Part 1a.

	Sample			
Parameter	1	1	3	4
d_{10}	0.30	0.20	0.31	0.13
$d_{15.9}$	0.36	0.22	0.36	0.16
d_{50}	0.81	0.49	0.72	0.41
d_{60}	1.05	0.60	0.90	0.60
$d_{84.1}$	1.90	1.05	1.30	1.00
M_g	0.81	0.49	0.72	0.41
s_g	2.3	2.2	2.0	2.6
ES	0.30	0.20	0.31	0.13
UC	3.5	3.0	2.9	4.6

Part b

To determine the amount of usable sand in stock sand **sample 1**, draw a line that represents the characteristics of the desired filter sand.



The amount of stock sand with a diameter less than the desired effective size (P_{10}) and the desired d_{60} (P_{60}) is 25 and 42.5 percent, respectively. Because the amount of stock sand between d_{60} and d_{10} represents 50 percent of the specified sand, the percentage of usable stock sand is

$P_{usable} = 2(P_{60} – P_{10}) = 2(42.5\% – 25\%) = 35\%$

The amount of stock sand A needed to produce 1 ton of the specified sand (ES = 0.45 mm and UC = 1.6) is

Stock sand needed = 1 ton / 0.35 = 2.86 ton

Summary of results for Problem 1, Part 1b.

Sand sample	P_{10}	P_{60}	P_{usable}	Amount stock sand needed to produce one ton of specified sand, ton
1	25	42.5	35	2.86
2	48	73	50	2.00
3	25	50	50	2.00
4	55	73	36	2.78

Part c

The specified sand may contain 10 percent below the specified effective size. The percentage of stock **sand 1** that is too fine is

$P_{too\ fine} = 25\% - 0.1(35\%) = 21.5\%$

The $P_{\text{too fine}}$ value corresponds to a sand diameter of 0.44 mm. Because P_{usable} and $P_{\text{too fine}}$ are now known, the percentage above which the sand is too coarse is

$$P_{\text{too coarse}} = P_{\text{usable}} + P_{\text{too fine}} = 35\% + 21.5\% = 56.5\%$$

The $P_{\text{too coarse}}$ value corresponds to a sand diameter of 0.92 mm.

A number 18 or 20 sieve with hole diameters of 0.841 and 1.00 mm, respectively, should be sufficient for removing the excess coarse sand.

Summary of results for Problem 1, Part 1c

Sand sample	$P_{\text{too fine}}$, p_1	$P_{\text{too coarse}}$, p_2	Minimum sand size, mm	Maximum sand size, mm	U.S. sieve number
1	21.5	56.5	0.44	0.92	18 or 20
2	43	93	0.4	1.2	16
3	20	70	0.41	1.02	18
4	51.4	87.4	0.42	1.1	16 or 18

Part d

The backwash rise rate of the backwashing filter must not exceed the settling velocity of the smallest particle to be retained in the filter. Fig. 5-20 may be used to estimate the backwash rise rate for **sand 1**, assuming a shape factor of 0.85, a specific gravity of 2.65, and settling in water at 20°C (kinematic viscosity = 1.003×10^{-6} m^2/s). For a sand particle with diameter of 0.44 mm, the backwash rise rate is 0.073 m/s. Alternately, the particle settling velocity may be calculated following the method outlined in Example 5-4.

Summary table for Problem 1, Part 1d.

Sand sample	Backwash rise rate needed to eliminate excess fine material, m/s
1	0.073
2	0.064
3	0.067
4	0.069

Part e

The value for $P_{\text{too fine}}$ from Problem 1c is used to solve this problem.

Fraction remaining to be removed = $P_{\text{too fine}}/P_{\text{too coarse}}$

= 21.5 / 56.5 = 0.381

Assuming that the coarse material has been eliminated with a sieve and that the fine material is to be removed during backwashing, the amount of sieved sand needed to result in a bed of usable sand with a depth of 600 mm is

Depth of sieved sand needed = (600 mm) / (1 – 0.381) = 969 mm

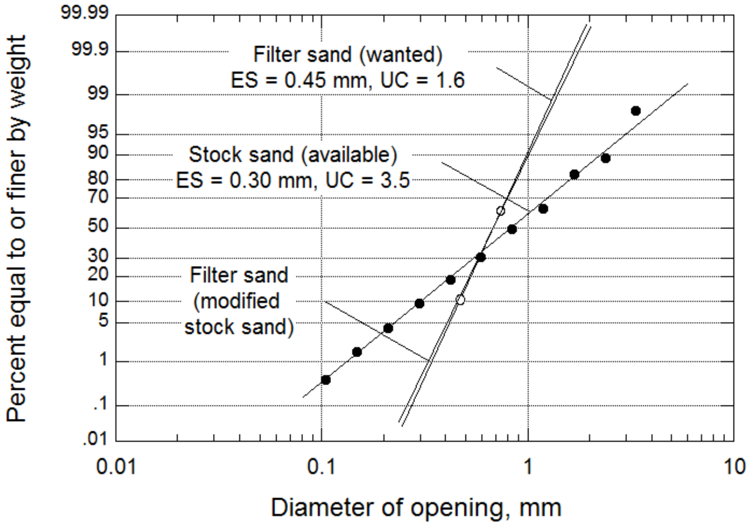
Summary table for Problem 1, Part 1e

Sand sample	$P_{\text{too fine}}$	$P_{\text{too coarse}}$	Fraction to be removed	Depth of sieved sand needed to get 600 mm of usable sand, mm
1	21.5	56.5	0.381	969
2	43	93	0.462	1116
3	20	70	0.286	840
4	51.4	87.4	0.588	1457

Part f

Compute the size distribution of the modified sand 1.

Size, mm	Original sand retained, %	Modified sand retained, %	Modified cumulative weight, %
0.44	0	0	0
0.59	10.5	30	30
0.84	20	57	87
0.92	4.5	13	100
	35	100	



Part g

Use the modified form of the Rose equation to determine the headloss.

Determine the clean-water headloss using Eq. (11-5).

$$h = \frac{1.067}{\phi}\frac{L v_s^2}{\alpha^4 g}\sum C_d \frac{p}{d_g}$$

Set up a computation table to determine the summation term in Eq. (11-5).

Sieve size or number	Fraction of sand retained	Geometric mean size, mm	Reynolds number, N_R	C_d	$C_d(p/d)$, m^{-1}
12-14	0.005	1.54	3.07	9.87	32
14-16	0.015	1.30	2.58	11.50	133
16-18	0.07	1.09	2.18	13.41	860
18-20	0.13	0.92	1.83	15.68	2,223
20-25	0.2	0.77	1.54	18.33	4,745
25-30	0.28	0.65	1.30	21.49	9,259
30-35	0.14	0.55	1.09	25.28	6,490
35-40	0.09	0.46	0.91	29.74	5,841
40-45	0.052	0.38	0.76	35.16	4,769
45-50	0.018	0.32	0.64	41.41	2,312
Sum					36,665

Determine the clean-water headloss through the stratified filter bed using Eq. (11-5).

$$h = \frac{1.067}{(0.75)} \frac{(0.6\,m)(0.00267\ m/s)^2}{(0.40)^4 (9.81\,m/s^2)} (36{,}665\ m^{-1}) = 0.89\ m$$

PROBLEM 11-2

Problem Statement - See text, page 1279

Solution

1. Determine the sphericity of filter medium 1 using equation Eq. (11-1).

   $\nu = 1.0574 \times 10^{-6}\ m^2/s$ (see Table C-1, Appendix C)

$$v_s = \frac{(240\ L/m^2 \cdot min)}{(60\ s/min)(1000\ L/m^3)} = 0.004\ m/s$$

$$N_R = \frac{\phi d v_s}{\nu} = \frac{(1)(0.00055\ m)(0.004\ m/s)}{1.0574\ x\ 10^{-6}\ m^2/s} = 2.08$$

$$f = 150\frac{1-\alpha}{\alpha^3} + 1.75 = 150\frac{1-0.4}{0.4^3} + 1.75 = 45.01$$

$$h = \frac{f}{\phi}\frac{1-\alpha}{\alpha^3}\frac{L}{d}\frac{v_s^2}{g} = \frac{(45.01)\left(1-0.4\right)\left(0.6\text{ m}\right)\left(0.004\text{ m/s}\right)^2}{(1)(0.4)^3\left(0.00055\text{ m}\right)(9.81\text{ m/s}^2)} = 0.751\text{ m}$$

2. Determine the headloss using the Fair-Hatch equation Eq. (11-2).

$$h = k\nu S^2\frac{\left(1-\alpha\right)^2}{\alpha^3}\frac{L}{d^2}\frac{v_s}{g}$$

$$= \left(5\right)(1.0574\text{ x }10^{-6}\text{ m}^2/\text{s})\left(6\right)^2\frac{\left(1-0.4\right)^2\left(0.6\text{ m}\right)\left(0.004\text{ m/s}\right)}{(0.4)^3\left(0.00055\text{ m}\right)^2(9.81\text{ m/s}^2)} = 0.866\text{ m}$$

3. Determine the headloss using the Rose equation Eq. (11-5).

$$C_d = \frac{24}{N_R} + \frac{3}{\sqrt{N_R}} + 0.34 = \frac{24}{2.08} + \frac{3}{\sqrt{2.08}} + 0.34 = 13.96$$

$$h = \frac{1.067}{\phi}C_d\frac{1}{\alpha^4}\frac{L}{d}\frac{v_s^2}{g} = \frac{\left(1.067\right)\left(1\right)\left(0.6\text{ m}\right)\left(0.004\text{ m/s}\right)^2}{\left(1\right)(0.4)^4\left(0.00055\text{ m}\right)(9.81\text{ m/s}^2)} = 1.035\text{ m}$$

4. Summary of results from Problem 11-2

Equation	Clean-water headloss, m
Carman-Kozeny	0.751
Fair-Hatch	0.866
Rose	1.035

PROBLEM 11-3

Problem Statement - See text, page 1280

Solution

1. Determine the headloss using the Kozeny equation Eq. (11-4).

$\nu = 1.139\text{ x }10^{-6}\text{ m}^2/\text{s}$ (see Table C-1, Appendix C)

$$v_s = \frac{(240\text{ L/m}^2\cdot\text{min})}{\left(60\text{ s/min}\right)(1000\text{ L/m}^3)} = 0.004\text{ m/s}$$

$$N_R = \frac{\phi d v_s}{\nu} = \frac{\left(1\right)\left(0.00055\text{ m}\right)\left(0.004\text{ m/s}\right)}{1.139\text{ x }10^{-6}\text{ m}^2/\text{s}} = 1.93$$

$$f = 150\frac{1-\alpha}{\alpha^3} + 1.75 = 150\frac{1-0.4}{0.4^3} + 1.75 = 45.01$$

$$h = \frac{k}{g}\nu\frac{(1-\alpha)^2}{\alpha^3}\left(\frac{6}{d}\right)^2 L\nu_s$$

$$= \frac{(5)(1.139\text{x}10^{-6}\text{m}^2/\text{s})(1-0.4)^2}{(9.81\,\text{m/s}^2)(0.4)^3}\left(\frac{6}{0.00055\text{ m}}\right)^2(0.6\text{ m})(0.004\text{ m/s}) = 0.932\text{ m}$$

2. Determine the headloss using the Ergun equation Eq. (11-9).

$$h = \frac{f}{\phi}\frac{(1-\alpha)}{\alpha^3}\frac{L}{d}\frac{v_s^2}{g}$$

$$= \left(\frac{45.01}{1}\right)\frac{(1-0.4)(0.6\text{ m})(0.004\text{ m/s})^2}{(0.4)^3(0.00055\text{ m})(9.81\,\text{m/s}^2)} = 0.751\,\text{m}$$

3. Determine the headloss using the Rose equation Eq. (11-5).

$$C_d = \frac{24}{N_R} + \frac{3}{\sqrt{N_R}} + 0.34 = \frac{24}{1.93} + \frac{3}{\sqrt{1.93}} + 0.34 = 13.55$$

$$h = \frac{1.067}{\phi}C_d\frac{1}{\alpha^4}\frac{L}{d}\frac{v_s^2}{g} = \frac{(1.067)(13.55)(1)(0.6\text{ m})(0.004\text{ m/s})^2}{(1)(0.4)^4(0.00055\text{ m})(9.81\,\text{m/s}^2)} = 1.00\text{ m}$$

4. Summary of results from Problem 11-2

Equation	Clean-water headloss, m
Kozeny	0.932
Ergun	0.751
Rose	1.00

PROBLEM 11-4

Problem Statement - See text, page 1280

Instructors Note: Problem 11-6 should be assigned along with Problem 11-4.

Solution

1. Determine the headloss for a sand diameter of 0.4 mm using the Rose equation Eq. (11-5).

$$N_R = \frac{\phi d v_s}{\nu} = \frac{(1)(0.00040\ \text{m})(0.004\ \text{m/s})}{(1.306 \times 10^{-6}\ \text{m}^2/\text{s})} = 1.23$$

$$C_d = \frac{24}{N_R} + \frac{3}{\sqrt{N_R}} + 0.34 = \frac{24}{1.23} + \frac{3}{\sqrt{1.23}} + 0.34 = 22.64$$

$$h = \frac{1.067}{\phi} C_d \frac{1}{\alpha^4} \frac{L}{d} \frac{v_s^2}{g} = \frac{(1.067)(22.64)(1)(0.75\ \text{m})(0.004\ \text{m/s})^2}{(1)(0.4)^4 (0.0004\ \text{m})(9.81\ \text{m/s}^2)} = 2.89\ \text{m}$$

2. Summary table for Problem 11-4

Sand diameter, mm	Clear-water headloss, m
0.4	2.89
0.45	2.30
0.5	1.88
0.6	1.33

PROBLEM 11-5

Problem Statement - See text, page 1280

Instructors Note: The instructor should specify the sand diameter(s) from Problem 11-4 to be used for solving Problem 11-5.

Solution

1. Construct a logarithmic probability plot with a line that represents the specified filter sand. The cumulative percent values that correspond to standard U.S. sieve sizes are then determined and used to construct a computation table.

   Computation table to determine clear-water headloss for filter sand with an effective size of 0.4 and a uniformity coefficient of 1.5.

Sieve size or number	Geometric mean size, mm	Percent of sand retained	Cumulative percent passing	Fraction of sand retained	Reynolds number, N_R	C_d	$C_d(p/d)$, m^{-1}
10-12	1.83	0	100	0	5.61	5.88	0
12-14	1.54	0	99.96	0	4.71	6.81	0
14-16	1.30	0.04	98.5	0.0004	3.97	7.90	2
16-18	1.09	1.46	94	0.0146	3.34	9.16	123
18-20	0.92	4.5	84	0.045	2.81	10.67	524
20-25	0.77	10	58	0.1	2.37	12.43	1609
25-30	0.65	26	33	0.26	1.99	14.52	5809
30-35	0.55	25	20	0.25	1.67	17.03	7805
35-40	0.46	13	5	0.13	1.40	19.97	5666
40-45	0.38	15	0.9	0.15	1.17	23.55	9212
45-50	0.32	4.1	0.125	0.041	0.99	27.66	3518
50-60	0.27	0.775	0.06	0.00775	0.83	32.38	921
60-70	0.23	0.065	0	0.00065	0.70	38.12	108
70-80	0.19	0.06	0	0.0006	0.59	44.89	140
Sum							34,267

Determine the clean-water headloss through the stratified filter bed using Eq. (11-5).

$$h = \frac{1.067}{(1)} \frac{(0.75\,m)(0.004\,m/s)^2}{(0.40)^4\,(9.81\,m/s^2)}(34{,}267\ m^{-1}) = 1.75\ m$$

Summary of results for Problem 11-5

Sand effective size, mm	Clean-water headloss, m
0.4	1.75
0.45	1.43
0.5	1.17
0.6	0.83

PROBLEM 11-6

Problem Statement - See text, page 1280

Instructors Note: The solution for Problem 11-3 is needed to complete Problem 11-6. The filtration rate is 240 L/m^2•min. The shape factor is 0.73.

Solution

1. Determine the headloss for anthracite with diameter of 2 mm using the Rose equation Eq. (11-5).

$$N_R = \frac{\phi d v_s}{\nu} = \frac{(0.73)(0.002\ \text{m})(0.004\ \text{m/s})}{(1.306 \times 10^{-6}\ \text{m}^2/\text{s})} = 4.47$$

$$C_d = \frac{24}{N_R} + \frac{3}{\sqrt{N_R}} + 0.34 = \frac{24}{4.47} + \frac{3}{\sqrt{4.47}} + 0.34 = 7.13$$

$$h = \frac{1.067}{\phi} C_d \frac{1}{\alpha^4} \frac{L}{d} \frac{v_s^2}{g} = \frac{(1.067)(7.13)(1)(0.3\ \text{m})(0.004\ \text{m/s})^2}{(0.73)(0.5)^4 (0.002\ \text{m})(9.81\ \text{m/s}^2)} = 0.0408\ \text{m}$$

2. The clean-water headloss ratio of anthracite to sand is then determined

Clean-water headloss ratio = 0.0408 m/2.89 m = 0.014

Summary table for Problem 11-5

Sand diameter, mm	Clean-water headloss ratio
0.4	0.014
0.45	0.018
0.5	0.022
0.6	0.031

3. The potential for intermixing to occur can be estimated using the relationship presented in Eq. (11-28). The recommended particle diameter can be calculated assuming a typical density (1.7) for the anthracite, alternately the anthracite density needed for a particle diameter of 2 mm can be computed.

$$d_1 = d_2 \left(\frac{\rho_2 - \rho_w}{\rho_1 - \rho_w} \right)^{0.667} = 0.4 \left(\frac{2.65 - 1}{1.7 - 1} \right)^{0.667} = 0.71\ \text{mm}$$

4. Summary of anthracite characteristics needed to avoid intermixing

Sand diameter, mm	Recommended diameter for anthracite (with density of 1.7), mm	Required density for anthracite with a diameter of 2 mm
0.4	0.71	1.15
0.45	0.8	1.18
0.5	0.89	1.21
0.6	1.06	1.27

PROBLEM 11-7

Problem Statement - See text, page 1280

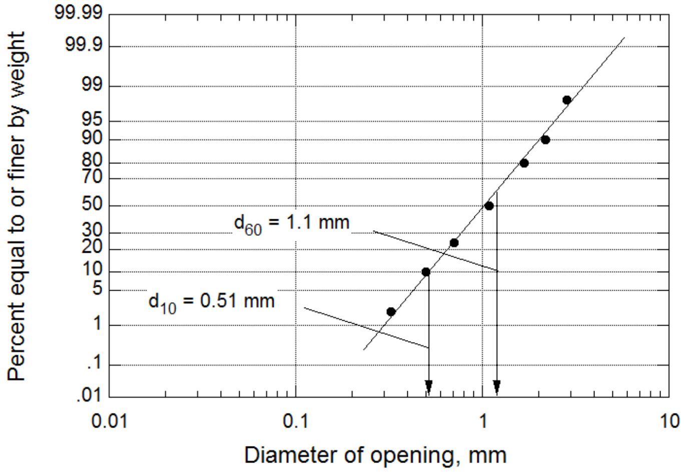
Instructors Note: Students should be advised that they will need to make assumptions for the computation of the clean-water headloss to complete Problem 11-7. The following values were used in the solution presented below. $v_s = 160\ \text{L/m}^2\cdot\text{min}$, $\phi = 0.85$, $\alpha = 0.40$

Solution

1. Compute the cumulative percent passing for **sand 1**:

Sieve number	Geometric mean size, mm	Percent retained	Cumulative percent passing
6-8	2.828	2	98
8-10	2.182	8	90
10-14	1.679	10	80
14-20	1.089	30	50
20-30	0.707	26	24
30-40	0.500	14	10
40-60	0.324	8	2
Pan		2	

2. Plot the cumulative percent passing versus the corresponding sieve size opening.



3. Determine the effective size and the uniformity coefficient.

   a. The d_{10} and d_{60} are obtained from the plot.

      d_{10} = 0.51 mm

      d_{60} = 1.1 mm

   b. The effective size and uniformity coefficient are:

      Effective size = d_{10} = 0.51 mm

      Uniformity coefficient = d_{10} / d_{60} = 1.1 / 0.51 = 2.2

4. Compute the clean-water headloss through the filter bed using Eq. (11-6). The method and parameters outlined in Example (11-1) are used to solve for the clean-water headloss through **sand 1**.

$$h=\frac{1.067}{\phi}\frac{L v_s^2}{\alpha^4 g}\sum C_d \frac{p}{d_g}$$

5. Set up a computation table to determine the summation term in Eq. (11-6).

Sieve size or number	Fraction of sand retained	Geometric mean size, mm	Reynolds number, N_R	C_d	$C_d(p/d)$, m^{-1}
6-8	2.828	0.02	6.39	5.28	37
8-10	2.182	0.08	4.93	6.56	240
10-14	1.679	0.1	3.79	8.20	489
14-20	1.089	0.3	2.46	12.00	3,307

20-30	0.707	0.26	1.60	17.73	6,515
30-40	0.500	0.14	1.13	24.41	6,835
40-60	0.324	0.08	0.73	36.62	9,041
60-100	0.193	0.02	0.44	59.91	6,208
Sum					32,673

6. Determine the headloss through the stratified filter bed using Eq. (11-6)

   $L = 0.6$ m

   $v_s = 0.00267$ m/s

   $\phi = 0.85$

   $\alpha = 0.40$

   $g = 9.81\ \mathrm{m/s^2}$

$$h = \frac{1.067}{(0.85)} \frac{(0.6\,\mathrm{m})(0.00267\,\mathrm{m/s})^2}{(0.40)^4 (9.81\,\mathrm{m/s^2})} (32{,}673\ \mathrm{m^{-1}}) = 0.7\ \mathrm{m}$$

7. Determine the recommended anthracite effective size needed to minimize intermixing using Eq. (11-28).

$$d_1 = d_2 \left(\frac{\rho_2 - \rho_w}{\rho_1 - \rho_w} \right)^{0.667} = 0.51 \left(\frac{2.65 - 1}{1.7 - 1} \right)^{0.667} = 0.90\ \mathrm{mm}$$

8. Summary table of results for Problem 11-7

		Sand			
Parameter	Unit	1	2	3	4
ES = d_{10}	mm	0.51	0.38	0.240	0.3
d_{60}	mm	1.1	0.7	0.700	0.7
UC		2.2	1.8	2.9	2.3
h	m	0.7	1.1	2.03	1.72
Anthracite d_{10}	mm	0.90	0.67	0.43	0.53

PROBLEM 11-8

Problem Statement - See text, page 1280

Instructors Note: The method outlined in the revised Example 11-2 is used to solve this problem. The kinematic viscotiy at 20ºC is 1.006 x 10^{-6} m^2/s, sand porosity of 0.4 should be assumed.

Solution

1. Set up computation table to determine the summation term in Eq. (11–19)

$$\frac{L_e}{L}=\left(1-\alpha\right)\Sigma\frac{p}{\left(1-\alpha_e\right)}\left(\frac{1}{100}\right)$$

Sieve size number	**Percent of sand retained**[a]	**Geometric Mean Size, mm**[b]	**Settling velocity (v_s), m/s**	**v/v_s**	**α_e**	**$p/(1-\alpha_e)$**
8-10	10	2,18[c]	0,304	0,0411	0,496	19,82
10-12	10	1,83	0,27	0,0463	0,509	20,35
12-18	30	1,3	0,21	0,0595	0,538	64,87
18-20	10	0,92	0,157	0,0796	0,573	23,42
20-30	34	0,71	0,123	0,1016	0,605	86,01
30-40	5	0,5	0,085	0,1471	0,656	14,53
40-50	1	0,35	0,055	0,2273	0,722	3,60
Summation						232,61

[b] based on sieve sizes given in Table 11-6

[c] $2.18=\sqrt{2.38x2}$

a. Determine the particle settling velocity using Fig. 5–20 in Chap. 5. Alternatively the particle settling velocity can be computed as illustrated in Example 5–5. The settling velocity values from Fig. 5–20 are entered in the computation table.

b. Determine the values of y/ys and enter the computed values in the computation table.

The backwash velocity is:
v = 0.75 m/min = 0.0125 m/s

c. Determine the values of α_e using Eq. (11-16) and enter the computed values in the computation Table.

$$\alpha_e = \left(\frac{0.0175}{0.304}\right)^{0.22} = 0.496$$

d. Determine the values for column 7 and enter the computed values in the computation table.

$$\frac{p}{(1-\alpha_e)} = \frac{10}{(1-0.496)} = 19.82$$

2. Determine the expanded bed depth using Eq. (11-19)

$$L_e = (0.9m)(1-0.4)(232.61)\left(\frac{1}{100}\right) = 1.17m$$

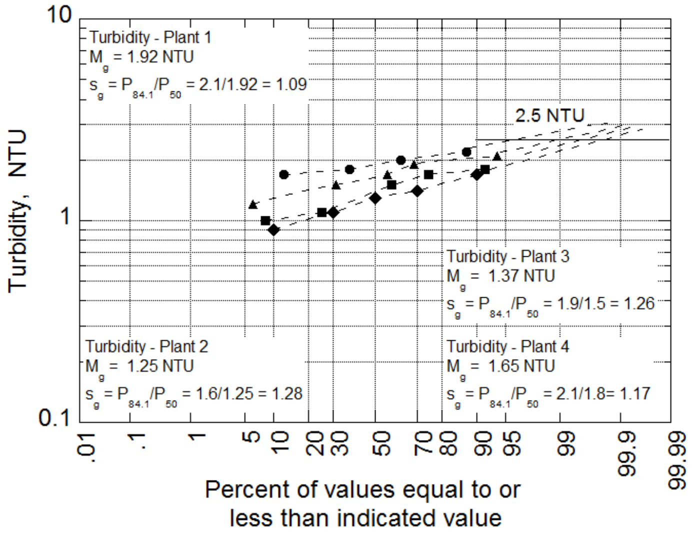
3. Becase the expanded porosity of the largest size bed fraction (0.496) is greater than the normal porosity of the filter material, the entire filter bed will be expanded.

PROBLEM 11-9

Problem Statement - See text, page 1281

Solution

1. The required plots for Plants 1,2, 3 and 4 are shown on the following figure



2. The geometric mean, Mg, and geometric standard deviation, sg, values for the four plants are shown on the above plot.
3. The probability of exceeding a turbidity value of 2.5, again obtained from the above plot is as follows.

   Plant 1, probability of exceeding 2.5 NTU = 100 - 99.1 = 0.90%

   Plant 2, probability of exceeding 2.5 NTU = 100 - 99.8 = 0.20%

   Plant 3, probability of exceeding 2.5 NTU = 100 - 99.3 = 0.70%

   Plant 4, probability of exceeding 2.5 NTU = 100 – 98.0 = 2.00%

PROBLEM 11-10

Problem Statement - See text, page 1281

Solution

1 Plot the individual and combined distributions on the same plot. The required figure is shown on the following page

2. Impact of using all of the data.

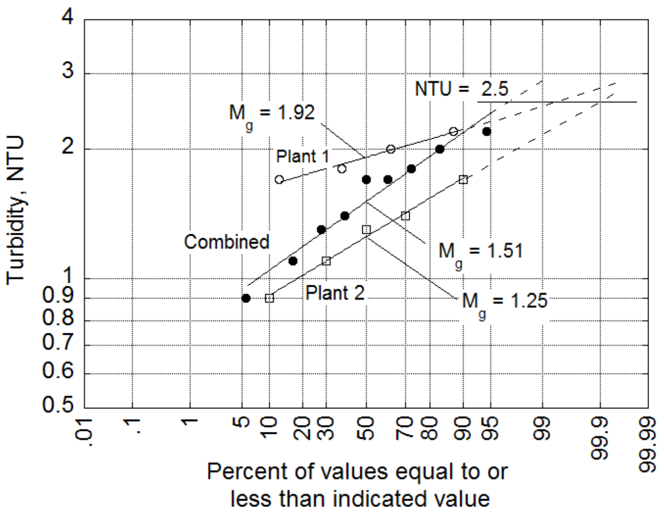
   As shown in the plot the geometric mean of the combined data set lies between the two individual data sets.

   1: Mg = 1.92 NTU, 2: Mg = 1.25 NTU, Combined sample: 1.51 NTU

   However, what is more significant is that the geometric standard, sg, of the combined distribution is greater than either Sample 1 or 2 (see Problem 11-9).

   1: sg = 1.09, 2: sg = 1.28, Combined sample: sg = 1.36 (P84.1/P50= 2.05/1.51).

   Thus the use of limited data can lead to misleading conclusions. For example, based on the combined data set the turbidity limit of 2.5 NTU would be exceeded more often, 4 percent (100 - 96) of the time versus 0.9 percent based on sample 1 and 0.2 percent based on sample 2.



PROBLEM 11-11

Problem Statement - See text, page 1281

Solution

1. Determine the total filter surface area needed for the filtration of 24,000 m^3/d at filtration rates of 200 L/m^2•min and 240 L/m^2•min.

$$\text{Surface area} = \frac{(24{,}000\ \text{m}^3/\text{d})}{(0.2\ \text{m}^3/\text{m}^2\cdot\text{min})\big(1440\ \text{min/d}\big)} = 83.3\ \text{m}^2$$

$$\text{Surface area} = \frac{(24{,}000\ \text{m}^3/\text{d})}{(0.24\ \text{m}^3/\text{m}^2\cdot\text{min})\big(1440\ \text{min/d}\big)} = 69.4\ \text{m}^2$$

2. Select a filter size and the number of filter units needed to allow one filter to be taken out of service for backwashing while not exceeding the maximum filtration rate applied to the remaining operational filters.

   Four filters with surface areas of 25 m^2 each will be sufficient for meeting the requirements.

3. Determine the percentage of filter output used for washing at backwashing rates of 960 and 40 L/m^2•min.

$$\begin{bmatrix}\text{Fraction of}\\ \text{filter output}\end{bmatrix} = \frac{(0.960\ \text{m}^3/\text{m}^2\cdot\text{min})(100\ \text{m}^2)\big(30\ \text{min/d}\big)}{(24{,}000\ \text{m}^3/\text{d})} = 0.12$$

$$\begin{bmatrix}\text{Fraction of}\\ \text{filter output}\end{bmatrix} = \frac{(0.04\ \text{m}^3/\text{m}^2 \cdot \text{min})(100\ \text{m}^2)(30\ \text{min/d})}{(24{,}000\ \text{m}^3/\text{d})} = 0.005$$

The percentage of filter output used for backwashing is 12 and 0.5 percent, for backwashing rates of 960 and 40 L/m^2•min, respectively.

4. Summary Table of results for problem 11-11

Flow (m^3/d)	Backwashing rates, L/m^2•min	
	960	40
	Filter output use for backwashing, %	
16,000	18	0.75
20,000	14.4	0.60
24,000	12	0.5

PROBLEM 11-12

Problem Statement - See text, page 1281

1. Determine the rejection and log rejection for each microorganism group for **water 1**.

	Water 1		Answer	
Microorganism	Feed water, org/mL	Permeate. org/mL	Rejection, %	Log rejection
HPC	6.5×10^7	3.3×10^2	99.99949	5.29
Total coliform	3.4×10^6	100	99.99706	4.53
Enteric virus	7×10^3	6.6×10^3	5.71429	0.026

2. Determine the percent rejection using Eq. (11-34)

$$R,\% = \left(1 - \frac{C_p}{C_f}\right) x\,100$$

$$R,\% = \left(1 - \frac{3.3 \times 10^2}{6.5 \times 10^7}\right) x\,100 = 99.99949$$

3. Determine the log rejection using Eq. (11-35)

$$R_{\log} = -\log(1 - R) = \log\left(\frac{C_f}{C_p}\right)$$

$$R_{log} = \log\left(\frac{6.5\ x\ 10^7}{3.3\ x\ 10^2}\right) = 5.29$$

4. Summary Table for Water 2

	Water 2		Answer	
Microorganism	Feed water, org/mL	Permeate. org/mL	Rejection, %	Log rejection
HPC	8.6×10^7	1.5×10^2	99.99983	5.76
Total coliform	5.0×10^6	60	100	104.92
Enteric virus	2.0×10^3	9.1×10^3	54.5	0.34

PROBLEM 11-13

Problem Statement - See text, page 1282

Solution: Part a

1. Determine feed stream flowrate at the entrance

   1.1 Calculate the cross-sectional area of one fiber lumen.

$$A_{fiber} = \frac{\pi}{4}d^2 = \frac{\pi}{4}(1.0\times10^{-3}\ \text{m})^2 = 7.85\times10^{-7}\ \text{m}^2$$

   1.2 Calculate feed flow to 1 fiber using Eq. (11-38).

$$Q_p = (v)(A_{fiber}) = (1\ \text{m/s})(7.85\times10^{-7}\ \text{m}^2) = 7.85\times10^{-7}\ \text{m}^3/\text{s}$$

   1.3 Determine the total flow by multiplying Qp, the result of the step 1.2, by the number of fibers in the module.

$$Q_F = (6000\ \text{fibers})(7.85\times10^{-7}\ \text{m}^3/\text{s})(3600\ \text{s/h}) = 16.96\ \text{m}^3/\text{h}$$

Solution: Part b

1. Determine the permeate flowrate

   1.1 Calculate the inside surface area of one fiber.

$$A_{fs} = \pi dL = \pi(1\times10^{-3}\ \text{m})(1.25\ \text{m}) = 3.93\times10^{-3}\ \text{m}^2$$

   1.2 Calculate permeate flow from 1 fiber using Eq. (11-32).

$$Q_{fiber} = (100\ \text{L/m}^2\cdot\text{h})(3.93\times10^{-3}\ \text{m}^2) = 0.393\ \text{L/h}$$

   1.3 Determine the total permeate flow, Qp, by multiplying the result from step b, by the number of fibers in the module.

$$Q_P = (6000\ \text{fibers})(0.393\ \text{L/h})(10^{-3}\ \text{m}^3/\text{L}) = 2.35\ \text{m}^3/\text{h}$$

Solution: Part c

1. Determine the retentate cross-flow velocity

   1.1 Calculate the retentate flow by mass balance using Eq. (11-36).

   $$Q_F = Q_P + Q_R$$

   $$Q_R = Q_F - Q_P = 16.96\ \text{m}^3/\text{h} - 2.35\ \text{m}^3/\text{h} = 14.61\ \text{m}^3/\text{h}$$

   1.2 Calculate the retentate cross-flow velocity.

   $$v_R = \frac{Q_R}{N_f a_f} = \frac{(14.61\ \text{m}^3/\text{h})}{(6000\ \text{fibers})(7.85 \times 10^{-7}\ \text{m}^2)(3600\ \text{s/h})} = 0.861\ \text{m/s}$$

Solution: Part d

1. Determine the ratio of the velocity through the membrane surface to the cross flow velocity

   1.1 Calculate the ratio of the feed velocity to the permeate velocity.

   $$\text{Ratio} = \frac{v_{fs}}{v_p} = \frac{(1\ \text{m/s})(10^3\ \text{L/m}^3)(3600\ \text{s / h})}{(100\ \text{L/m}^2 \cdot \text{h})} = 36{,}000$$

   1.2 Comment:

   The water velocity parallel to the membrane surface is 36,000 times greater than the velocity toward the membrane. This high cross-flow velocity results in a strong shear force that is not present in dead-end filtration. The shear force helps to reduce the accumulation of particles at the membrane surface. As a result, cross-flow filters foul at a slower rate than dead-end filters and are typically able to operate at a higher average flux.

Solution: Part e

1. Determine the ratio of the permeate flowrate to the feed stream flowrate,

   1.1 Ratio:

   $$\text{Ratio} = \frac{Q_P}{Q_F} = \frac{(2.35\ \text{m}^3/\text{h})}{(16.96\ \text{m}^3/\text{h})} = 0.139$$

   1.2 Comment:

The permeate flow is only 13.9 percent of the feed flow. Thus this membrane would not be suitable in reuse applications

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PROBLEM 11-14

Problem Statement - See text, page 1282

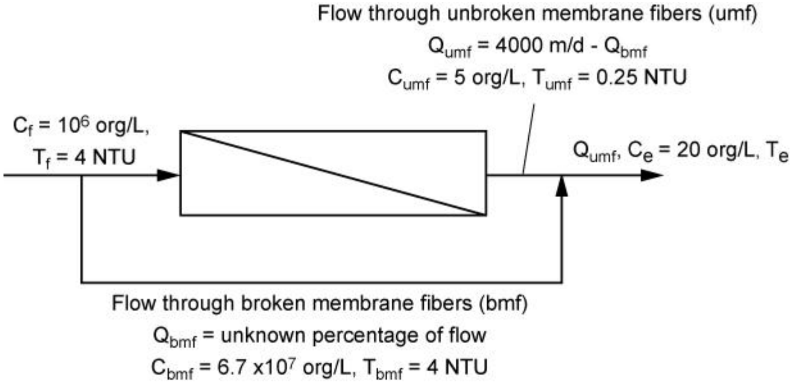
Solution

1. Calculate the log rejection for microorganisms with no broken fibers using Eq. (11-35).

$$R_{\log} = \log\left(\frac{C_f}{C_p}\right) = \log\left(\frac{6.7\,x\,10^7\ \text{org/L}}{5\ \text{org/L}}\right) = 7.13$$

2. Determine the number of broken fibers.

   a. Prepare a mass balance diagram for the condition with the broken fibers



   b. Write mass balance equation for microorganisms in the effluent from the membrane and solve for effluent microorganism concentration

$$Q_{bmf} = \frac{C_e Q_e - C_{umf}\,Q_e}{C_{bmf} - C_{umf}}$$

$$= \frac{(200\ \text{org/L})(4000\,\text{m}^3/\text{d}) - (5\ \text{org/L})(4000\,\text{m}^3/\text{d})}{6.7\,x\,10^7\ \text{org/L} - 5\ \text{org/L}}$$

$$= 0.01164\ \text{m}^3/\text{d}$$

   c. Calculate the number of broken fibers

$$\text{Broken fibers} = \left[\frac{(0.01164\ \text{m}^3/\text{d})}{(4000\ \text{m}^3/\text{d})}\right]5000 = 0.0146\ \text{fibers}$$

Thus, the increase in the organism count cannot be attributed to a broken fiber. A more likely explanation for the observed increase in the number of microorganisms in the effluent is membrane deterioration

3. Based on the computations presented in Example 11-5, the impact of the observed membrane deterioration would be unmeasurable.

PROBLEM 11-15

Problem Statement - See text, page 1282

Solution

Advantages	Disadvantages
Depth filtration	
• Well established technology • Particle removal efficiency depends on the nature of the pretreatment process(es)	• Relatively high head loss • Relatively expensive if concrete construction is used • Backwash water storage required • High backwash water percentage (e.g., 8 to 15 percent of applied flow)
Surface filtration	
• Low head loss (e.g., 250 to 300 mm) • Lower in cost as compared to depth filters or microfiltation • Different cloths are available for different applications • Very low backwash water percentage (e.g., 2 to 4 percent of applied flow)	• Newer technology • Easy to retrofit into existing traveling bridge filter basins

Microfiltration	
• Predictable effluent particle size distribution • Partial removal of indicator organisms (total and fecal colifirms)	• Relatively high pressure or vacuum required • Relatively complex mechanically • Membranes may be difficult to clean

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PROBLEM 11-16

Problem Statement - See text, page 1282

Instructors Note: The method outlined in the revised Example 11-6 is used to solve this problem. The following mass transfer coefficients should be used:
kw = 1x 10^{-6} m/s•bar and k_i = 6 x 10^{-8} m/s

Solution

1. Estimate the membrane area using Eq. (11-38) for **water 1**.

$F_w = k_w(\Delta P_a - \Delta \Pi)$

$= (1.0 \times 10^{-6}$ m/s•bar)(27.50 bar) $= 2.75 \times 10^{-5}$ m/s

$Q_p = F_w \times A$

$$A = \frac{(0.88 \times 4000\ \text{m}^3/\text{d})(1\ \text{d}/86{,}400\ \text{s})}{(2.75 \times 10^{-5}\ \text{m/s})} = 1{,}481\ \text{m}^2$$

2. Estimate the permeate TDS concentration using Eq. (11-39) and the area computed in Step 1.

$$F_s = k_s\ \Delta C_s = \frac{Q_p(10^{-3}\text{m}^3/\text{L})C_p}{A}$$

Substituting for ΔC_i and solving for C_p yields:

$$C_p = \frac{k_s\left[(C_f + C_c)/2\right]A}{Q_p + k_s A}$$

Assume $C_c \approx 10C_f$ (Note: If the estimated C_c value and the computed value of C_c, as determined below, are significantly different, the value of C_p must be recomputed)

$$Q_p = (0.88 \text{ x } 4000 \text{ m}^3/\text{d})(1 \text{ d}/86{,}400 \text{ s}) = 0.0407 \text{ m}^3/\text{s}$$

$$C_p = \frac{(6 \text{ x} 10^{-8} \text{ m/s})\left[(2.85 \text{ kg/m}^3 + 28.5 \text{ kg/m}^3)/2\right](1481 \text{ m}^2)}{(0.0407 \text{ m}^3/\text{s}) + (6 \text{ x} 10^{-8} \text{ m/s})(1481 \text{m}^2)} = 0.034 \text{ kg/m}^3$$

Because the permeate solute concentration is less than the required value (0.200 kg/m3), the membrane area can be reduced by blending the permeate flow with a portion of the influent feed.

3. Perform a materials balance around the membrane system to determine the amount of influent feed flow (Q_r) that is to be blended with the permeate flow to obtain the desired effluent concentration (Cblend).

$$Q_r = \frac{(Q_f R C_p) - (C_{blend} Q_f R)}{[C_{blend}(1 - R) - C_f + RC_p]}$$

$$= \frac{(4000 \text{m}^3/\text{d})(0.88)(0.034 \text{kg/m}^3) - (0.200 \text{kg/m}^3)(4000 \text{m}^3/\text{d})(0.88)}{[(0.200 \text{kg/m}^3)(1 - 0.88)] - (2.85 \text{kg/m}^3) + (0.88)(0.034 \text{kg/m}^3)]}$$

$$= 208.8 \text{m}^3/\text{d}$$

4. Compute the membrane area using the new feed flow rate (4000 m^3/d – 208.8 m^3/d = 3791.2 m^3/d).

   Q_p = Fw x A

$$A = \frac{(0.88 \text{ x } 3791.2 \text{ m}^3/\text{d})(1 \text{ d}/86{,}400 \text{ s})}{(2.75 \text{ x} 10^{-5} \text{ m/s})} = 1{,}404.1 \text{m}^2$$

5. Compute the new permeate concentration, as outlined above, using the new membrane area.

   Q_p = Fw x A

$$C_p = \frac{(6 \text{ x} 10^{-8} \text{ m/s})\left[(2.85 \text{ kg/m}^3 + 28.5 \text{ kg/m}^3)/2\right](1404 \text{ m}^2)}{(0.0386 \text{ m}^3/\text{s}) + (6 \text{ x} 10^{-8} \text{ m/s})(1404 \text{ m}^2)}$$

$$= 0.034 \text{ kg/m}^3$$

   Because the permeate concentration is the same as determined in Step 2 above, blending 209 m^3/d of feed water with the permeate, will result in a blended product water with a TDS of about 0.200 kg/m^3.

3. Estimate the rejection rate using Eq. (11-41).

$$R,\% = \frac{C_f - C_p}{C_f} \times 100$$

$$R = \frac{(2.85\,kg/m^3 - 0.034\,kg/m^3)}{(2.85\,kg/m^3)} \times 100 = 98.8\%$$

4. Estimate the concentrate stream TDS using Eq. (11-44).

$$C_c = \frac{Q_f\,C_f - Q_p\,C_p}{Q_c}$$

$$C_c = \frac{(0.0439\ m^3/s)(2.85\,kg/m^3) - (0.0439\ m^3/s)(0.88)(0.034\,kg/m^3)}{(0.0439\ m^3/s)(1-0.88)}$$

$$= 23.5\ kg/m^3$$

5. Summary of results from Problem 11-16.

Parameter	Unit	Water 1	2	3	4
Qr	m^3/d	208.8	785.7	3639.9	725.1
Area	m^2	1481	2292	7358	3318
R	%	98.8	98.7	98.8	99.2
Cc	kg/m^3	23.5	31.6	18.0	19.1

PROBLEM 11-17

Problem Statement - See text, page 1282

Solution

1. Determine the permeate flowrate with Eq. (11-43) and estimate the feed water TDS with Eq. (11-44) for water 1.

$$Q_p = Q_f - Q_c = 4000\ m^3/d\ -\ 350\ m^3/d\ =\ 3650\ m^3/d$$

$$C_f = \frac{Q_p\,C_p + Q_c\,C_c}{Q_f}$$

$$C_f = \frac{(3650\ m^3/d)(65\ g/m^3) + (350\ m^3/d)(1500\ g/m^3)}{(4000\ m^3/d)} = 191\,g/m^3$$

2. The recovery rate is found with Eq. (11-40).

$$r,\ \% \ = \ \frac{Q_p}{Q_f}\cdot 100 = \frac{(3650\ m^3/d)}{(4000\ m^3/d)}\ x\ 100 = 91\%$$

3. Estimate the rejection rate using Eq. (11-41).

$$R,\% = \frac{C_f - C_p}{C_f}\cdot 100$$

$$R = \frac{[(191\ -65)\ g/m^3]}{(191\,kg/m^3)}\ x\ 100 = 66\%$$

4. Summary of results for Problem 11-17

Item	Unit	Reverse osmosis unit			
		1	2	3	4
C_f	g/m^3	191	329	1742	2583
Q_p	m^3/d	3650	5400	500	1000
r	%	91	90	6	10
R	%	66	73	93	93

PROBLEM 11-18

Problem Statement - See text, page 1283

Solution

1. Determine the permeate flowrate for **water 1** using Eq. (11-40).

$$Q_p = \frac{r\cdot Q_f}{100} = \frac{(88\%)(4000\ m^3/d)}{100} = 3520\ m^3/d$$

2. Rearrange Eq. (11-38) to compute the water mass transfer coefficient, k_W.

$$k_w = \frac{(Q_p)}{(A)(\Delta P_a - \Delta\Pi)} = \frac{(3520\ m^3/d)(10^3\,kg/m^3)}{(1600\ m^2)(2.7\,x\,10^6\ kg/m\bullet s^2)(86{,}400\ s/1d)}$$

$$= 9.09\ x\ 10^{-9}\ s/m$$

3. Estimate the concentrate stream TDS using Eq. (11-44).

$$C_c \ = \ \frac{Q_f\ C_f\ -\ Q_p\ C_p}{Q_c}$$

$$C_c = \frac{(4000\ m^3/d)(2500\ g/m^3) - (3520\ m^3/d)(20\ g/m^3)}{(4000\ m^3/d\ -\ 3520\ m^3/d)}$$

$$= 20{,}687\ g/m^3 = 20.69\ kg/m^3$$

4. Compute the solute concentration gradient and mass transfer rate coefficient using Eq. (11-39).

$$\Delta C = \left[\frac{C_f + C_c}{2}\right] - C_p = \left[\frac{2.5\ kg/m^3 + 20.69\ kg/m^3}{2}\right] - 0.02\ kg/m^3$$

$$= 11.57\ kg/m^3$$

$$k_i = \frac{(Q_p)(C_p)}{(A)(\Delta C)} = \frac{(3520\ m^3/d)(0.02\ kg/m^3)}{(1600\ m^2)(11.57\ kg/m^3)(86{,}400\ s/d)} = 4.4\ x\ 10^{-8}\ m/s$$

2. Summary of results from Problem 11-18.

		Reverse osmosis unit			
Item	Unit	1	2	3	4
Q_p	m^3/d	3,520	4,950	17,800	8,600
k_w	s/m	9.09×10^{-9}	1.35×10^{-8}	7.66×10^{-9}	6.03×10^{-9}
C_c	kg/m^3	20.7	32.6	47.9	19.1
ΔC	kg/m^3	11.6	17.9	26.5	10.9
k_i	m/s	4.4×10^{-8}	9.43×10^{-8}	3.23×10^{-8}	3.82×10^{-8}

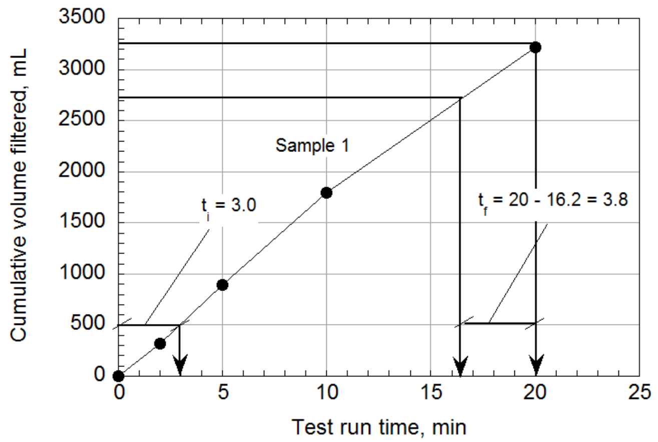
PROBLEM 11-19

Problem Statement - See text, page 1283

Solution

1. To compute the SDI, a minimum sample volume of 1 L must be filtered. Eq. (11-45) is used to compute the SDI for **water sample 1**.

2. Plot the cumulative volume filtered for **water sample 1** as a function of run time and determine the time required to filter the initial and final 500 mL.



2. Calculate the SDI using Eq. (11-45)

$$\mathrm{SDI} = \frac{100\left[1-\left(t_i / t_f\right)\right]}{t} = \frac{100\left[1-\left(3.0\ \mathrm{min}/3.8\ \mathrm{min}\right)\right]}{20\ \mathrm{min}} = 1.05$$

Because the SDI value is less than 3, **water sample 1** will not require pretreatment before reverse osmosis treatment will be effective.

3. Summary of results from Problem 11-19

	Water sample			
Item	1	2	3	4
SDI	1.05	0.66	1.14	2.46
Pretreatment required	No	No	No	No

PROBLEM 11-20

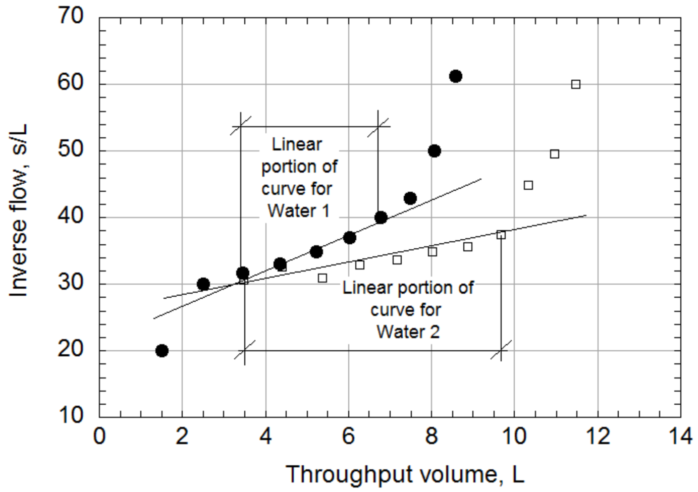
Problem Statement - See text, page 1283

1. Prepare data for Samples 1 and 2 to determine the modified fouling index (MFI).

	Water 1			Water 2		
Time, min	Filtered volume, L	Incremental volume, L	Inverse flow, s/L	Filtered volume , L	Incremental volume, L	Inverse flow, s/L
0				0		
0.5	1.50	1.50	20.0	1.50	1.50	20.0
1.0	2.50	1.00	30.0	2.50	1.00	30.0
1.5	3.45	0.95	31.6	3.48	0.98	30.6

2.0	4.36	0.91	33.0	4.40	0.92	32.6
2.5	5.22	0.86	34.8	5.37	0.97	30.9
3.0	6.03	0.81	37.0	6.28	0.91	32.9
3.5	6.78	0.75	40.0	7.17	0.89	33.7
4.0	7.48	0.70	42.9	8.03	0.86	34.9
4.5	8.08	0.60	50.0	8.87	0.84	35.7
5.0	8.57	0.49	61.2	9.67	0.80	37.5
5.5				10.34	0.97	44.8
6.0				10.97	0.63	49.6
6.5				11.47	0.50	60.0

2. Prepare a plot of the data prepared in Step 2 for Samples 1 and 2 to determine the modified fouling index (MFI). The required plot is given below.



3. Determine the MFI values using the values from the above plot

   a. For **Water 1**

$$\text{MFI} = \frac{37-30}{6.03-2.5} = 1.98\ \text{s/L}^2$$

Based on the data presented in Table 11-26, **water 1** can be used with nanofiltration and both hollow fiber and spiral wound reverse osmosis membranes

   a. For Water 2

$$\text{MFI} = \frac{37.5-30}{9.8-2.5} = 1.03\ \text{s/L}^2$$

Based on the data presented in Table 11-26, **water 2** can be used with nanofiltration and both hollow fiber and spiral wound reverse osmosis membranes

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PROBLEM 11-21

Problem Statement - See text, page 1283

Solution

1. Calculate the current for **400 cell pairs** using Eq. (11-49)

$$i = \frac{FQ_pN_{inf}E_r}{nE_c}$$

$$= \frac{(96{,}485\ \text{A}\cdot\text{s/g-eq})(28.9\ \text{L/s})(0.13\ \text{g-eq/L})(0.5)}{(400)(0.90)}$$

$$= 504.08\ \text{A}$$

2. Determine the power required using Eq. (11-50)

$$P = R(i)^2$$

$$p = (5.0\ \Omega)(504.16\ \text{A})^2 = 1{,}270{,}468\ \text{W} = 1270\ \text{kW}$$

3. Determine the power requirement per m3 of treated water

$$\text{Power consumption} = \frac{(1270\ \text{kW})(24\ \text{h/d})}{(2500\ \text{m}^3\text{/d})(0.9)} = 13.55\ \text{kWh/m}^3$$

4. Determine the daily cost to operate the electrodialysis unit

$$\text{Cost} = (\$0.13/\text{kWh})(13.55\ \text{kWh/m}^3)(2500\ \text{m}^3\text{/d}) = \$4{,}404/\text{d}$$

PROBLEM 11-22

Problem Statement - See text, page 1283

Solution

1. Review the three artciles related to disposal of nanofiltration, reverse osmosis, and elecetrodialysis.
2. Prepare a table to discuss the type of process combinations that are being proposed accoring to the article review.

   Processes used to deal with brine from nanofiltration, reverse osmosis and electrodialysis in no special order.

Process	Brine treament/disposal
Nanofiltration	Discharge to collection system, depending on quantity, concentration with forward osmosis, solar evaporation, thermal evaporation
Reverse osmosis	Discharge to collection system, depending on quantity, concentration with forward osmosis, solar evaporation, thermal evaporation, combination of evaporator and crystallizer, recovery of salts, chemical (lime typically) precipitation, deep subsurface well injection, disposal to the ocean via a brine outfall
Electrodialysis	Discharge to collection system, depending on quantity, concentration with forward osmosis, solar evaporation, thermal evaporation, recovery of salts

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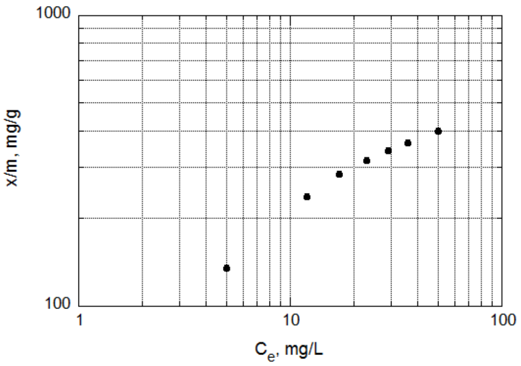
PROBLEM 11-23 - See text, page 1284

Solution

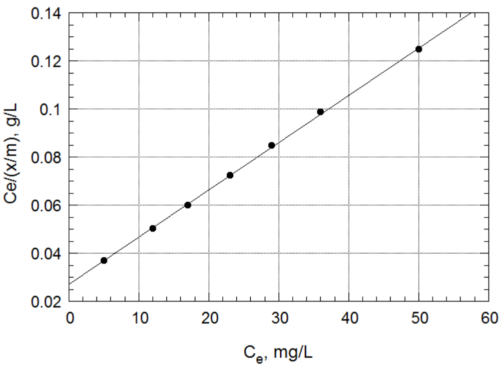
1. Following Example 11-11, construct a computation table for the values needed to plot the Freundlich and Langmuir isotherms for **water 1**.

Adsorbate concentration, mg/L				
C_o	C_e	$C_o - C_e$	x/m, mg/g	C_e/(x/m)
140	5	135	135	0.0370
250	12	238	238	0.0504
300	17	283	283	0.0601
340	23	317	317	0.0726
370	29	341	341	0.0850
400	36	364	364	0.0989
450	50	400	400	0.1250

2. Plot the Freundlich and Langmuir adsorption isotherms using the data developed in step 1.



Freundlich isotherm



Langmuir isotherm

2. Because the plot for the Langmuir isotherm is linear, the Langmuir isotherm is more suitable to describe the data.

3. Summary of results for Problem 11-23

	Water sample			
	1	2	3	4
Best fit isotherm	Langmuir	Langmuir	Langmuir	Freundlich

PROBLEM 11-24

Problem Statement - See text, page 1284

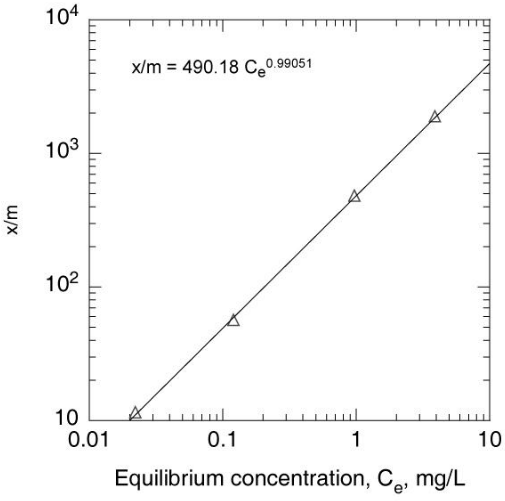
Solution

1. Derive the values needed to plot the Freundlich and Langmuir adsorption isotherms using the batch adsorption test data. The required table for **Sample 1** is shown below:

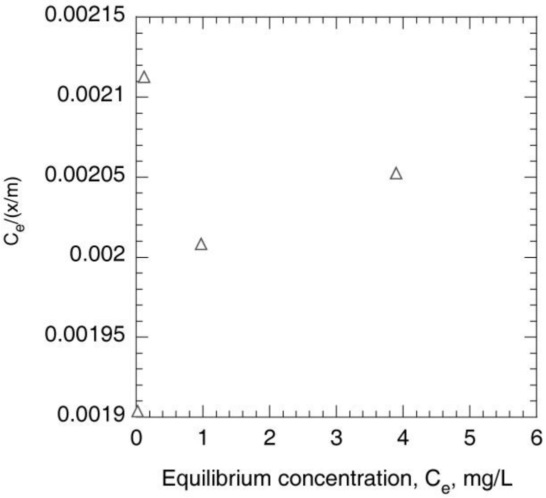
Adsorbate concentration, mg/L					
C_o	C_e	$C_o - C_e$	m, g	x/m, mg/g	Ce/(x/m)
5.8	5.8	0	0.000	--	--
5.8	3.9	1.9	0.001	1900	0.002053
5.8	0.97	4.83	0.010	483	0.002008
5.8	0.12	5.68	0.100	56.8	0.002113
5.8	0.022	5.778	0.500	11.556	0.001904

2. Plot the Freundlich and Langmuir adsorption isotherms using the data developed in Step 1 and determine which isotherm best fits the data.

   a. The required plots for **Sample 1** are given below.



Freundlich isotherm plot

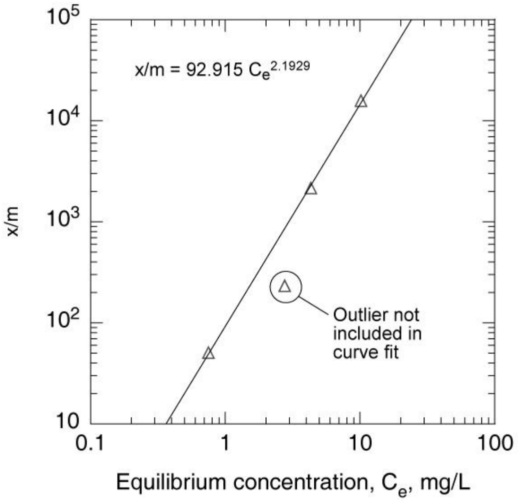


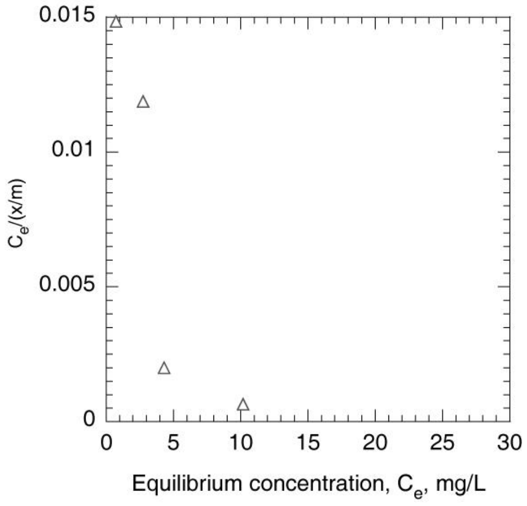
Langmuir isotherm plot

   b. From the above plots, the experimental data are best represented by the Freundlich isotherm as indicated by the linear curve fit. Because the plot for the Langmuir isotherm is not linear, use of the Langmuir adsorption isotherm is inappropriate.

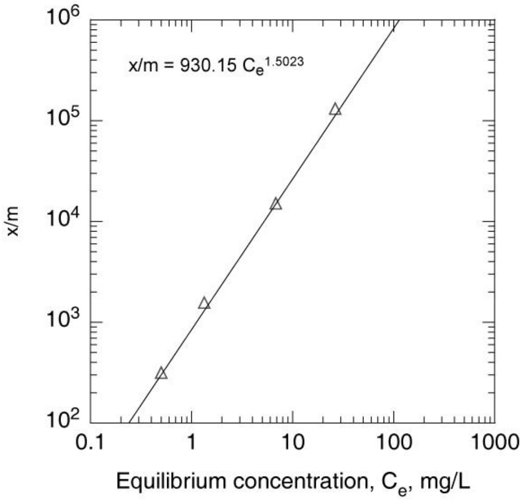
   c. For reference, the plots for Samples 2 (Freundlich), 3 (Freundlich), and 4 (Langmuir) are shown below.

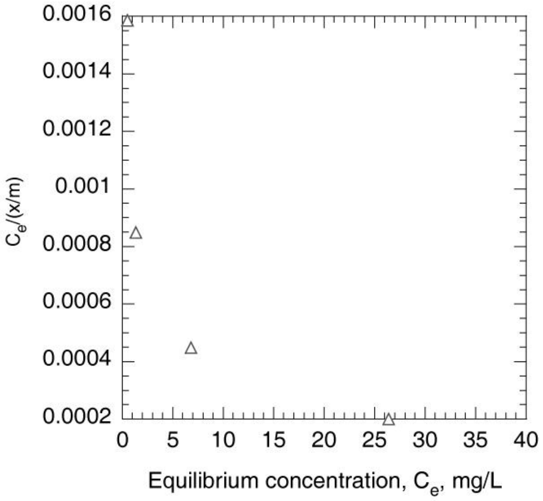
Sample 2:



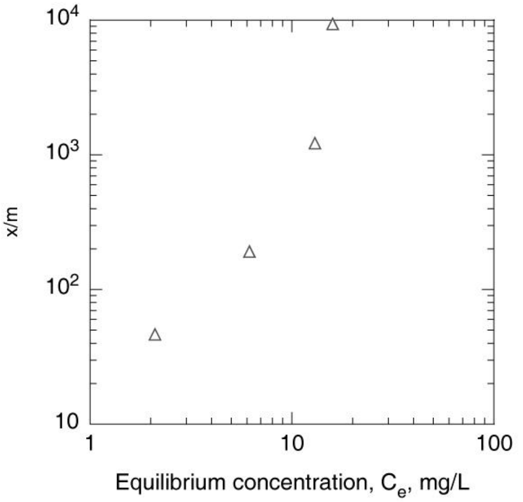


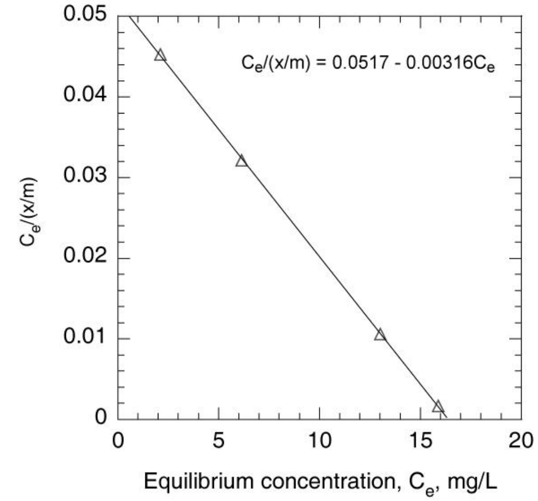
Sample 3:





Sample 4:





3. Determine the adsorption isotherm model parameters. The values of the isotherm coefficients can be determined using the spreadsheet function such as "Add Trendline" in Excel.

   a. **Sample 1** is characterized by the Freundlich isotherm with the form

   $$\frac{x}{m} = 490.18\,C_e^{0.99051}$$

   , thus Kf = 490.18, and n = 1/0.99051 = 1.0096.

b. **Sample 2** is characterized by the Freundlich isotherm with the form $\frac{x}{m} = 92.915\,C_e^{2.1929}$, thus Kf = 92.915, and n = 1/2.1929 = 0.456.

c. **Sample 3** is characterized by the Freundlich isotherm with the form $\frac{x}{m} = 930.15\,C_e^{1.5023}$, thus Kf = 930.15, and n = 1/1.5023 = 0.666.

d. **Sample 4** is characterized by the Langmuir isotherm with the form $\frac{C_e}{(x/m)} = 0.0517 - 0.00316\,C_e$, thus a = 1/0.00316 = 316.5, and b = 1/(0.0517 x 316.5) = 0.0611.

PROBLEM 11-25

Problem Statement - See text, page 1284

Instructors Note: Problem 11-25 should be assigned along with Problem 11-24

Solution

1. Estimate the amount of carbon needed to reduce the wastewater COD from 30 mg/L to 2 mg/L using Eq. (11-55) and Eq. (11-57). The required computations for Samples 1, 2, 3, and 4 are shown below.

   Sample 1:

$$m = \frac{x}{K_f\,C_e^{1/n}} = \frac{(30\,\text{mg/L} - 2\text{mg/L})(4800\,\text{m}^3\,/\text{d})(10^3\ \text{L/m}^3\,)}{(490.18)(2^{0.99051})(10^3\ \text{g/kg})} = 138.0\,\text{kg/d}$$

   Sample 2:

$$m = \frac{x}{K_f\,C_e^{1/n}} = \frac{(30\,\text{mg/L} - 2\,\text{mg/L})(4800\,\text{m}^3\,/\text{d})(10^3\ \text{L/m}^3\,)}{(92.915)(2^{2.1929})(10^3\ \text{g/kg})} = 316.3\ \text{kg/d}$$

   Sample 3:

$$m = \frac{x}{K_f\,C_e^{1/n}} = \frac{(30\,\text{mg}/\text{L} - 2\,\text{mg}/\text{L})(4800\,\text{m}^3\,/\,\text{d})(10^3\,\text{L}/\text{m}^3\,)}{(930.15)(2^{1.5023})(10^3\ \text{g}/\text{kg})} = 51.0\,\text{kg}/\text{d}$$

   Sample 4:

$$m = \frac{(x)(1 + bC_e\,)}{abC_e} = \frac{(134{,}400{,}000\,\text{mg}/\text{d})[1 + (0.0611)(2\,\text{mg}/\text{L})]}{(316.5)(0.0611)(2\,\text{mg}/\text{L})(10^3\ \text{g}/\text{kg})} = 3900\,\text{kg}/\text{d}$$

PROBLEM 11-26

Problem Statement - See text, page 1284

Instructors Note: It should be noted that the responses will vary regarding the number of contacts, mode of operation, other design variables. Several of the processes may not be feasible due to the low adsorption capacity for some of the compounds.

Solution

1. Develop design data for the carbon adsorption system based on the procedure presented in Example 10-12. The following data is shown for chloroform.

    a. Estimate the GAC usage rate for chloroform. Assuming the adsorption would follow the Freundlich isotherm, the GAC usage rate is estimated using Eq. (11-60) and Eq. (11-55). From Table 10-42, Kf = 2.6 (mg/g)

    $$\frac{m_{GAC}}{Qt} = \frac{C_o - C_e}{q_e} = \frac{C_o - C_e}{K_f C_e^{1/n}}$$

    $$= \frac{(0.00045\ \mathrm{mg/L})}{(2.6\,(\mathrm{mg/g})(\mathrm{L/mg})]\,(0.00005\ \mathrm{mg/L})^{0.73}}$$

    = 0.239 g GAC/L

    b. Determine the mass of carbon required for a 10 min EBCT.

    The mass of GAC in the bed = $V_b \rho GAC$ = EBCT x Q x ρGAC

    Carbon required = 10 min (2777,78) L/min) (450 g/L) = 1.25 x 10^7 g

    c. Determine the volume of water treated using a 10 min EBCT.

    $$\text{Volume of water treated} = \frac{\text{Mass of GAC for given EBCT}}{\text{GAC usage rate}}$$

    $$\text{Volume of water treated} = \frac{1.25\ \mathrm{x} 10^7\ \mathrm{g}}{(\,0.239\ \mathrm{g\ GAC/L})} = 5.24\ \mathrm{x}\ 10^7\ \mathrm{L}$$

    d. Determine the bed life.

    $$\text{Bed life} = \frac{\text{Volume of water treated for given EBCT}}{Q}$$

$$\text{Bed life} = \frac{5.24 \text{ x } 10^7 \text{ L}}{(2777{,}78 \text{ L / min})(1440 \text{ min/ d})} = 13.1 \text{ d}$$

2. Select the number of contactors to be used, mode of operation, and the carbon requirements

   a. The number of contactors used will depend on the desired reliability and practicality of replacing the carbon media. In general, a minimum of two contactors should be used, with the second contactor serving as a standby unit.

   b. The mode of operation will depend on the desire to maximize the use of carbon and the volume of flow that can be processed by each contactor. For example, two parallel trains of carbon contactors arranged in series will allow for reliable operation several weeks before carbon replacement was needed and also allow one train to be taken off-line for maintenance while the other train remains on-line.

   c. The carbon requirement, as determined in Step 1a is

   $$(0.239 \text{ g GAC/L})\bullet(4 \times 10^6 \text{ L/d})\bullet(10^{-3} \text{ Kg/g}) = 955{,}10\text{Kg/d}$$

3. Prepare a summary table of the results

Parameter	Unit	Chloroform	Heptachlor	Methylene chloride	NDMA
Kf	(mg/g)(L/mg)1/n	2.6	1220	1.3	220
1/n	-	0.73	0.95	1.16	0.37
Flowrate	m^3/d	4000	4500	5000	6000
Co	ng/L	500	50	2000	200
Ce	ng/L	50	10	10	10
GAC	g/L	450	450	450	450
EBCT	min	10	10	10	10
Usage rate	g GAC/L	0.239	0.002	965.85	$2.73 \text{x} 10^{-3}$
Mass of carbon for 10 min EBCT	g	$1.25 \text{x} 10^7$	$1.41 \text{x} 10^7$	$1.56 \text{x} 10^7$	$1.88 \text{x} 10^7$
Volume of water treated	L	5.24×10^7	$7.63 \text{x} 10^9$	$1.62 \text{x} 10^4$	$6.87 \text{x} 10^9$

Bed life	d	13.1	1695	0.0032	1.14×10^3
Carbon requirements	kg/d	955	8.3	$4{,}83 \times 10^6$	1.64×10^1

PROBLEM 11-27

Problem Statement - See text, page 1284

Solution

The adsorbability of the compounds listed in Table 11-42 can be determined by inspection of the isotherm parameters (i.e.: Freundlich capacity factor) or by calculating the amount of carbon required for removal. The compounds are presented in the following list.

Five more readily absorbable	Five less readily absorbable
PCB	N-Dimethylnitrosamine
Heptachlor	Chloroethene
PCB 1232	Benzene
DDT	Methylene chloride
PCB 1221	1,1,1-Trichloroethane

PROBLEM 11-28

Problem Statement - See text, page 1284

Solution

1. For **water 1**, determine the empirical constants from the plot constructed in Problem 11-23. Because the Langmuir isotherm was found to be suitable for water 1, the constants will be determined from the Langmuir isotherm plot using Eq. (11-58).

$$\frac{C_e}{(x/m)} = \frac{1}{ab} + \frac{1}{a} C_e$$

The slope of the line is 1/a and for water 1 is equal to 0.00195. The intercept when C_e = 0 is the value of 1/ab and is equal to 0.0275. Thus the values for the constants a and b are 506.8 and 0.0728, respectively.

2. Estimate the amount of carbon needed to reduce the wastewater COD from 120 to 20 mg/L using Eq. (11-58).

$$m = \frac{(x)(1+bC_e)}{abC_e} = \frac{(5 \text{ x } 10^8 \text{ mg})\left[1+(0.0728)(20 \text{ mg/L})\right]}{(506.8)(0.0728)(20 \text{ mg/L})(10^6 \text{ mg/1 kg})} = 1{,}664 \text{ kg/d}$$

3. Summary of results for Problem 11-28

Water sample	Constants				Mass of activated carbon needed, kg/d
	Langmuir		Freundlich		
	a	b	K_f	1/n	
1	506.8	0.073			1,664
2	330.6	0.064			2,693
3	424.8	1.152			1,228
4			69.4	0.414	2,085

PROBLEM 11-29

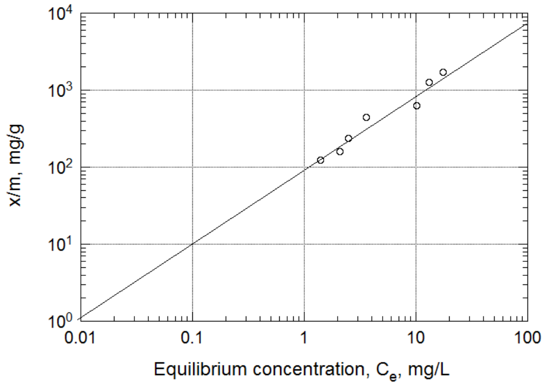
Problem Statement - See text, page 1285

Solution

Derive the values needed to plot the Freundlich adsorption isotherm using the test data for **water 1**.

Carbon dose, mg/L	C_e, mg/L	$(C_o - C_e)$, mg/L	x/m, mg/g
0	25.9	0	
5	17.4	8.5	1700
10	13.2	12.7	1270
25	10.2	15.7	628
50	3.6	22.3	446
100	2.5	23.4	234
150	2.1	23.8	159
200	1.4	24.5	123

2. Plot the Freundlich adsorption isotherm using the data developed in Step 1 for water 1.



3. Determine the adsorption isotherm coefficients. When x/m versus C_e is plotted on log-log paper, the intercept when C_e = 1.0 is the value of x/m and the slope of the line is equal to 1/n. Thus, x/m = 90, and K_f = 90. When x/m = 1.0, C_e = 0.011, and 1/n = 0.99. The resulting expression of the Freundlich isotherm is

$$x/m = 90\ C_e^{0.99}$$

Summary of results from Problem 11-29

Water	K_f	1/n
1	90.2	0.992
2	133.1	0.413
3	24.8	0.6
4	162.6	0.288
5	89.7	0.252
6	161.2	0.366

PROBLEM 11-30

Problem Statement - See text, page 1285

Solution

Instructors Note: Two solutions are presented for Problem 11-30 because of the differing volatility of organic compounds including those in this problem. The first solution, **Part A**, is based on using the pressure drop diagram (Fig. 11-67) to determine the required column sizing. The second solution, **Part B**, is for compounds that are extremely volatile (i.e., with large Henry's law constants). Extremely volatile compounds require so little air flow that the pressure drop is not an issue and hence Fig. 11-67 does not apply. Although extremely volatile compounds can be stripped by natural draft alone, it is common practice to use a minimum air to water ratio (e.g., 20 : 1). The procedure for chloroethene, an extremely volatile compound, is illustrated in **Part B.**

Solution – Part A

The methods outlined in Examples 11-15 and 11-16 are used as a template for the following solution for trichloroethylene (TCE) in **water 1**.

1. Determine the influent and effluent mole fractions of TCE in the liquid using Eq. (2-3).

$$X_B = \frac{n_B}{n_A + n_B}$$

where x_B = mole fraction of solute B

n_B = number of moles of solute B

n_A = number of moles of solute A

$$C_o = \frac{[(1 \times 10^{-4})/131.39]}{\{55.5 + [(1 \times 10^{-4})/131.39]\}} = 1.37 \times 10^{-8} \text{ mole TCE/mole } H_2O$$

$$C_e = \frac{[(5 \times 10^{-6})/131.39]}{\{55.5 + [(5 \times 10^{-6})/131.39]\}} = 6.87 \times 10^{-10} \text{ mole TCE/mole } H_2O$$

2. Convert the Henry's law constant from Table 2-7, page 100, to the form used in Eq. (11-79) using Eq. (2-51) and determine the effluent mole fraction of TCE in the air leaving the tower using Eq. (11-79).

$$H_u = \frac{H}{RT} = \frac{(0.00553 \text{ m}^3/\text{atm} \bullet \text{mole})}{(8.206 \times 10^{-5})(293.15 \text{ K})} = 0.23$$

H = (H_u)(4.559)(293.15 K) = 307.4 atm

$$y_e = \frac{H}{P_T} C_o = \left(\frac{307.4 \text{ atm}}{1 \text{ atm}}\right) 1.37 \times 10^{-8} = 4.22 \times 10^{6} \text{ mole TCE/mole air.}$$

Determine the gas to liquid ratio using Eq. (11-81) rearranged as follows

$$\frac{G}{L} = \frac{P_T}{H} \text{ x } \frac{(C_o - C_e)}{C_o} = \frac{(C_o - C_e)}{y_e}$$

$$\frac{G}{L} = \frac{\left[(1.37 \text{ x } 10^{-8} - 6.86 \text{ x } 10^{-10}) \text{ mole TCE/mole } H_2O\right]}{(4.22 \text{ x } 10^{-6} \text{ mole TCE/mole air})}$$

$$\frac{G}{L} = 0.00309 \frac{\text{mole air}}{\text{mole } H_2O}$$

4. Convert the moles of air and water to liters of air and water.

For air at 20°C:

0.00309 mole x 24.1 L/mole = 0.0745 L

For water:

$$1.0 \text{ mol } H_2O \text{ x } \left(\frac{18 \text{ g}}{\text{mole}}\right)\left(\frac{1 \text{ L}}{10^3 \text{ g}}\right) = 0.018 \text{ L}$$

$$\frac{G}{L} = \frac{0.0745 \text{ L}}{0.018 \text{ L}} = 4.137 \text{ L/L} = 4.137 \text{ m}^3/\text{m}^3$$

5. Determine the total quantity of air required based on ideal conditions.

$$\text{Air required} = \frac{(4.14 \text{ m}^3/\text{ m}^3)(3000 \text{ m}^3/\text{d})}{(1440 \text{ min/d})} = 8.62 \text{ m}^3/\text{min}$$

6. To determine the height of the stripping tower, several assumptions must be made.
   a. Select a packing material. Assume a packing factor of 50.
   b. Select a stripping factor. Assume a stripping factor of 3.
   c. Select an acceptable pressure drop. Assume a pressure drop of 200 (N/m^2)/m (see Table 11-45)
7. Determine the cross-sectional area of the stripping tower using the pressure drop plot given in Fig. 11-67.
   a. Determine the value of the ordinate for a stripping factor of 3.

$$S = \frac{G}{L} \text{ x } \frac{H}{P_T} = \frac{\text{G mole air}}{\text{L mole water}} \text{ x } \frac{307.4 \text{ atm}}{1.0 \text{ atm}} = \frac{\text{G mole air}}{\text{L mole water}} \text{ x } 307.4$$

$$S = 307.4 \text{ x} \left(\frac{\text{G mole air}}{\text{L mole water}}\right)\left(\frac{28.8 \text{ g}}{\text{mole air}}\right)\left(\frac{\text{mole water}}{18 \text{ g}}\right) = 491.9 \frac{G' \text{ g}}{L' \text{ g}}$$

$$\frac{L'}{G'} = \frac{(491.9 \text{ kg/kg})}{3} = 164$$

$$\frac{L'}{G'}\left(\frac{\rho_G}{\rho_L - \rho_G}\right)^{1/2} \approx \frac{L'}{G'}\left(\frac{\rho_G}{\rho_L}\right)^{1/2} = (164 \text{ kg/kg})\left[\frac{(1.204 \text{ kg/m}^3)}{(998.2 \text{ kg/m}^3)}\right]^{1/2}$$

$$\frac{L'}{G'}\left(\frac{\rho_G}{\rho_L}\right)^{1/2} = 5.7$$

b. Determine the corresponding value on the abscissa. For an ordinate value of 5.7 and a pressure drop of 200 (N/m^2)/m, the abscissa value is 0.0015.

c. Using an abscissa value 0.0015, determine the loading rate using Eq. (11-103)

$$G' = \left[\frac{(\text{value from y axis})(\rho_G)(\rho_L - \rho_G)}{(C_f)(\mu_L)^{0.1}}\right]^{1/2}$$

$$G' = \left[\frac{(0.0015)(1.204)(998.2 - 1.204)}{(50)(0.001)^{0.1}}\right]^{1/2} = 0.268 \text{ kg/m}^2 \cdot \text{s}$$

L’ = 164 G’ = 164 x 0.268 kg/m^2·s = 43.9 kg/m^2·s

d. Substitute known values and solve for the diameter of the tower

$$D = \left\{\frac{4}{3.14} \text{ x } \frac{(3000 \text{ m}^3\text{/d})(998.2 \text{ kg/m}^3)}{[(0.268 + 43.9) \text{ kg/m}^2 \cdot \text{s}]} \text{ x } \frac{1 \text{ d}}{86{,}400 \text{ s}}\right\}^{1/2} = 1.0 \text{ m}$$

8. Determine the height of the transfer unit using Eq. (11-96)

$$HTU = \frac{L}{K_L a A} = \left\{\frac{(3000 \text{ m}^3/\text{d})}{(0.0176/\text{s})[(3.14/4)(1.0)^2]}\right\} \text{ x } \frac{1 \text{ d}}{86{,}400 \text{ s}} = 2.52 \text{ m}$$

9. Determine the number of transfer unit using Eq. (11-98)

$$NTU = \left[\frac{3}{3-1}\right] \ln\left[\frac{(100/5)(3-1)+1}{3}\right] = 3.92$$

10. Determine the theoretical height of the stripping tower packing using Eq. (11-95)

    Z = HTU x NTU = 2.52 x 3.92 = 9.9 m

11. Summary table of results from Problem 11-30

Compound	Water 1			Water 2		
	Air, m^3/min	D, m	Z, m	Air, m^3/min	D, m	Z, m
Chlorobenzene	12.89	1.07	9.23	12.78	1.07	8.70
Chloroethene[a]	0.75	1.29	7.34	0.76	1.29	8.45
TCE	8.62	1.00	9.87	8.57	1.00	9.48
Toluene	7.41	0.96	9.13	7.21	0.96	7.76

[a] Based on assumed air to water ratio (G'/L') of 20 m^3 air/m^3 water (see **Solution Part B**).

Solution – Part B

The methods outlined in Examples 11-15 and 11-16 are used as a template for the following solution for chloroethene in water A.

1. Determine the influent and effluent mole fractions of chloroethene in the liquid using Eq. (2-2).

$$x_B = \frac{n_B}{n_A + n_B}$$

where x_B = mole fraction of solute B

n_B = number of moles of solute B

n_A = number of moles of solute A

$$C_o = \frac{[(1\,x\,10^{-4})/62.5]}{\{55.5 + [(1\,x\,10^{-4})/62.5]\}} = 2.88\,x10^{-8}\ \text{mol chloroethene / mol } H_2O$$

$$C_e = \frac{[(5\,x\,10^{-6})/62.5]}{\{55.5 + [(5\,x\,10^{-6})/62.5]\}} = 1.44\ x\ 10^{-9}\ \text{mol chloroethene / mole } H_2O$$

2. Convert the Henry's law constant from Table 16-12, page 1769, to the form used in Eq. (11-79) using Eq. (2-51) and determine the effluent mole fraction of chloroethene in the air leaving the tower using Eq. (11-79).

$$H_u = \frac{H}{RT} = \frac{(0.064\ \text{m}^3/\text{atm}\bullet\text{mole})}{(8.206\ \text{x}\ 10^{-5})(293.15\ \text{K})} = 2.66$$

H = (H_u)(4.559)(293.15 K) = 3556 atm

$$y_e = \frac{H}{P_T}C_o = \left(\frac{3556\ \text{atm}}{1\ \text{atm}}\right)2.88\ \text{x}\ 10^{-8}$$

$$= 1.03\ \text{x}\ 10^{-4}\ \text{mole chloroethene/mole air}$$

3. Determine the gas to liquid ratio using Eq. (11-81) rearranged as follows

$$\frac{G}{L} = \frac{P_T}{H}\ \text{x}\ \frac{(C_o - C_e)}{C_o} = \frac{(C_o - C_e)}{y_e}$$

$$\frac{G}{L} = \frac{[(2.88\ \text{x}\ 10^{-8} - 1.44\ \text{x}\ 10^{-9})\ \text{mole chloroethene/mole H}_2\text{O}]}{\left(1.44\ \text{x}\ 10^{-9}\ \dfrac{\text{mole chloroethene}}{\text{mole air}}\right)}$$

$$\frac{G}{L} = 0.000267\ \frac{\text{mole air}}{\text{mole H}_2\text{O}}$$

4. Convert the moles of air and water to liters of air and water.

For air at 20°C:

(0.000267 mole)(24.1 L/mole) = 0.006435 L

For water:

$$1.0\ \text{mol H}_2\text{O x}\left(\frac{18\,\text{g}}{\text{mole}}\right)\left(\frac{1\,\text{L}}{1000\,\text{g}}\right) = 0.018\,\text{L}$$

$$\frac{G}{L} = \frac{0.006435\ \text{L}}{0.018\ \text{L}} = 0.357\,\text{L/L} = 0.357\ \text{m}^3/\text{m}^3$$

5. Determine the total quantity of air required based on ideal conditions.

$$\text{Air required} = \frac{(0.357\ \text{m}^3/\ \text{m}^3)\ (3000\ \text{m}^3/\text{d})}{(1440\ \text{min/d})} = 0.745\,\text{m}^3/\text{min}$$

6. To determine the height of the stripping tower, several assumptions must be made.
   a. Select a packing material. Assume a packing factor of 50.
   b. Select a stripping factor. Assume a stripping factor of 3.

c. Select an acceptable pressure drop. Assume a pressure drop of 200 $(N/m^2)/m$ (see Table 11-45)

7. Determine the cross-sectional area of the stripping tower using the pressure drop plot given in Fig. 11-67. Because chloroethene is extremely volatile, the stripping tower can not be designed using the procedure outlined in Example 11-16. An alternate method, in which the air to water ratio is assumed to be 20 m^3 air/m^3 water, is used below to compute the dimensions of the stripping tower.

   a. Determine the value of the ordinate for Fig. 11-67.

$$\frac{G'}{L'} = \left(\frac{20\ \text{m}^3\ \text{air}}{\text{m}^3\ \text{water}}\right)\left(\frac{1.204\ \text{kg}}{\text{m}^3\ \text{air}}\right)\left(\frac{\text{m}^3\ \text{water}}{1000\ \text{kg}}\right) = 0.0241\ \text{kg air / kg water}$$

$$\frac{L'}{G'} = \frac{1}{(0.0241\ \text{kg/kg})} = 41.5$$

$$\frac{L'}{G'}\left(\frac{\rho_G}{\rho_L - \rho_G}\right)^{1/2} \approx \frac{L'}{G'}\left(\frac{\rho_G}{\rho_L}\right)^{1/2} = (41.5\ \text{kg/kg})\left(\frac{1.204\ \text{kg/m}^3}{998.2\ \text{kg/m}^3}\right)^{1/2}$$

$$\frac{L'}{G'}\left(\frac{\rho_G}{\rho_L}\right)^{1/2} = 1.44$$

   b. Determine the corresponding value on the abscissa. For an ordinate value of 1.44 and a pressure drop of 200 $(N/m^2)/m$, the abscissa value is 0.008.

   c. Using an abscissa value 0.008, determine the loading rate using Eq. (11-103)

$$G' = \left(\frac{(\text{value from y axis})(\rho_G)(\rho_L - \rho_G)}{(C_f)(\mu_L)^{0.1}}\right)^{1/2}$$

$$G' = \left(\frac{(0.008)(1.204)(998.2 - 1.204)}{(50)(0.001)^{0.1}}\right)^{1/2} = 0.619\ \text{kg/m}^2\cdot\text{s}$$

$L' = 41.5\ G' = 41.5 \times 0.619\ \text{kg/m}^2\cdot\text{s} = 25.7\ \text{kg/m}^2\cdot\text{s}$

   d. Substitute known values and solve for the diameter of the tower

$$D = \left[\left(\frac{4}{3.14}\right)\left\{\frac{(3000\ \text{m}^3/\text{d})(998.2\ \text{kg/m}^3)}{[(0.619 + 25.7)\ \text{kg/m}^2\cdot\text{s}]}\right\}\left(\frac{1\,\text{d}}{86{,}400\ \text{s}}\right)\right]^{1/2} = 1.3\ \text{m}$$

8. Determine the height of the transfer unit using Eq. (11-96)

$$\mathrm{HTU} = \frac{L}{K_L a A} = \left\{\frac{(3000\ \mathrm{m^3/d})}{\left[(0.0141/\mathrm{s})[(3.14/4)(1.0)^2\right]}\right\}\left(\frac{1\,\mathrm{d}}{86{,}400\ \mathrm{s}}\right) = 1.87\ \mathrm{m}$$

9. Determine the number of transfer unit using Eq. (11-98)

$$\mathrm{NTU} = \left[\frac{3}{3-1}\right]\ln\left[\frac{(100/5)(3-1)+1}{3}\right] = 3.92$$

10. Determine the theoretical height of the stripping tower packing using Eq. (11-95)

Z = HTU x NTU = 1.87 x 3.92 = 7.34 m

PROBLEM 11-31

Problem Statement - See text, page 1285

Solution

Write the basic exchange and equilibrium reactions using Eq. (11-114).

$\mathrm{RNa} + \mathrm{K^+} \rightarrow \mathrm{RK} + \mathrm{Na^+}$

$$1.46 = \frac{[\mathrm{Na^+}]\ X_{RK}}{[\mathrm{K^+}]\ X_{RNa}}$$

2. Determine the residual potassium concentration.

$$X_{RK} = \frac{n_K}{n_{Na} + n_K} \qquad X_{RK} = \frac{n_{Na}}{n_{Na} + n_K}$$

$$1.46 = \frac{[\mathrm{Na^+}]\ n_K}{[\mathrm{K^+}]\ n_{Na}}$$

$[\mathrm{K^+}] = 2 - n_K$

$$n_a = 5\mathrm{g}\ \mathrm{x}\ \frac{4\mathrm{meq}}{\mathrm{g}} - n_K = 20\mathrm{meq} - n_K$$

$[\mathrm{Na^+}] = n_K + 0.5\mathrm{meq}$

3. Substitute and solve by successive trials.

$$1.46 = \frac{(n_K + 0.5)\, n_K}{(2 - n_K)(20 - n_K)}$$

$$1.46 = \frac{n_K^2 + 0.5 n_K}{(20 - 22\, n_K + n_K^2)}$$

$n_K = 1.838$

Residual potassium concentration = 2 – 1.838 = 0.162 meq

PROBLEM 11-32

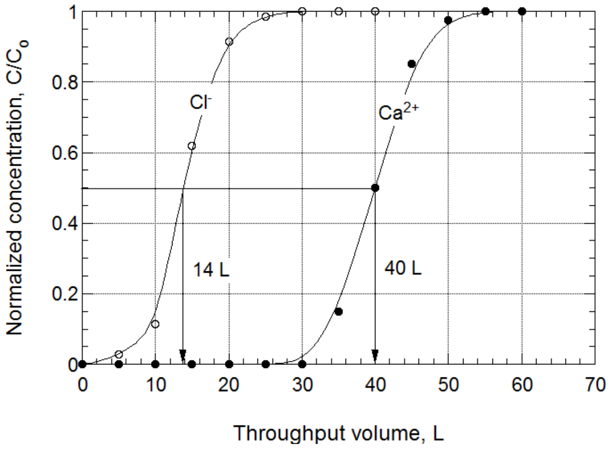
Problem Statement - See text, page 1285 - 1286

Solution

Instructors Note: The amount of resin used in the column study was not provided in the problem statement. For the solution below, a value of 0.1 kg is used, following Example 11-17.

Solution

1. Prepare a plot of the normalized concentrations of Cl^- and Ca^{+2} as a function of the throughput volume. The required plot for resin A is given below.



2. Determine the exchange capacity.

The exchange capacity (EC) of the resin in meq/kg is:

$$EC = \frac{V C_o}{R}$$

$$EC = \frac{(40\ L - 14 L)\left[\frac{(40\ mg/L)}{(20 mg/meq)}\right]}{0.1\ kg\ of\ resin} = 520\ meq/kg\ of\ resin$$

3. Determine the mass and volume of resin required to treat 4000 m^3 of water to reduce the Ca^{2+} concentration from 125 mg/L to 45 mg/L.

   a. Determine the meq of Ca^{2+}.

$$Ca^{2+}, meq/L = \frac{(125\ -\ 45)\ mg/L as\ Ca^{2+}}{(20\ mg/meq)} = 4\ meq/L$$

   b. The required exchange capacity is equal to

$$(4.0\ meq/L)(4000\ m^3/d)(10^3\ L/m^3)\ =\ 16\ x\ 10^6\ meq$$

   c. The required mass of resin is:

$$R_{mass}, kg = \frac{16\ x\ 10^6\ meq}{(520\ meq/kg\ of\ resin)} = 30{,}769\ kg/d\ of\ resin$$

   d. Assume the density of the resin is 700 kg/m^3 and determine the required volume of resin.

$$R_{vol}, m^3 = \frac{30{,}769\ kg\ of\ resin}{(700\ \ kg/m^3)} = 44\ m^3/d\ of\ resin$$

4. Summary of results for Problem 11-32

Item	Resin 1	Resin 2
EC, meq/kg	520	394
Mass, kg/d	30,769	40,609
Volume, m^3/d	44	58

PROBLEM 11-33

Problem Statement - See text, page 1286

Solution

Use the resin properties determined in Problem 11-32.

1. Determine the mass and volume of resin required to treat 5,500 m^3 of water to reduce the Mg^{2+} concentration from 115 to 15 mg/L, using resin 1.
   a. Determine the meq of $Mg^{2+.}$

$$Mg^{2+}, meq/L = \frac{\left[(115 - 15)\ mg/L\,as\,Mg^{2+}\right]}{(12.15\ mg/meq)} = 8.2\ meq/L$$

   b. The required exchange capacity is equal to

$$(8.2\ meq/L)(5500\ m^3/d)(10^3\ L/m^3) = 45.3\ x\ 10^6\ meq$$

   c. The required mass of resin is:

$$R_{mass}, kg = \frac{45.3\ x\ 10^6\ meq}{(520\ meq/kg\ of\ resin)} = 87{,}052\ kg/d\ of\ resin$$

   d. Assume the density of the resin is 700 kg/m^3 and determine the required volume of resin.

$$R_{vol}, m^3 = \frac{87{,}052\ kg\ of\ resin}{(700\ \ kg/m^3)} = 124.4\ m^3/d\ of\ resin$$

2. Summary of results for Problem 11-33

	Resin 1	Resin 2
EC, meq/kg	520	394
Mass, kg/d	87,053	114,892
Volume, m^3/d	124	164

PROBLEM 11-34

Problem Statement - See text, page 1286

Solution

1. Setup a computation table to compute the values needed to solve the problem, the values for wastewater 1 are shown below.

Wastewater 1

Cation	Conc., mg/L	mg/meq	meq/L	Anion	Conc., mg/L	mg/meq	meq/L
Ca^{2+}	82.2	20.04	4.10	HCO_3^-	304.8	61.02	5.00

Mg^{2+}	17.9	12.15	1.47	SO_4^{2-}	0	48.03	0.00
Na^+	46.4	23.00	2.02	Cl^-	58.1	35.45	1.64
K^+	15.5	39.10	0.40	NO_3^-	82.5	62.01	1.33
		Σcations	7.99			Σanions	7.96

2. Estimate the selectivity coefficient (see Table 11-49). To apply Eq. (11-129) the system must be reduced to two components. For this purpose, HCO_3^- and Cl^- are combined into a single component. Using a selectivity value of 4 for nitrate, the selectivity coefficient is estimated as follows:

$$K_{HCO_3^- \to NO_3^-} = \frac{4.0}{0.4} = 10.0$$

$$K_{Cl^- \to NO_3^-} = \frac{4.0}{1.0} = 4.0$$

$$K_{\left[(HCO_3^-)(Cl^-)\right] \to NO_3^-} = 7.0 \quad \text{(estimated)}$$

3. For the equilibrium condition ($C_e/C_o = 1.0$), estimate the nitrate equivalent fraction in solution.

$$X_{NO_3^-} = \frac{1.33}{7.96} = 0.167$$

4. Compute the equilibrium resin composition using Eq. (11-129).

$$\frac{\bar{X}_{B^+}}{1-\bar{X}_{B^+}} = \left[K_{A^+ \to B^+}\right]\left[\frac{X_{B^+}}{1-X_{B^+}}\right]$$

$$\frac{\bar{X}_{NO_3^-}}{1-\bar{X}_{NO_3^-}} = 7.0\left[\frac{0.167}{1-0.167}\right]$$

$$\bar{X}_{NO_3^-} = 0.584$$

Thus, 58 percent of the exchange sites on the resin can be used for the removal of nitrate

5. Determine the limiting operating capacity of the resin for the removal of nitrate.

Limiting operating capacity = (1.8 eq/L of resin)(0.584) = 1.05 eq/L of resin

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PROBLEM 11-35

Problem Statement - See text, page 1286

Solution

1. Setup a computation table to compute the values needed to solve the problem, the values for **wastewater 1** are shown below.

Wastewater 1

Cation	Conc., mg/L	mg/meq	meq/L	Anion	Conc., mg/L	mg/meq	meq/L
Ca^{2+}	82.2	20.04	4.10	HCO_3^-	321	61.02	5.26
Mg^{2+}	17.9	12.15	1.47	SO_4^{2-}	65	48.03	1.35
Na^+	46.4	23.00	2.02	Cl^-	22	35.45	0.62
K^+	15.5	39.10	0.40	NO_3^-	46	62.01	0.74
		Σcations	7.99			Σanions	7.97

2. Estimate the selectivity coefficient (see Table 11-49). To apply Eq. (11-129) the system must be reduced to two components. For this purpose, HCO_3^-, Cl^-, and NO_3^- are combined into a single monovalent component. The selectivity coefficient is estimated as follows:

$$K_{HCO_3^- \rightarrow SO_4^{2-}} = \frac{0.15}{0.4} = 0.4$$

$$K_{Cl^- \rightarrow SO_4^{2-}} = \frac{0.15}{1.0} = 0.15$$

$$K_{NO_3^- \rightarrow SO_4^{2-}} = \frac{0.15}{4.0} = 0.04$$

$$K_{\left[(NO_3^-)(HCO_3^-)(Cl^-)\right] \rightarrow SO_4^{2-}} = 0.2 \quad \text{(estimated)}$$

3. For the equilibrium condition ($C_e/C_o = 1.0$), estimate the sulfate equivalent fraction in solution.

$$X_{SO_4^{2-}} = \frac{1.35}{7.97} = 0.17$$

4. Compute the equilibrium resin composition using Eq. (11-129).

$$\frac{\bar{X}_{B^{2-}}}{\left(1-\bar{X}_{B^{2-}}\right)^2} = \left[K_{A^- \to B^{2-}}\right]\frac{\bar{C}}{C}\left[\frac{X_{B^{2-}}}{\left(1-X_{B^{2-}}\right)^2}\right]$$

$$\frac{\bar{X}_{SO_4^{2-}}}{\left(1-\bar{X}_{SO_4^{2-}}\right)^2} = 0.17\frac{2.5}{0.00798}\left[\frac{0.17}{\left(1-0.17\right)^2}\right]$$

$$\bar{X}_{SO_4^{2-}} = 0.78$$

Thus, 78 percent of the exchange sites on the resin will be in the divalent form at equilibrium. The relative amount of NO_3^- can be estimated by assuming that the remaining 22 percent of the resin sites are in equilibrium with a solution of NO_3^-, HCO_3^-, and CL^- with the same relative concentration as the feed.

The equivalent fraction of nitrate in the solution will then be:

$$X_{NO_3^-} = \frac{0.74}{6.62} = 0.112$$

The selectivity coefficient for the monovalent system is estimated:

$$K_{HCO_3^- \to NO_3^-} = \frac{4.0}{0.4} = 10.0$$

$$K_{Cl^- \to NO_3^-} = \frac{4.0}{1.0} = 4.0$$

$$K_{\left[(HCO_3^-)(Cl^-)\right] \to NO_3^-} = 7.0 \quad \text{(estimated)}$$

Compute the equilibrium resin composition using Eq. (11-129).

$$\frac{\bar{X}'_{B^+}}{1-\bar{X}'_{B^+}} = \left[K_{A^+ \to B^+}\right]\left[\frac{X'_{B^+}}{1-X'_{B^+}}\right]$$

$$\frac{\bar{X}'_{NO_3^-}}{1-\bar{X}'_{NO_3^-}} = 7.0\left[\frac{0.112}{1-0.112}\right]$$

$$\bar{X}'_{NO_3^-} = 0.47$$

The fraction of the total resin capacity in the nitrate form is then computed.

$$\bar{X}_{NO_3^-} = \left(1-\bar{X}_{SO_4^{2-}}\right)\left(\bar{X}'_{NO_3^-}\right) = (0.22)(0.47) = 0.105$$

4. Determine the limiting operating capacity of the resin for the removal of nitrate.

   Limiting operating capacity = (2.5 eq/L of resin)(0.105) = 0.26 eq/L of resin

5. Determine the volume of water that can be treated during a service cycle.

$$\text{Vol} = \frac{(\text{nitrate removal capacity of resin, eq/L of resin})}{(\text{nitrate in solution, eq/L of water})}$$

$$= \frac{(0.26\text{ eq/L of resin})}{(0.798 \times 10^{-3}\text{ eq/L of water})} = 355\ \frac{\text{L of water}}{\text{L of resin}}$$

6. Summary of results for Problem 11-35

Wastewater	Volume of water treated per service cycle, L water/L resin
1	355
2	0[a]
3	279
4	154

[a] Removal of sulfate will exhaust the resin exchange capacity

PROBLEM 11-36

Problem Statement - See text, page 1286

Solution

1. Prepare a table to summarize the chemical properties of importance for determining the advanced treatment process that should be considered. For some of the compounds to be investigated, the data presented in Table 16-12, page

1769, may be used to find chemical properties, other compounds will require review of other literature references.

Compound	Formula	mw	H, m^3-atm/mole	Solubility, mg/L
Benzene	C_6H_6	78.1	5.5 E-3	1,780
Chloroform	$CHCl_3$	119.4	3.1 E-3	7,840
Dieldrin	$C_{12}H_8Cl_6O$	380.9	1.0 E-5	0.195
Heptachlor	$C_{10}H_5Cl_7$	373.3	2.9 E-4	0.18
N-Nitrosodi-methylamine	$C_2H_6N_2O$	74.1	No data	1,000,000
Trichloroethylene	C_2HCl_3	131.4	9.9 E-3	1,280
Vinyl chloride	C_2H_3Cl	62.5	2.8 E-2	8,800

2. Prepare a table to summarize the compounds and the treatment processes that are expected to be effective for removal of that compound. Table 11-3 may be useful as a guide in process selection.

Compound	Advanced treatment processes for removal of specified compound[a]
Benzene	Adsorption, may be possible with reverse osmosis, electrodialysis, gas stripping.
Chloroform	Adsorption, reverse osmosis, electrodialysis, gas stripping.
Dieldrin	Adsorption, reverse osmosis, electrodialysis.
Heptachlor	Adsorption, reverse osmosis, electrodialysis.
N-Nitrosodi-methylamine	May be possible with adsorption, significant removal has been achieved with reverse osmosis, electrodialysis, advanced oxidation (especially with UV generation of hydroxyl radicals)
Trichloroethylene	Adsorption, reverse osmosis, electrodialysis, advanced oxidation, gas stripping,
Vinyl chloride	Adsorption, may be possible with reverse osmosis, electrodialysis, advanced oxidation, gas stripping,

[a] Descriptions of the various processes are presented in the following table

Advanced treatment process discussed in Chap. 11 and their applications.

Advanced treatment process	Typical applications
Depth filtration	Removal of suspended and colloidal constituents by exclusion based on constituent size.
Surface filtration	Removal of particulate matter suspended in a liquid by

	passing the liquid through a thin septum, usually a cloth or metal medium.
Membrane filtration processes (Micro and ultra filtration)	Removal of suspended and colloidal constituents by exclusion based on constituent size.
Membrane filtration processes (reverse osmosis)	Removal of dissolved constituents by preferential diffusion using a pressure-driven,semipermeable membrane.
Electrodialysis	Removal of suspended, colloidal, and dissolved constituents by exclusion in ion selective membranes.
Adsorption	Removal of dissolved organic materials by sequestration on a solid phase medium. See Table 11-40.
Gas stripping	Removal of volatile compounds by transfer from the liquid phase to the air phase. Compounds with a low Henry's constant are the most amenable to stripping.
Ion exchange	Removal of cationic and anion compounds by displacement of other ions on a prepared medium
Distillation	Removal of suspended and dissolved compounds by water vaporization and condensation, volatile compounds may carry-over into effluent.

12

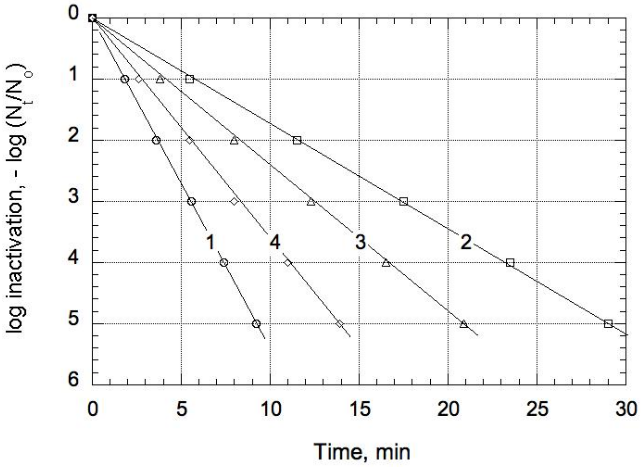
DISINFECTION PROCESSES

PROBLEM 12-1

Problem Statement - See text, page 1434

Solution

1. Plot –log (N_t/N_o) versus time



2. Solve for the constant k in Chicks law

   log(N_t/N_o) = -k t

   -5 = - (k/min)(9.2 min)

   k = 0.543/mim

Water	k/min
1	0.543
2	0.172
3	0.239
4	0.360

3. Use the van’t Hoff-Arrhenius equation [Eq. (12-7)] to determine the new innactivation constatnts at 12°C.

$$\ln\left(\frac{k_2}{k_1}\right) = \frac{E\left(T_2 - T_1\right)}{RT_1T_2}$$

$$k_2 = k_1 \exp\left[\frac{E\left(T_2 - T_1\right)}{RT_1T_2}\right]$$

$$k_2 = (0.543 / \text{min})\exp\left[\frac{(52\ \text{kJ / mole})(10^3\ \text{J / kJ})(285 - 293)}{(8.3444\ \text{Jmole} \bullet \text{K})(285)(293)}\right]$$

$$= 0.299 / \text{min}$$

Water	$k_{20°C}$/min^{-1}	$k_{12°C}$/min^{-1}
1	0.543	0.299
2	0.172	0.095
3	0.239	0.131
4	0.360	0.198

PROBLEM 12-2

Problem Statement - See text, page 1434

Instructors Note: A chlorine residual was was not given in Problem 1. In the following solution for effluent sample 1 of Problem 1, the chlorine residual at 60 min was assumed to be 2 mg/L. Other values can be specified. The key learning of this problem is see how important temperature and time is in the disinfection process.

Solution

1. Determine the chlorine dose at 60 min and 20°C. Assume Eqs. (12-3) and (12-6) can be used.

2. Determine the value of the specific lethality Λ for Sample 1.

   For the purpose of this analysis, assume the coefficient n in Eq. (12-3) is equal to 1.0.

   $k = \Lambda C^n$

   For effluent sample 1, the k value is 0.543/min (base 10) at 20°C with a residual chlorine concentration of 2.0 mg/L. Thus,

   Λ = k/C = (0.543/min)/(2 mg/L) = 0.272 L/mg•min

3. Determine the required residual chlorine concentration at 20°C using Eq. (12-5)

$$-\log\frac{N_t}{N_o} = (\Lambda_{\text{base }10})Ct$$

$$-\log 10^{-5} = (0.272)(C)(60\,\text{min})$$

$$C = -(-5)/(0.272)(60\,\text{min}) = 0.306\,\text{mg/L}$$

4. Determine the specific lethality Λ at 15 and 25°C using Eq. (12-7)

$$\ln\frac{\Lambda_2}{\Lambda_1} = \frac{E(T_2 - T_1)}{RT_2T_1}$$

a. Λ at 15°C (288 K)

$$\ln\frac{(0.272\ \text{L/mg}\bullet\text{min})}{\Lambda_{15}} = \frac{(52{,}000\,\text{J/mole})\,[(293-288)\text{K}]}{(8.3144\,\text{J/mole}\bullet\text{K})(293)(288)}$$

$$\frac{(0.272\ \text{L/mg}\bullet\text{min})}{\Lambda_{15}} = e^{0.371} = 1.449$$

$$\Lambda_{15} = (0.272\ \text{L/mg}\bullet\text{min})/1.449 = 0.188\ \text{L/mg}\bullet\text{min}$$

a. Λ at 25°C (298 K)

$$\ln\frac{(0.272\ \text{L/mg}\bullet\text{min})}{\Lambda_{25}} = \frac{(52{,}000\,\text{J/mole})[(293-298)\text{K}]}{(8.3144\,\text{J/mole}\bullet\text{K})(293)(298)}$$

$$\frac{(0.272\ \text{L/mg}\bullet\text{min})}{\Lambda_{25}} = e^{-0.358} = 0.699$$

$$\Lambda_{25} = (0.272\ \text{L/mg}\bullet\text{min})/.699 = 0.389\ \text{L/mg}\bullet\text{min}$$

5. Determine the required residual chlorine concentration at 15 and 25°C using Eq. (12-6)

$$-\log\frac{N_t}{N_o} = (\Lambda_{\text{base }10})Ct = D$$

a. Concentration, C, at 15°C

$$-\log 10^{-4} = (0.188\ \text{L/mg}\bullet\text{min})(C)(60\ \text{min})$$

$$C = -(-4)/(0.188\ \text{L/mg}\bullet\text{min})(60\ \text{min}) = 0.35\ \text{mg/L}$$

b. Concentration, C, at 25°C

$$-\log 10^{-4} = (0.699 \text{ L/mg} \bullet \text{min})(\text{C})(60 \text{ min})$$

$$\text{C} = -(-4)/(0.389 \text{ L/mg} \bullet \text{min})(60 \text{ min}) = 0.17 \text{ mg/L}$$

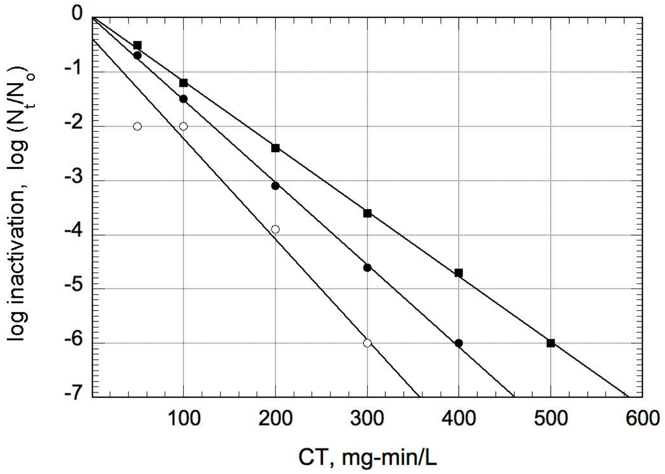
PROBLEM 12-3

Problem Statement - See text, page 1434

Solution

Part a

1. Plot log (N_t/N_o) versus CT



2. The coefficient of specific lethality in Eq. (12-6) is equal to the slope of the linear curve through the plotted data.

$$\log\left(\frac{N_t}{N_o}\right) = -\Lambda_{\text{base10}}(\text{CT})$$ for dilution constant n = 1

3. Determine the time required to achieve desired residual coliform.

Log reduction to achieve 200 MPN/100 mL:

$$\log\left(\frac{N_t}{N_o}\right) = 3.7$$

Log reduction to achieve 1000 MPN/100 mL:

$$\log\left(\frac{N_t}{N_o}\right) = 3.0$$

Use the coefficient of specific lethality calculated in part 2 to find the required contact time.

$$CT = \frac{\log\left(\frac{N_t}{N_o}\right)}{-\Lambda_{base10}}$$

		CT, mg-min/L given residual coliform	
Sample	$\Lambda_{base\ 10}$	200 MPN/100 mL	1000 MPN/100 mL
1	-0.0185	200	162
2	-0.0152	244	198
3	-0.0120	309	250

Part b

1. Given the average winter flowrate of 26,000 the volume required to achieve a 60 minute contact time is

$$26{,}000\ \mathrm{m^3/d} \times \frac{60\ \mathrm{min}}{[(60\ \mathrm{min/h})/(24\ \mathrm{h/d})]} = 1083\ \mathrm{m^3}$$

2. The minimum dose required to achieve desired residual coliform is

$$C = CT/T$$

	Chlorine concentration, mg/L given residual coliform	
Sample	200 MPN/100 mL	1000 MPN/100 mL
1	4798	3891
2	5848	4743
3	7412	6011

3. The mass of chlorine required annually to achieve the desired residual coliform for average and peak flowrates are

$$Cl_2\ \text{required} = (C_{Cl}, \mathrm{mg/L})(Q, \mathrm{m^3/d})(1000\ \mathrm{L/m^3})(10^{-6}\ \mathrm{kg/mg})(365\ \mathrm{d/y})$$

For average flowrate,

Sample	Chlorine mass, kg/y given residual coliform	
	200 MPN/100 mL	1000 MPN/100 mL
1	40,276,072	32,665,368
2	49,094,749	39,817,637
3	62,221,980	50,464,302

For peak flowrate,

	Chlorine mass, kg/y given residual coliform	
Sample	200 MPN/100 mL	1000 MPN/100 mL
1	80,552,143	65,330,735
2	98,189,498	79,635,275
3	124,443,959	100,928,604

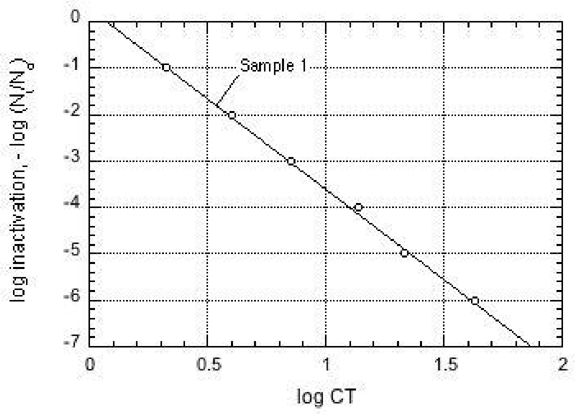
PROBLEM 12-4

Problem Statement - See text, page 1435

Instructors Note: Although "time" is listed in the data table the correct heading should be CT, mg•min/L

Solution

1. Plot –log (N_t/N_o) versus CT for the selected water sample. Sample 1 is shown on the plot below.



2. Determine the value of b and n in Eq. (12-27). The coefficient values are given in the table below for CT > b. Note that n is equal to the negative slope of the curve while b is the log-transformed x-intercept.

Wastewater	b	n
1	1.194	3.885
2	2.938	2.771
3	1.350	3.122
4	1.587	2.853

3. Check coefficients for Water 1. The CT value is equal to 42.3 for a 6 log reduction.

$$-\log(N/N_o) = n[\log(CT) - \log(b)]$$

$$= 3.885[\log(42.3) - \log(1.194)] = 6.0 \text{ ok}$$

4. Determine the innactivation achieved for a CT value of 10 for Water 1 as further check.

$$-\log(N/N_o) = n[\log(CT) - \log(b)]$$

$$= 3.885[\log(10) - \log(1.194)] = 3.6 \text{ ok (see above plot)}$$

PROBLEM 12-5

Problem Statement - See text, page 1435

Solution

1. Determine effective chlorine dose for **Sample 1** taking into account losses:
   a. Summer

      Effective chlorine dosage = (20 - 2.0) mg/L = 18.0 mg/L

   b. Winter

      Effective chlorine dosage = (10.0 - 2.0) mg/L = 8.0 mg/L

2. Estimate the effluent coliform concentration using the Collins-Selleck Model, Eq. (12-27) and the given coefficients.

$$N/N_o = (CT/b)^{-n}$$

a. Summer

$$N_t / 10^7 = (18 \text{x} 45 / 4.0)^{-2.8} = 3.48 \text{x} 10^{-7}$$
$$N_t = 3.48 / 100 \text{ mL}$$

b. Winter

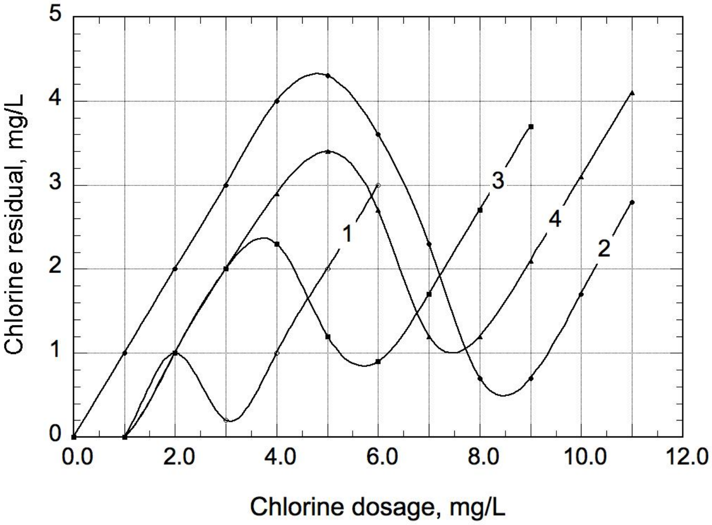
$$N_t / 10^7 = (8 \text{x} 45 / 4.0)^{-2.8} = 3.37 \text{x} 10^{-6}$$
$$N_t = 3.37 / 100 \text{mL}$$

PROBLEM 12-6

Problem Statement - See text, page 1435-1536

Solution

1. Plot the given chlorination data



2. The dosage at the breakpoint is:

Wastewater	Dosage, mg/L
1	3.1
2	8.5
3	5.75
4	7.5

3. Chlorine dose to obtain a free residual of 1.0 g/m^3

Wastewater	Dosage, mg/L
1	4.1

2	9.8
3	7.1
4	8.9

PROBLEM 12-7

Problem Statement - See text, page 1436

Solution

1. Estimate the required Cl_2 dosage using the molecular ratio developed in Example 12-3, page 1319

   kg Cl_2/d = (4800 m^3/d)[(4 – 1) g/m^3](7.6 g/g)(1 kg/10^3 g) = 109.4 kg/d

2. Determine the alkalinity required

   a. When using lime to neutralize the acidity, the required alkalinity ratio is 14.3 as developed in Example 12-3, page 1319

   b. The required alkalinity is

$$\text{Alk} = \frac{\left[(14.3\ \text{mg/L alk})/(\text{mg/L NH}_4^+)\right]\left[(4\ -\ 1)\ \text{mg/L NH}_4^+\right](4800\ \text{m}^3/\text{d})}{(10^3\ \text{g/kg})}$$

$$= 205.9\ \text{mg/L as CaCO}_3$$

3. Determine whether sufficient alkalinity is available to neutralize the acid during breakpoint chlorination

   Because the available alkalinity (125, 145, and 165 mg/L) are all less than the required alkalinity (205.9 mg/L), alkalinity will have to added to complete the reaction.

4. Determine the increment of TDS added to the reclaimed water. Using the data reported in Table 12-10, the TDS increase per mg/L of ammonia consumed when CaO is used to neutralize the acid formed is equal to 12.2 to 1.

   TDS increment = 12.2 (4 – 1) mg/L = 36.6 mg/L

PROBLEM 12-8

Problem Statement - See text, page 1436

Solution

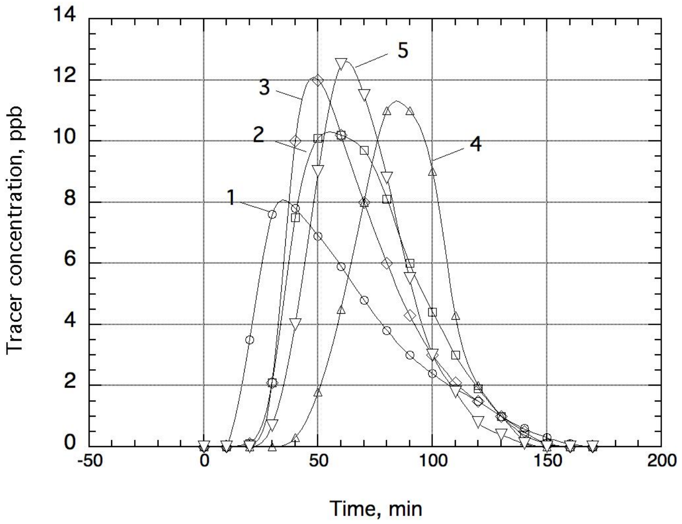
Instructors Note: Although a number of agencies switched from gaseous chlorine to hypochlorite for reasons of safety, it should be noted that some large agencies have switched back to gaseous chlorine.

PROBLEM 12-9

Problem Statement - See text, page 1436-1437

Solution

1. Prepare a plot of the given tracer data (Note this plot is not required, but is included to allow selection of the individual tracer curve).



2. Determine the mean hydraulic residence time, and variance for the tracer response data using equations given in Table 12-19.

   a. Set up the required computation table. In setting up the computation table given below for Sample 1, the Δt value was omitted as it appears in both the numerator and in the denominator of the equations used to compute the residence time and the corresponding variance.

Time, t , min	Conc., C, ppb	t x C	t^2x C	Cumulative conc.	Cumulative percentage

0	0	0	0	0	0.0
10	0	0	0	0	0.0
20	3.5	70	1400	3.5	6.8
30	7.6	228	6840	11.1	21.7
40	7.8	312	12,480	18.9	37.0
50	6.9	345	17,250	25.8	50.5
60	5.9	354	21,240	31.7	62.0
70	4.8	336	23,520	36.5	71.4
80	3.8	304	24,320	40.3	78.9
90	3.0	270	24,300	43.3	84.7
100	2.4	240	24,000	45.7	89.4
110	1.9	209	22,990	47.6	93.2
120	1.5	180	21,600	49.1	96.1
130	1.0	130	16,900	50.1	98.0
140	0.6	84	11,760	50.7	99.2
150	0.3	45	6750	51	99.8
160	0.1	16	2560	51.1	100.0
Total	51.1	3123	237,910		

b. Determine the mean hydraulic residence time

$$t_m \simeq \frac{\sum t_i C_i \Delta t_i}{\sum C_i \Delta t_i} = \frac{3123}{51.1} = 61.1\,\text{min}$$

c. Determine the variance

$$\sigma_t^2 \simeq \frac{\sum t_i^2 C_i \Delta t_i}{\sum C_i \Delta t_i} - (\tau_{\Delta c})^2 = \frac{237910}{51.1} - (61.1)^2 = 922.6\ \text{min}^2$$

σ_t = 30.4 min

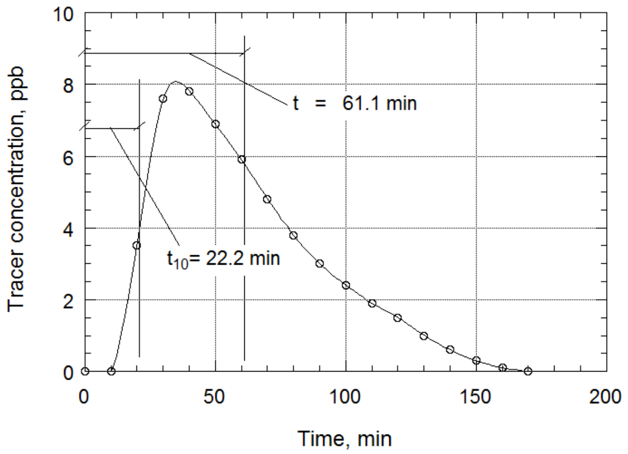
d. Determine the t_{10} time using the cumulative percentage values.

Because of the short time interval, a linear interpolation method can be used.

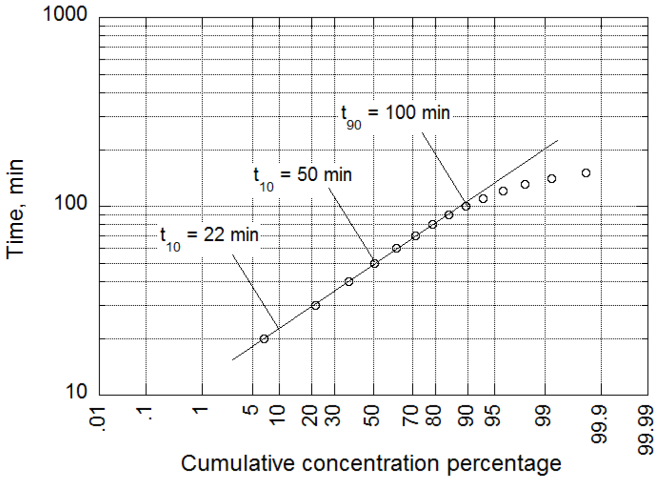
(21.7% - 6.8%)/(30 min - 20 min) = 1.49 %/min

20 min + (10% - 6.8%)/(1.48%/min) = 22.2 min

e. Identify the mean hydraulic residence and t_{10} times on the tracer curve for Basin 1.



2. Another technique that can be used to obtain the above times is to plot the cumulative concentration data on log-probability paper. Such a plot is also useful for determining the MDI. The required plot is given below



The mean hydraulic retention and t_{10} times are read directly from the above plot

t_{50} = 50 min

t_{10} = 22 min

3. Determine the MDI and the corresponding volume efficiency using the expressions given in Table 12-19 and the values from the plot given in Step 2 above.

   a. The Morrill Dispersion Index is:

$$\text{Morrill Dispersion Index, MDI} = \frac{t_{90}}{t_{10}} = \frac{100}{23} = 4.35$$

Because a MDI value below 2.0 has been established by the U.S. EPA as an effective design (U.S. EPA, 1986), the performance of Basin 2 would be classified as poor.

b. The corresponding volumetric efficiency for the chlorine contact basin is

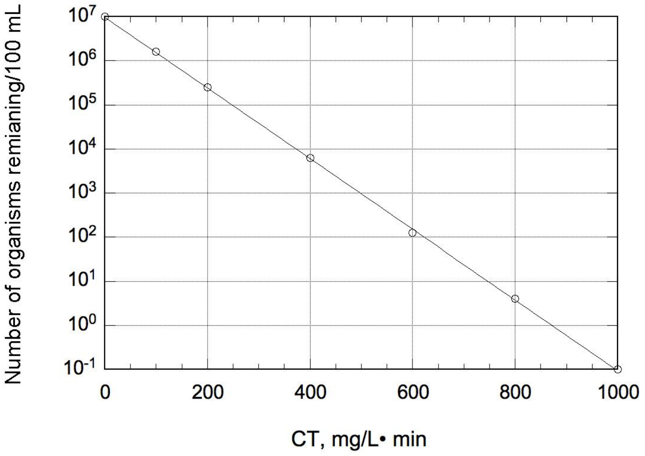
$$\text{Volumetric efficiency,\%} = \frac{1}{\text{MDI}} = \frac{1}{4.35} \text{ x } 100 = 23\%$$

PROBLEM 12-10

Problem Statement - See text, page 1437

Solution

1. Plot the dose-response data for enteric virus.



2. Set up a computation table to determine the number of organisms remaining in the effluent for chlorine contact basin 1.

Time, min	Tracer conc., mg/L	$C\Delta t$	E(t)	$C_r t$	Number of organisms remaining,	Number of organisms remaining in

					N(θ) MPN/100 mL	effluent, ΔN MPN/100 mL
0	0	0	0	0	9,860,000	0.0
10	0	0	0	50	3,916,844	0.0
20	0	0	0	100	1,555,950	0.0
30	0.1	1	0.004	150	618,095	2247.6
40	2	20	0.073	200	245,535	17,857.1
50	7.3	73	0.265	250	97,538	25,891.9
60	7	70	0.255	300	38,747	9862.8
70	5.2	52	0.189	350	15,392	2910.5
80	3.3	33	0.120	400	6114	733.7
90	1.7	17	0.062	450	2429	150.2
100	0.7	7	0.025	500	965	24.6
110	0.2	2	0.007	550	383	2.8
120	0	0	0	600	152	0.0
130	0	0	0	650	60	0.0
140	0	0	0	700	24	0.0
150	0	0	0	750	10	0.0
160	0	0	0	800	4	0.0
Sum		275	1.000			59,681.1

The number of organisms remaining in the effluent leaving the chlorine contact basin is $\sum[N(\theta) \times E(t)\Delta t]$ = 59,681 MPN/100 mL

3. Estimate the chlorine residual needed to achieve 4 log removal.

   Using the plot presented in step 1, a CT value of 500 mg/L·min results in 4 log removal. The theoretical detention time for basin 1 is 80 min. The estimated chlorine residual needed is 500 mg/L·min / 80 min = 6.25 mg/L.

Chlorine contact basin	Number of organisms remaining in effluent	Chlorine residual needed to 10^4 log removal
1	59,681	6.25
2	17,238	5.88
3	8,777	5.56
4	3,364	5.00

PROBLEM 12-11

Problem Statement - See text, page 1438

Solution

1. Determine the amount of chlorine to be removed each year for treated effluent with a chlorine residual of 5.0 mg/L as Cl_2 and a plant with a flowrate of 1400 m^3/d, for example.

$$\text{Cl}_2 \text{ removed} = \left(\frac{5 \text{x} 10^{-6} \text{ kg}}{\text{L}}\right)\left(\frac{1400 \text{ m}^3}{\text{d}}\right)\left(\frac{10^3 \text{ L}}{\text{m}^3}\right)\left(\frac{365 \text{ d}}{\text{y}}\right) = 2{,}555 \text{ kg/y}$$

2. Write the pertinent reactions for the dechlorination of chlorine residual as Cl_2 and determine the stoichiometric amount of the dechlorinating agent needed.

   a. Sulfur dioxide

$$\underset{(64)}{SO_2} + \underset{(71)}{Cl_2} + 2H_2O \rightarrow SO_4^{2-} + 4Cl^- + 4H^+$$

The amount of sulfur dioxide needed per mg/L of Cl_2 is 64/71 = 0.9 mg/L. The annual amount of sulfur dioxide needed is 0.9 x 2555 kg/y = 2300 kg.

Flow rate, m^3/d	Amount of sulfur dioxide needed			
	Chlorine residual as Cl_2, mg/L			
	5.0	6.5	8.0	7.7
1400	2300	2989	3679	3542
3800	6242	8114	9986	9612

4500	7392	9608	11,826	11,382
7600	12,483	16,228	19,973	19,224

b. Sodium sulfite

$$\underset{(126)}{Na_2SO_3} + \underset{(71)}{Cl_2} + H_2O \rightarrow Na_2SO_4 + 2HCl$$

The amount of sulfur sulfite needed per mg/L of Cl_2 is 126/71 = 1.78 mg/L. The annual amount of sodium sulfite needed is 1.78 x 2555 kg/y = 4548 kg.

Flow rate, m^3/d	Amount of sodium sulfite needed			
	Chlorine residual as Cl_2, mg/L			
	5.0	6.5	8.0	7.7
1400	4548	5913	7277	7004
3800	12,344	16,048	19,751	19,010
4500	14,619	19,003	23,389	22,512
7600	24,689	32,095	39,502	38,021

c. Sodium bisulfite

$$\underset{(104)}{NaHSO_3} + \underset{(71)}{Cl_2} + H_2O \rightarrow NaHSO_4 + 2HCl$$

The amount of sulfur bisulfite needed per mg/L of Cl_2 is 104/71 = 1.46 mg/L. The annual amount of sodium bisulfite needed is 1.46 x 2555 kg/y= 3730 kg.

Flow rate, m^3/d	Amount of sodium bisulfite needed			
	Chlorine residual as Cl_2, mg/L			
	5.0	6.5	8.0	7.7
1400	3730	4850	5968	5745
3800	10,125	13,163	16,200	15,593
4500	11,991	15,587	19,184	18,465
7600	20,250	26,325	32,400	31,186

d. Sodium metabisulfite

$$\underset{(190)}{Na_2S_2O_5} + \underset{(71)}{Cl_2} + 3H_2O \rightarrow 2NaHSO_4 + 4HCl$$

The amount of sodium metabisulfite needed per mg/L of Cl_2 is 190/71 = 2.68 mg/L. However, sodium metabisulfite does not follow stoichiometric ratios due to the pH dependence of this reaction. Use the value of 1.34 as presented in Table 12-15. The annual amount of sodium metabusulfite needed is 1.34 x 2555 kg/y = 3424 kg.

Flow rate, m^3/d	Amount of sodium metabisulfite needed			
	Chlorine residual as Cl_2, mg/L			
	5.0	6.5	8.0	7.7
1400	3424	4451	5478	5273
3800	9293	12,081	14,869	14,311
4500	11,005	14,306	17,608	16,947
7600	18,586	24,162	29,737	28,622

e. Activated carbon

$$\underset{(12)}{C} + \underset{2(71)}{2Cl_2} + 2H_2O \rightarrow 4HCL + CO_2$$

The amount of carbon needed per mg/L of Cl_2 is 12/142 = 0.085 mg/L. The annual amount of carbon needed is 0.085 x 2555 kg/y = 217 kg.

Flow rate, m^3/d	Amount of activated carbon needed			
	Chlorine residual as Cl_2, mg/L			
	5.0	6.5	8.0	7.7
1000	217	282	347	334
3800	589	766	943	908
4500	698	907	1117	1075
7600	1179	1533	1886	1816

PROBLEM 12-12

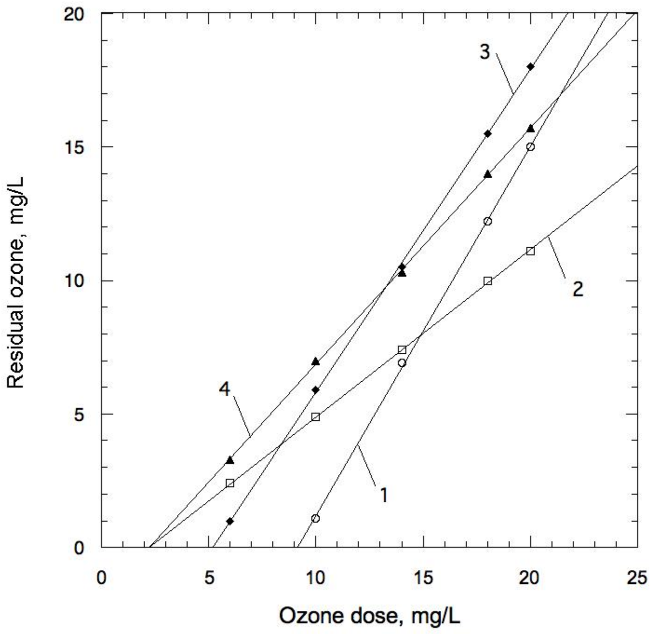
Problem Statement - See text, page 1438

Solution

1. The immediate ozone demand is determined by plotting the steady-state test results.

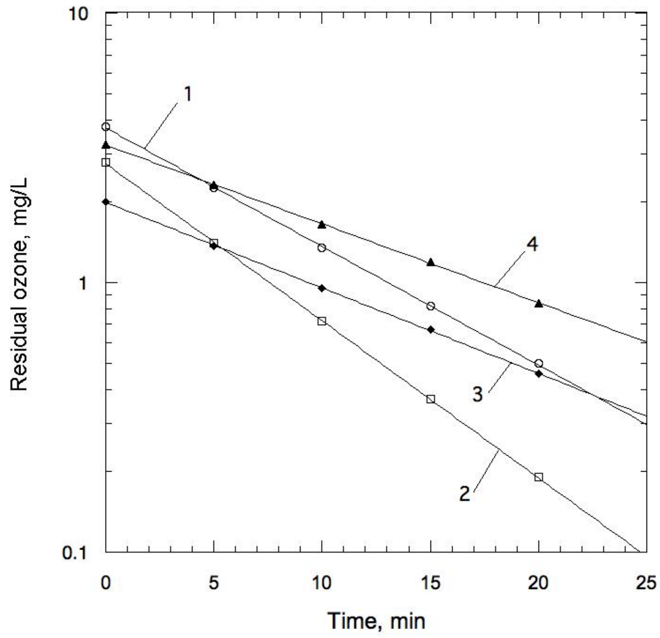
    a. The immediate ozone demand corresponds to the x-intercept. From the plot below, the values are as follows,

Wastewater number	Immediate ozone demand, mg/L
1	9.1
2	2.2
3	5.2
4	2.2



2. The first order decay equation for 25°C is determined by plotting the decay data on a log-normal scale.

    a. The required plot is given below.



b. The corresponding first order decay equations are as follows,

Wastewater number	First-order equation
1	$C_{\text{residual ozone}} = (9.1\text{ mg/L})e^{-0.101t}$
2	$C_{\text{residual ozone}} = (2.2\text{ mg/L})\ e^{-0.134t}$
3	$C_{\text{residual ozone}} = (5.2\text{ mg/L})\ e^{-0.073t}$
4	$C_{\text{residual ozone}} = (2.2\text{ mg/L})\ e^{-0.067t}$

where t = contact time, min

3. Determine the degree of inactivation for an ozone contactor at 15°C given 4 compartments after ozone injection and the following,

a. $\Lambda_{25°C}$ = 0.15 L/mg·min

HRT = 3 min each compartment

E = 48 kJ/mole = 48,000 J/mole

b. Refer to Eq. (12-6) to determine the degree of inactivation.

$$log\frac{N_t}{N_o} = -\Lambda_{\text{base 10}}\text{CT}$$

c. The coefficient of specific lethality for the new temparature is determined using Eq. (12-7)

$$\ln\frac{\Lambda_2}{\Lambda_1} = \frac{E(T_2 - T_1)}{RT_2T_1} = \frac{(48{,}000\,\text{J/mole})[(298 - 288)\text{K}]}{(8.3144\,\text{J/mole}\bullet\text{K})(298)(288)} = -0.6727$$

$$\Lambda_{15} = (\Lambda_{25})(e^{-0.6727}) = (0.15)(0.5104) = 0.077$$

d. Estimate the ozone residual in each compartment using the decay curve above.

$$C = (9.1\text{ mg/L})e^{-0.101\times\,t} = (9.1\text{ mg/L})e^{-0.101\times\,3} = 6.75\text{ mg/L}$$

Compartment	Time	Ozone residual, mg/L			
	min	1	2	3	4
2	3	6.75	1.45	4.17	1.81
3	6	4.99	0.97	3.35	1.48
4	9	3.68	0.65	2.69	1.21
5	12	2.72	0.43	2.16	0.99

e. Using the data from the table above, determine the CT value for the ozone contactor, noting that a typical t_{10}/t ratio of 0.6 can be used as determined in Example 12-8.

$$CT = \sum_{i=2}^{b} C_iT_i = \left[\left(6.75 + 4.99 + 3.68 + 2.72\right)\text{mg/L}\right]\left(3\text{ min} \times 0.6\right)$$
$$= 32.65\text{ mg}\cdot\text{min/L}$$

Wastewater number	CT, mg-min/L
1	32.65
2	6.29
3	22.26
4	9.91

f. Compute the degree of inactivation using the coefficient of specific lethality and CT values determined above.

$$\log\frac{N_t}{N_o} = -\Lambda_{\text{base 10}}CT = \left(0.29\right)\left(32.65\right) = 9.6$$

Wastewater number	$\log(N_t/N_o)$
1	2.5
2	0.48
3	1.7
4	0.76

PROBLEM 12-13

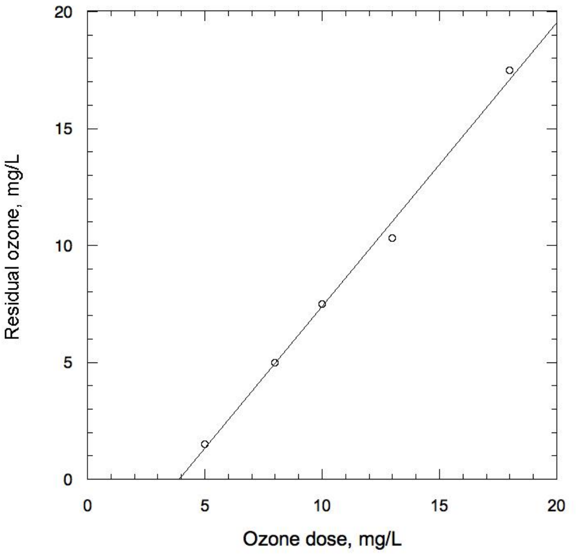
Problem Statement - See text, page 1438-1439

Instructors Note: Assume the contact time in each reactor is 3 min and the t_{10}/t ratio is 0.6.

Solution

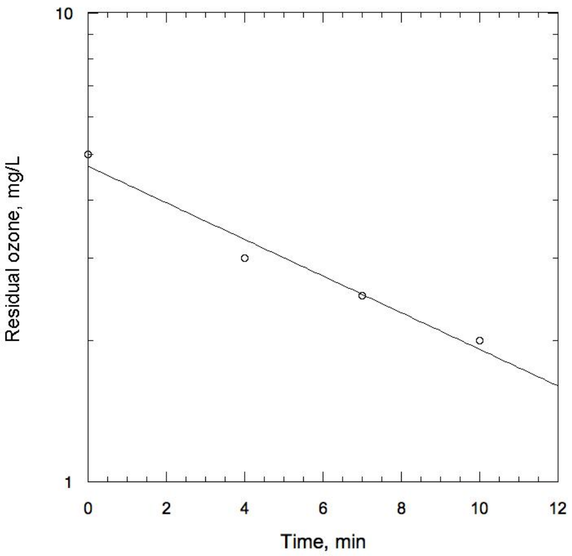
1. The immediate ozone demand is determined by plotting the steady-state test results.

   a. The immediate ozone demand corresponds to the x-intercept and is equal to 3.95 mg/L.



2. The first order decay equation for 20°C is determined by plotting the decay data on a log-normal scale.

   a. The required plot is given below.



b. The corresponding first order decay equation is

$C_{\text{residual ozone}} = (3.95\ \text{mg/L})e^{-0.090\,t}$

where t = contact time, min

3. Estimate the log reduction in *Cryptosporidium* that can be achieved at 5°C given a 4-compartment ozone contactor and the following,

a. Find the coefficient of specific lethality from Table 12-11

$\Lambda_{20°C} = 0.24\ \text{L/mg·min}$

E = 54 kJ/mole = 54,000 J/mole

b. To determine the log reduction refer to Eq. (12-6).

$$\log\frac{N_t}{N_o} = -\Lambda_{\text{base }10}CT$$

c. The coefficient of specific lethality for the new temparature is determined using Eq. (12-7)

$$\ln\frac{\Lambda_{20}}{\Lambda_5} = \frac{E(T_{20} - T_5)}{RT_{20}T_5} = \frac{54{,}000\ \text{J/mole}\,(293 - 278)\text{K}}{(8.3144\ \text{J/mole}\bullet\text{K})(293)(278)} = 1.196$$

$$\Lambda_5 = \frac{\Lambda_{20}}{e^{1.196}} = \frac{0.24}{3.31} = 0.073$$

d. Estimate the ozone residual in each compartment using the decay curve above.

$$C = (4.72 \text{ mg/L})e^{-0.090 \times t} = (4.72 \text{ mg/L})e^{-0.090 \times 3 \text{ min}} = 3.6 \text{ mg/L}$$

Compartment	Time	Ozone residual,
	min	mg/L
2	3	3.6
3	3	2.8
4	3	2.1

e. Using the data from the table above, determine the CT value for the ozone contactor, noting that a typical t_{10}/t ratio of 0.6 can be used.

$$\begin{aligned} CT &= \sum_{i=2}^{b} C_i T_i = \left[(3.6 + 2.8 + 2.1)\text{mg/L}\right](3 \text{ min} \times 0.6) \\ &= 15.22 \text{ mg} \cdot \text{min/L} \end{aligned}$$

f. Compute the degree of inactivation using the coefficient of specific lethality at 5°C and CT value determined above.

$$\log\frac{N_t}{N_o} = -\Lambda_{\text{base 10}}CT = (0.073)(15.22) = 1.1 \text{ log inactivation}$$

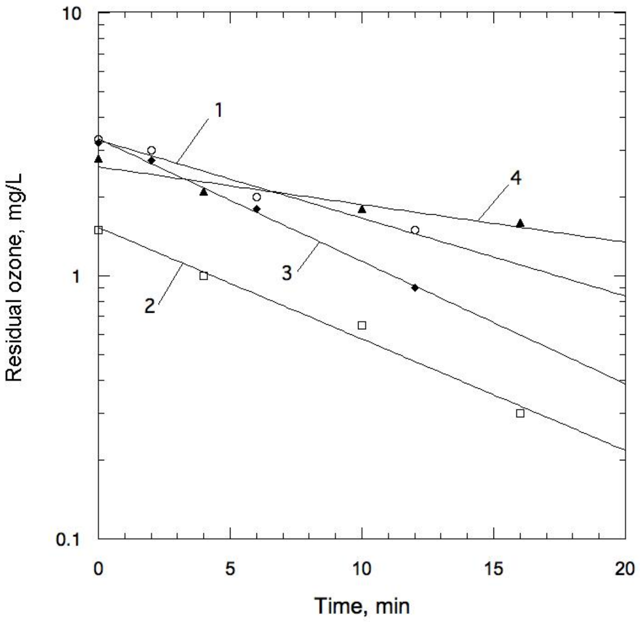
PROBLEM 12-14

Problem Statement - See text, page 1439

Solution

1. The first order decay equation is determined by plotting the decay data on a log-normal scale.

   a. The required plot is given below.



b. The corresponding first order decay equations are

Test 1: $C_{\text{residual ozone}} = (3.28 \text{ mg/L})e^{-0.068\ t}$

Test 2: $C_{\text{residual ozone}} = (1.53 \text{ mg/L})e^{-0.098\ t}$

Test 3: $C_{\text{residual ozone}} = (3.32 \text{ mg/L})e^{-0.107\ t}$

Test 4: $C_{\text{residual ozone}} = (2.60 \text{ mg/L})e^{-0.033\ t}$

where t = contact time, min

3. Compute the ozone residual through each successive compartment using the decay curve given the theoretical detention time in each basin is 3 min, t_{10}/t = 0.65 and the following,

   a. The immediate ozone demand is given by the y-intercept from the above decay equations.

   b. The contact time required to achieve a 3-log reduction is given in Table 12-5 is between 12 and 13 mg-min/L.

   c. The resulting CTs and required number of compartments are given in the table below.

Compartment no.	Time, min	Ozone residual, mg/L			
		Test number			
		1	2	3	4
2	3	2.68	1.14	2.41	2.35
3	3	2.18	0.85	1.75	2.13
4	3	1.78	0.63	1.27	1.93
5	3	-	0.47	0.92	-
	CT:	13.0	8.6	12.4	12.5
	Required No. of Compartments:	3	NA	4	3

PROBLEM 12-15

Problem Statement - See text, page 1439

Solution

Instructors Note: The use of ozone for the disinfection of secondary effluents has not proven to be cost effective due to the demand of the residual organic matter. Although ozone has been used for the disinfection of tertiary treated effluents there are, at present, no full scale installations.

The following are useful sources of information

Bataller, M. E Veliz, L. .A Fernandez, C. Hernandez, I. Fernandez, C. Alvarez, and E. Sanchez (2005) "Secondary Effluent Treatment with Ozone," proceedings 17th World Ozone Congress, Strabourg, IOA 17th World Ozone Congress – Strasbourg, France

Leverenz, H., J. Darby, and G. Tchobanoglous (2006) Evaluation of Disinfection Units for Onsite Wastewater Treatment Systems, Center for Environmental and Water Resources Engineering (2006-1), University of California, Davis.

Paraskeva, P., S.D. Lambert, and N.J. D Graham (1998) "Influence of Ozonation Conditions on Treatability of Secondary Effluents," *Ozone Sci. Engr.* **20**, 2, 133-150.

Paraskeva, P., and N.J. D Graham (2002) "Ozonation of Municipal Wastewater Effluents," *Water Environ. Res.,* **74**, 6, 569-581.

Xu, P., M.L. Janex, P. Savoye, A. Cockx, and V Lazarova (2008) "Wastewater Disinfection by Ozone: main Parameters for process Design," *Water Res.,* **36**, 4, 1043-1055.

PROBLEM 12-16

Problem Statement - See text, page 1439

Solution

The following are useful sources of information

Antonelli M, S. Rossi, V. Mezzanotte, and C. Nurizzo (2006) "Secondary Effluent Disinfection: PAA long Term Efficiency," *Environ. Sci. Technol.*, **40**, 15, 4771-4775.

Caretti C., and C. Lubello (2003) "Wastewater Disinfection with PAA and UV Combined Treatment: a Pilot Plant Study," *Water Res*., **37**, 10, 2365-2371.

City of Ames (2009) Wastewater Disinfection Technologies Study, Report prepared by Stanley Consultants, Ames, IA.

Gehr, R., M. Wagner M., P. Veerasubramanian, and P. Payment P. (2003) "Disinfection Efficiency of Peracetic Acid, UV and Ozone after Enhanced Primary Treatment of Municipal Wastewater," *Water Res*. **37**, 19, 4573-4586.

Kitis, M. (2004) "Disinfection of Wastewater With Peracetic Acid: A Review," *Environment International*, **30**, 1, 47-55.

Rossi S, M. Antonelli, V. Mezzanotte, and C. Nurizzo (2007) "Peracetic Acid Disinfection: A Feasible Alternative to Wastewater Chlorination," *Water Environ. Res.,* **79,** 4, 341-350.

Zanetti, F., G. De Luca, R. Sacchetti, and S. Stampi (2007) "Disinfection Efficiency of Peracetic Acid (PAA): Inactivation of Coliphages and Bacterial Indicators in a Municipal Wastewater Plant," *Environ. Technol.*, **28**, 11, 1265-1271.

PROBLEM 12-17

Problem Statement - See text, page 1439

Solution

1. Using Eq. (12-65) estimate the delivered dose

$$D_{CB} = I_o t(1-R)P_f\left[\frac{(1-10^{-k_{254}d})}{2.303(k_{254}d)}\right]\left(\frac{L}{L+d}\right)$$

$$D = (10 \text{ x } 30)(1-0.025)(0.94)\left[\frac{(1-10^{-0.065 \text{ x} 1})}{2.303(0.065 \text{ x} 1)}\right]\left(\frac{48}{48+1}\right)$$

D = (300) (0.975) (0.94) (0.928) (0.976) = 250.1 mJ/cm^2

2. Determine the best estimate of uncertainty for the computed UV dose. The uncertainty of the computed dose can be estimated using Eq. (12-67). The procedure is illustrated for one of the variables and summarized for the remaining variables.

   a. Consider the variability in the measured time, t. The partial derivative of the expression used in step one with respect to t is

$$U_t = U_{t_e}\frac{\partial E}{\partial V_n} = t_e\left\{I_m(1-R)P_f\left[\frac{(1-10^{-\alpha d})}{2.303(\alpha d)}\right]\left(\frac{L}{L+d}\right)\right\}$$

$$U_t = 1.0\left\{D = (10)(1-0.025)(0.94)\left[\frac{(1-10^{-0.065 \text{ x} 1})}{2.303(0.065 \text{ x} 1)}\right]\left(\frac{48}{48+1}\right)\right\}$$

U_t = 8.34 mJ/cm^2

Percent = 100 U_t/D = (100 x 8.34)/250.1 = 3.33%

   b. Similarly for the remaining variables the corresponding values of the partial derivatives are as given below

U_{I_m} = 12.51 mJ/cm^2 and 5.0%

U_{P_f} = 5.32 mJ/cm^2 and 2.13%

U_a = -1.40 mJ/cm^2 and -0.56%

U_d = -1.17 mJ/cm^2 and -0.47%

U_L = 0.053 mJ/cm^2 and 0.02%

c. The best estimate of uncertainty using Eq. (12-68) is

$U = [(8.34)^2 + (12.51)^2 + (5.32)^2 + (-1.40)^2 + (-1.17)^2 + (0.053)^2]^{1/2}$

U = 16.05 mJ/cm^2

Percent = (100 x 16.05)/250.1 = 6.42 percent

3. Based on the above uncertainty computation the most likely UV dose is

250.1 ± 16.1 mJ/cm^2

PROBLEM 12-18

Problem Statement - See text, page 1439

Instructors Note: The correct derivation of the formula for the average intensity is given in Example 2-5 and corresponds to the first moment about the y axis as follows:

$$I_{avg} = I_o \times \frac{-k\int_0^d e^{-kx}dx}{-k\int_0^d dx} = I_o \times \frac{(1 - e^{-kd})}{kd}$$

where k = absorbance coefficient = (2. 306)(a.u./cm)

a.u. = absorbance units, cm^{-1}

Solution

1. Select an absorbance value and solve corrected equation from derivation in Example 2-5 for the average UV intensity. Absorbance values ranging from 0.35 to 0.10 are representative of raw wastewater.

$$I_{avg} = I_o \times \frac{\left(1 - e^{-kd}\right)}{kd}$$

$$= (12\ \text{mW/cm}^2)\left[\frac{(1 - e^{-0.115\ \text{cm}^{-1} \times 1.0\ \text{cm}})}{(0.115\ \text{cm}^{-1} \times 10\ \text{cm})}\right] = 11.34\ \text{mW/cm}^2$$

Absorbance, au/cm	Absorbance coefficient, cm^{-1}	Average intensity, mW/cm^2				
		Depth, cm				
		1	2.2	1.4	1.5	1.6
0.05	0.1150	11.34	10.60	11.08	11.02	10.96
0.1	0.2303	10.72	9.41	10.26	10.15	10.04
0.2	0.4606	9.62	7.54	8.84	8.66	8.49
0.3	0.6909	8.66	6.17	7.69	7.47	7.26

PROBLEM 12-19

Problem Statement - See text, page 1439

Solution

1. Compute the average UV intensities at the depths of 10 and 20 mm using the formula given in Problem 12-18.

   a. For a depth of 10 mm and an absorbance value of 0.05 cm^{-1}:

$$I_{avg} = I_o \times \frac{\left(1 - e^{-kd}\right)}{kd}$$

$$I_{avg} = (8\ \text{mW/cm}^2)\left[\frac{(1 - e^{-0.115\ \text{cm}^{-1} \times 1.0\ \text{cm}})}{(0.115\ \text{cm}^{-1} \times 10\ \text{cm})}\right] = 7.56\ \text{mW/cm}^2$$

   b. For a depth of 20 mm and an absorbance value of 0.05 cm^{-1}:

$$I_{avg} = (8\ \text{mW/cm}^2)\left[\frac{(1\text{-}\ e^{-0.115\ \text{cm}^{-1}\ \text{x}\ 2.0\ \text{cm}})}{(0.115\ \text{cm}^{-1}\ \text{x}\ 2.0\ \text{cm})}\right] = 7.15\ \text{mW/cm}^2$$

2. Determine the ratio of UV intensity (I_{avg}) at 10 and 20 mm to correct the applied UV dose reported in Problem 12-18.

$$\frac{I_{avg,20mm}}{I_{avg,10mm}} = \frac{(7.15\ \text{mW/cm}^2)}{(7.56\ \text{mW/cm}^2)} = 0.946$$

3. The effect of the increased depth would be an average light intensity 95.6% that at 10 mm for a water with absorbance of 0.05 cm^{-1}. The relationship between light intensiy at 10 and 20 mm for the various absorbance values are given in the table below.

		Average intensity, mW/cm^2		
		Depth, cm		
Absorbance, cm^{-1}	Absorbance coefficient, k	1	2	Ratio, %
0.05	0.115	7.557	7.147	94.6
0.1	0.230	7.146	6.411	89.7
0.2	0.461	6.411	5.228	81.5
0.3	0.691	5.777	4.336	75.1

PROBLEM 12-20

Problem Statement - See text, page 1440

Solution

1. Determine the mean, standard deviation, confidence interval and prediction interval for the dose response data. Because the data are normally distributed, student-t statistics may be applied.
   a. Determine the average and standard deviation for each investigated dose.

      For the dose of **60**, the average log reduction is 3.50

      For the dose of **60** the standard deviation is 1.02

      The observed mean and standard deviation for each dose is provided in the following table.

Applied UV dose, mJ/cm^2	Log reduction, -log N/N$_0$						
	Test						
	1	2	3	4	5	Mean	Standard deviation
20	0.9	1.7	1.4	1.1	1.0	1.22	0.29
40	1.7	3.3	2.6	2.2	1.8	2.32	0.58
60	2.4	5.2	4.1	3.0	2.8	3.50	1.02
80	3.5	6.5	5.1	4.3	3.7	4.62	1.09
100	4.3			5.5	4.7	4.83	0.50
120	4.9			6.2	5.4	5.50	0.54

b. Determine the 75% confidence interval.

i. For a dose of **60**, the 75% confidence interval is calculated using the following expression:

$$75\%\ \text{confidence limit} = \bar{x} \pm t_{0.125}\left(\frac{s}{\sqrt{n}}\right)$$

where x = mean log reduction for UV dose of **60** = 3.50

$t_{0.125}$ = student t value associated with a 75% level of confidence 1.344.
Note that the degrees of freedom are n-1 = 4.

n = number of replicates = 5.

s = sample standard deviation = 1.02.

$$75\%\ \text{confidence limit} = 3.50 \pm 1.344\left(\frac{1.02}{\sqrt{5}}\right) = 3.50 \pm 0.6130$$

ii. The 75% confidence interval associated with each investigated UV dose are provided in the table given below.

Applied UV dose, mJ/cm^2	Log reduction, -log(N/N$_0$)	
	Lower 75% C.I.	Upper 75% C.I.
20	0.763	1.008
40	1.619	1.803
60	2.465	2.609
80	3.291	3.435
100	4.097	4.281
120	4.892	5.137

b. Determine the 75% prediction interval.

   i. The 75% prediction interval is calculated using a standard statisitcal analysis program.

Applied UV dose, mJ/cm^2	Log reduction, -log(N/N$_0$)	
	Lower 75% P.I.	Upper 75% P.I.
20	0.677	1.095
40	1.519	1.904
60	2.353	2.721
80	3.179	3.547
100	3.996	4.381
120	4.805	5.223

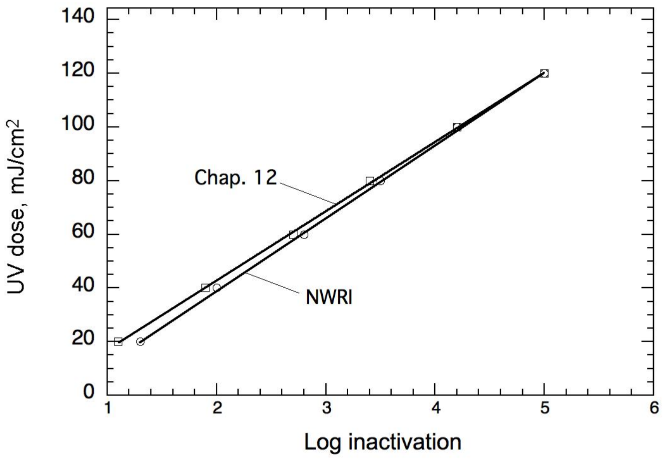
2. Using the lower 75% prediction interval given in the above table, a design UV dose of 100.12 ± 0.50 mJ/cm^2 is required to obtain a 4-log removal of MS2.

PROBLEM 12-21

Problem Statement - See text, page 1440

Solution

1. The required plot is shown below.



2. The difference between the two dose response curves is minimal. The inactivation achieved at each dose is fairly consistent across the experimental data although the two curves diverge for lower UV doses. It is not necessary to perform a unique dose response curve for every UV disinfection system manufactured because often the target log inactivation is 4 or 5, where the data are very similar. It is adequate to use a standard dose response curve for equipment testing purposes.

PROBLEM 12-22

Problem Statement - See text, page 1440-1441

Solution

Solution Water 1

1. Perform a log transformation of the phage data for water 1. The required transformations are presented below.

		Water 1, phage/mL			
Flowrate, L/min	Replicate	Inlet	Log transform	Outlet	Log transform
200	1	9.65×10^6	6.98	1.88×10^2	2.27
200	2	1.00×10^7	7.00	1.54×10^2	2.19
200	3	1.15×10^7	7.06	1.68×10^2	2.23
Average			7.01		
400	1	1.00×10^7	7.00	3.65×10^2	2.56
400	2	1.29×10^7	7.11	3.39×10^2	2.53
400	3	9.55×10^6	6.98	3.29×10^2	2.53
Average			7.03		
600	1	1.23×10^7	7.09	1.12×10^4	4.05
600	2	1.05×10^7	7.02	9.03×10^3	3.96
600	3	1.25×10^6	7.10	8.56×10^3	3.93
Average			7.07		
800	1	1.13×10^7	7.05	4.79×10^4	4.68
800	2	1.08×10^7	7.03	8.35×10^4	4.92
800	3	8.95×10^6	6.95	6.61×10^4	4.82
Average			7.01		

2. Prepare a statistical analysis of the a log transformed data developed in Step 1. The results of the required statistical analysis are presented below.

Flowrate, L/min	Replicate	Log inactivation	Average log inactivation	Standard deviation	75% confidence
200	1	4.74			
200	2	4.82	4.78	0.04	4.74
200	3	4.78			
400	1	4.47			
400	2	4.50	4.49	0.02	4.47
400	3	4.50			
600	1	3.02			
600	2	3.11	3.09	0.06	3.03
600	3	3.14			
800	1	2.33			
800	2	2.09	2.20	0.11	2.09
800	3	2.19			

The 75% confidence interval is determined as follows

$$75\%\text{ confidence limit} = \bar{x} \pm t_{0.125}\left(\frac{s}{\sqrt{n}}\right)$$

where x = mean log reduction

$t_{0.125}$ = student t value associated with a 75% level of confidence is 1.604 for two degrees of freedom (n - 1 = 2, where n = 3).

For example, for a flowrate of 200 L/min

$$75\%\text{ confidence limit} = 4.78 \pm 1.604\left(\frac{0.04}{\sqrt{3}}\right) = 4.78 \pm 0.04$$

3 Assign UV dosages to the hydraulic loading rates, and present results graphically.

a. Prepare a summary table

Flowrate, L/min	Hydraulic loading rate, L/min•lamp	75% confidence log-inactivation	Equivalent UV dose^b, mJ/cm^2
200	50	4.74	113
400	100	4.47	106
600	150	3.03	69
800	200	2.09	45

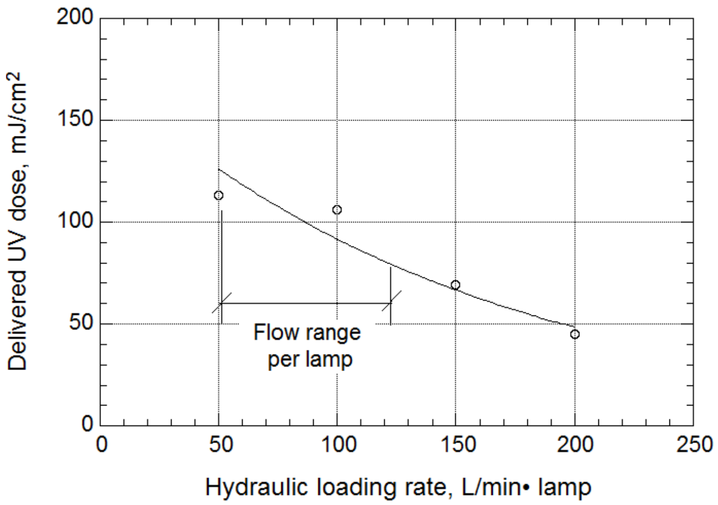
b. Determine the equivalent dose using the inactivation equation from Example 12-12. The equation of the linear regression used to determine the required dose as a function of log MS2 inactivation is follows.

$$\text{UV dose} = \frac{\text{log inactivation} - 0.326}{0.0389}$$

For example for a flowrate of 200 L/min

$$\text{Dose, mJ/cm}^2 = \frac{\text{log inactivation} - 0.326}{0.0389} = \frac{4.74 - 0.323}{0.0389} = 113\ \text{mJ/cm}^2$$

c. Plot the UV dosages determined in the previous step. The results are plotted in the following figure.



4. Determine the flow per lamp over which the system will deliver 100 mJ/cm^2. From the plot given above, the system is capable of delivering a dose of 80 mJ/cm^2 within the range of 50 to 120 L/min•lamp.

Solution Water 2

1. Perform a log transformation of the phage data for water 2. The required transformations are presented below.

Flowrate, L/min	Replicate	Water 2, phage/mL			
		Inlet	Log	Outlet	Log

			transform		transform
200	1	1.05×10^7	7.02	2.19×10^2	2.34
200	2	6.98×10^6	6.84	1.54×10^2	2.19
200	3	1.15×10^7	7.06	1.70×10^2	2.23
Average			6.97		
400	1	1.00×10^7	7.00	3.75×10^2	2.57
400	2	1.23×10^7	7.09	3.62×10^2	2.56
400	3	1.12×10^7	7.05	3.08×10^2	2.49
Average			7.05		
600	1	1.20×10^7	7.08	1.32×10^4	4.12
600	2	1.05×10^7	7.02	1.05×10^4	4.02
600	3	9.55×10^6	6.98	9.95×10^3	4.00
Average			7.03		
800	1	1.03×10^7	7.01	5.95×10^4	4.77
800	2	1.19×10^7	7.08	1.00×10^5	5.00
800	3	1.11×10^7	7.05	7.68×10^4	4.89
Average			7.05		

2. Prepare a statistical analysis of the a log transformed data developed in Step 1. The results of the required statistical analysis are presented below.

Flowrate, L/min	Replicate	Log inactivation	Average log inactivation	Standard deviation	75% confidence
200	1	4.63	4.72	0.07	4.65
200	2	4.78			
200	3	4.74			
400	1	4.48	4.51	0.04	4.47
400	2	4.49			
400	3	4.56			
600	1	2.91	2.98	0.06	2.92
600	2	3.01			
600	3	3.03			
800	1	2.28	2.16	0.10	2.06
800	2	2.05			
800	3	2.16			

3. Assign UV dosages to the hydraulic loading rates, and present results graphically.

   a. Prepare a summary table

Flowrate, L/min	Hydraulic loading rate, L/min•lamp	75% confidence log-inactivation	Equivalent UV dose[b], mJ/cm^2
200	50	4.65	111
400	100	4.47	106
600	150	2.92	66
800	200	2.06	44

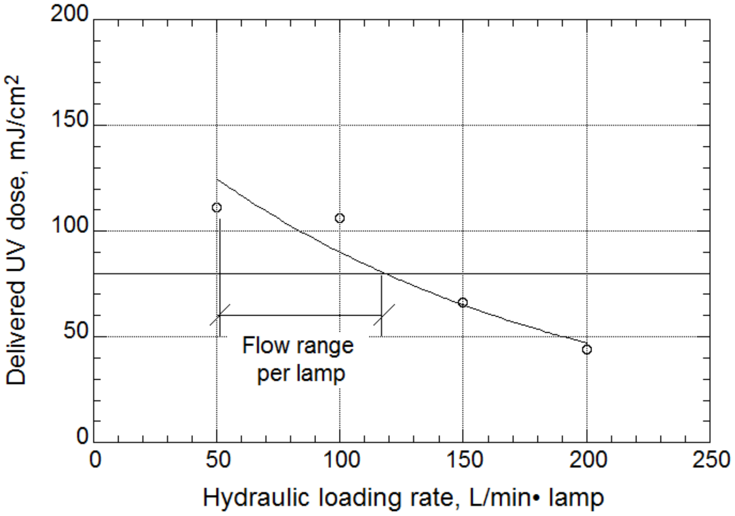
b. Determine the equivalent dose using the inactivation equation from Example 12-12. The equation of the linear regression used to determine the required dose as a function of log MS2 inactivation is follows.

$$\text{UV dose} = \frac{\text{log inactivation} - 0.326}{0.0389}$$

For example for a flowrate of 200 L/min

$$\text{Dose, mJ/cm}^2 = \frac{\text{log inactivation} - 0.326}{0.0389} = \frac{4.65 - 0.326}{0.0389} = 111\,\text{mJ/cm}^2$$

c. Plot the UV dosages determined in the previous step. The results are plotted in the following figure.



4. Determine the flow per lamp over which the system will deliver 100 mJ/cm^2. From the plot given above, the system is capable of delivering a dose of 80 mJ/cm^2 within the range of 50 to 115 L/min•lamp.

PROBLEM 12-23

Problem Statement - See text, page 1441

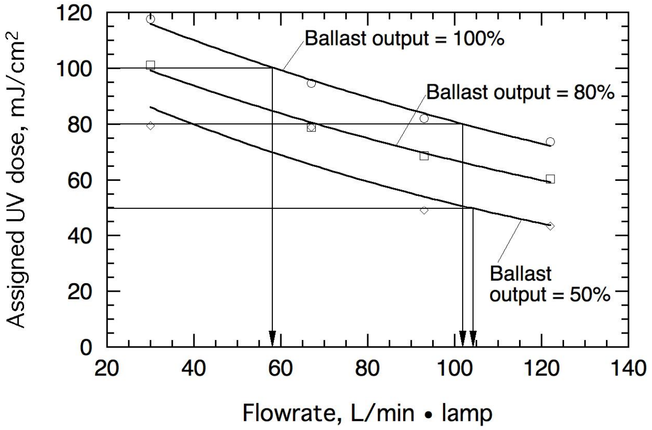
Solution

1. The student can chose a dose response curve to use. The standard NWRI (2012) dose response curve is used here.

$$\text{UV dose} = \frac{\text{log inactivation} - 0.5464}{0.0368}$$

2. Calculate the assigned UV dose using the chosen dose response curve.
3. Correct for lamp fouling by multiplying UV dose by 60%.
4. Plot the flowrate in units of L/min-lamp and the assigned UV dose in units of mJ/cm^2. The resulting plot and tabulation table are below.

					Log transformed values		
Ballast output, %	Flowrate, L/min-lamp	Avg. log inactivation	Assigned UV dose, mJ/cm^2		Flowrate L/min-lamp	Assigned UV dose, mJ/cm^2	
			No Fouling	Fouling		No Fouling	Fouling
100	30	7.7559	195.9	117.5	1.477	2.292	1.375
100	67	6.3555	157.9	94.71	1.824	2.198	1.319
100	93	5.5775	136.7	82.03	1.970	2.136	1.281
100	122	5.0718	123.0	73.78	2.086	2.090	1.254
80	30	6.7445	168.4	101.1	1.477	2.226	1.336
80	67	5.3830	131.4	78.86	1.824	2.119	1.271
80	93	4.7606	114.5	68.71	1.970	2.059	1.235
80	122	4.2549	100.8	60.46	2.086	2.003	1.202
50	30	5.4219	132.5	79.49	1.477	2.122	1.273
50	67	5.3830	131.4	78.86	1.824	2.119	1.271
50	93	3.5547	81.75	49.05	1.970	1.912	1.147
50	122	3.2046	72.23	43.34	2.086	1.859	1.115



5. The maximum flowrates over which the UV disinfection system will deliver the required dose for each ballast setting, taking into account fouling and aging, are taken from the plot and given in the summary table below.

Ballast output, %	Max. flowrate, L/min-lamp
100	58
80	102
50	104

PROBLEM 12-24

Problem Statement - See text, page 1441

Solution

1. Perform a multiple linear regression analyis using a standard statistial analysis program. The regression equation can be expressed in both log-transformed and non-transformed values. The results of the multiple linear regression analysis are given in the tables below. Both the lower 75 percent CI and PI values are also given. The corresponding regression equation is:

$$\text{Inactivation} = 2.107 - (4.089 \times \text{Flow}) + (5.730 \times \text{Ballast})$$

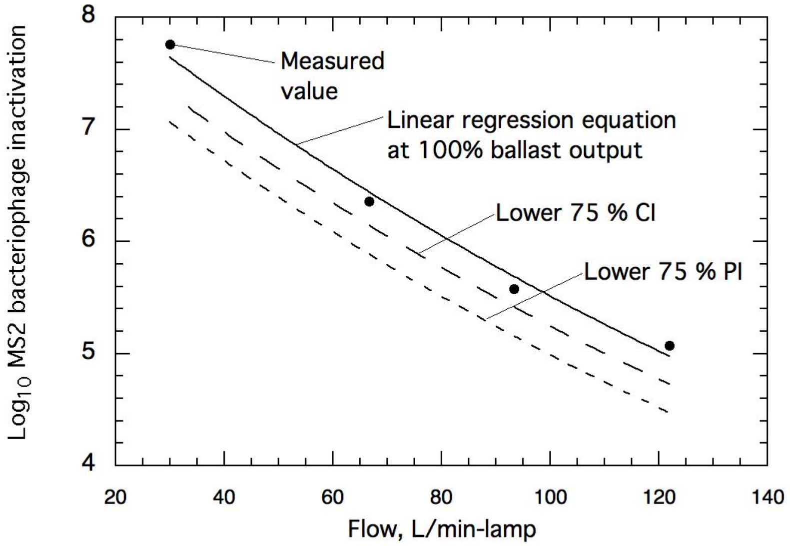
where inactivation, flow, and ballast values are the log-transformed values or

$$\text{Inactivation} = (10^{2.109})[(\text{Flow})^{-4.089}][(\text{Ballast})^{5.730}]$$

where inactivation, flow, and ballast values are in actual units

Log-transformed values				
Flowrate, L/min-lamp	Average log inactivation	Predicted log inactivation	Predicted, 75% C.I. log inactivation	Predicted, 75% P.I. log inactivation
100 % ballast output				
1.477	7.756	7.531	7.219	6.940
1.824	6.356	6.112	5.901	5.568
1.970	5.578	5.515	5.288	4.964
2.086	5.072	5.040	4.778	4.474
80 % ballast output				
1.477	6.745	6.975	6.701	6.403
1.824	5.383	5.556	5.405	5.032
1.970	4.761	4.959	4.787	4.429
2.086	4.255	4.484	4.268	3.938
50 % ballast output				
1.477	5.422	5.805	5.472	5.203
1.824	5.383	4.386	4.144	3.829
1.970	3.555	3.789	3.533	3.226
2.086	3.205	3.315	3.027	2.737

2. The measured inactivation values at a 100% ballast ouput, the regression curve, and lower 75th percent CI and PI regression curves are plotted below. Note that the true design curve must take lamp aging and fouling into consideration.



PROBLEM 12-25

Problem Statement - See text, page 1441

Solution

Instructor Note: Cleaning is a major issue in the application of low-pressure low-intensity and low-pressure high-intensity UV disinfection systems. In low-pressure low-intensity lamp systems, the UV lamps are cleaned externally from the UV reactor whereas in low-pressure high-intensity cleaning of the lamps are cleaned in place with an integral wiper system.

This problem may not be feasible unless the date is set back to 1995. Little comparative work on the difference between low-pressure low-intensity and low-pressure high-intensity UV lamps has been published in the last 5-10 years. Alternatively, the students could be asked to review the City of Ames and/or the URS Corporation et al. reports, given below, and comment briefly on how the UV disinfection option was assessed and/or faired against other disinfection technologies.

The following are useful sources of information

Chen, Z. El Jack, W. Horvath, J.F. Stahl, and J.F. Kuo (1999) Low-Pressure High-Intensity UV Lamps Used on Tertiary Effluent, *County Sanitation Districts of Los Angeles County*, Whittier, CA.

City of Ames (2009) Wastewater Disinfection Technologies Study, Report prepared by Stanley Consultants, Ames, IA.

URS Corporation, Stan Tec, Inc., and University at Buffalo (2004) Evaluation of Ultraviolet (UV) Radiation Disinfection Technologies for Wastewater Treatment Plant Effluent, Report prepared For New York State Energy Research and Development Authority, National Grid Corporation, and Erie County Department of Environment and Planning Southtowns Sewage Agency

Moreland, V., and P. Ono (2001) Primary Effluent Disinfection - Necessary Procedures In UV System Design for Low Water Quality Applications (To Pilot or not to Pilot?)," 394-408, Proceedings of the Water Environment Federation Annual Conference 2001 Water Environment Federation, Alaxandria, VA.

Schwartzel, D.T., and G. Sakamoto (1996) "Pilot Testing High-Intensity UV Lamp Technology to Meet California Wastewater Reclamation Criteria," Proceedings Disinfecting Wastewater for Discharge and Reuse, *Water Environment Federation*, Portland, OR.

Kwan, A.; J. Archer; F. Soroushian; A. Mohammed; and G. Tchobanoglous (1996) "Factors for Selection of a High-Intensity UV Disinfection System for a Large-Scale Application." Proceedings Water Environment Federation (WEF) Speciality Conference: Disinfecting Wastewater for Discharge and Reuse, *Water Environment Federation*, Portland, OR.

Darby, J., M. Heath, J. Jacangelo, F. Loge, P. Swaim, and G. Tchobanoglous, Comparison of UV Irradiation to Chlorination: Guidance for Achieving Optimal UV Performance, Project 91-WWD-1, *Water Environment Research Foundation, Alexandria*, Virginia, 1995

PROBLEM 12-26

Problem Statement - See text, page 1441

Solution

1. Find D, the time required to achieve 1-log reduction at 82 °C, using Eq. (12-76). Use D and T values for MS2 coliphage given on Table 12-36; the values are D = 14s at T = 70°C where Z = 10°C.

$$\log\left(\frac{D_1}{D_2}\right)=\frac{(T_2-T_1)}{Z}$$

$$D_2 = D_1/10^{\left[\frac{(T_2-T_1)}{Z}\right]} = 14s/10^{\left[\frac{(82-70)}{10}\right]} = 0.88\ s$$

2. Assuming a log-linear response (i.e. no shoulder or tailing effects), the time required for a 4-log reduction is (4) (0.88 s) = 3.5 s.

3. The CDPH requirement is adequate (factor of safety = 2.8).

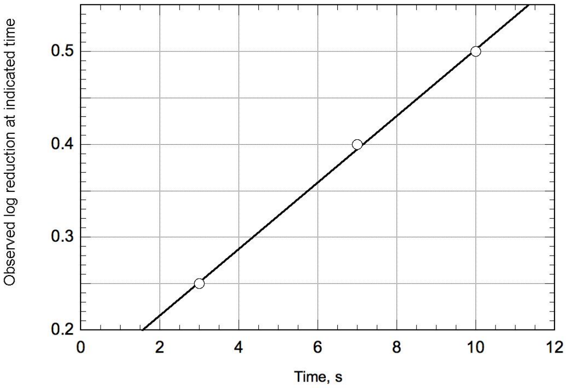
PROBLEM 12-27

Problem Statement - See text, page 1441

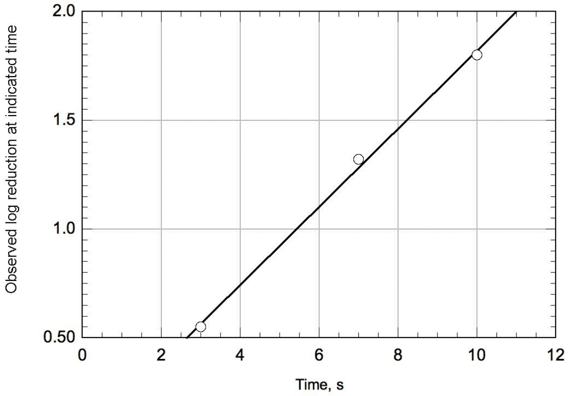
Solution

1. Plot the log reduction per second for each temperature to find D.

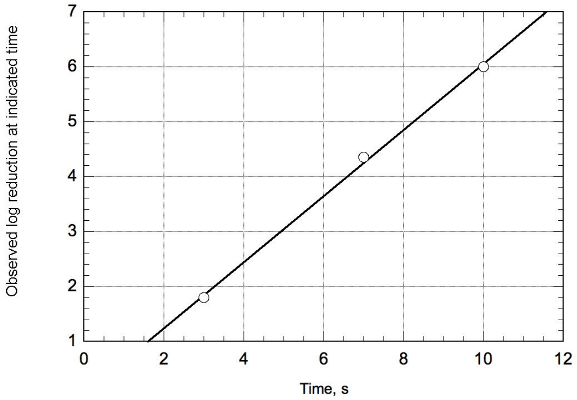
   Plot for 60°C:



   Plot for 65°C:



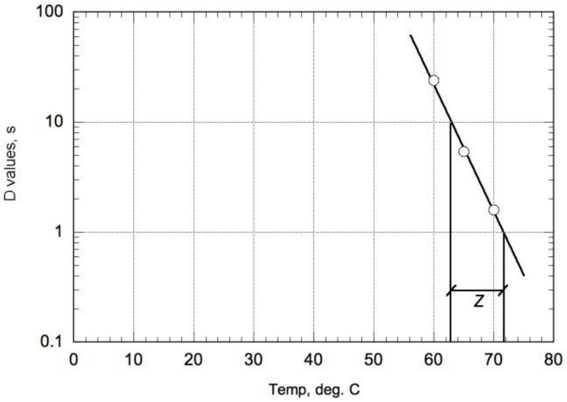
   Plot for 70°C:



2. The D values are obtained by fitting a linear curve to the data and solving for the independent variable, time, when the dependent variable, log reduction, is set to one.

Temp., °C	D value,s
60	24
65	5.4
70	1.6

3. Using a log-normal scale, plot the D value for each temperature to find Z.



4. The Z value is obtained by fitting a curve to the data. The curve is exponential.

$$D = 2.53 \text{ x } 10^8 \cdot e^{-0.27T}$$

5. To achieve a 1-log reduction in D, the temperatures must be obtained for two D vaues that are 1-log apart. Chose D = 10 s and D = 1 s.

   a. For D = 10 s, the temperature is:

$$T_1 = \frac{\ln\left(D / 2.53 \times 10^8\right)}{-0.27}$$

$$= \frac{\ln\left(10 / 2.53 \times 10^8\right)}{-0.27} = 63.1\ ^\text{o}\text{C}$$

   b. For D = 1 s, the temperature is:

$$T_2 = \frac{\ln\left(1 / 2.53 \times 10^8\right)}{-0.27} = 71.6\ ^\text{o}\text{C}$$

6. Obtain Z from Eq. (12-77).

$$Z = \left(T_2 - T_1\right) = 71.6 - 63.1 = 8.5\ ^\text{o}\text{C}$$

   This Z value is reasonable given the ranges of typical values in Table 12-36.

7. Find D, the time required to achieve 1-log reduction at 68 °C, using Eq. (12-76). Use any D and T values; here those for 65 °C are used.

$$\log\left(\frac{D_1}{D_2}\right) = \frac{\left(T_2 - T_1\right)}{Z}$$

$$D_2 = D_1 / 10^{\left[\frac{(T_2 - T_1)}{Z}\right]} = 5.4s / 10^{\left[\frac{(68-65)}{8.5}\right]} = 2.4\ s$$

8. Assuming a log-linear response (i.e. no shoulder or tailing effects), the time required for a 4-log reduction is (4) (2.4s) = 9.6 s.

13

TREATMENT AND PROCESSING OF RESIDUALS AND BIOSOLIDS

PROBLEM 13-1

Problem Statement - See text, page 1554

Solution

1. Determine the percent reduction in volume using the approximate method.

$$\frac{V_2}{V_1} = \frac{P_1}{P_2}$$

where V_1, V_2 = sludge volumes

P_1, P_2 = percent of solid matter

$$\text{Percent reduction} = \left(\frac{V_1 - V_2}{V_1}\right)100$$

$$= \left(\frac{V_1 - V_2}{V_1}\right)100 = \left(1 - \frac{P_1}{P_2}\right)100$$

$$= \left(1 - \frac{0.02}{0.05}\right)100 = 60\%$$

2. Determine the average specific gravity of all the solids in the sludge using Eq. (13-1).

$$\frac{W_s}{S_s \rho_w} = \frac{W_f}{S_f \rho_w} + \frac{W_v}{S_v \rho_w}$$

$$\frac{W_s}{S_s} = \frac{W_f}{S_f} + \frac{W_v}{S_v}$$

$$\frac{1}{S_s} = \frac{0.30}{2.00} + \frac{0.70}{1.00} = 0.85$$

$$S_s = \frac{1}{0.85} = 1.18$$

3. Determine the specific gravity of the sludge.

a. At 98 percent water content:

$$\frac{1}{S_{sl}} = \frac{0.02}{1.18} + \frac{0.98}{1.00} = 0.997$$

$$S_{sl} = \frac{1}{0.997} = 1.003$$

b. At 95 percent water content:

$$\frac{1}{S_{sl}} = \frac{0.05}{1.18} + \frac{0.95}{1.00} = 0.993$$

$$S_{sl} = \frac{1}{0.993} = 1.008$$

4. Determine the volume of a kilogram of sludge using Eq. (14-2).

$$V = \frac{W_s}{\rho_w S_{sl} P_s}$$

a. At 98 percent water content:

$$V = \frac{1\text{ kg}}{(10^3\text{ kg/m}^3)(1.003)(0.02)} = 0.0499\text{ m}^3$$

b. At 95 percent water content.

$$V = \frac{1\text{ kg}}{(10^3\text{ kg/m}^3)(1.003)(0.05)} = 0.0199\text{ m}^3$$

5. Determine the percentage volume reduction.

$$\text{Percent reduction} = \left(\frac{V_1 - V_2}{V_1}\right)100$$

$$= \left(1 - \frac{0.0199}{0.0499}\right)100 = 60.2\,\%$$

PROBLEM 13-2

Problem Statement - See text, page 1554

Solution

1. Determine the volume of sludge pumped if the primary and waste activated sludge (WAS) are pumped separately and the WAS is not thickened.

   a. The mass of primary sludge on a wet basis is:

$$\text{Mass} = \frac{(200\ \text{g/m}^3)(40{,}000\ \text{m}^3/\text{d})(0.60)}{(0.05)(10^3\ \text{g/1 kg})} = 96{,}000\ \text{kg/d}$$

   b. The volume of primary sludge (using the specific gravity for primary sludge from table 13-7) is:

$$\text{Volume} = \frac{(96{,}000\ \text{kg/d})}{(10^3\ \text{kg/m}^3)(1.02)} = 94.1\,\text{m}^3/\text{d}$$

   c. The volume of WAS is 400 m^3/d (given).

   d. The total amount of sludge pumped to the digester is:

   Volume = (94.1 + 400) m^3/d = 494.1 m^3/d

2. Determine the volume of sludge pumped if the WAS is thickened separately in a gravity belt thickener.

   a. The dry mass of WAS (using the specific gravity for WAS from Table 13-7) is:

   Mass of WAS = (400 m^3/d)(1.05)(1000 kg/m^3)(0.005) = 2100 kg/d

   b. The volume of WAS after thickenening (TWAS) to 6% is:

$$\text{Volume} = \frac{(2100\ \text{kg/d})}{(10^3\ \text{kg/m}^3)(1.05)(0.06)} = 33.3\ \text{m}^3/\text{d}$$

   c. The volume of sludge pumped to the digester is:

   Volume = (94.1 + 33.3) m^3/d = 127.4 m^3/d

3. Determine the percent reduction in the daily volume of sludge pumped to the digester resulting from thickening the waste activated sludge.

$$\text{Reduction, \%} = \frac{[(494.1 - 127.4)\text{kg/d}]}{(494.1\ \text{kg/d})}(100) = 74.2$$

PROBLEM 13-3

Problem Statement - See text, page 1554

Solution

1. Calculate the maximum amount of dilution water allowable.

   Pertinent data: Maximum hydraulic loading rate = 12 $m^3/m^2 \bullet d$ (given)

   Hydraulic loading rate without dilution water = 7.13 $m^3/m^2 \bullet d$ (step 4 of Example 14-4)

   Dilution water = (12 – 7.13) $m^3/m^2 \bullet d$ = 4.87 $m^3/m^2 \bullet d$

   With a total gravity thickening surface area of 409.7 m^2, the total dilution flowrate is 1995 m^3/day.

PROBLEM 13-4

Problem Statement - See text, pages 1554

Solution

1. Determine the required digester volume using the volatile solids loading method.
   a. Determine the volume of VSS per day knowing that the sludge production is 5700 kg/d from example 13-5

      Volume of VSS/d to digester = (5700 kg/d)(0.75 g VSS/g TSS)

      = 4275 kg VSS/d

   b. Determine the required digester volume

$$\text{Volume} = \frac{(4275\ \text{kg VSS/d})}{(2.4\ \text{kg VSS/m}^3 \bullet \text{d})} = 1781\ \text{m}^3$$

2. Determine the required digester volume using population basis.

   Volume = (70,000 people)(50 $m^3/10^3$) = 3500 m^3

3. Prepare a summary table to compare the three methods used to estimate the required digester volume.

Method	Volume, m^3
Example 14-5	1677
Volatile solids loading	1781
Population basis	3500

PROBLEM 13-5

Problem Statement - See text, page 1555

Solution

1. Determine the mass of sludge produced each day.

$$\text{Mass} = \frac{(8000\ \text{m}^3/\text{d})(200\ \text{g/m}^3)}{(0.04)(10^3\ \text{g}/1\ \text{kg})} = 40{,}000\ \text{kg/d}$$

2. Determine the daily volume of sludge produced.

   a. Using Eq. (13-1, the specific gravity of the solids is:

$$\frac{1}{S_s} = \frac{0.25}{2.60} + \frac{0.75}{1.30} = 0.67$$

$$S_s = \frac{1}{0.67} = 1.49$$

   b. The specific gravity of the sludge is:

$$\frac{1}{S_{sl}} = \frac{0.04}{S_s} + \frac{0.96}{S_w}$$

$$\frac{1}{S_{sl}} = \frac{0.04}{1.49} + \frac{0.96}{1.00} = 0.987$$

$$S_{sl} = \frac{1}{0.987} = 1.013$$

   c. The sludge volume is:

$$\text{Volume} = \frac{(40{,}000\ \text{kg/d})}{(1000\ \text{kg/m}^3)(1.013)} = 39.5\ \text{m}^3/\text{d}$$

3. Determine the required digester volume using a hydraulic detention time (τ) of 20 d.

   Digester Volume = (39.5 m^3/d)(20 d) = 790 m^3

4. Determine the minimum digester capacity using the volatile solids loading factors given in Table 13-29, page 1510.

   Volatile solids loading factor = 1.4 $\text{kg/m}^3\text{•d}$

   (τ = 20 d, sludge concentration = 4%)

   a. The amount of volatile solids produced per day is:

$$\text{Mass}_{\text{VSS}} = \frac{(8000\ \text{m}^3/\text{d})(200\ \text{g/m}^3)(0.75)}{(10^3\ \text{g}/1\ \text{kg})} = 1200\ \text{kg/d}$$

b. The minimum required digester volume is:

$$\text{Digester volume} = \frac{(1200\ \text{kg/d})}{(1.4\ \text{kg/m}^3)} = 857\ \text{m}^3/\text{d}$$

5. Determine the minimum digester capacity:

a. Using a 3.2 kg VSS/m^3•d loading parameter (Table 13-28, point in mid-range), the required digester volume is:

$$\text{Digester volume} = \frac{(1200\ \text{kg/d})}{(3.2\ \text{kg/m}^3\text{•d})} = 375\ \text{m}^3$$

PROBLEM 13-6

Problem Statement - See text, page 1555

Solution

1. The theortetical temperature increase can be determined using Fig. 13-16 by knowing the specific quicklime dosage.

$$\text{Quicklime dosage} = \frac{300\ \text{kg CaO}}{(750\ \text{kg dry sludge/d})} = 0.4\ \text{kg CaO/kg dry sludge}$$

2. From Table 13-16, the theoretical temperature increase is 28ºC.

3. The advantages and disadvantages of switching from lime stabilization to anaerobic digestion are listed below:

Advantages	Disadvantages
• Anaerobic digestion followed by dewatering will reduce the total volume required for transport. Mass to dewatering will also be less • Anaerobic digestion allows for energy recovery potential • Eliminates costs required to purchase quicklime	• Major capital cost with building anaerobic digesters • Anaerobic digestion consumes a larger footprint • Anearobic digestion requires more skilled operation staff

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PROBLEM 13-7

Problem Statement - See text, page 1555

1. Calculate the net mass of cell tissue produced using Eq. (13-13).

   S_o = 300 kg/d

   S = (300 kg/d)(1 – 0.75) = 75 kg/d

   S_o – S = (300 – 75) kg/d = 225 kg/d

   $$P_x = \frac{(0.10)(225\,\text{kg/d})}{[1+(0.02/\text{d})(40\,\text{d})]} = 12.5\,\text{kg/d}$$

2. Calculate the volume of methane produced using Eq. (13-12) and a conversion factor at 35°C = 0.40.

   $$V_{CH_4} = (0.40)[(S_o - S)(Q)(10^3\ \text{g/kg})^{-1} - 1.42P_x]$$

   $$V_{CH_4} = (0.40)[(225\,\text{kg/d}) - 1.42\,(12.5\,\text{kg/d})] = 62\,\text{m}^3/\text{d}$$

PROBLEM 13-8

Problem Statement - See text, page 1555

Instructors Note: The answer to this question will vary depending upon the sources of reference material investigated.

Problem Analysis and/or Resolution

1. These three parameters (volatile acids concentration, pH, and alkalinity) along with gas production should be monitored simultaneously and correlated in terms of observed changes such as an increase in the volatile acids concentration and a drop in pH, alkalinity, and gas production. Plots of volatile acids and alkalinity will track trends in digester performance and indicate when changes in either or both parameters (an increase in volatile acids and a decrease in alkalinity) may result in possible instability.
2. Volatile acids concentration is perhaps the best parameter because of the rapid response time of the test.

3. Similarly, plots of methane and carbon dioxide composition in the digester gas are also helpful in measuring digester performance and detecting possible instability.

A useful reference is "Operation of Municipal Wastewater Treatment Plants," 7th ed., published by the Water Environment Federation, 2007.

PROBLEM 13-9

Problem Statement - See text, page 1555

Solution

1. Determine the heat requirement to raise the temperature of the incoming sludge to 35°C.

   Assume the specific gravity of the sludge to be 1.02

   Assume the existing contents of the digester are at a temperature of 35°C

   a. The mass flow of the sludge is:

      Density of water at 14°C = 999.2 kg/m^3 [Appendix C, Table C-1]

      $$\text{Mass flow} = (15\ \text{m}^3/\text{d})(1.02)(999.2\ \text{kg/m}^3) = 15{,}288\ \text{kg/d}$$

   b. Compute the heating requirement for sludge

      $q = (15{,}288\ \text{kg/d})[(35 - 14)^\circ\text{C}](4200\ \text{J/kg}\bullet{}^\circ\text{C})$

      $q = 13.48 \times 10^8$ J/d

2. Determine the area of the walls, roof, and floor.

   a. Wall area.

      i Above ground

      $$A_{\text{wall (above)}} = \pi(11\ \text{m})(4\ \text{m}) = 138.2\ \text{m}^2$$

      ii. Below ground

      $$A_{\text{wall (above)}} = \pi(11\ \text{m})(4\ \text{m}) = 138.2\ \text{m}^2$$

   b. Roof area.

      $$A_{\text{roof}} = \pi\left(\frac{11\ \text{m}}{2}\right)\sqrt{\left(\frac{11\ \text{m}}{2}\right)^2 + (0.6\ \text{m})^2} = 95.6\ \text{m}^2$$

   c. Floor area.

$$A_{floor} = \pi \left(\frac{11\ m}{2}\right)\sqrt{\left(\frac{11\ m}{2}\right)^2 + (1.2\ m)^2} = 97.3\ m^2$$

3. Determine the heat losses by conduction using Equation 13-17, page 1525.

$q = UA\Delta T$

where q = heat loss, J/d

U = overall coefficient of heat transfer, $W/m^2 \cdot {}^oC$ (Note: W = J/s)

A = cross-sectional area, m^2

ΔT = temperature drop across surface, ^oC

a. Walls

i. Above ground

$q_{above} = (0.85\ W/m^2 \bullet {}^oC)(138.2\ m^2)[35 - (-15)^oC](86{,}400 s/d)(J/W \bullet s)$

$= 5.07 \times 10^8$ J/d

ii. Below ground

$q_{below} = (1.2\ W/m^2 \bullet {}^oC)(138.2\ m^2)[(35 - 5)^oC](86{,}400\ s/d)(J/W \bullet s)$

$= 4.30 \times 10^8$ J/d

b. Roof

$q_{roof} = (1.0\ W/m^2 \bullet {}^oC)(95.5\ m^2)[35 - (-15)^oC](86{,}400\ s/d)(J/W \bullet s)$

$= 4.13 \times 10^8$ J/d

c. Floor

$q_{floor} = (1.2\ W/m^2 \bullet {}^oC)(97.3\ m^2)[(35 - 5)^oC](86{,}400\ s/d)(J/W \bullet s)$

$= 3.03 \times 10^8$ J/d

d. Total losses

$q_t = [(5.07 + 4.30 + 4.13 + 3.03) \times 10^8]$ J/d $= 16.53 \times 10^8$ J/d

4. Determine the required capacity of the heat exchanger.

$q_{he} = [(13.48 \times 10^8) + (16.53 \times 10^8)]$ J/d

$= 30.01 \times 10^8$ J/d $= 3 \times 10^6$ kJ/d

PROBLEM 13-10

Problem Statement - See text, pages 1555-1556

Solution

1. Determine the volume of sludge at current conditions going into the digester

$$\text{Volume} = \frac{(25{,}000\ \text{kg/d})}{(10^3\ \text{kg/m}^3)(1.03)(0.05)} = 485.4\ \text{m}^3/\text{d}$$

2. Determine current HRT when one digester is out of service

$$\text{HRT} = \frac{(6200\ \text{m}^3)(2)}{(485.4\ \text{m}^3/\text{d})} = 25.5\ \text{d}$$

3. Determine the volume of sludge at future conditions (based on data set 1) going into the digester

$$\text{Volume} = \frac{(55{,}000\ \text{kg/d})}{(10^3\ \text{kg/m}^3)(1.03)(0.05)} = 1068.0\ \text{m}^3/\text{d}$$

4. Determine total required digester volume to maintain 15 d HRT
Digester Volume = (15 d)(1068.0 m^3/d) = 16,020 m^3

5. Determine additional digester volume required
Additional Digester Volume = 16,020 m^3 – 2(6200 m^3) = 3620 m^3
Note: One additional 6200 m^3 digester could be added if it was desired to have the new digester be the same size as the existing tanks.

6. If thermal hydrolysis was added and the solid content going to the digester was 9% then the volume would be:

$$\text{Volume} = \frac{(55{,}000\ \text{kg/d})}{(10^3\ \text{kg/m}^3)(1.03)(0.09)} = 593.3\ \text{m}^3/\text{d}$$

7. Determine the digester HRT

$$\text{HRT} = \frac{(6200\ \text{m}^3)(2)}{(593.3\ \text{m}^3/\text{d})} = 20.9\ \text{d}$$

With thermal hydrolysis the existing digester volume is sufficent

8. Determine the theoretical thermal hydrolysis steam requirement

$$\frac{M_{\text{Steam}}}{M_S} = \frac{\left(C_{PS} + \frac{C_{PW}}{W_S} - C_{PW}\right)(T_H - T_{raw})}{H - C_{PW}(T_H - T_{ref})}$$

$$\frac{M_{Steam}}{M_S} = \frac{\left[(1.5\ kJ/kg \bullet C) + \dfrac{(4.18\ kJ/kg \bullet C)}{0.16} - (4.18\ kJ/kg \bullet C)\right][(110-10)^o C]}{(2785\ kJ/kg) - (4.18\ kJ/kg \bullet C)[(110-0)^o C]}$$

$$= 1.0\ \ (kg\ steam)/(\ kg\ sludge)$$

$$M_{Steam} = \left(\frac{1.0\ kg\ steam}{kg\ sludge}\right)(55{,}000\ kg/d) = 55{,}000\ \ kg\,steam/d$$

PROBLEM 13-11

Problem Statement - See text, page 1556

Solution

1. Determine the current and future volumetric flowrates (using data set 1)

$$\text{Volume (current)} = \frac{(500\ kg/d)}{(10^3\ kg/m^3)(1.01)(0.01)} = 49.5\ m^3/d$$

$$\text{Volume (future)} = \frac{(1500\ kg/d)}{(10^3\ kg/m^3)(1.01)(0.01)} = 148.5\ m^3/d$$

2. Determine the current and future Digester HRTs. Note that since there is no decanting, HRT = SRT

$$\text{HRT (current)} = \frac{3000\ \ m^3}{(49.5\ \ m^3/d\ )} = 60.6\ d$$

$$\text{HRT (future)} = \frac{3000\ \ m^3}{(148.5\ \ m^3/d\ )} = 20.2\ d$$

3. Determine the current aeration requirements

   a. First base this on summer requirements and use Fig. 13-35 to determine VSR. The (T)(SRT) = (25°C)(60 d) = 1500 °C•d which is about 50% VSR.

   b. Determine the oxygen requirement

   O_2 requirement = (2.3)(500 kg/d)(0.65 gVSS/gTSS)(0.5)

= 373.8 kg O_2/d

c. Determine the air requirement. For the density of air, see Appendix B-1.

$$\text{Air requirement} = \frac{(373.8\,\text{kg O}_2/\text{d})}{(0.232\,\text{kg O}_2/\text{kg air})(1.204\,\text{kg/m}^3)} = 1338\,\text{m}^3/\text{d}$$

d. Determine the required blower size assuming 10% oxygen transfer efficiency

$$\text{Blower} = \frac{(1338\ \text{m}^3/\text{d})}{(0.1)(1440\,\text{min/d})} = 9.29\ \text{m}^3/\text{min}$$

e. Determine the required blower size to meet mixing requirement (From Table 13-44 mixing requirements are approximately 0.03 $m^3/m^3 \cdot min$)

Blower = (0.03 $m^3/m^3 \cdot min$)(3000 m^3) = 90 m^3/min

Blower is sized to meet mixing requirements

4. Determine the future aeration requirements

a. If future conditions are anticipated to remain 50% VSR

O_2 req. = (2.3)(1500 kg/d)(0.65 VSS/TSS)(0.5) = 1121.4 kg O_2/d

c. Determine the air requirement using the same density as part 3.c.

$$\text{Air requirement} = \frac{(1121.4\,\text{kg O}_2/\text{d})}{(0.232\,\text{kg O}_2/\text{kg air})(1.204\,\text{kg/m}^3)} = 4014.6\,\text{m}^3/\text{d}$$

d. Determine the required blower size assuming 10% oxygen transfer efficiency

$$\text{Blower} = \frac{(4014.6\ \text{m}^3/\text{d})}{(0.1)(1440\,\text{min/d})} = 27.9\ \text{m}^3/\text{min}$$

The existing blower is sufficiently sized to meet the future required oxygen demand for aerobic digestion

5. One possible option is to build a new aerobic digester tankage. The new volume required is

New Digester Volume = (60 d)(148.5 m^3/d) – (3000 m^3) = 5910 m^3

Two additional 3000 m^3 digester reactors could be installed at the site.

6. An alternative option is to thicken the sludge in the current aerobic digester. The percent solids required is.

$$\text{Solids required, \%} = \frac{(1338\ \text{kg/d})(60\ \text{d})}{(3000\ \text{m}^3)(10^3\ \text{kg/m}^3)(1.01)}(100) = 2.97$$

Thickening the waste activated sludge prior to entering the digester is one option to consider. If this option is employed the diffusers and blower should be checked to ensure it’s compatible with the higher solids content. Also it may be possible to increase capacity by adding in decanting cycles.

The option of thickening verses building new reactors would likely save costs and also reduce plant footprint which can be critical at some sites.

14

BIOSOLIDS PROCESSING, RESOURCE RECOVERY, AND BENEFICIAL USE

PROBLEM 14-1

Problem Statement - See text, page 1651

Solution

1. Compute the number and size of belt filter presses required

   a. Determine the wet mass of thickened biosolids produced

      Biosolids mass flow (wet) = (55,000 L/d)(1 kg/L)(1.02) = 56,100 kg/d

   b. Determine the hourly mass flowrate on a wet and dry basis for 8 h/d and 5 d/wk operation

      Hourly flowrate (wet) = (56,100 kg/d)(7 d/wk / 5 d/wk)(1 d/8 h)

      = 9818 kg/h

      @ 2.8% dry solids

      Hourly flowrate (dry) = (9818 kg/h) (0.028) = 274.9 kg/h

   c. Determine the required belt filter press width

      Belt filter width = (274.9 kg/h) / (280 kg/m·h) = 0.98 m

      Based the loading rate requirements either one operational 1-m belt filter press or two 0.5-m belt filter presses are required. To account for equipment redundancy one additional unit could also be incorporated. For the purpose of this problem it will be assumed that two 1-m belt fitler presses will be provided (1 duty + 1 standby)

2 . Determine the capture rate – To determine the capture rate a mass balance around the belt filter press needs to be set up. There are two unknowns; the dewatered cake production (define as DC kg/h) and the filtrate flowrate (define as F L/min). Two equations need to be set up to

   a. First set up a dry solids mass balance

      Dry solids in = dry solids out + dry solids in filtrate

274.9 kg/h = (0.26)(DC kg/h) + (F L/min)(800 mg/L)(1 kg/10^6 mg)(60 min/h)

274.9 kg/h = (0.26)DC kg/h + 0.048 F (kg/h)

b. Second set up a total mass balance

Sludge in + washwater in = sludge out + filtrate out

9,818 kg/h + (90 L/min)(1 kg/L)(60 min/h)

= (F L/min)(1 kg/L)(1.01)(60 min/h) + DC kg/h

15,218 kg/h = 60.6 F (kg/h) + DC kg/h

c. Solve equation from part a. for DC

$$DC = \frac{274.9 - 0.048\ F}{0.26}$$

d. Plug equation from Part c. into equation from Part b. and solve for F.

$$15{,}218 = 60.6\ F + \frac{274.9 - 0.048\ F}{0.26}$$

15,218 = 60.42 F + 1,057.31

F = 234.4 L/min

e. Solve for DC using equation derived in part c.

$$DC = \frac{274.9 - 0.048\ (234.4)}{0.26} = 1014\, kg/h$$

f. Determine the dry solids production

(1,014 kg/h)(0.26) = 263.6 kg/h

g. Determine the solids capture rate

Capture rate, % = (dry solids out)/(dry solids in)(100)

Capture rate, % = (263.6 kg/h)/(274.9 kg/h)(100)

Capture rate, % = 95.9

3. Determine daily number of hours required for a sustained 5-d peak solids load

From Fig. 3-13(b) the peaking factor for a 5-d peak for TSS is approximately 2. Based on this the loading at a 5-d peak is:

5-d sustained peak = (56,100 kg/d) (2) (0.028) = 3142 kg/d

If 5-d per week operation is maintained then the press would need to process: (3142 kg/d)(7/5) = 4398 kg/d

With one unit in operation:

Daily hours = (4398 kg/d)/(280 kg/h) = 15.7 h/d

If both the duty and standby unit are operating

Daily hours = (4398 kg/d)/[(280 kg/h)(2)] = 7.9 h/d

PROBLEM 14-2

Problem Statement - See text, page 1652

Solution

1. Determine the molecular formula of the dried sludge.
   a. For 100 g of sludge the mass of each element is:

      C = 52.1 g

      O = 38.3 g

      H = 2.7 g

      N = 6.9 g

   b. For 100 g of sludge the number of moles of each element is:

      C = 52.1 g/(12 g/mole) = 4.34 moles

      O = 38.3 g/(16 g/mole) = 2.39 moles

      H = 2.7 g/(1 g/mole) = 2.70 moles

      N = 6.9 g/(14 g/mole) = 0.49 moles

   c. The molecular formula of the sludge is:

      $C_{4.34}O_{2.39}H_{2.70}N_{0.49}$

2. Determine the amount of O_2 required to oxidize the sludge completely using Equation 14-3, page 1603.

   $C_aO_bH_cN_d + (a + 0.25c - 0.5b)\ O_2 \rightarrow a\ CO_2 + 0.5c\ H_2O + 0.5d\ N_2$

   $C_{4.34}O_{2.39}H_{2.70}N_{0.49} + 3.82\ O_2 \rightarrow 4.34\ CO_2 + 1.35\ H_2O + 0.25\ N_2$

   Mass of O_2 = (3.82 mole O_2) x (32 g O_2 / mole O_2)

$$O_2\,\text{required} = \frac{122.2\text{ g } O_2}{100\text{ g sludge}} = 1.222\text{ g } O_2\text{ / g sludge}$$

3. Determine the amount of air required.

   Assume that air contains 23 percent oxygen (mass).

$$\text{Air required} = \frac{(1.222\text{ g } O_2\text{ / g sludge})}{(0.23\text{ g } O_2\text{ / g air})} = 5.31\text{ g} O_2\text{ / g sludge}$$

= 5.31 kg O_2 / kg sludge

PROBLEM 14-3

Problem Statement - See text, page 1652

Solution

1. Determine the fuel value of the primary sludge using Eq. (14-5).

   Q = 33.83 C + 144.7 (H – O/8) + 9.42 S

   Pertinent data: C = 0.645
   H = 0.085
   O = 0.21
   S = 0.04

   Q = {33.83(0.645) + 144.7 [0.085 – (0.21/8)] + 9.42 (0.04)} MJ/kg

   Q = 21.82 + 8.5 + 0.37 = 30.69 MJ/kg

   The computed value is at the high end of the range given in Table 14-17.

PROBLEM 14-4

Problem Statement - See text, page 1652

Solution

NOTE: The solution provided below is based on the 20% solids content factor

1. Convert the volumetric flowrate to a mass flowrate and calculate the dry sludge production

   Sludge production (wet) = M_{wet} = (1000 m^3/d)(1000 kg/m^3)(1.05)

   M_{wet} = 1,050,000 kg/d (wet)

Sludge production (dry) = (1,050,000 kg/d)(0.2)

M_{dry} = 210,000 kg/d (dry)

2. Deterine the daily mass of water to heat

Water = 1,050,000 kg/d – 210,000 kg/d

$M_{W,Tot}$ = 840,000 kg/d

3. Deterine the daily mass of water to evaporate

Water evap = 1,050,000 kg/d – (210,000 kg/d)/0.92

$M_{W,Evap}$ = 821,739 kg/d

3. Determine theoretical drying heat requirement (Q_{TH}) using the following equation

$Q = (M_{dry}Cp_{dry} + M_{W,Tot}\,Cp_W)(T_{out} - T_{in}) + M_{W,Evap}\,H_{W,Evap}$

Where,

Cp_{dry} (dry solids heat capacity) = 1.5 kJ/kg·°C

Cp_W (heat capacity of water) = 4.18 kJ/kg·°C

$H_{W,Evap}$ (latent heat of evaporation) = 2,260 kJ/kg

T_{in} = 20°C

T_{out} = 100°C

Q_{TH} = [(210,000 kg/d)(1.5 kJ/kg·°C) + (840,000 kg/d)(4.18 kJ/kg·°C)]
x(100°C – 20°C) + (821,739 kg/d)(2260 kJ/kg)

$Q_{TH} = 2.16 \times 10^9$ kJ/d (or approx 25,000 kW)

4. Determine the fuel requirement assuming 5% heat loss and 85% heater efficiency (η_{Heater})

Heat loss = $Q_L = (2.16 \times 10^9 \text{ kJ/d})(0.05) = 1.08 \times 10^8$ kJ/h

Total fuel requirement = $(Q_{TH} + Q_L)/\eta_{Heater}$

$= [(2.16 \times 10^9 + 1.08 \times 10^8) \text{ kJ/h}] / 0.85 = 2.66 \times 10^9$ kJ/h (~30,800 kW)

PROBLEM 14-5

Problem Statement - See text, page 1652

Solution

1. Determine the amount of compostable solid waste (SW) generated each day.

SW_{total} = (25,000 people)(2 kg/person•d)(0.55) = 27,500 kg/d

2. Determine the dry weight of the compostable solids and the weight of water in the compostable fraction.

   SW_{dry} = (1 – 0.22) 27,500 kg/d = 21,450 kg/d

   SW_{H_2O} = 0.22 (27,500) = 6,050 kg/d

3. Solve for the weight of sludge solids, S_{total} that must be added to achieve a final moisture content of 55%.

$$0.55 = \frac{S_{H_2O} + SW_{H_2O}}{S_{H_2O} + S_{dry} + SW_{H_2O} + SW_{dry}}$$

$$0.55 = \frac{S_{H_2O} + \ 6050 \text{ kg/d}}{S_{H_2O} + S_{dry} + \ 27{,}500 \text{ kg/d}}$$

But S_{H_2O} = (1-0.22)(S_{H_2O} + S_{dry})

S_{H_2O} = 3.55 S_{dry}

$$0.55 = \frac{3.55\ S_{dry} + 6050 \text{ kg/d}}{3.55\ S_{dry} + S_{dry} + 27{,}500 \text{ kg/d}}$$

2.50 S_{dry} + 15,125 kg/d = 3.55 S_{dry} + 6050 kg/d

1.05 S_{dry} = 9075 kg/d

S_{dry} = 8643 kg/d

S_{total} = (8643 kg/d)/0.22 = 39,286 kg/d

Therefore, 39,286 kg/d of sludge at 22 percent solids are needed to achieve the required final moisture content of 55%.

4. Determine the amount of sludge produced each day.

S_{dry} = (0.12 kg/person•d)(25,000 people) = 3000 kg/d

S_{total} = (3000 kg/d)/0.05 = 60,000 kg/d

Therefore, an excess amount of sludge is available for mixing with the solids waste for composting.

PROBLEM 14-6

Problem Statement - See text, page 1652

Instructors Note: This problem is intended to have the student consider the various factors, economic as well as non-economic, in developing alternative solutions and recommendations for a practical application. In making a recommendation in actual practice, a number of conditions will have to be considered that are site specific and include cost and environmental factors. Some of those conditions are cited under the solution below. The instructor may want to add other factors or constraints to the problem. Because a community size of 200,000 people was specified, the treatment plant is of medium size and a reasonable level of operating skills can be assumed in the analysis.

Solution

1. Determine the amount and characteristics of the biosolids to be processed. Because the biosolids are a mixture of digested primary and waste activated sludge, dewatering to obtain a specific moisture content of the dewatered biosolids may be an important consideration.
2. Evaluate the general operating performance and advantages and disadvantages of the three specified types of sludge dewatering equipment: belt press dewatering, centrifugation, and pressure filter press dewatering. The advantages and disadvantages cited in Table 14-2 will be helpful as a starting point. Other references where case studies are cited would be useful. Because of the size of the system, newer dewatering technologies such as rotary presses and screw presses may require numerous units

which may make the required footprint and total cost prohibititive but they should be considered in the items listed in part 3 below.

3. Determine the cost factors that will be needed in a life cycle cost analysis such as:
   a. Number and size of units
   b. Equipment cost
   c. Operating and maintenance cost factors
   d. Space requirements
   e. Ancillary equipment such as chemical feeders, process water, pumping systems, conveying and materials handling equipment, and odor control
   f. Impact of the amount and quality of return flows from the dewatering units
4. Determine the general characteristics of the dewatered biosolids and how they relate to meeting the requirements for transport to the disposal site and the conditions for disposal.

Evaluate environmental considerations such as noise, odor control, traffic for sludge trucks, disposal site characteristics that affect system selection

PROBLEM 14-7

Problem Statement - See text, pages 1653

Instructors Note: This problem is intended to help the student understand in detail the solids balance procedure. A spreadsheet program can be used to solve the problem or successive iterations can be used in a manner similar to Example 14-3.

Solution – for Data Set 1

A summary table is given below for three iterations using the same procedure as Example 14-3. Detailed computations are given after the summary table.

No.	Item	Units	1^{st} iter	2^{nd} iter	3^{rd} iter
a.	Primary settling				
	Influent flowrate	m^3/d	54,000	54,000	54,000
	Recycled flowrate	m^3/d	0	966	528
	Influent TSS_M	kg/d	17,550	17,550	17,550
	Recycled TSS_M	kg/d	0	1,481	1,541
	Total TSS_M entering the primary tanks	kg/d	17,550	19,031	19,091
	Influent BOD_M	kg/d	18,360	18,360	18,360
	Recycled BOD_M	kg/d	0	631	648
	Total BOD_M entering the primary tanks	kg/d	18,360	18,991	19,008
	BOD_M removed	kg/d	6,059	6,267	6,273
	BOD_M to secondary	kg/d	12,301	12,724	12,735
	TSS_M removed (to digester)	kg/d	12,285	13,322	13,364
	TSS_M to secondary	kg/d	5,265	5,709	5,727
b.	Volatile fraction of the primary sludge	%	65.6	65.6	65.6
c.	Secondary process				
	BOD_C influent to the aeration tank	mg/L	228	231	234
	P_X(VSS)	kg/d	3,743	3,831	3,882
	TSS_M wasted	kg/d	4,679	4,827	4,852
	BOD_M effluent	kg/d	1,080	1,080	1,080
	TSS_M effluent	kg/d	1,188	1,188	1,188
	TSS_M to thickener	kg/d	3,491	3,639	3,664
	Flowrate to thickener	m^3/d	798	354	355
d.	Flotation thickener				
	Thickened sludge flowrate	m^3/d	78.5	81.9	82.4
	Flowrate recycled to the plant influent	m^3/d	719.5	272.1	272.6
	TSS_M sent to the digester	kg/d	3,142	3,275	3,298
	TSS_M recycled to plant influent	kg/d	349	364	366
	BOD_M recycled to plant influent	kg/d	223	228	230
e.	Sludge digestion				
	TSS_M fed to the digester	kg/d	15,776	16,597	16,662
	Total flowrate to the digester	m^3/d	292	303.9	305
	VSS_M fed to the digester	kg/d	10,582	11,706	11,752

	VSS_M destroyed	kg/d	5,291	5,853	5,876
	Mass flow to the digester, primary	m^3/d	204,750	222,033	222,733
	Mass flow to the digester, secondary	m^3/d	87,275	81,875	82,450
	Mass flow to the digester, total	m^3/d	292,025	303,908	305,183
	Fixed solids	kg/d	5,194	4,891	4,910
	Total solids in digested sludge	kg/d	10,485	10,744	10,786
	Gas produced	kg/d	5,219	6,776	6,803
	Mass output	kg/d	286,806	297,132	298,380
	Supernatant solids to plant influent	kg/d	428	457	459
	Digested solids to dewatering	kg/d	10,057	10,287	10,327
	Supernatant flowrate to plant influent	m^3/d	85.6	91.4	91.8
	Digested sludge flowrate	m^3/d	201.1	205.7	206.5
	BOD_M recycled to plant influent	kg/d	86	91	92
	TSS_M recycled to plant influent	kg/d	428	457	459
f.	Sludge dewatering				
	Sludge cake solids	kg/d	9,353	9,567	9,604
	Sludge cake volume	m^3/d	40	41	41.2
	Centrate flowrate to plant influent	m^3/d	161	164.7	165.3
	Centrate BOD_M to plant influent	kg/d	322	329	331
	Centrate TSS_M to plant influent	kg/d	704	720	723
g.	Summary of recycle flows and loads				
	Flowrate	m^3/d	966.1	528.2	529.7
	BOD_M	kg/d	631	648	653
	TSS_M	kg/d	1,481	1,541	1,528

Computation procedure

1. Convert the given constituent concentrations to daily mass values.

   a. BOD_M in influent.

$$BOD_M = \frac{(54{,}000\,m^3/d)(340\,g/m^3)}{(10^3\,g/kg)} = 18{,}360\,kg/d$$

   b. Total suspended solids (TSS_M) in influent.

$$\text{TSS}_{\text{M}} = \frac{(54{,}000\,\text{m}^3/\text{d})(350\,\text{g}/\text{m}^3)}{(10^3\,\text{g}/\text{kg})} = 18{,}900\,\text{kg}/\text{d}$$

c. Total suspended solids after grit removal.

$$\text{TSS}_{\text{M}} = \frac{(54{,}000\,\text{m}^3/\text{d})(325\,\text{g}/\text{m}^3)}{(10^3\,\text{g}/\text{kg})} = 17{,}550\,\text{kg}/\text{d}$$

2. Prepare the first iteration of the solids balance. [Note: Values with an asterisk (*) are operating parameters from Example 14-3)].

   a. Primary settling.

      i. BOD_M removed = 0.33* (18,360 kg/d) = 6059 kg/d

      ii. BOD_M to secondary = (18,360 – 6059) kg/d = 12,301 kg/d

      iii. TSS_M removed = 0.7* (17,550 kg/d) = 12,285 kg/d

      iv. TSS_M to secondary = (17,550 – 12,285) kg/d = 5265 kg/d

   b. Determine the volatile fraction of the primary sludge.

      i. Volatile suspended solids (VSS_M) in influent prior to grit removal, kg/d

         VSS_M = (0.67*)(18,900 kg/d) = 12,663 kg/d

      ii. VSS_M removed in grit chamber

         VSS_M= (0.10*)(18,900 – 17,550) kg/d = 135 kg/d

      iii. VSS_M in secondary influent

         VSS^M= (0.85*)(5265 kg/d) = 4475 kg/d

      iv. VSS_M in primary sludge

         VSS_M = (12,663 - 135 – 4475) kg/d = 8053 kg/d

      v. Volatile fraction in primary sludge

$$\text{Volatile fraction} = \frac{(8053\,\text{kg}/\text{d})}{(12{,}285\,\text{kg}/\text{d})}(100\%) = 65.6\%$$

   c. Secondary process.

i. Determine the BOD influent concentration (BOD_C) to the aeration tank. (Note: the flowrate of the primary clarifier underflow is neglected).

$$BOD_C = \frac{(12{,}301\ kg/d)(10^3\ g/kg)}{(54{,}000\ m^3/d)} = 228\ mg/L$$

ii. Determine the mass of VSS produced that must be wasted using Eq. (8-19).

$$P_{x,VSS} = \frac{Y_{obs}\,Q\,(S_o - S)}{(10^3\ g/kg)}$$

$$P_{x,VSS} = \frac{(0.3125^*)(54{,}000\ m^3/d)[(228 - 6.2^*)\ g/m^3]}{(10^3\ g/1\ kg)} = 3743\ kg/d$$

iii. Determine the TSS_M that must be wasted.

TSS_M = (3743 kg/d)/0.80* = 4679 kg/d

iv. Determine the effluent mass quantities.

BOD_M = (54,000 m^3/d)(20 g/m^3*)/(10^3 g/kg) = 1080 kg/d

TSS_M = (54,000 m^3/d)(22 g/m^3*)/(10^3 g/kg) = 1188 kg/d

v. Determine the waste quantities discharged to the thickener (assume wasting from the aeration tank).

TSS_M = (4679 – 1188) kg/d = 3491 kg/d

$$Flowrate = \frac{(3491 kg/d)(10^3\ g/kg)}{(4375\ g/m^3)^*} = 798\ m^3/d$$

d. Flotation thickener.

i. Determine the flowrate of the thickened sludge.

$$Flowrate = \frac{(3491\ kg/d)(0.9^*)}{(10^3\ kg/m^3)(0.04)^*} = 78.5\ m^3/d$$

ii. Determine the flowrate recycled to the plant influent.

Recycled flowrate = (798 – 78.5) m^3/d = 719.5 m^3/d

iii. Determine the TSS_M to the digester.

TSS_M = (3491 kg/d)(0.9*) = 3142 kg/d

iv. Determine the suspended solids recycled to the plant influent.

TSS_M = (3491- 3142) kg/d = 349 kg/d

iv. Determine the BOD concentration and mass in the recycled flow.

$$TSS_C = \frac{(349\ kg/d)}{(719.5\ m^3)(1\ kg/10^3\ g)^*} = 485\ g/m^3 \text{ in recycle flow}$$

BOD_C of TSS = (485 g/m^3)(0.65*)(1.42*)(0.68*) = 304 g/m^3

Total BOD_C = (304 + 6.2) g/m^3 = 310 g/m^3

BOD_M = (719.5 m^3/d)(310 g/m^3)/(10^3 g/kg) = 223 kg/d

e. Sludge digestion.

i. Determine the total solids fed to the digester and the corresponding flow.

TSS_M = (12,285 + 3,491) kg/d = 15,776 kg/d

= 292 m^3/d

ii. Determine the VSS fed to the digester.

VSS_M = 0.656 (12,285 kg/d) + 0.80 (3491 kg/d) = 10,582 kg/d

iii. Determine the VSS destroyed.

VSS_M destroyed = 0.5* x 10,582 kg/d = 5291 kg/d

iv. Determine the mass flow to the digester.

Primary sludge:

$$\text{Mass flowrate} = \frac{(12{,}285\ kg/d)}{(0.06)} = 204{,}750\ kg/d$$

Thickened waste activated sludge:

$$\text{Mass flowrate} = \frac{(3491\ \text{kg/d})}{(0.04)} = 87{,}275\ \text{kg/d}$$

Total mass flow = (204,750 + 87,275) kg/d = 292,025 kg/d

v. Determine the mass quantities of gas and sludge after digestion.

Fixed solids = $TSS_M - VSS_M$ = (15,776 – 10,582) kg/d

= 5194 kg/d

TSS_M in digested sludge = [5194 + 0.5(10,582)] kg/d

= 10,485 kg/d

Gas production =

= (1.12 m^3/kg *)(0.5)(10,582 kg/d)(0.86)(1.024 kg/m^3*)

= 5219 kg/d

Mass balance of digester output (solids and liquid)

Mass input	292,025 kg/d
Less gas	– 5219 kg/d
Mass output	286,806 kg/d

vi. Determine the flowrate distribution between supernatant and digested sludge (S = supernatant).

$$\frac{S}{0.005} = \frac{(10{,}485\ \text{kg/d}) - S}{(0.05)} = 286{,}806$$

S + 1049 – 0.1S = 1434 kg/d

S = 428 kg/d

Digested solids = (10,485 – 428) kg/d = 10,057 kg/d

$$\text{Supernatant flowrate} = \frac{(428\,\text{kg/d})}{(0.005)(10^3\ \text{kg/m}^3)} = 85.6\ \text{m}^3\text{/d}$$

$$\text{Digested sludge flowrate} = \frac{(10{,}057\ \text{kg/d})}{(0.05)(10^3\ \text{kg/m}^3)} = 201.1\text{m}^3\text{/d}$$

vii. Establish the characteristics of the recycle flow to the plant influent.

Flowrate = 85.6 m^3/d

BOD_M = (85.6 m^3/d) (1000 g/m^3)(10^3 g/1 kg) = 86 kg/d

TSS_M = (85.6 m^3/d) (5000 g/m^3)(10^3 g/1 kg) = 428 kg/d

f. Sludge dewatering

i. Determine the sludge cake characteristics.

Digested solids = 10,057 kg/d (0.93) = 9353 kg/d

$$\text{Volume} = \frac{(9353\ \text{kg/d})}{(0.22)(1.06)(10^3\ \text{kg/m}^3)} = 40\ \text{m}^3/\text{d}$$

ii. Determine the centrate characteristics.

Flowrate = (201 – 40) m^3/d = 161 m^3/d

BOD_M = (161 m^3/d) (2000 g/m^3)/(10^3 g/1 kg) = 322 kg/d

TSS_M = (10,057 kg/d)(0.07) = 704 kg/d

g. Prepare a summary table of the recycle flows and waste characteristics for the first iteration.

Operation	Flow, m^3/d	BOD, kg/d	TSS, kg/d
Flotation thickener	719.5	223	349
Digester supernatant	85.6	86	428
Centrate	161.0	322	704
Totals	966.1	631	1481

3. Prepare the second iteration of the solids balance.

a. Primary settling

i. Operating parameters = same as those in the first iteration.

ii. TSS_M and BOD_M entering the primary tanks.

TSS_M = Influent TSS_M + recycled TSS_M

= (17,550 + 1481) kg/d = 19,031 kg/d

Total BOD_M = influent BOD_M + recycled BOD_M

= (18,360 + 631) kg/d = 18,991 kg/d

iii. BOD_M removed = 0.33(18,991 kg/d) = 6267 kg/d

iv. BOD_M to secondary = (18,991 – 6267) kg/d = 12,724 kg/d

v. TSS_M removed = 0.7(19,031 kg/d) = 13,322 kg/d

vi. TSS_M to secondary = (19,301 – 13,322) kg/d = 5709 kg/d

b. Volatile fraction of the primary sludge and effluent suspended solids; use volatile fraction from first iteration.

c. Secondary process

i. Operating parameters = same as those for the first iteration and as follows:

Aeration tank volume = 4700 m^3 SRT = 10 d

Y = 0.50 kg/kg $k_d = 0.06\ d^{-1}$

ii. Determine the BOD_C in the influent to the aeration tank

Flowrate to aeration tank = influent flowrate + recycle flowrate

= (54,000 + 966) m^3/d = 54,966 m^3/d

$$BOD_C = \frac{(12{,}724\,kg/d)(10^3\,g/1\,kg)}{(54{,}966\,m^3/d)} = 231\ g/m^3$$

iii. Determine the new concentration of mixed liquor VSS.

$$X_{VSS} = \frac{(10\,d)(54{,}966\,m^3/d)(0.5)[(231-6.2)\,g/m^3]}{4700\,m^3\,[1+(0.06\,d^{-1})(10\,d)]} = 8216\ g/m^3$$

iv. Determine the mixed liquor TSS.

X_{TSS} = 8216/0.8 = 10,270 g/m^3

v. Determine the cell growth.

$P_{x,VSS} = Y_{obs}\,Q(S_o - S)\,/(10^3\ g/kg)$

$$= \frac{0.3125(54{,}966\ \text{m}^3/\text{d})[(231-6.2)\text{g}/\text{m}^3]}{(10^3\ \text{g}/1\ \text{kg})} = 3861\ \text{kg/d}$$

$P_{x,TSS}$ = 3861/0.8 = 4827 kg/d

vi. Determine the waste quantities discharged to the thickener.

Effluent TSS_M = 1188 kg/d (specified in the first iteration)

Total TSS_M to be wasted to the thickener = (4827 – 1188) kg/d

Total TSS_M = 3639 kg/d

$$\text{Flowrate} = \frac{(3639\ \text{kg}/\text{d})(10^3\text{g}/1\text{kg})}{(10{,}270\ \text{g}/\text{m}^3)} = 354\ \text{m}^3/\text{d}$$

d. Flotation thickeners

i. Operating parameters: same as first iteration

ii. Determine the flowrate of the thickened sludge.

$$\text{Flowrate} = \frac{(3639\ \text{kg}/\text{d})(0.9)}{(10^3\ \text{kg}/\text{m}^3)(0.04)} = 81.9\ \text{m}^3/\text{d}$$

iii. Determine the flowrate recycled to the plant influent.

Recycled flowrate = (354 – 81.9) m^3/d = 272.1 m^3/d

iv. Determine the TSS_M to the digester.

TSS_M = (3639 kg/d)(0.9) = 3275 kg/d

v. Determine the TSS_M recycled to the plant influent.

TSS_M = (3639 – 3275) kg/d = 364 kg/d

vi. Determine the BOD_C of the suspended solids in the recycled flow

$$TSS_C\ \text{in recycle flow} = \frac{(364\ \text{kg}/\text{d})(10^3\ \text{g}/\text{kg})}{(272.1\ \text{m}^3/\text{d})} = 1337\ \text{g/m}^3$$

BOD_C of suspended solids = (1337 g/m^3)(0.65)(1.42)(0.68)

= 839 g/m^3

BOD_M = (839 g/m^3)(272.1 m^3/d)/(10^3 g/kg) = 228 kg/d

e. Sludge digestion

i. Operating parameters - same as first iteration

ii. Determine the total solids fed to the digester and the corresponding flowrate.

TSS_M = TSS_M from primary settling plus waste TSS_M from thickener

TSS_M = (13,322 + 3275) kg/d = 16,597 kg/d

$$\text{Total flowrate} = \frac{(13{,}322\ \text{kg/d})}{0.06(10^3\ \text{kg/m}^3)} + \frac{(3275\ \text{kg/d})}{0.04(10^3\ \text{kg/m}^3)}$$

$$= (222 + 81.9)\ \text{m}^3/\text{d} = 303.9\ \text{m}^3/\text{d}$$

iii. Determine the total VSS_M fed to the digester.

VSS_M = 0.682(13,322 kg/d) + 0.80(3275 kg/d)

= (9086 + 2620) kg/d = 11,706 kg/d

$$\%\ \text{VSS in mixture fed to digester} = \frac{(11{,}706\ \text{kg/d})}{(16{,}597\ \text{kg/d})}(100) = 70.5\%$$

iv. Determine the VSS_M destroyed.

VSS_M destroyed = 0.5(11,706 kg/d) = 5853 kg/d

v. Determine the mass flow to the digester.

Primary sludge at 6% solids:

$$\text{Mass flow} = \frac{(13{,}322\ \text{kg/d})}{0.06} = 222{,}033\ \text{kg/d}$$

Thickened waste activated sludge at 4% solids:

$$\text{Mass flow} = \frac{(3275\ \text{kg/d})}{0.04} = 81{,}875\ \text{kg/d}$$

Total mass flow = (222,033 + 81,875) kg/d = 303,908 kg/d

vi. Determine the mass quantities of gas and sludge after digestion.

Fixed solids = TSS_M - VSS_M = (16,597– 11,706) kg/d

= 4891 kg/d

TSS in digested sludge = 4891 kg/d + 0.5(11,706) kg/d

= 10,744 kg/d

Gas production assuming that the density of digester gas is equal to 0.86 times that of air (1.202 kg/m^3):

Gas = (1.12 m^3/kg)(5853 kg/d)(0.86)(1.202 kg/m^3) = 6776 kg/d

Mass balance of digester output:

Mass input	303,908 kg/d	
Less gas	- 6776 kg/d	
Mass output	297,132 kg/d	(solids and liquid)

vii. Determine the flowrate distribution between the supernatant at 5,000 mg/L and digested sludge at 5 percent solids. Let S = kg/d of supernatant suspended solids.

$$\frac{S}{0.005} = \frac{(10{,}744\,\text{kg/d}) - S}{(0.05)} = 297{,}132$$

S + 1074 – 0.1S = 1486 kg/d

S = 457 kg/d

Digested solids = (10,744 – 457) kg/d = 10,287 kg/d

$$\text{Supernatant flowrate} = \frac{(457\ \text{kg/d})}{(0.005)(10^3\ \text{kg/m}^3)} = 91.4\ \text{m}^3\text{/d}$$

$$\text{Digested sludge flowrate} = \frac{(10{,}287\ \text{kg/d})}{(0.05)(10^3\ \text{kg/m}^3)} = 205.7\text{m}^3\text{/d}$$

viii. Establish the characteristics of the recycled flow (supernatant).

BOD_M = (91.4 m^3/d)(1000 g/m^3)/(10^3 g/1 kg) = 91 kg/d

TSS_M= (91.4 m^3/d)(5000 g/m^3)/(10^3 g/1 kg) = 457 kg/d

f. Sludge dewatering.

i. Determine the sludge cake characteristics.

Digested solids = 10,287 kg/d (0.93) = 9567 kg/d

$$\text{Volume} = \frac{\left(9567\ \text{kg/d}\right)}{(0.22)(1.06)(10^3\ \text{kg/m}^3)} = 41\ \text{m}^3\text{/d}$$

ii. Determine the centrate characteristics.

Flowrate = (205.7 – 41) m^3/d = 164.7 m^3/d

BOD_M = (164.7 m^3/d) (2000 g/m^3)/(10^3 g/kg) = 329 kg/d

TSS_M = (10,287 kg/d)(0.07) = 720 kg/d

g. Prepare a summary table of the recycle flows and waste characteristics for the second iteration

Operation/process	Flow, m^3/d	BOD_M, kg/d	TSS_M, kg/d	Change from previous iteration Flow, m^3/d	Change from previous iteration BOD_M, kg/d	Change from previous iteration TSS_M, kg/d
	272.1	228	364	-447.4	5	15
Digester supernatant	91.4	91	457	5.8	5	29
Centrate	164.7	329	720	3.7	7	16
Totals	528.2	648	1,541	-437.9	17	60

4. Prepare the third iteration of the solids balance.

a. Primary settling.

i. Operating parameters = same as those in the second iteration.

ii. TSSM and BODM entering the primary tanks.

TSSM = Influent TSS_M + recycled TSS_M

= (17,550 + 1541) kg/d = 19,091 kg/d

Total BOD_M = influent BOD_M + recycled BOD_M

= (18,360 + 648) kg/d = 19,008 kg/d

iii. BOD_M removed = 0.33(19,008 kg/d) = 6273 kg/d

iv. BOD_M to secondary = (19,008 – 6273) kg/d = 12,735 kg/d

v. TSS_M removed = 0.7(19,091 kg/d) = 13,364 kg/d

vi. TSS_M to secondary = (19,091 – 13,364) kg/d = 5727 kg/d

b. Volatile fraction of the primary sludge and effluent suspended solids; use volatile fraction from second iteration.

c. Secondary process

i. Operating parameters = same as those for the second iteration and as follows:

Aeration tank volume = 4700 m^3 SRT = 10 d

Y = 0.50 kg/kg $k_d = 0.06\ d^{-1}$

ii. Determine the BOD_C in the influent to the aeration tank

Flowrate to aeration tank = influent flowrate + recycle flowrate

= (54,000 + 528) m^3/d = 54,528 m^3/d

$$BOD_C = \frac{(12{,}735\ kg/d)(10^3\ g/1\,kg)}{(54{,}528\ m^3/d)} = 234\ g/m^3$$

iii. Determine the new concentration of mixed liquor VSS.

$$X_{VSS} = \frac{(10\,d)(54{,}528\ m^3/d)(0.5)[(234-6.2)\,g/m^3]}{4700\ m^3[1+(0.06\,d^{-1})(10\,d)]} = 8259\ g/m^3$$

iv. Determine the mixed liquor TSS.

X_{TSS} = 8,259/0.8 = 10,323 g/m^3

v. Determine the cell growth.

$P_{X,VSS} = Y_{obs}Q(S_o - S)\ /(10^3\ g/kg)$

$$= \frac{0.3125(54{,}528\,m^3/d)[(234-6.2)\,g/m^3]}{(10^3\ g/1\,kg)} = 3882\ kg/d$$

$P_{X,TSS}$ = 3882/0.8 = 4852 kg/d

vi. Determine the waste quantities discharged to the thickener.

Effluent TSS_M = 1188 kg/d (specified in the first iteration)

Total TSS_M to be wasted to the thickener = (4852 – 1188) kg/d

= 3664 kg/d

$$\text{Flowrate} = \frac{(3664\ \text{kg/d})(10^3\ \text{g/1kg})}{(10{,}323\ \text{g/m}^3)} = 355\ \text{m}^3/\text{d}$$

d. Flotation thickeners

i. Operating parameters: same as second iteration

ii. Determine the flowrate of the thickened sludge.

$$\text{Flowrate} = \frac{(3664\ \text{kg/d})(0.9)}{(10^3\ \text{kg/m}^3)(0.04)} = 82.4\ \text{m}^3/\text{d}$$

iii. Determine the flowrate recycled to the plant influent.

Recycled flowrate = (355 – 82.4) m^3/d = 272.6 m^3/d

iv. Determine the TSS_M to the digester.

TSS_M = (3664 kg/d)(0.9) = 3298 kg/d

v. Determine the TSS_M recycled to the plant influent.

TSS_M = (3664 – 3298) kg/d = 366 kg/d

vi. Determine the BOD_C and BOD_M of the TSS in the recycled flow

$$TSS_C\ \text{in recycle flow} = \frac{(366\ \text{kg/d})(10^3\ \text{g/1kg})}{(272.6\ \text{m}^3/\text{d})} = 1343\ \text{g/m}^3$$

BOD_C of TSS = (1343 g/m^3)(0.65)(1.42)(0.68) = 843 g/m^3

BOD_M = (843 g/m^3)(272.6 m^3/d)/(10^3 g/1 kg) = 230 kg/d

e. Sludge digestion

i. Operating parameters - same as second iteration

ii. Determine the total solids fed to the digester and the corresponding flowrate.

TSS_M = TSS_M from primary settling + waste TSS_M from thickener

TSS_M = (13,364 + 3298) kg/d = 16,662 kg/d

$$\text{Total flowrate} = \frac{(13{,}364\ \text{kg/d})}{0.06(10^3\ \text{kg/m}^3)} + \frac{(3298\ \text{kg/d})}{0.04(10^3\ \text{kg/m}^3)}$$

$$= (223 + 82)\ \text{m}^3/\text{d} = 305\ \text{m}^3/\text{d}$$

iii. Determine the total VSS_M fed to the digester.

VSS_M = 0.682(13,364 kg/d) + 0.80(3298 kg/d)

= (9114 + 2638) kg/d = 11,752 kg/d

$$\%\ \text{VSS in mixture fed to digester} = \frac{(11{,}752\ \text{kg/d})}{(16{,}662\ \text{kg/d})}(100) = 70.5\%$$

iv. Determine the VSS_M destroyed.

VSS_M destroyed = 0.5(11,752 kg/d) = 5876 kg/d

v. Determine the mass flow to the digester

Primary sludge at 6% solids:

$$\text{Mass flow} = \frac{(13{,}364\ \text{kg/d})}{0.06} = 222{,}733\ \text{kg/d}$$

Thickened waste activated sludge at 4% solids:

$$\text{Mass flow} = \frac{(3298\ \text{kg/d})}{0.04} = 82{,}450\ \text{kg/d}$$

Total mass flow = (222,733 + 82,450) kg/d = 305,183 kg/d

vi. Determine the mass quantities of gas and sludge after digestion.

Fixed solids = TSS_M - VSS_M = (16,662– 11,752) kg/d

= 4910 kg/d

TSS in digested sludge = 4910 kg/d + 0.5(11,752) kg/d

= 10,786 kg/d

Gas production assuming that the density of digester gas is equal to 0.86 times that of air (1.202 kg/m^3):

Gas = $(1.12\ m^3/kg)(5876\ kg/d)(0.86)(1.202\ kg/m^3) = 6803\ kg/d$

Mass balance of digester output:

Mass input	305,183 kg/d
Less gas	– 6803 kg/d
Mass output	298,380 kg/d (solids and liquid)

vii. Determine the flowrate distribution between the supernatant at 5000 mg/L and digested sludge at 5 percent solids. Let S = kg/d of supernatant suspended solids.

$$\frac{S}{0.005} = \frac{(10{,}786\ kg/d) - S}{(0.05)} = 298{,}380\ kg/d$$

$S + 1079 - 0.1S = 1492\ kg/d$

$S = 459\ kg/d$

Digested solids = (10,786 – 459) kg/d = 10,327 kg/d

$$\text{Supernatant flowrate} = \frac{(459\ kg/d)}{(0.005)(10^3\ kg/m^3)} = 91.8\ m^3/d$$

$$\text{Digested sludge flowrate} = \frac{(10{,}327\ kg/d)}{(0.05)(10^3\ kg/m^3)} = 202\ m^3/d$$

viii. Establish the characteristics of the recycled flow (supernatant).

$BOD_M = (91.8\ m^3/d)(1000\ g/m^3)/(10^3\ g/1\ kg) = 92\ kg/d$

$TSS_M = (91.8\ m^3/d)(5000\ g/m^3)/(10^3\ g/1\ kg) = 459\ kg/d$

f. Sludge dewatering.

i. Determine the sludge cake characteristics.

Digested solids = (10,327 kg/d)(0.93) = 9604 kg/d

$$\text{Volume} = \frac{(9604\ kg/d)}{(0.22)(1.06)(10^3\ kg/m^3)} = 41.2\ m^3/d$$

ii. Determine the centrate characteristics.

Flowrate = (206.5 – 41.2) m^3/d = 165.3 m^3/d

BOD_M = (165.3 m^3/d) (2000 g/m^3)/(10^3 g/kg) = 331 kg/d

TSS_M = (10,327 kg/d)(0.07) = 723 kg/d

g. Prepare a summary table of the recycle flows and waste characteristics for the third iteration.

Operation/process	Flow, m^3/d	BOD_M, kg/d	TSS_M, kg/d	Incremental change from previous iteration Flow, m^3/d	 BOD_M, kg/d	 TSS_M, kg/d
Flotation thickener	272.6	230	368	0.5	2	2
Digester supernatant	91.8	92	454	0.4	1	2
Centrate	165.3	331	702	0.6	2	3
Totals	529.7	653	1,524	1.5	5	7

Because the incremental change is less than 5%, this is the final iteration.

PROBLEM 14-8

Problem Statement - See text, pages 1653

Solution – for Parameter series A

1. Determine the daily TSS_M loading rate.

$$TSS_M = \frac{(4000\ m^3/d)(10^3\ g/m^3)}{(10^3\ g/1\ kg)} = 4000\ kg/d$$

2. Prepare the first iteration of the solids balance.

a. Primary settling

i. Suspended solids removed and sent to the thickener

TSS_M = 0.75 (4,000 kg/d) = 3,000 kg/d

ii. Volume of sludge $= \dfrac{(3000\ \text{kg/d})}{(0.07)(1.1)(10^3\ \text{kg/m}^3)} = 39.0\ \text{m}^3/\text{d}$

iii. TSS_M to filter = (4000 - 3000) kg/d = 1000 kg/d

iv. Volume of filter influent = (4000 – 39.0) m^3/d = 3961 m^3/d

b. Alum addition

i. Dosage = (3961 m^3/d)(10 g/m^3) (1 kg/10^3 g) = 39.6 kg/d

ii. Volume $= \dfrac{(39.6\ \text{kg/d})}{(0.5\ \text{kg/L solution})} = 79.1\,\text{L/d} = 0.079\,\text{m}^3/\text{d}$

c. Filter operation.

i. TSS_M in influent = (600 + 39.6) kg/d = 639.6 kg/d

ii. TSS_M removed = (0.90)(639.6 kg/d) = 575.6 kg/d

iii. Backwash volume $= \dfrac{(575.6\ \text{kg/d})}{(0.06)(1.08)(10^3\ \text{kg/m}^3)}$ = 8.9 m^3/d

iv. Effluent TSS mass and concentration

TSS_M = (639.6 - 575.6) kg/d = 64 kg/d

Volume of effluent = (3956 + 0.079 - 8.9) m^3/d = 3,947 m^3/d

$$\text{TSS}_\text{C} = \frac{(64\,\text{kg/d})(10^3\,\text{g}/1\,\text{kg})}{(3947\,\text{m}^3/\text{d})} = 16.2\ \text{g/m}^3$$

d. Thickener

i. Determine the solids distribution from the thickener.

a) Solids balance.

3400 kg/d = 0.12 S + [(500 g/m^3)/(10^3 g/1 kg) V]

where S = mass of sludge, kg/d

V = volume of effluent, m^3/d

b) Volume balance.

$$44.2\,\text{m}^3/\text{d} = \frac{S}{(1.25)(10^3\,\text{kg/m}^3)} + V$$

Solving for S and V: S = 28,244 kg/d

V = 21.6 m^3/d

ii. TSS_M to filter press = 0.12 (28,244 kg/d) = 3389.2 kg/d

iii. TSS_M to plant influent = (3400 – 3389.2) kg/d = 10.8 kg/d

iv. Volume of thickened sludge $= \dfrac{(3389.2\ \text{kg/d})}{(0.12)(1.25)(10^3\ \text{kg/m}^3)}$ = 22.6 m^3/d

v. Volume of effluent = 21.6 m^3/d

e. Ferric chloride addition

i. Ferric chloride dosage = (0.01)(3389.2 kg/d) = 33.9 kg/d

ii. Volume of dosage $= \dfrac{(33.9\,\text{kg/d})}{(2.0)(10^3\,\text{kg/m}^3)}$ = 0.016 m^3/d

iii. TSS_M sent to filter press = (3389.2 + 33.9) kg/d = 3,423.1 kg/d

f. Filter press

i. Determine the solids distribution.

a) Solids balance.

3423.1 kg/d = 0.4 S + [(200 g/m^3)/(10^3 g/1 kg) V]

where S = mass of sludge, kg/d

V = volume of effluent, m^3/d

b) Volume balance.

$$22.6\,\text{m}^3/\text{d} = \frac{S}{(1.6)(10^3\,\text{kg/m}^3)} + V$$

Solving for S and V: S = 8549.1 kg/d; V = 17.3 m^3/d

ii. TSS_M in cake = (0.40)(8549.1 kg/d) = 3419.6 kg/d

iii. TSS_M in filtrate = (3423.1 – 3419.6) kg/d = 3.5 kg/d

iv. Volume of cake $= \dfrac{(3419.6\ \text{kg/d})}{(0.40)(1.6)(10^3\ \text{kg/m}^3)}$ = 5.3 m^3/d

v. Volume of filtrate = 17.3 kg/d

g. Prepare a summary of the recycle flows and suspended solids for the first iteration.

Operation/process	Flow, m^3/d	TSS_M, kg/d

Filter	8.9	575.6
Thickener	21.6	10.8
Filter press	17.3	3.5
Total	47.8	589.8

3. Prepare the second iteration of the solids balance.

   a. Primary settling

      i. Influent TSS_M= (4000 + 589.9) kg/d = 4589.9 kg/d

      ii. TSS_M removed = (0.85)(4589.9 kg/d) = 3901.4 kg/d

      iii. $\text{Volume of sludge} = \dfrac{(3901.4\ \text{kg/d})}{(0.07)(1.1)(10^3\ \text{kg/m}^3)} = 50.7\ \text{m}^3/\text{d}$

      iv. TSS_M to filter = (4589.9 - 3901.4) kg/d = 688.5 kg/d

      iv. Volume of filter influent = (4000 + 47.8 – 50.7) m^3/d

      = 3997.1 m^3/d

   b. Alum addition

      i. Dosage = (3,997.1 m^3/d)(10 g/m^3)/(10^3 g/1 kg) = 40.0 kg/d

      ii. $\text{Volume} = \dfrac{(40.0\ \text{kg/d})}{(0.5\ \text{kg/L solution})} = 80\ \text{L/d} = 0.080\ \text{m}^3/\text{d}$

   c. Filter operation

      i. TSS_M in influent = (688.5 + 40.0) kg/d = 728.5 kg/d

      ii. TSS_M removed = (0.90)(728.5 kg/d) = 655.6 kg/d

      iii. $\text{Backwash volume} = \dfrac{(655.6\ \text{kg/d})}{(0.06)(1.08)(10^3\ \text{kg/m}^3)} = 10.1\ \text{m}^3/\text{d}$

      iv. Effluent TSS mass and concentration

      TSS_M = (728.5 - 655.6) kg/d = 72.9 kg/d

      Volume of effluent = 3,987.1 m^3/d

      $TSS_C = \dfrac{(72.9\ \text{kg/d})(10^3\ \text{g/1kg})}{(3987.1\ \text{m}^3/\text{d})}$ = 18.3 g/m^3

   d. Thickener

      i. Determine the solids distribution from the thickener.

a) Solids balance

$3901.4 \text{ kg/d} = 0.12 \text{ S} + [(500 \text{ g/m}^3)/(10^3 \text{ g/1 kg}) \text{ V}]$

b) Volume balance

$$50.7 \text{ m}^3/\text{d} = \frac{\text{S}}{1.25\ (10^3 \text{ kg/m}^3)} + \text{V}$$

Solving for S and V: S = 32,408 kg/d; V = 24.8 m^3/d

ii. TSS_M to filter press = 0.12 (32,408 kg/d) = 3889.0 kg/d

iii. TSS_M to plant influent = (3901.4 - 3889.0) kg/d = 12.4 kg/d

iv. Volume of thickened sludge =

$$= \frac{(3889.0 \text{ kg/d})}{0.12(1.25)(10^3 \text{ kg/m}^3)} = 25.9 \text{ m}^3/\text{d}$$

v. Volume of effluent = 24.8 m^3/d

e. Ferric chloride addition

i. Ferric chloride dosage = 0.01 (3,889.0 kg/d) = 38.9 kg/d

ii. Volume of dosage $= \dfrac{(38.9 \text{ kg/d})}{(2.0)(10^3 \text{ kg/m}^3)} = 0.019 \text{ m}^3/\text{d}$

iii. TSS_M sent to filter press = (3889.0 + 38.9) kg/d = 3927.9 kg/d

f. Filter press

i. Determine the solids distribution.

a) Solids balance.

$3927.9 \text{ kg/d} = 0.4 \text{ S} + [(200 \text{ g/m}^3)/(10^3 \text{ g/kg}) \text{ V}]$

b) Volume balance.

$$25.9 \text{ m}^3/\text{d} = \frac{\text{S}}{(1.6)(10^3 \text{ kg/m}^3)} + \text{V}$$

Solving for S and V: S = 9809.9 kg/d; V = 19.8 m^3/d

ii. TSS_M in cake = 0.40 (8809.9 kg/d) = 3924.0 kg/d

iii. TSS_M in filtrate = (3927.9 – 3924.0) kg/d = 3.9 kg/d

iv. Volume of cake $= \dfrac{(3924.0\ \text{kg/d})}{(0.40)(1.6)(10^3\ \text{kg/m}^3)} = 6.1\ \text{m}^3/\text{d}$

v. Volume of filtrate = 19.8 kg/d

g. Prepare a summary of the recycle flows and suspended solids for the second iteration.

			Incremental values	
Operation/process	Flow, m^3/d	TSS, kg/d	Flow, m^3/d	TSS, kg/d
Filter	10.1	656.6	1.2	80.0
Thickener	24.8	12.4	3.2	1.6
Filter press	19.8	3.9	2.5	0.4
Total	54.7	671.9	6.9	82.0

4. Prepare the third iteration of the solids balance.

a. Primary settling

i. Influent suspended solids = (4000 + 671.9) kg/d = 4671.9 kg/d

ii. Suspended solids removed = (0.85)(4671.9 kg/d) = 3971.1 kg/d

iii. Volume of sludge $= \dfrac{(3971.1\ \text{kg/d})}{(0.07)(1.1)(10^3\ \text{kg/m}^3)} = 51.6\ \text{m}^3/\text{d}$

iv. Suspended solids to filter= (4671.9 - 3971.1) kg/d = 700.8 kg/d

v. Volume of filter influent = (4000 + 54.7 – 51.6) m^3/d

= 4003.1 m^3/d

b. Alum addition

i. Dosage = (4003.1 m^3/d)(10 g/m^3) (1 kg/10^3 g) = 40.0 kg/d

ii. Volume $= \dfrac{(40.0\ \text{kg/d})}{(0.5\ \text{kg/L solution})} = 80\ \text{L/d} = 0.080\ \text{m}^3/\text{d}$

c. Filter operation

i. Total solids in influent = (700.8 + 40.0) kg/d = 740.8 kg/d

ii. Suspended solids removed = (0.90)(740.8 kg/d) = 666.7 kg/d

iii. Backwash volume $= \dfrac{(666.7 \text{ kg/d})}{(0.06)(1.1)(10^3 \text{ kg/m}^3)} = 10.1 \text{ m}^3\text{/d}$

iv. Effluent TSS mass and characteristics

TSS_M = (740.8 - 666.7) kg/d = 74.1 kg/d

Volume of effluent = (4003.1 + 0.1 - 10.1) m^3/d = 3993.1 m^3/d

$$TSS_C = \frac{(74.1 \text{ kg/d})(10^3 \text{ g/kg})}{(3993.1 \text{ m}^3\text{/d})} = 18.6 \text{ g/m}^3$$

d. Thickener

i. Determine the solids distribution from the thickener.

a) Solids balance.

3971.1 kg/d = 0.12 S + [(500 g/m^3)/(10^3 g/1 kg) V]

b) Volume balance.

$$51.6 \text{ m}^3\text{/d} = \frac{S}{(1.25)(10^3 \text{ kg/m}^3)} + V$$

Solving for S and V: S = 32,988 kg/d; V = 25.2 m^3/d

ii. TSS_M to filter press = 0.12 (32,988 kg/d) = 3958.5 kg/d

iii. TSS_M to plant influent = (3971.1 - 3958.5) kg/d = 12.6 kg/d

iv. Volume of thickened sludge

$$= \frac{(3958.5 \text{ kg/d})}{(0.12)(1.25)(10^3 \text{ kg/m}^3)} = 26.4 \text{ m}^3\text{/d}$$

v. Volume of effluent = 25.2 m^3/d

e. Ferric chloride addition

i. Ferric chloride dosage = 0.01 (3958.5 kg/d) = 39.6 kg/d

ii. Volume of dosage $= \dfrac{(39.6 \text{ kg/d})}{(2.0)(10^3 \text{ kg/m}^3)} = 0.020 \text{ m}^3\text{/d}$

iii. TSS_M to filter press = (3958.5 + 39.6) kg/d = 3998.1 kg/d

f. Filter press

i. Determine the solids distribution.

a) Solids balance.

3998.1 kg/d = 0.4 S + [(200 g/m^3)/(10^3 g/1 kg) V]

b) Volume balance.

$$26.4\ \mathrm{m^3/d} = \frac{S}{(1.6)(10^3\ \mathrm{kg/m^3})} + V$$

Solving for S and V: S = 9985.2 kg/d; V = 20.2 m^3/d

ii. TSS_M in cake = 0.40 (9985.2 kg/d) = 3994.1 kg/d

iii. TSS_M in filtrate = (3998.1 - 3944.1) kg/d = 4.0 kg/d

iv. Volume of cake $= \dfrac{(3994.1\ \mathrm{kg/d})}{(0.40)(1.6)(10^3\ \mathrm{kg/m^3})} = 6.2\ \mathrm{m^3/d}$

v. Volume of filtrate = 20.2 kg/d

g. Prepare a summary of the recycle flows and suspended solids for the third iteration.

			Incremental values	
Operation/process	Flow, m^3/d	TSS_M, kg/d	Flow, m^3/d	TSS_M, kg/d
Filter	10.1	666.7	0.0	11.1
Thickener	25.2	12.6	0.4	0.2
Filter press	20.2	4.0	0.4	0.1
Total	55.5	683.3	0.8	11.4

Because the incremental change is less than 5%, this is the final iteration.

PROBLEM 14-9

Problem Statement - See text, page 1654

The HHV for the biosolids in Example14-2 (on a dry basis) was 17.88 MJ/kg based on the lab measurements. In order to estimate the heating value for the solids for 25% solids the solids percentage can simply be applied to the HHV on a dry basis which equals 4.47 MJ/kg. At 25% solids, 75% of the biosolids going to the incinerator are water and would require 2.3 MJ/kg H_2O of latent heat to evaporate. Although there is sufficent energy in the biosolids to meet the latent heat requirements to evaporate the water, this does not account for all of the heating requirmements in the system. Besides evaporating water, the energy to heat the flue gas, ash, and water vapor to the desired operating temperture also have to be considered as well as heat losses from the system. This heat balance is shown in Eq. 14-9. As can be found by comparing the heating requirements at various solid contents, as the solid content goes up the amount of energy produced drops and the need for supplemental energy may not be required.

In addition, many modern incinerators, also incorporate heat recovery where combustion air to the incinerator is preheated with flue gas exiting the incinerator. This preheating system improves the overall efficiency of the incinerator and can allow biosolids with higher moisure contents to be burned autothermally where in other cases they may not be.

PROBLEM 14-10

Problem Statement - See text, page 1654

Solution

1. Determine the biosolids application rate for the first year.
    a. Determine the amount of biosolids that must be applied during the first year to meet the nitrogen requirement.

       From Table 14-29, the nitrogen uptake for Reed canary grass is about 400 kg/ha•y.

       Compute the biosolids application rate for the first year. A nitrogen mineralization rate of 30% occurs during the first year (given in problem statement). Let X = biosolids application rate.

       Nitrogen uptake rate (400 kg/ha•y)(1 y) = X (0.03)(0.30)

$$\text{Biosolids application rate} = \frac{(400\,\text{kg/ha}\bullet\text{y})(1\text{ y})}{(0.03)(0.30)} = 44{,}444\ \text{kg/ha}$$

b. The amount of nitrogen applied is (44,444 kg/ha)(0.03) = 1,333 kg/ha

c. The residual nitrogen remaining at the end of year 1 is:

Residual nitrogen = (1333 – 400) kg/ha = 933 kg/ha

d. The residual nitrogen remaining from the first year application that is mineralized and is available for crop uptake for year 2 is:

Nitrogen available for crop uptake = (0.15) 933 kg/ha = 140 kg/ha

Residual nitrogen = (933 – 140) kg/ha = 793 kg/ha

Crop uptake nitrogen for year 2 = (400 – 140) kg/ha = 260 kg/ha

2. Determine the application rate of biosolids for year 2 to supply the nitrogen needed for crop uptake and the residual nitrogen.

a. Determine the amount of biosolids that must be applied during the second year to meet the nitrogen requirement.

$$\text{Biosolids application rate} = \frac{(260\ \text{kg/ha}\bullet\text{y})(1\text{ y})}{(0.03)(0.30)} = \ 28{,}889\,\text{kg/ha}$$

b. The amount of nitrogen applied is (28,889 kg/ha)(0.03) = 867 kg/ha

c. The residual nitrogen for year 2 is:

Residual nitrogen = [(1 – 0.30) 867 + 793] kg/ha = 1400 kg/ha

1. A computation table for these and subsequent years is given below.

Application	Biosolids applied, kg/ha	Nitrogen, kg/ha		Annual mineralization rate	Nitrogen, kg/ha	
		Applied in biosolids	Residual from prior year's application		Crop uptake	Residual
Year 1	44,444	1,333	0	0.30	400	933
Year 2						
Residual from year 1			933	0.15	140	793
New application	28,889	867		0.30	260	607
Year 3						
Residual from year 1			793	0.05	40	753
Residual from year 2			607	0.15	91	516
New application	29,889	897		0.30	269	628

Year 4						
Residual from year 1			753	0.05	38	715
Residual from year 2			516	0.05	26	490
Residual from year 3			628	0.15	94	534
New application	26,889	807		0.30	242	565
Year 5						
Residual from year 1			715	0.05	36	679
Residual from year 2			490	0.05	25	465
Residual from year 3			534	0.05	27	507
Residual from year 4			565	0.15	85	480
New application	25,222	757		0.30	227	530

PROBLEM 14-11

Problem Statement - See text, page 1654

Solution

1. Determine the yearly allowable mass loading to the soil.

$$\text{Loading rate} = \frac{(10\,\text{kg/ha})}{(50\,\text{y})} = 0.2\,\text{kg/ha} \bullet \text{y}$$

2. Determine the yearly allowable biosolids application rate. Note: 50 ppm = 50 kg/10^6 kg.

$$\text{Application rate} = \frac{(0.2\ \text{kg/ha} \bullet \text{y})}{(50\ \text{kg}/10^6\,\text{kg})} = 4000\ \text{kg/ha} \bullet \text{y}$$

PROBLEM 14-12

Problem Statement - See text, page 1654

Solution

Advantages	Disadvantages
Liquid biosolids transport	
• Ease and speed of loading and unloading • Dual-purpose, self-contained tank trucks equipped with subsurface injectors can be used, thus eliminating intermediate storage and pumping • Tank trucks are less susceptible to spills and odors	• Generally suitable for comparatively short hauling distances (less than one hour one-way travel time) • Dual purpose vehicles can only carry relatively small amounts of liquid biosolids
Dewatered biosolids transport	
• Fewer trips to disposal site are needed • Longer haul distances are more economical than liquid transport • Sludge cake less susceptible to load shifting than liquid sludge	• Special water-tight truck bodies are required to prevent leakage • Re-handling and transfer to spreading equipment often is required • Open truck bodies need to be covered to control odors and vectors

PROBLEM 14-13

Problem Statement - See text, page 1654

Solution

1. The advantages and limitations are summarized in the following table.

Advantages	Limitations
• Depending on the biosolids characteristics and specific site conditions, biosolids can be transported long distances • Pipeline facilities may be less expensive than truck hauling for long distance transport of biosolids • Pipelines may have a less environmental impact than truck hauling	• Hydraulic characteristics of biosolids can vary widely and have to be investigated carefully to identify critical design parameters • Special pumping equipment may be required and must be designed for high and variable friction losses • Maintenance provisions must be included for cleaning of pipeline and servicing, repair, and replacement of pumping equipment and other appurtenances • Rights-of-way and easements for pipeline may be difficult to obtain • Thickening characteristics at receiving point may be adversely affected by pumping and transport • Corrosion protection of pipeline must be considered

2. The types of facilities required include:
    - Pumping station typically containing a sludge grinder or sludge screen, sludge pumps (for types and application see Table 13-13 of text), source of flushing water, cleaning station for insertion of a cleaning tool (commonly termed a "pig"), and ancillary valves and controls, especially to control pressure surges (water hammer) in the case of emergency shutdown of pumping equipment.
    - For long pipelines, an intermediate cleaning station for reception and insertion of a cleaning tool, and, in some cases, a booster pumping station.
    - At the terminus of the pipeline, a biosolids storage tank and sludge transfer pumping facilities
    - For liquid sludge application, a vehicle similar to one of the types shown on Fig. 14-35
3. Operation and maintenance considerations include odor control at the biosolids storage tank and the land application site, uniform application of biosolids at proper application rates, redundant equipment, and good housekeeping.

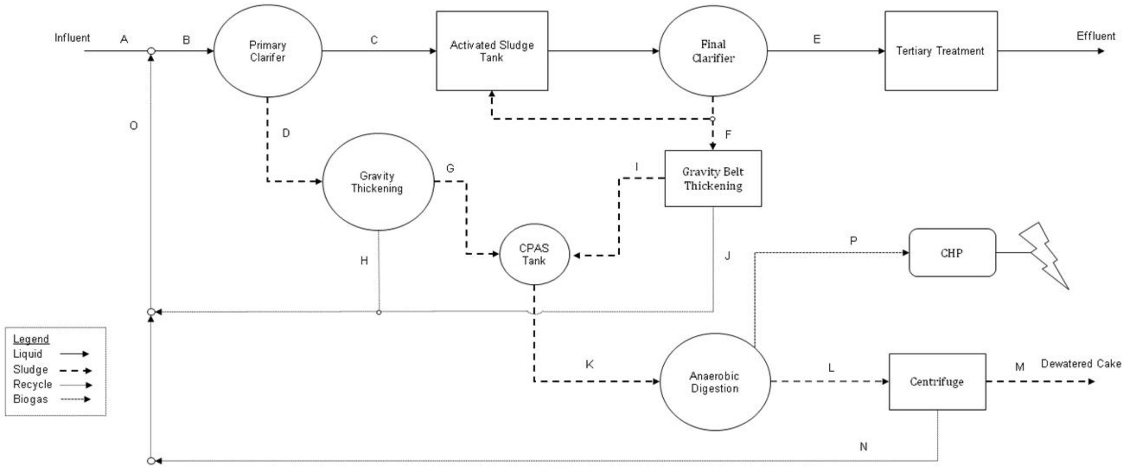
PROBLEM 14-14

Problem Statement - See text, pages 1654

Instructors Note: This problem is intended to help the student understand in detail the solids balance procedure. It is recommended for the student to work in groups and set up a spreadsheet program to solve the problem. For the computations presented below, the unit g/m^3 is used in lieu of mg/L.

Solution

Before starting the problem a process flow diagram of the treatment plant should be set up similar to the one shown below.



To fully solve the problem it is recommended that the student use a spreadsheet software to set up the mass balance calculations. An output matrix from a sheet may look similar to the one shown below. The output matrix shows conditions at Annual Average without accounting for Reycle (AA-NR), Annual Average with Recycle (AA-WR). The matrix also shows the mass balance at Max Month, Max Week and Max Day conditions. Details of the specific calcuations are shown below this table. The specific caclulations are shown with and without the impact of the recycle stream at average daily conditions. Alternatively, the iterative procedure could also be used as shown in Example 14-3.

Stream	Para- meter	Units	AA - NR	AA - WR	Max Month	Max Week	Max Day
Influent (A)	Flow	m^3/d	500,000	500,000	650,000	700,000	750,000
	Flow (wet)	kg/d	500,000,000	500,000,000	650,000,000	700,000,000	750,000,000
	TSS	mg/L	430	430	430	430	430
	VSS	mg/L	345	345	345	345	345
	BOD	mg/L	335	335	335	335	335
	TSS	kg/d	215,000	215,000	279,500	301,000	322,500
	VSS	kg/d	172,500	172,500	224,250	241,500	258,750
	BOD	kg/d	167,500	167,500	217,750	234,500	251,250

Influent + recycle (B)	Flow	m^3/d	500,000	513,512	667,566	718,917	770,268
	Flow (wet)	kg/d	500,000,000	513,512,250	667,565,924	718,917,149	770,268,374
	TSS	mg/L	430	446	446	446	446
	VSS	mg/L	345	355	355	355	355
	BOD	mg/L	335	345	345	345	345
	TSS	kg/d	215,000	229,157	297,904	320,819	343,735
	VSS	kg/d	172,500	182,520	237,275	255,527	273,779
	BOD	kg/d	167,500	177,127	230,266	247,978	265,691
Secondary treatment influent (C)	Flow	m^3/d	492,833	505,874	657,636	708,223	758,811
	Flow (wet)	kg/d	492,833,333	505,873,692	657,635,799	708,223,168	758,810,537
	TSS	mg/L	218	226	226	226	226
	VSS	mg/L	175	180	180	180	180
	BOD	mg/L	238	245	245	245	245
	TSS	kg/d	107,500	114,578	148,952	160,410	171,868
	VSS	kg/d	86,250	91,260	118,638	127,764	136,890
	BOD	kg/d	117,250	123,989	161,186	173,585	185,984
Primary sludge (D)	Flow	m^3/d	7167	7639	9930	10,694	11,458
	Flow (wet)	kg/d	7,166,667	7,638,558	9,930,125	10,693,981	11,457,837
	% TSS rem	%	50%	50%	50%	50%	50%
	% BOD rem	%	30%	30%	30%	30%	30%
	TSS	mg/L	15,000	15,000	15,000	15,000	15,000
	VSS	mg/L	12,035	11,947	11,947	11,947	11,947
	BOD	mg/L	7012	6957	6957	6957	6957
	TSS	kg/d	107,500	114,578	148,952	160,410	171,868
	VSS	kg/d	86,250	91,260	118,638	127,764	136,890
	BOD	kg/d	50,250	53,138	69,080	74,394	79,707
Secondary effluent (E)	Flow	m^3/d	486,816	499,502	649,353	699,303	749,254
	BOD	mg/L	10	10	10	10	10
Waste activated sludge (F)	Flow	m^3/d	6017	6371	8283	8920	9557
	Flow (wet)	kg/d	6,017,232	6,371,274	8,282,657	8,919,784	9,556,912
	Y_{obs}	g VSS/g BOD	0.375	0.375	0.375	0.375	0.375
	VS/TS %	% VS/TS	70%	70%	70%	70%	70%
	TSS	mg/L	10,000	10,000	10,000	10,000	10,000

	VSS	mg/L	7000	7000	7000	7000	7000
	TSS	kg/d	60,172	63,713	82,827	89,198	95,569
	VSS	kg/d	42,121	44,599	57,979	62,438	66,898
Thickened primary sludge (G)	Flow	m^3/d	1983	2114	2748	2959	3170
	Flow (wet)	kg/d	2,042,500	2,176,989	2,830,086	3,047,785	3,265,484
	S.G.		1.03	1.03	1.03	1.03	1.03
	Capture rate	%	95%	95%	95%	95%	95%
	TS	kg/d	102,125	108,849	141,504	152,389	163,274
	VS	kg/d	81,938	86,697	112,706	121,376	130,045
	TS	% TS	5%	5%	5%	5%	5%
	VS%	% VS	80.2%	79.6%	79.6%	79.6%	79.6%
Gravity thickener effluent (H)	Flow	m^3/d	5124	5462	7100	7646	8192
	Flow (wet)	kg/d	5,124,167	5,461,569	7,100,040	7,646,197	8,192,353
	TSS	mg/L	1049	1049	1049	1049	1049
	VSS	mg/L	842	835	835	835	835
	BOD	mg/L	658	658	658	658	658
	TSS	kg/d	5375	5729	7448	8020	8593
	VSS	kg/d	4313	4563	5932	6388	6844
	BOD	kg/d	3374	3596	4674	5034	5394
Thickened waste activated sludge (I)	Flow	m^3/d	925	979	1273	1371	1469
	Flow (wet)	kg/d	952,728	1,008,785	1,311,421	1,412,299	1,513,178
	S.G.		1.03	1.03	1.03	1.03	1.03
	Capture rate	%	95%	95%	95%	95%	95%
	TS	kg/d	57,164	60,527	78,685	84,738	90,791
	VS	kg/d	40,015	42,369	55,080	59,317	63,553
	TS	% TS	6%	6%	6%	6%	6%
	VS%	% VS	70.0%	70.0%	70.0%	70.0%	70.0%
Gravity belt thickener effluent (J)	Flow	m^3/d	5065	5362	6971	7507	8044
	Flow (wet)	kg/d	5,064,504	5,362,489	6,971,236	7,507,485	8,043,734
	TSS	mg/L	594	594	594	594	594
	VSS	mg/L	416	416	416	416	416
	BOD	mg/L	373	373	373	373	373
	TSS	kg/d	3009	3186	4141	4460	4778
	VSS	kg/d	2106	2230	2899	3122	3345
	BOD	kg/d	1888	1999	2599	2799	2999

Combined primary and activated sludge (K)	Flow	m^3/d	2908	3093	4021	4330	4639
	Flow (wet)	kg/d	2,995,228	3,185,774	4,141,506	4,460,084	4,778,661
	S.G.		1.03	1.03	1.03	1.03	1.03
	TS	kg/d	159,289	169,377	220,190	237,127	254,065
	VS	kg/d	121,952	129,066	167,786	180,692	193,599
	TS	% TS	5.3%	5.3%	5.3%	5.3%	5.3%
	VS%	% VS	76.6%	76.2%	76.2%	76.2%	76.2%
	Tank volume	m^3	40	40	40	40	40
	HRT	min	19.8	18.6	14.3	13.3	12.4
Digester	Dig Volume	m^3	12,490	12,490	12,490	12,490	12,490
	No. of digesters		4	4	5	5	5
	HRT	d	17.2	16.2	15.5	14.4	13.5
	VSS LR	$kg/m^3 \cdot d$	2.4	2.6	2.7	2.9	3.1
	Sludge heating	kJ/d	3.77E+08	4.01E+08	5.22E+08	5.62E+08	6.02E+08
Digested sludge (L)	Flow	m^3/d	2,849	3,030	3,939	4,242	4,545
	Flow (wet)	kg/d	2,934,252	3,121,241	4,057,614	4,369,738	4,681,862
	VSR	% VSR	50%	50%	50%	50%	50%
	VSR	kg/d	60,976	64,533	83,893	90,346	96,799
	S.G.		1.03	1.03	1.03	1.03	1.03
	TS	kg/d	98,313	104,844	136,297	146,781	157,266
	VS	kg/d	60,976	64,533	83,893	90,346	96,799
	TS	% TS	3.4%	3.4%	3.4%	3.4%	3.4%
	VS%	% VS	62.0%	61.6%	61.6%	61.6%	61.6%
Dewatered sludge production (M)	Flow	m^3/d	394	420	547	589	631
	Flow (wet)	kg/d	406,074	433,050	562,965	606,270	649,575
		tonne/d	406	433	563	606	650
	S.G.		1.03	1.03	1.03	1.03	1.03
	Capture rate	%	95%	95%	95%	95%	95%
	TS	kg/d	93,397	99,601	129,482	139,442	149,402
	VS	kg/d	57,927	61,306	79,698	85,829	91,959
	TS	% TS	23%	23%	23%	23%	23%
	VS%	% VS	62.0%	61.6%	61.6%	61.6%	61.6%

Centrifuge effluent (N)	Flow	m^3/d	2528	2688	3495	3763	4032
	Flow (wet)	kg/d	2,528,178	2,688,191	3,494,649	3,763,468	4,032,287
	TSS	mg/L	1944	1950	1950	1950	1950
	VSS	mg/L	1206	1200	1200	1200	1200
	BOD	mg/L	1500	1500	1500	1500	1500
	TSS	kg/d	4916	5242	6815	7339	7863
	VSS	kg/d	3049	3227	4195	4517	4840
	BOD	kg/d	3792	4032	5242	5645	6048
Total recycled flow (O)	Flow	m^3/d	12,717	13,512	17,566	18,917	20,268
	Flow (wet)	kg/d	12,716,849	13,512,250	17,565,924	18,917,149	20,268,374
	TSS	mg/L	1046	1048	1048	1048	1048
	VSS	mg/L	744	742	742	742	742
	BOD	mg/L	712	712	712	712	712
	TSS	kg/d	13,299	14,157	18,404	19,819	21,235
	VSS	kg/d	9,467	10,020	13,025	14,027	15,029
	BOD	kg/d	9,054	9,627	12,516	13,478	14,441
Biogas production (P)	Flow	m^3/h	2414	2554	3321	3576	3832
	Gas prod.	m^3/kg VSR	0.95	0.95	0.95	0.95	0.95
	Gas heat value	kJ/m^3	22,400	22,400	22,400	22,400	22,400
	Energy In gas	kJ/d	1.30E+09	1.37E+09	1.79E+09	1.92E+09	2.06E+09
	Boiler Output	kJ/d	1.04E+09	1.10E+09	1.43E+09	1.54E+09	1.65E+09
	η_{boiler}	%	80%	80%	80%	80%	80%
	CHP electric	kW	5,707	6,040	7,852	8,456	9,060
	η_{el}	%	38%	38%	38%	38%	38%
	CHP thermal	kJ/d	5.19E+08	5.49E+08	7.14E+08	7.69E+08	8.24E+08
	η_{th}	%	40%	40%	40%	40%	40%

As shown in the matrix above, the BOD, TSS and VSS loads in the recycle stream are; 9627 kg/d, 14,157 kg/d and 10,020 kg/d respectively. The flowrate of recycle is approximately 13,512 m^3/d.

1. To determine the amount of primary sludge, PS (stream D):

   Without recycle:

$$\text{PS} = (500{,}000\ \text{m}^3/\text{d})(430\ \text{g/m}^3)(0.5)\left(\frac{1\,\text{kg}}{10^3\ \text{g}}\right) = 107{,}500\ \text{kg/d}$$

Assume the VSS/TSS ratio in the influent is also the same as the primary sludge which is (345/430) = 0.8

At 1.5% TS (or 15,000 mg/L TSS concentration), the volume of primary sludge is

$$\text{Volume PS} = \frac{(107{,}500\ \text{kg/d})}{(15{,}000\ \text{g/m}^3)}\left(\frac{10^3\ \text{g}}{1\ \text{kg}}\right) = 7167\ \text{m}^3/\text{d}$$

With recycle, account for impact from total recycle (stream O), which based on the mass balance output includes 14,157 kg/d of TSS in the plant recycle:

$$\text{PS} = \left[(500{,}000\ \text{m}^3/\text{d})(430\ \text{g/m}^3)\left(\frac{1\,\text{kg}}{10^3\ \text{g}}\right) + (14{,}157\ \text{kg/d})\right](0.5)$$

$$= 114{,}578\ \text{kg/d}$$

It is known that the VSS/TSS in the influent is 0.8. The VSS/TSS in the recycle sludge is 0.71. The VSS/TSS of the primary sludge with recycle is

$$\%\ \text{VS/TS} = \frac{\left[(500{,}000\ \text{m}^3/\text{d})(345\ \text{g/m}^3)\left(\frac{1\,\text{kg}}{10^3\ \text{g}}\right) + (14{,}157\ \text{kg/d})(0.71)\right](0.5)}{(114{,}578\ \text{kg/d})}(100)$$

$$= 79.7\%\ \text{VS/TS}$$

At 1.5% TS (or 15,000 mg/L TSS concentration), the volume of primary sludge with recycle is:

$$\text{Volume PS} = \frac{(114{,}580\ \text{kg/d})}{(15{,}000\ \text{g/m}^3)}\left(\frac{10^3\ \text{g}}{1\,\text{kg}}\right) = 7639\ \text{m}^3/\text{d}$$

2. Determine the average amount of WAS produced (stream F).

   Before determining the waste activated sludge production the secondary treatment influent (stream C) needs to be determined in terms of volume, mass, TSS and BOD concentration

   Without recycle the BOD and TSS loads are:

$$\text{BOD} = (500{,}000\ \text{m}^3/\text{d})(335\ \text{g/m}^3)(1-0.3)\left(\frac{1\ \text{kg}}{10^3\ \text{g}}\right) = 117{,}250\ \text{kg/d}$$

$$\text{TSS} = (500{,}000\ \text{m}^3/\text{d})(430\ \text{g/m}^3)(1-0.5)\left(\frac{1\ \text{kg}}{10^3\ \text{g}}\right) = 107{,}500\ \text{kg/d}$$

In order to determine concentration, the volumetric flow needs to be determined:

Volume to secondary = (500,000 - 7167) m^3/d = 492,833 m^3/d

$$\text{BOD}_c = \left[\frac{(117{,}250\ \text{kg/d})}{(492{,}833\ \text{m}^3/\text{d})}\right]\left(\frac{10^3\ \text{g}}{1\text{kg}}\right) = 238\ \text{g/m}^3$$

$$\text{TSS}_c = \left[\frac{(107{,}500\ \text{kg/d})}{(492{,}833\ \text{m}^3/\text{d})}\right]\left(\frac{10^3\ \text{g}}{1\text{kg}}\right) = 218\ \text{g/m}^3$$

With recycle, accounting for 9,627 kg/d BOD and 14,157 kg/d TSS

$$\text{BOD} = \left[(500{,}000\ \text{m}^3/\text{d})(335\ \text{g/m}^3)\left(\frac{1\text{kg}}{10^3\ \text{g}}\right) + (9627\ \text{kg/d})\right](1-0.3)$$

$$= 123{,}989\ \text{kg/d}$$

$$\text{TSS} = \left[(500{,}000\ \text{m}^3/\text{d})(430\ \text{g/m}^3)\left(\frac{1\text{kg}}{10^3\ \text{g}}\right) + (14{,}157\ \text{kg/d})\right](1-0.5)$$

$$= 114{,}578\ \text{kg/d}$$

Volume to secondary = (500,000 + 13,512 - 7,639) m^3/d = 505,874 m^3/d

$$\text{BOD}_c = \left[\frac{(123{,}989\ \text{kg/d})}{(505.873\ \text{m}^3/\text{d})}\right]\left(\frac{10^3\ \text{g}}{1\text{kg}}\right) = 245\ \text{g/m}^3$$

$$\text{TSS}_c = \left[\frac{(114{,}578\ \text{kg/d})}{(505{,}873\ \text{m}^3/\text{d})}\right]\left(\frac{10^3\ \text{g}}{1\text{kg}}\right) = 226\ \text{g/m}^3$$

After knowing the secondary treament influent characteristics, the WAS production (stream F) in terms of VSS content (P_x) can be determined using Eq. (8-19), where the substrate S is BOD

$$P_x = Y_{obs}Q(S_o - S)$$

First Y_{obs} needs to be determined from Eq. 7-58, Part A.

$$= \frac{0.6}{1 + (0.06\,d^{-1})(10\,d)} = 0.375$$

Using the calculated Y_{obs}, and knowing the VSS/TSS ratio in the WAS is 0.7 the WAS production can be estimated.

Without recycle:

$$P_x = (0.375)\left[(117{,}250\ kg/d) - (492{,}833\ \ m^3/d)(10\,g/m^3)\left(\frac{1\,kg}{10^3\,g}\right)\right]$$

$$= 42{,}121\,kg\,VSS/d$$

$$WAS = \frac{(42{,}121\,kg\ VSS/d)}{(0.7\ kg\ VSS/kg\ TSS)} = 60{,}172\ kg/d$$

With recycle:

$$P_x = (0.375)\left[(123{,}989\ kg/d) - (505{,}873\ \ m^3/d)(10\,g/m^3)\left(\frac{1\,kg}{10^3\,g}\right)\right]$$

$$= 44{,}599\,kg\,VSS/d$$

$$WAS = \frac{(44{,}599\ kg\ VSS/d)}{(0.7\ kg\ VSS/kg\ TSS)} = 63{,}713\ kg/d$$

3. Determine the average amount of thickened primary sludge (TPS) as shown for (stream G)

Without accounting for recycle:

TPS = (107,500 kg/d)(0.95) = 102,125 kg/d (dry)

= (102,125 kg/d)/(0.05) = 2,042,500 kg/d (wet)

Accounting for recycle:

TPS = (114,578 kg/d)(0.95) = 108,849 kg/d (dry)

= (108,849 kg/d)/(0.05) = 2,176,989 kg/d (wet)

The volume of overflow returned to the primary clarifer can be determined

$$\text{Volume overflow } = \left[\frac{(114{,}580\ \text{kg/d})}{[0.015(1.5\%)]} - (2{,}176{,}989\ \text{kg/d})\right]\left(\frac{\text{m}^3}{10^3\ \text{kg}}\right) = 5462\ \text{m}^3/\text{d}$$

The mass of TSS in the overflow is 5729 kg/d (TSS_C = 1049 g/m^3) and it can be assumed that the TSS/VSS ratio is the same as primary sludge. The overflow needs to be accounted for in the recycle load.

4. Determine the average amount of thickened waste activated sludge (TWAS) as shown for (stream I)

Without accounting for recycle:

TWAS = (60,172 kg/d)(0.95) = 57,164 kg/d (dry)

= (57,164 kg/d)/(0.06) = 952,728 kg/d (wet)

Accounting for recycle:

TWAS = (63,713 kg/d)(0.95) = 60,527 kg/d (dry)

= (60,527 kg/d)/(0.06) = 1,008,785 kg/d (wet)

The volume of filtrate returned to the primary clarifer can be determined

$$\text{Volume filtrate} = \left[\frac{(63{,}713\ \text{kg/d})}{[0.01(1.0\%)]} - (1{,}008{,}785\ \ \text{kg/d})\right]\left(\frac{\text{m}^3}{10^3\ \text{kg}}\right) = 5362\ \text{m}^3/\text{d}$$

The mass of TSS in the filtrate is 3,186 kg/d (TSS_C = 594 mg/L) and it can be assumed that the TSS/VSS ratio is the same as WAS. The filtrate needs to be accounted for in the recycle load.

5. Combined Primary and Activated Sludge (CPAS) shown as (stream K)

Determine the combined solid content (% TS), combined volatile content (% VS), and volume flow out of the CPAS. Use that information to determine CPAS HRT

Without accounting for recycle:

CPAS (dry) = (102,125 + 57,164) kg (dry)/d = 159,289 kg (dry)/d

CPAS (wet) = (2,042,500 + 952,723) kg (dry)/d = 2,995,228 kg (wet)/d

$$\text{TS,\%} = \frac{(159{,}289\ \text{kg/d})}{(2{,}995{,}228\ \text{kg/d})}(100) = 5.3$$

To determine combined volatile content it is known that the VSS/TSS ratio in the influent is also the same as the primary sludge which is (345/430) = 0.8 and that the VSS/TSS ratio in the waste activated sludge is 0.7.

$$\mathrm{VS/TS,\%} = \left\{\frac{[(102{,}125)(0.8)+(57{,}164)(0.7)\ \mathrm{kg/d}]}{(159{,}289\ \mathrm{kg/d})}\right\}(100) = 76.6$$

The volumetric flow to the CPAS tank and HRT are calculated as:

$$Q_{\mathrm{CPAS}} = \frac{(2{,}995{,}223\ \mathrm{kg/d})}{(10^3\ \mathrm{kg/m^3})(1.03)} = 2908\ \mathrm{m^3/d}$$

$$\mathrm{HRT} = \left[\frac{(40\ \mathrm{m^3})}{(2908\ \mathrm{m^3/d})}\right]\left(\frac{1440\ \mathrm{min}}{1\ \mathrm{d}}\right) = 19.8\ \mathrm{min}$$

Accounting for recycle:

CPAS (dry) = (108,849 + 60,527) kg (dry)/d = 169,377 kg (dry)/d

CPAS (wet) = (2,176,982 + 1,008,789) kg (dry)/d = 3,185,774 kg (wet)/d

$$\mathrm{\%TS} = \left[\frac{(169{,}377\ \mathrm{kg/d})}{(3{,}185{,}774\ \mathrm{kg/d})}\right](100\%) = 5.3\%\ \mathrm{TS}$$

It has been previously calculated that the VSS/TSS ratio in the primary sludge is 0.797 and that the VSS/TSS ratio in the waste activated sludge is 0.7.

$$\mathrm{VS/TS,\%} = \left\{\frac{[(108{,}849)(0.797)+(60{,}527)(0.7)\ \mathrm{kg/d}]}{(169{,}377\ \mathrm{kg/d})}\right\}(100) = 76.2$$

The volumetric flow to the CPAS tank and HRT are calculated as:

$$Q_{\mathrm{CPAS}} = \frac{(3{,}185{,}774\ \mathrm{kg/d})}{(10^3\ \mathrm{kg/m^3})(1.03)} = 3093\ \mathrm{m^3/d}$$

$$\mathrm{HRT} = \left[\frac{40\ \mathrm{m^3}}{(3093\ \mathrm{m^3/d})}\right]\left(\frac{1440\ \mathrm{min}}{1\ \mathrm{d}}\right) = 18.6\ \mathrm{min}$$

6. Anaerobic Digestion Complex Calculations – For the sake of simplicity the calculations below are shown only for the loadings accounting for recycle. First calculate the usable volume of the the anaerobic digester using the following equation.

$$V_{Dig} = \frac{\pi D^2}{4} SWD + \frac{1}{3}\frac{\pi D^2}{4} H_{cone}$$

All values are given and the cone depth (H_{cone}) can be determined from the slope

$$H_{cone} = \frac{D}{(2)(10)} = \frac{(37 m)}{(2)(10)} = 1.85 m$$

$$V_{Dig} = \frac{\pi(37\ m)^2}{4}(11\ m) + \frac{1}{3}\frac{\pi(37\ m)^2}{4} 1.85\ m = 12{,}490\ m^3$$

a. Determine number of digesters – The digester inlet flow (stream K) with recycle which is 3,185,774 kg (wet)/d or 3093 m^3/d and because the max month peaking factor is 1.3, the flow at max month conditions can be estimated to be (3093 m^3/d)(1.3) = 4021 m^3/d. Knowing the flow, the number of digesters (N_{Dig}) can be estimated below.

$$N_{Dig} = \frac{(HRT)(Q)}{V_{Dig}} = \frac{(15\ d)(4021\ m^3/d)}{12{,}490\ m^3} = 4.8$$

Based on the computed value at least 5 digesters should be provided. A sixth digester may also be recommended if full redundancy is desired at max month conditions.

b. The number of digesters required to operate at annual average conditions, assuming 15 day HRT is desired is

$$N_{Dig} = \frac{(15\ d)(3093\ m^3/d)}{12{,}490\ m^3} = 3.7$$

At least four digesters should be in service during annual average conditions

c. To determine the volatile loading rate, the The VS load to the digester at average conditions needs to be determined.

VS = (169,377 kg /d)(0.762) = 129,066 kg/d

At max month conditions, the VS_{MM} load can be estimated assuming the VS/TS content is the same at both annual average and max month conditions

VS_{MM} = (129,066 kg/d)(1.3) = 167,786 kg/d

The VS loading rate at average conditions, assuming 4 digesters in service is:

$$\text{VS loading rate (AA)} = \frac{(129{,}066\ \text{kg/d})}{(4)(12{,}490\ \text{m}^3)} = 2.6\ \text{kg/m}^3\cdot\text{d}$$

If 5 digesters are in service the VS loading rate is:

$$\text{VS loading rate (AA)} = \frac{(129{,}066\ \text{kg/d})}{(5)(12{,}490\ \text{m}^3)} = 2.1\ \text{kg/m}^3\cdot\text{d}$$

At max month conditions with 5 digesters in service, the VS loading rate is:

$$\text{VS loading rate (MM)} = \frac{(167{,}786\ \text{kg/d})}{(5)(12{,}490\ \text{m}^3)} = 2.7\ \text{kg/m}^3\cdot\text{d}$$

At all conditions, the VS loading rate is within the normal range (1.6 – 4.8) kg/m^3·d as listed in Table 13-28.

d. The energy requirement to heat the sludge at annual average conditions from 5°C to 35°C is:

$q = (3{,}185{,}774\ \text{kg/d})(4.2\ \text{kJ/kg}\bullet{}^{o}\text{C})(35 – 5)\ {}^{o}\text{C} = 4.01 \times 10^{8}\ \text{kJ/d}$

For a real world design, the digester heat loss would not be zero and a heat loss calculation similar to what is shown in Example 13-7 should be performed. The calculations can be repeated at other conditions such as max month, max week or max day depending on desired design criteria for heating system.

e. At max day conditions the following parameters; flow (Q_{CPAS} at max day) and volatile loading (VS_{MD}) are needed and can be estimated if it is assumed that the TS and VS concentrations are the same at max day as annual average conditions.

Q_{CPAS} at max day = (3093 m^3/d)(1.5) = 4639 m^3/d

VS_{MD} = (129,066 kg/d)(1.5) = 193,599 kg/d

With 5 digesters in service the HRT would be:

$$\text{HRT} = \frac{(5)(12{,}490\ \text{m}^3)}{(4639\ \text{m}^3/\text{d})} = 13.5\ \text{d}$$

And the VS loading rate would be:

$$\text{VS loading rate (MD)} = \frac{(193{,}599\ \text{kg/d})}{(5)(12{,}490\ \text{m}^3)} = 3.1\,\text{kg/m}^3 \cdot \text{d}$$

At max day conditions, the HRT drops below the 15 d threshold for Class B but the volatile loading rate is still within the stated range according to Table 13-28. Because the max day loading is likely short instantaneous peak, maintaining the digester in service could be suitable as the relatively large volume and HRT will help buffer instantaneous peaks. If the peak loading is sustained and the digester becomes overloaded, sludge could be bypassed around the digester and either hauled or dewatered and hauled but these type practices are generally avoided except for emergency situations. Some plants have provisions for alkaline stabilization as back up processing outlets.

NOTE: The assumption for TS and VS concentration being the same at max day loadings is not always accurate and more detailed plant records should be consulted when setting the plant design basis and accounting for peak loads.

7. The amount of biogas produced (V_{DG}) at average conditions as shown in (Stream P) is:

   Without accounting for recycle:

   V_{DG} = (0.95 m^3/kg VSR)(159,289 kg /d)(0.766 kg VS/kg TS)(0.5) (1 d/24 h)
   = 2414 m^3/h

   Accounting for recycle:

   V_{DG} = (0.95 m^3/kg VSR)(169,377 kg /d)(0.762 kg VS/kg TS)(0.5) (1 d/24 h)
   = 2554 m^3/h

8. The CHP calculations presented below are just shown for annual average conditions accounting for recycle.

   a. The amount of electricity that can be produced is:

      Electricity = (2554 m^3/h)(22,400 kJ/m^3)(0.38)(1 h/3600 s) = 6040 kW

   b. The amount of heat that can be recovered from CHP is:

Heat = (2554 m^3/h)(22,400 kJ/m^3)(0.4)(24 h/1 d) = 5.49 x10^8 kJ/d

Beause the wintertime heat requirement to heat the sludge is 4.01 x10^8 kJ/d, there is sufficient energy available in the heat recovery from the CHP system. However, it should be noted that the digester heat requirement does not account for digester heat losses which must be considered for real world plant design.

9. The calculation below estimates how much gas is not used for digester heating (H_{DLO}), if the digester gas is heated with a boiler fired on digester gas. The calculation is shown for annual average wintertime conditions accounting for recycle:

   H_{DLO} = (2554 m^3/h)(22,400 kJ/m^3) (24 h/1 d) – (4.01 x10^8 kJ/d)/0.8
   = 8.72 x10^8 kJ/d

   The amount of electricity that can be produced with the leftover gas is:

   Electricity = (8.72 x10^8 kJ/d)(0.38)(1 d/86400 s) = 3,833 kW

10. Based on the energy management options, the scenario resulting from part 8 provides a higher electrical potential then from part 9 while also satisfying the thermal requirements for digestion. From an energy management standpoint, scenario 8 is more favorable.

11. Dewatering Calculations

    a. The dry solids loading going to the centrifuges after digestion (stream L) is:

       Without accounting for recycle:

       Cent. feed (VS) = (159,289 kg /d)(0.766 kg VS/kg TS)(1 – 0.5)
       = 60,976 kg VS/d

       Assume inert solids pass through

       Cent feed (inert) =
       159,289 kg /d - (159,289 kg /d)(0.766 kg VS/kg TS)
       = 37,337 kg inert/d

       Cent Feed (TS) = VS + inert = (60,976 + 37,274)kg/d
       = 98,313 kg/d

       Accounting for recycle:

Cent. feed (VS) = (169,377 kg /d)(0.762 kg VS/kg TS)(1 – 0.5)

= 64,533 kg VS/d

Assume inert solids pass through

Cent feed (inert) =

169,377 kg /d – (169,377 kg /d)(0.762 kg VS/kg TS)

= 40,311 kg inert/d

Cent feed (TS) = VS + inert = (64,533 + 40,312)kg/d

= 104,844 kg/d

b. The volatile solids content of the digested biosolids is:

Without accounting for recycle

$$\mathrm{VS/TS,\%} = \frac{(60{,}976\ \mathrm{kg\ VS/d})}{(98{,}313\ \mathrm{kg/d})}(100) = 62.0$$

Accounting for recycle:

$$\mathrm{VS/TS,\%} = \frac{(64{,}533\ \ \mathrm{kg\ VS/d})}{(104{,}844\ \mathrm{kg/d})}(100\%) = 61.6$$

c. To estimate the solid content of the digested biosolids, assume that the all of the water passes through the digester to the digester effluent.

Without accounting for recycle:

Water In feed sludge = 2,995,228 kg (wet)/d – 159,289 kg (dry)/d

= 2,835,939 kg/d

$$\mathrm{TS,\%} = \frac{(98{,}313\ \mathrm{kg/d})}{[(98{,}313 + 2{,}835{,}939)\ \mathrm{kg/d}]}(100) = 3.4$$

Accounting for recycle:

Water In feed sludge = 3,185,774 kg (wet)/d - 169,377 kg (dry)/d

= 3,016,397 kg/d

$$\mathrm{TS,\%} = \left\{\frac{(104{,}844\ \mathrm{kg/d})}{[(104{,}844 + 3{,}016{,}397)\ \mathrm{kg/d}]}\right\}(100) = 3.4$$

d. Volumetric Flow of digested sludge can be calculated as the following.

Without accounting for recycle:

$$\text{Volume digested} = \frac{[(98{,}313 + 2{,}835{,}939)\ \text{kg/d}]}{(1000\ \text{kg/m}^3)(1.03)} = 2849\ \text{m}^3/\text{d}$$

Accounting for recycle:

$$\text{Volume digested} = \frac{[(104{,}844 + 3{,}016{,}397)\ \text{kg/d}]}{(1000\ \text{kg/m}^3)(1.03)} = 3030\ \text{m}^3/\text{d}$$

e. Centrifuge design:

The wet tonnes of sludge cake that are produced at average daily conditions are:

Without accounting for recycle:

$$\text{Wet tonnes (cake)} = \left[\frac{(98{,}313\ \text{kg/d})(0.95)}{(0.23)}\right]\left(\frac{1\,\text{tonne}}{10^3\ \text{kg}}\right) = 406\ \text{tonne/d}$$

Accounting for recycle:

$$\text{Wet tonnes (cake)} = \left[\frac{(104{,}844\ \text{kg/d})(0.95)}{(0.23)}\right]\left(\frac{1\,\text{tonne}}{10^3\ \text{kg}}\right) = 433\ \text{tonne/d}$$

The centrate calculations are shown below only for the scenario with recycle. If the iterative approach were used a similar methodology could be used for the conditions without recycle initially before repeating the steps. Before determining the volume and solid content of the recycle stream, the total mass of the recycle stream first needs to be determined.

$$\text{Centrate} = \left[(104{,}844 + 3{,}016{,}397)\ \text{kg/d}\right] - \left[\frac{(104{,}844\ \text{kg/d})(0.95)}{(0.23)}\right]$$

$$\text{Centrate} = 2{,}688{,}191\ \text{kg/d}$$

Assuming a specific gravity of 1.0 the volumetric flow of the recycle stream is:

$$\text{Volume centrate} = \frac{(2{,}688{,}191\ \text{kg/d})}{(1000\ \text{kg/m}^3)} = 2688\ \text{m}^3/\text{d}$$

$$\text{TS, \%} = \left\{ \frac{(104{,}844\ \text{kg/d})(1 - 0.95)}{[(2{,}688{,}191\ \text{kg/d})\ \text{kg/d}]} \right\}(100) = 0.195 \ \text{ or } 1950\ \text{mg/L}$$

It is given that the BOD concentration is 1500 mg/L in the centrate meaning the mass of BOD recycled is 4032 kg/d. The mass of TSS in the centrate is 5242 kg/d.

To fully carry out the iterative solution, the total recycle stream (stream O) must be accounted for in the overall mass balance. In order to estimate the BOD concentration in the gravity thickener overflow and the gravity belt filtrate, it can be assumed that 65% of the solids are biodegradable and that the value of BOD_c can be obtained by multiplying the value of UBOD by a factor of 0.68.

For the gravity thickener overflow with a TSS load of 5729 kg/d, the BOD in the recycle:

BOD (GT overflow) = (5729 kg/d)(0.65)(1.42)(0.68)
= 3596 kg/d

For the gravity belt thickener filtrate with a TSS load of 3,186 kg/d, the BOD in the recycle:

BOD (GBT overflow) = (3186 kg/d)(0.65)(1.42)(0.68)
= 1999 kg/d

A table of the recycle flows is shown below:

Parameter	Units	Gravity thickener	Gravity belt thickener	Centrate	Total recycle
Flow	m^3/d	5462	5362	2688	13,512
TSS	kg/d	5729	3186	5242	14,157
%VS/TS	%	79.6	70	61.6	70.8
VSS	kg/d	4563	2230	3227	10,020
BOD	kg/d	3596	1999	4032	9627

15

PLANT RECYCLE FLOW TREATMENT AND NUTRIENT RECOVERY

Problem 15-1

Problem Statement – see text on page 1728

Instructors Note: In the water balance, reactions involving water during anaerobic digestion are not included in the calculations for simplicity. See Eq. (10-2), Chap. 10, for chemical reaction stoichiometry. Water is also consumed in the formation of bicarbonate from CO_2. Digester gas will be saturated with water, which also contributes to water loss. In total, a 1 to 2 percent error is introduced if these mechanisms for water loss are not included in the water mass balance. In the calculation of sidestream total suspended solids, the conventional method of calculating the solids capture efficiency across the solids dewatering process is used as follows.

$$\text{Capture efficiency} = \frac{\text{Feed solids} \ - \ \text{sidestream suspended solids}}{\text{Feed solids}} \times 100\%$$

The total solids concentration of the digested solids is used typically in this calculation rather than suspended solids due to the difficulty of filtering the digested solids sample for the suspended solids measurement. During the measurement of total solids, ammonium bicarbonate thermally decomposes, resulting in a loss of mass from the sample. The measured total solids concentration can be corrected by adding a calculated ammonium bicarbonate mass to the total solids (sidestream ammonium-N data are used for this correction). The sidestream suspended solids concentration is calculated with measured and corrected measured digested solids total solids concentrations to illustrate the magnitude of ammonium bicarbonate mass loss on the total solids measurement.

Solution

1. The average daily sidestream volume and constituent concentrations are calculated by performing solids, water and nutrient balances across the digestion and solids dewatering processes as follows.

   a. Calculate the solids and water mass rates to the digester using the information presented in the problem statement.

   Total solids = $(530\ \text{m}^3/\text{d})(1000\ \text{kg/m}^3)(1.02\ \text{kg/kg})(0.045\ \text{kg TS/kg})$
   = 24,327 kg/d

   Volatile solids = (24,327 kg/d)(0.78 kg VS/kg TS) = 18,975 kg/d

   Fixed solids = 24,327 kg/d - 18,975 kg/d = 5352 kg/d

   Water = $(530\ \text{m}^3/\text{d})(1000\ \text{kg/m}^3)(1.02\ \text{kg/kg})(1 - 0.045)$
   = 516,273 kg/d

   b. Calculate the soluble TKN created during digestion.

   Soluble TKN mass = (18,975 kg VS/d)(0.065 kg N/kg VS) –
   (9488 kg VS/d)(0.065 kg N/kg VS) = 617 kg N/d

$$\text{Soluble TKN concentration} = \frac{(617\ \text{kg N/d})(10^6\ \text{mg/1 kg})}{(516{,}273\ \text{kg H}_2\text{O/d})(1\ \text{L/1kg})}$$

$$= 1195\ \text{mg N/L}$$

   c. Calculate phosphate created during digestion assuming that organically bound soluble phosphorus is insignificant in comparison to phosphate.

   PO_4-P mass = (18,975 kg VS/d)(0.015 kg P/kg VS)
   – (9488 kg VS/d)(0.015 kg P/kg VS) = 142 kg P/d

$$\text{PO}_4\text{-P concentration} = \frac{(142\ \text{kg P/d})(10^6\ \text{mg/1 kg})}{(516{,}273\ \text{kg H}_2\text{O/d})(1\ \text{L/1kg})}$$

$$= 275\ \text{mg-P/L}$$

   d. Calculate digester effluent solids and water mass rates. Measured and corrected measured total solids mass rates are calculated as follows.

$$\text{Volatile solids} = (18{,}975\ \text{kg/d})\left(1 - \frac{50\%\ \text{destruction efficiency}}{100\%}\right)$$

$$= 9488\ \text{kg/d}$$

Measured total solids = 9488 kg VSS/d + 5352 kg fixed solids/d

= 14,840 kg/d

Water = 516,273 kg/d

(water loss by reactions and evaporation are ignored)

e. The corrected total solids are calculated as follows. For simplicity, 100 percent of the soluble TKN calculated above is assumed to be ammonia-N.

$$NH_4HCO_3\ \text{mass rate} = \frac{(617\ \text{kg N/d})\left(79\ \frac{\text{kg } NH_4HCO_3}{\text{kg-mole}}\right)}{\left(14\ \frac{\text{kg N}}{\text{kg-mole N}}\right)}$$

$$= 3481\ \text{kg/d}$$

Total solids, corrected = measured total solids

+ ammonium bicarbonate

= 14,840 kg/d + 3481 kg NH_4HCO_3/d

= 18,321 kg/d

f. Calculate the sidestream total suspended solids mass rates based on measured and corrected measured feed total solids as follows.

$$\text{Capture efficiency, \%} = \frac{\text{Feed solids} - \text{sidestream suspended solids}}{\text{Feed solids}}(100)$$

Rearranging and simplifying this equation gives:

$$\text{Sidestream suspended solids} = (\text{Feed solids})\left(1 - \frac{\text{capture efficiency}}{100}\right)$$

Sidestream suspended solids based on measured feed total solids

$$= (14{,}840\ \text{kg/d})\left(1 - \frac{95}{100}\right) = 742\ \text{kg/d}$$

Sidestream suspended solids based on corrected measured feed total

$$\text{solids} = (18{,}321\,\text{kg/d})\left(1 - \frac{95}{100}\right) = 916\ \text{kg/d}$$

g. Calculation of the sidestream flow requires the calculation of the dewatered biosolids cake water content. Because the conventional method of calculating capture efficiency was used in the estimation of the sidestream suspended solids, the cake total solids is the difference between the feed total solids and the sidestream suspended solids. For simplicity, the measured feed total solids are used as follows.

Cake total solids = 14,840 kg/d – 742 kg/d = 14,098 kg/d

$$\text{Water content of cake} = \frac{(14{,}098\ \text{kg/d})\left(1 - \frac{22\%}{100\%}\right)}{\left(\frac{22\%}{100\%}\right)} = 49{,}984\ \text{kg/d}$$

h. Calculate the sidestream flow, total suspended solids concentration and TKN concentration.

Water mass rate = 516,273 kg/d – 49,647 kg/d = 466,626 kg/d

Assuming a specific gravity of 1.0:

$$\text{Sidestream flowrate} = (466{,}626\ \text{kg/d})\left(\frac{1\,\text{L}}{\text{kg}}\right)\left(\frac{1\,\text{m}^3}{10^3\ \text{L}}\right)$$

$$= 466.6\ \text{m}^3/\text{d}$$

Sidestream suspended solids concentration based on measured feed total

$$\text{solids} = \left[\frac{(742\,\text{kg/d})}{(466.6\,\text{m}^3/\text{d})}\right]\left(\frac{10^6\ \ \text{mg}}{1\text{kg}}\right)\left(\frac{1\,\text{m}^3}{10^3\ \text{L}}\right) = 1590\,\text{mg/L}$$

Sidestream suspended solids concentration based on corrected measured

$$\text{feed total solids} = \left[\frac{(916\ \ \text{kg/d})}{(466.6\,\text{m}^3/\text{d})}\right]\left(\frac{10^6\ \text{mg}}{1\text{kg}}\right)\left(\frac{1\ \text{m}^3}{10^3\ \ \text{L}}\right) = 1963\,\text{mg/L}$$

The TKN concentration of the sidestream is the sum of the particulate TKN and the soluble TKN. The nitrogen content of the digested volatile solids is provided in the problem statement.

$$\text{Volatile fraction of suspended solids} = \frac{(9488\ \text{kg VS/d})}{(14{,}840\ \ \text{kg TS/d})} = 0.639$$

Sidestream volatile suspended solids concentration

= (1590 mg TSS/L)(0.639) = 1016 mg VSS/L

$$\begin{aligned}\text{TKN} &= (1016\ \text{mg VSS/L})(0.065\ \text{mg N/mg VSS}) + 1195\ \text{mg N/L}\\ &= 1261\,\text{mg N/L}\end{aligned}$$

i. Summary of sidestream flow and nutrient concentrations:

Flow rate = 466.6 m^3/d

TKN concentration = 1261 mg/L

Soluble TKN concentration = 1195 mg/L

Soluble phosphorus concentration = 275 mg/L

TSS concentration = 1590 mg/L

2. The sidestream flow and constituent concentrations at the peak solids rate to the digester are calculated similarly. For simplicity, the calculations are based on the digester effluent measured total solids concentration. If the corrected measured total solids concentration is used, the procedure shown above for correction of the total solids is employed.

a. Calculate the solids and water mass rates to the digester:

Total solids = (700 m^3/d)(10^3 kg/m^3)(1.02 kg/kg)(0.045 kg TS/kg)

= 32,130 kg/d

Volatile solids = (32,130 kg/d)(0.78 kg VS/kg TS) = 25,061 kg/d

Fixed solids = 32,130 kg/d – 25,061 kg/d = 7069 kg/d

Water = (700 m^3/d)(10^3 kg/m^3)(1.02 kg/kg)(1 – 0.045)

= 681,870 kg/d

b. Calculate digester effluent solids and water mass rates.

Volatile solids = (25,061 kg/d)(1 – 0.45) = 13,784 kg/d

Total solids (measured) = 13,784 kg/d + 7069 kg fixed solids/d

= 20,853 kg/d

Water = 681,870 kg/d

c. Calculate soluble TKN created during digestion.

$$\text{Soluble TKN mass} = (25{,}061\text{ kg VS / d})(0.065\text{ kg N / kg VS}) - (13{,}784\text{ kg VS / d})(0.065\text{ kg N / kg VS})$$

$$= 733\text{ kg N / d}$$

$$\text{Soluble TKN concentration} = \frac{(733\text{ kg N/d})(10^6\text{ mg / 1kg})}{(681{,}870\text{ kg H}_2\text{O/d})(1\text{ L/1 kg})}$$

$$= 1075\text{ mg N/L}$$

d. Calculate phosphate created during digestion:

$$\text{PO}_4\text{-P mass} = (25{,}061\text{ kg VS / d})(0.015\text{ kg P / kg VS}) - (13{,}784\text{ kg VS/d})(0.015\text{ kg P/kg VS}) = 169\text{ kg P/d}$$

$$\text{PO}_4\text{-P concentration} = \frac{(169\text{ kg P/d})(10^6\text{ mg / 1kg})}{(681{,}870\text{ kg H}_2\text{O/d})(1\text{L/1 kg})}$$

$$= 248\text{ mg P/L}$$

e. Calculate the sidestream suspended solids mass rate.

$$\text{Sidestream suspended solids} = (20{,}853\text{ kg/d})\left(1 - \frac{95}{100}\right) = 1043\text{ kg/d}$$

f. Calculate dewatered biosolids cake solids and water mass rates.

Total solids = 20,853 kg / d – 1043 kg / d = 19,810 kg / d

$$\text{Water mass rate} = \frac{(19{,}810\text{ kg/d})(1 - 0.22)}{0.22} = 70{,}325\text{ kg/d}$$

g. Calculate the sidestream flow, total suspended solids concentration and TKN concentration.

Water mass rate = 681,870 kg/d – 70,235 kg/d = 611,635 kg/d

$$\text{Sidestream flowrate} = (611{,}636\ \text{kg/d})\left(\frac{1\,\text{L}}{\text{kg}}\right)\left(\frac{1\,\text{m}^3}{10^3\ \text{L}}\right)$$

$$= 611.6\ \text{m}^3/\text{d}$$

$$\text{Sidestream suspended solids concentration} = \left[\frac{(1043\ \text{kg/d})}{(611.6\ \text{m}^3/\text{d})}\right]\left(\frac{10^6\ \text{mg}}{1\,\text{kg}}\right)\left(\frac{1\,\text{m}^3}{10^3\ \text{L}}\right)$$

$$= 1705\ \text{mg/L}$$

h. Calculate the TKN concentration.

$$\text{Volatile fraction of suspended solids} = \frac{(13{,}784\ \text{kg VS/d})}{(20{,}853\ \text{kg TS/d})} = 0.661$$

Sidestream volatile suspended solids concentration

= (1705 mg TSS/L)(0.661) = 1127 mg VSS/L

$$\text{TKN} = (1127\ \text{mg VSS/L})(0.065\ \text{mg N/mg VSS}) + 1075\ \text{mg N/L} = 1148\ \text{mg N/L}$$

i. Summary of sidestream flow and nutrient concentrations:

Flow rate = 611.6 m^3/d

TKN concentration = 1148 mg/L

Soluble TKN concentration = 1075 mg/L

Soluble phosphorus concentration = 248 mg/L

TSS concentration = 1705 mg/L

Problem 15-2

Problem Statement— see text on page 1728

Solution

Given information:

Flow rate during biosolids dewatering, $Q_{dw} = 83\ \text{m}^3/\text{h}$

Run time, t_{run} = 6 d/w and 8 h/d

1. Calculate the tank volume required for full equalization of the sidestream so that the equalized flow is returned continuously at constant flowrate to the mainstream plant.

Apply Eq. (15-1).

$N = 2\ d$

$D_{dw} = 6\ d/w$

$$V_{eq} = (N)(Q_{dw})(\frac{1}{7}D_{dw})$$

$$Q_{dw} = (83\ m^3/h)(8\ h/d) = 664\ m^3/d$$

$$V_{eq} = (2d)(664\ m^3/d)\left[\frac{(6\ d/w)}{(7\ d/w)}\right] = 1138\ m^3$$

2. Calculate the required volume if the equalized sidestream is to be returned to the mainstream plant seven days per week between the hours of 10 p.m. and 6 a.m.

The equalization volume is identical to the volume calculated in Part 1. The only difference in the equalization tank design is the capacity of the pump that sends sidestream to the plant.

Problem 15-3

Problem Statement—see text on page 1729

Solution

1. Estimate $FeCl_3$ demand at a dosage rate of 2 kg Fe/kg P for the sidestream ortho-P = 190 mg/L presented in Problem 15-2.

$$Q_{dw} = (83\ m^3/h)(8\ h/d) = 664\ m^3/d$$

$$\text{Phosphate-P load} = (664\ m^3/d)(190\ mg/L)\left(\frac{1\,kg}{10^6\ mg}\right)\left(\frac{10^3\ L}{1 m^3}\right)$$
$$= 126\ \text{kg-P/d}$$

$$\text{Fe requirement} = (126\ \text{kg-P/d})(2\ \text{kg Fe/kg P})$$
$$= 252\ \text{kg-Fe/d}$$

Molecular weight of ferric chloride = 162.3 g/mole

$$\text{FeCl}_3\text{ requirement} = (252\text{ kg Fe/d})\left(\frac{162.3\text{ kg FeCl}_3}{55.8\text{ kg Fe}}\right)$$

$$= 733\text{ kg FeCl}_3\text{/d}$$

$$\text{Solution volume} = (733\text{ kg FeCl}_3\text{/d})\left(\frac{1\text{ kg solution}}{0.37\text{ kg FeCl}_3}\right)\left(\frac{1\text{m}^3}{10^3\text{ kg}}\right)\left(\frac{1}{1.4}\right)$$

$$= 1.415\text{ m}^3\text{/d}$$

2. Estimate struvite production rate for a crystallizer effluent PO_4-P concentration is 15 mg/L and 100% struvite recovery efficiency.

First, calculate the molecular weight of $MgNH_4PO_4\text{-}6H_2O$.

$$\text{Molecular weight} = 24.3 + 18 + 95 + 6(18) = 245.3$$

Calculate struvite production:

Crystallizer effluent PO_4-P = 15 mg/L

$$\text{Phosphate removed} = (664\text{ m}^3\text{/d})(190\text{ mg P/L} - 15\text{ mg P/L})\left(\frac{1\text{kg}}{10^6\text{ mg}}\right)\left(\frac{10^3\text{ L}}{1\text{m}^3}\right)$$

$$= 116\text{ kg-P/d}$$

$$\text{Struvite mass} = (116\text{ kg P/d})\left(\frac{245.3\text{ kg struvite}}{31\text{kg P}}\right)$$

$$= 918\text{ kg struvite/d}$$

Problem 15-4

Problem Statement—see text on page 1729

Solution

1. Calculate NH_3-N in crystallizer effluent using the struvite production rate calculated in Problem 15-3.

$$\text{N-removed} = (918\text{ kg struvite/d})\left(\frac{14\text{ kg N}}{245.3\text{ kg struvite}}\right)$$

$$= 52.4\text{ kg/d}$$

$$\text{Ammonia-N} = (1050\text{ mg/L}) - \left[\frac{(52.4\text{ kg N/d})}{(664\text{ m}^3\text{/d})}\right]\left(\frac{10^6\text{ mg}}{1\text{kg}}\right)\left(\frac{1\text{m}^3}{10^3\text{ L}}\right)$$

$$= 971\text{ mg-N/L}$$

2. Estimate the deammonification SBR volume requirement using the sidestream equalized flow rate calculated in Problem 15-2 and the given data presented in Problem 15-3(b).

   a. The first step is to calculate the sidestream volume fed to the SBR during each cycle:

      Given operating conditions: 3 SBR cycles/d

      Equalized sidestream flow rate, $Q_{dw} = 664\ \text{m}^3/\text{d}$

      $$\text{Feed volume/cycle} = (664\ \text{m}^3/\text{d})\left(\frac{1\ \text{d}}{3\ \text{SBR cycles}}\right)$$

      $$= 221.3\ \text{m}^3/\text{cycle}$$

   b. In the second step, calculate the total oxygen demand per SBR cycle:

      Total oxygen demand = nitrogenous oxygen demand + carbonaceous oxygen demand

      For a crystallizer effluent ammonia-N concentration of 971 mg/L and 100% ammonia removal, the nitrogenous oxygen demand per SBR cycle is

      $$(221.3\ \text{m}^3/\text{cycle})(971\ \text{mg N/L})\left(\frac{1\ \text{kg}}{10^6\ \text{mg}}\right)\left(\frac{10^3\ \text{L}}{1\ \text{m}^3}\right)\left(\frac{1.83\ \text{kg O}_2}{\text{kg N}}\right)$$

      $$= 393\ \text{kg O}_2/\text{cycle}$$

      The carbonaceous oxygen demand is 8% of the nitrogenous oxygen demand (given condition):

      Carbonaceous oxygen demand

      $= (0.08)(393\ \text{kg O}_2/\text{cycle}) = 31\ \text{kg O}_2/\text{cycle}$

      Total oxygen demand per cycle = $31\ \text{kg O}_2 + 393\ \text{kg O}_2 = 424\ \text{kg O}_2$

   c. Calculate the duration of each SBR cycle when the SBR is being aerated:

      For 3 SBR cycles per day with 1 h settle and 1 h decant periods, the fill/react time per cycle = 6 h/cycle

      $$\text{Aerobic time per SBR cycle} = (6\ \text{h/cycle})(0.66)$$

      $$= 3.96\ \text{h/cycle}$$

d. Calculate the minimum SBR liquid volume based on a maximum OUR of 150 mg/L•h for the aeration system and the maximum liquid volume with sidestream volume treated per SBR cycle:

$$\text{Actual Oxygen Rate } (\text{AOR}) = (424\ \text{kg O}_2/\text{cycle})(1\ \text{cycle}/3.96\ \text{aerobic h})$$
$$= 107\ \text{kg O}_2/\text{h}$$

$$\text{Min. liquid volume } = (107\ \text{kg O}_2/\text{h})\left(\frac{10^6\ \text{mg}}{1\,\text{kg}}\right)\left(\frac{\text{L}\cdot\text{h}}{139\ \text{mg}}\right)$$
$$= 769{,}800\ \text{L}$$
$$= 769.8\ \text{m}^3$$

Max. liquid volume = 769.8 + 221.3 = 991 m^3

Problem 15-5

Problem Statement—see text on page 1729-1730

Instructors Note: The purpose of this problem is to illustrate the importance of biological heat generation in biological processes treating sidestream or high strength industrial wastewaters.

Solution

1. Calculate the heat released by nitrification-denitrification, nitritation-denitritation and deammonification using the performance criteria presented in the problem statement.

i. Nitrification-Denitrification

The first step is to calculate the ammonia load and the ammonia removed in the process. The following conditions apply:

Q = 600 m^3/d

NH_3-N = 900 mg/L

95% NH_3-N removal;

Ammonia-N load =

$$\text{Ammonia-N load} = (600\ \text{m}^3/\text{d})(900\ \text{mg N/L})\left(\frac{1\,\text{kg}}{10^6\,\text{mg}}\right)\left(\frac{10^3\,\text{L}}{1\,\text{m}^3}\right)$$
$$= 540\ \text{kg-N/d}$$

$$\text{Ammonia-N load} = (600\ \text{m}^3/\text{d})(900\ \text{mg N/L})\left(\frac{1\,\text{kg}}{10^6\,\text{mg}}\right)\left(\frac{10^3\,\text{L}}{1\,\text{m}^3}\right)$$
$$= 540\ \text{kg-N/d}$$

The COD required for denitrification is calculated using the following conditions:

95% NO_3-N removal

Y_H = 0.2 g VSS/g COD

Calculate the nitrate-N mass that is denitrified:

$$\text{NO}_3\text{-N load} = (513\ \text{kg N/d})(0.95)$$
$$= 487\ \text{kg-N/d}$$

Apply Eq. (7-126) to calculate the COD required to denitrify 1 kg of nitrate-N:

$$\text{COD}/\text{N} = \frac{2.86}{1-1.42(0.2)} = 3.99\ \text{kg COD/kg N}$$

Calculate the biological heat produced by nitrification and denitrification using the information in Table 15-9:

Biological heat production

$$= \left(513\,\frac{\text{kg N}}{\text{d}}\right)\left(-21.8\,\frac{\text{MJ}}{\text{kg N}}\right)$$
$$+\left(3.99\,\frac{\text{kg COD}}{\text{kg N}}\right)\left(487\,\frac{\text{kg N}}{\text{d}}\right)\left\{\left[(-13.6)+(20.7)(0.2)\right]\frac{\text{MJ}}{\text{kg COD}}\right\}$$

= –29,565 MJ/d

ii. Nitritation-Denitritation

Based on the performance criteria, the ammonia removal efficiency for nitritation-denitritation is equal to nitrification-denitrification. Therefore, Ammonia load removed = 513 kg/d (calculated above)

Calculate the nitrite-N load that is removed based on a 95% removal efficiency:

$$\text{NO}_2\text{-N removed} = (513 \text{ kg N/d})(0.95) = 487 \text{ kg/d}$$

Use Eq. (15-12) to calculate the COD required to reduce 1 kg of nitrite-N.

$$\text{COD}/\text{N} = \frac{1.71}{1-1.42(0.2)} = 2.39 \text{ kg COD/kg N}$$

Calculate the biological heat produced by nitrification and denitrification using the information in Table 15-9:

Biological heat generation =

$$= \left(513\frac{\text{kg N}}{\text{d}}\right)\left(-14.3\frac{\text{MJ}}{\text{kg N}}\right) + \left(2.39\frac{\text{kg COD}}{\text{kg N}}\right)\left(487\frac{\text{kg N}}{\text{d}}\right)\left\{\left[(-17.0)+(25.5)(0.2)\right]\frac{\text{MJ}}{\text{kg COD}}\right\}$$

= -21,187 MJ/d

iii. Deammonification

The ammonia-N load removed by the deammonification process is identical to nitrification-denitrification and nitritation-denitritation:

Ammonia load removed = 513 kg/d (calculated above)

Using the information in Table 15-9, calculate the heat generated by deammonification:

$$\begin{aligned}\text{Biological heat generation} &= (513 \text{ kg/d})(-18.6 \text{ MJ/kg N})\\ &= -9542 \text{ MJ/d}\end{aligned}$$

2. Calculate the fraction of heat that must be removed from each process to avoid an operating temperature from increasing above 38°C. The sidestream temperature is 35°C.

   i. Nitrification-Denitrification

   The heat that can be retained by the process is the heat that increases the sidestream from 35°C to the maximum reactor temperature of 38°C. The sensible heat is calculated as follows, using the density of pure water as an approximation of sidestream density:

   Heat capacity of water at 35°C = 4.178 J/g•°C

   Density of water = 994 kg/m^3 (Appendix C)

   Heat required to increase the sidestream temperature from 35 to 38°C is:

$$\text{Heat required} = \left(4.178 \frac{\text{J}}{\text{g}\cdot{}^\circ\text{C}}\right)\left(\frac{1\ \text{MJ}}{10^6\ \text{J}}\right)\left(\frac{10^3\ \text{g}}{1\ \text{kg}}\right)\left(\frac{994\ \text{kg}}{1\ \text{m}^3}\right)(3^\circ\text{C})$$

$$= 12.5\ \text{MJ/m}^3$$

   In the next step, the heat generated per unit volume of sidestream is calculated using the heat generation rate calculated in Part 1(i) above.

$$\text{Heat generation per volume sidestream} = \frac{(-29{,}565\ \text{MJ/d})}{(600\ \text{m}^3/\text{d})} = -49.3\ \text{MJ/m}^3$$

   The fraction of the heat generated by nitrification-denitrification that must be removed or lost is calculated as follows:

   Fraction of heat that must be lost or removed

$$= \frac{(49.3\ \text{MJ/m}^3 - 12.5\ \text{MJ/m}^3)}{(49.3\ \text{MJ/m}^3)} = 0.746\text{, or } 74.6\%$$

   ii. Nitritation-Denitritation

   The heat that must be removed from the nitritation-denitritation process is calculated similarly.

$$\text{Heat generation per volume sidestream} = \frac{(-21{,}186\ \text{MJ/d})}{(600\ \text{m}^3/\text{d})} = -35.3\ \text{MJ/m}^3$$

   Fraction of heat removed/lost

$$= \frac{(35.3\ \text{MJ/m}^3 - 12.5\ \text{MJ/m}^3)}{(35.3\ \text{MJ/m}^3)} = 0.646\text{, or }64.6\%$$

iii. Deammonification

The heat that must be removed from the deammonification process is similarly calculated.

$$\text{Heat generation} = \frac{(-9542\ \text{MJ/d})}{(600\ \text{m}^3/\text{d})} = -15.9\ \text{MJ/m}^3$$

Fraction of heat removed/lost

$$= \frac{(15.9\ \text{MJ/m}^3 - 12.5\ \text{MJ/m}^3)}{(15.9\ \text{MJ/m}^3)} = 0.214\text{, or }21.4\%$$

Problem 15-6

Problem Statement—see text on page 1730

Solution

1. Nitrification-Denitrification

The first step in the calculation of aeration energy is the calculation of nitrogenous and carbonaceous oxygen demands per SBR cycle using the information provided in the problem statement.

$$\text{Sidestream volume per SBR cycle} = \frac{(600\ \text{m}^3/\text{d})}{3\ \text{d}} = 200\ \text{m}^3$$

$$\text{Ammonia-N load per SBR cycle} = \left(200\ \text{m}^3/\text{cycle}\right)(900\ \text{mg/L})\left(\frac{10^3\ \text{L}}{1\text{m}^3}\right)\left(\frac{1\text{kg}}{10^6\ \text{mg}}\right)$$

$$= 180\ \text{kg N/cycle}$$

In the calculation of nitrogenous oxygen demand, the ammonia-N removed for cell mass growth would be removed from the ammonia-N load to reduce the amount of ammonia that is nitrified and denitrified. For simplicity, nitrogen removal for cell mass synthesis is ignored in the calculations shown below. However, the students may account for nitrogen removal by assimilation using the net heterotrophic yield provided in one of the tables in the problem statement and using a nitrogen content of 0.1 kg N/kg VSS. Under the warm conditions of a sidestream reactor at a total SRT greater than 5 days, the net yield of autotrophic biomass is sufficiently low that ammonia removed for autotrophic cell mass synthesis can be ignored.

$$\text{Nitrogenous oxygen requirement} = \left(180\,\frac{\text{kg N}}{\text{cycle}}\right)\left(4.57\,\frac{\text{kg O}_2}{\text{kg N}}\right) = 822.6\,\frac{\text{kg O}_2}{\text{cycle}}$$

In the calculation of carbonaceous oxygen demand, the student may assume the COD destroyed aerobically is proportional to the aerobic fraction of the fill/react period where the reactor is being filled continuously during this period. In reality, the fraction of the COD that is degraded aerobically is dependent on the relative aerobic and anoxic degradation rates, but assuming equal reaction rates for simplicity only introduces a small error in the calculation of the overall oxygen demand.

$$\begin{aligned}\text{COD load per SBR cycle} &= (200\ \text{m}^3/\text{cycle})(200\ \text{mg/L})\left(\frac{10^3\ \text{L}}{\text{m}^3}\right)\left(\frac{1\ \text{kg}}{10^6\ \text{mg}}\right)\\ &= 40\ \text{kg/cycle}\end{aligned}$$

$$\begin{aligned}\text{Carbonaceous Oxygen requirement} &= \left(40\,\frac{\text{kg}}{\text{cycle}}\right)\left[1-\left(1.42\,\frac{\text{kg}}{\text{kg}}\right)\left(0.2\,\frac{\text{kg VSS}}{\text{kg COD}}\right)\right](0.66)\\ &= 18.9\,\frac{\text{kg O}_2}{\text{cycle}}\end{aligned}$$

After calculation of the nitrogenous and carbonaceous oxygen demands, the minimum liquid volume is calculated using the maximum OUR of 150 mg/L•h for the aeration system. Assuming 100% ammonia and COD removal in the calculation of reactor volume is common in the design of a SBR for sidestream treatment since it provide a conservative estimate of the minimum liquid volume requirement. In the calculation of aeration energy performed later in the problem solution, the ammonia and COD removal efficiencies are applied.

$$\text{Aerobic time per SBR cycle} = \left(6\,\frac{\text{h}}{\text{cycle}}\right)(0.66) = 3.96\,\frac{\text{h}}{\text{cycle}}$$

$$\text{Minimum liquid volume} = \left[822.6\,\frac{\text{kg O}_2}{\text{cycle}} + 18.9\,\frac{\text{kg O}_2}{\text{cycle}}\right]\left(\frac{\text{cycle}}{3.96\text{ h}}\right)\left(\frac{\text{L}\cdot\text{h}}{150\text{ mg}}\right)\left(\frac{10^6\text{mg}}{\text{kg}}\right)$$

$$= 1{,}416{,}667\text{ L} = 1417\text{m}^3$$

The maximum liquid volume of the SBR is the minimum volume plus the sidestream and dilution water volumes per SBR cycle.

$$\text{Maximum liquid volume} = (\text{minimum volume, m}^3) + (\text{volume per cycle, m}^3/\text{cycle})$$

$$= 1417\text{ m}^3 + \left[\left(200\,\frac{\text{m}^3}{\text{d}}\right)\left(\frac{1\text{ d}}{3\text{ cycles}}\right) + \left(200\,\frac{\text{m}^3}{\text{cycle}}\right)\right]$$

$$= 1684\text{ m}^3$$

The dimensions of the SBR are determined to estimate the average sidewater depth during the fill/react period. The average depth is also used to estimate the average aeration energy per SBR cycle. An accurate estimate of aeration energy would account for non-linearity in aeration energy with diffuser submergence depth, in which the air flow calculation would be conducted incrementally from the minimum to the maximum depth and integrated over the fill/react period. However, in the absence of data on the Specific Oxygen Transfer Efficiency (SOTE) as a function of depth, the average aeration energy can be estimated by calculating the air flow rate at the average fill depth during each SBR cycle.

For a maximum sidewater depth of 7 m:

$$\text{Surface area} = \frac{1684\text{ m}^3}{7\text{ m}} = 240.6\text{ m}^2$$

$$\text{Minimum sidewater depth} = \frac{1417\text{ m}^3}{240.6\text{ m}^2} = 5.89\text{ m}$$

$$\text{Average sidewater depth} = \frac{7\text{ m} + 5.89\text{ m}}{2} = 6.45\text{ m}$$

$$\text{Average diffuser submergence} = 6.45\text{ m} - 0.25\text{ m} = 6.2\text{ m}$$

Eq. (5-70) is applied to calculate the AOTR to SOTR ratio:

$$\text{AOTR} = \text{SOTR}\left(\frac{\tau\beta\Omega C^*_{\infty,20} - C}{C^*_{\infty,20}}\right)\theta^{T-20}\alpha F$$

where

$\tau = \dfrac{C^*_{s,T}}{C^*_{s,20}}$, and

$$C^*_{S,T}(34°\text{C}, 1\text{atm}) = 7.05\,\text{mg/L} \quad \text{(Appendix E)}$$

$$C^*_{S,T}(20°\text{C}, 1\text{atm}) = 9.08\,\text{mg/L} \quad \text{(Appendix E)}$$

$$\tau = \frac{C^*_{s,T}}{C^*_{s,20}} = \frac{(7.05\text{ mg/L})}{(9.08\text{ mg/L})} = 0.776$$

$$\Omega = \frac{P_b}{P_s} = \frac{99.97\ \text{kPa}}{101.325\ \text{kPa}} = 0.987$$

$$C^*_{\infty,20} = C^*_{s,20}\left[1 + d_e\left(\frac{D_f}{P_s}\right)\right]$$

where $d_e = 0.4$; D_f =diffuser submergence, m; and $P_s = 10.33$m

$$C^*_{\infty,20} = (C^*_{S,20})\left[1 + d_e\left(\frac{D_f}{P_s}\right)\right] = (9.08\text{ mg/L})\left[1 + 0.4\left(\frac{6.2\text{ m}}{10.33\text{ m}}\right)\right] = 11.26\text{ mg/L}$$

Values of the remaining aeration parameters in Eq. (5-70) are provided in the problem statement.

$$\begin{aligned}\frac{\text{AOTR}}{\text{SOTR}} &= \left[\frac{\tau\beta\Omega C^*_{\infty,20} - C}{C^*_{\infty,20}}\right]\theta^{T-20}\alpha F \\ &= \left[\frac{(0.776)(0.95)(0.987)(11.26) - 2.0}{11.26}\right](1.024^{34-20})(0.5)(0.85) \\ &= 0.326\end{aligned}$$

In the next step, the AOTR for the aerated periods of the fill/react period is calculated with the nitrogeneous and carbonaceous oxygen demands calculated above and the actual ammonia and COD removal efficiencies provided in the problem statement.

$$\text{AOTR} = \frac{\left[(822.6\text{ kg O}_2)(0.9) + (18.9\text{ kg O}_2)(0.95)\right]}{3.96\text{ h}} = 191.5\,\frac{\text{kg O}_2}{\text{h}}$$

The SOTR is calculated with the AOTR to SOTR ratio as follows.

$$\text{SOTR} = \frac{(191.5\text{ kg O}_2/\text{h})}{0.326} = 587.4\text{ kg O}_2/\text{h}$$

The air flow rate at the mid-fill depth is calculated using the SOTE value per unit depth. The value provided in the problem statement is common for fine bubble diffusers over a narrow depth change. The non-linearity of SOTE with depth requires significant detailed data. In the absence of this information, the error introduced by assuming that SOTE is linear from the minimum to the maximum sidewater depths is small and acceptable for this analysis.

$$\text{Standard air flow rate} = \left(\frac{\text{SOTR}}{\text{SOTE}}\right) \Big/ \left[(\text{Density of air})\left(\frac{\text{Mass O}_2}{\text{Mass air}}\right)\right]$$

Where:

$$\rho_{\text{air},20°\text{C},1\text{atm}} = 1.204\,\frac{\text{kg air}}{\text{m}^3}\text{, and}$$

Fraction of air composed of oxygen = $0.2318\,\frac{\text{kg O}_2}{\text{kg air}}$ (Appendix B).

SOTE = (0.06/m)(6.2 m) = 0.372

$$\text{Standard air flow rate} = \left[\frac{(587.4\text{ kg O}_2/\text{h})}{0.372}\right]\left(\frac{\text{m}^3}{1.204\text{ kg air}}\right)\left(\frac{\text{kg air}}{0.2318\text{ kg O}_2}\right)$$

$$= 5658\text{ m}^3/\text{h} = 1.57\text{ m}^3/\text{s}$$

In the final step, aeration energy is calculated by applying Eq. (5-77). The site ambient conditions are near standard conditions. A correction to actual conditions is typically performed, in which the air mass flow rate is calculated at the annual average ambient conditions (temperature, pressure and relative humidity). For simplicity, the students may calculate the power requirement for the air blower with standard air flow rate calculated above and the air density at standard conditions.

$$p_w = \frac{wRT_1}{28.97ne}\left[\left(\frac{p_1}{p_2}\right)^{0.283} - 1\right]$$

Where:
p_w = power consumption, kW
w = air mass flow rate, kg/s
T_1 = blower inlet temp, K
p_1 = blower inlet pressure, atm
p_2 = blower outlet pressure, atm
n = (k-1)/k = 0.283 (air)
e = total efficiency
$R = 8.314$, J/mole °K

The inlet blower pressure is the average ambient pressure minus the pressure drop across the blower inlet.

$$\text{Blower inlet pressure} = 99.97\,\text{kPa} - 1.7\,\text{kPa} = 98.27\,\text{kPa}$$

The blower outlet pressure is calculated by summing the barometric pressure, the pressure drop through the air piping, values and diffusers, and the mid-fill diffuser submergence depth.

$$\text{Blower outlet pressure} = \left(\frac{6.2\text{ m}}{10.33\text{ m}}\right)(101.325\text{ kPa}) + 12\text{ kPa} + 99.97\text{ kPa}$$
$$= 172.78\text{ kPa}$$

$$\text{Overall efficiency} = (0.90)(0.75) = 0.675$$

$$w = (1.57\text{ m}^3/\text{s})(1.204\text{ kg/m}^3) = 1.89\text{ kg/s}$$

$$P_w = \frac{(1.89\text{ kg/s})(8.314\text{ kJ/kmole °K})(273.15\text{K} + 20\text{K})}{(28.97)(0.283)(0.675)}\left[\left(\frac{172.78}{98.27}\right)^{0.283} - 1\right]$$
$$= 140.6\text{ kW}$$

$$\text{Aeration energy} = (140.6\text{ kW})\left(3.96\frac{\text{h}}{\text{cycle}}\right)\left(3\frac{\text{cycles}}{\text{d}}\right) = 16\text{ kWh/d}$$

Mixing energy is calculated with the maximum liquid volume, as indicated in the problem statement. Because the mixer(s) only operate during the anoxic phase of each aeration cycle, the total anoxic time is applied to the calculation as follows.

$$\text{Mixing energy} = \frac{\left(4\ \text{W/m}^3\right)\left(1684\ \text{m}^3\right)\left(2.04\frac{\text{h}}{\text{cycle}}\right)\left(3\frac{\text{cycle}}{\text{d}}\right)\left(\frac{1\,\text{kW}}{10^3\ \text{W}}\right)}{0.84} = 49\ \text{kWh/d}$$

2. Nitritation-Denitritation

The procedure for calculating aeration and mechanical mixing energy consumption rates for nitritation-denitritation is identical to the procedure used above for the nitrification-denitrification operating condition.

Calculate the nitrogenous and carbonaceous oxygen demands for the calculation of the minimum liquid depth.

$$\text{Nitrogenous Oxygen requirement} = \left(180\frac{\text{kg N}}{\text{cycle}}\right)\left(3.43\frac{\text{kg O}_2}{\text{kg N}}\right) = 617.4\frac{\text{kg O}_2}{\text{cycle}}$$

$$\text{Carbonaceous Oxygen requirement} = 18.9\frac{\text{kg O}_2}{\text{cycle}}$$

$$\text{Minimum Liquid volume} = \left[617.4\frac{\text{kg O}_2}{\text{cycle}} + 18.9\frac{\text{kg O}_2}{\text{cycle}}\right]\left(\frac{\text{cycle}}{3.96\ \text{AER h}}\right)\left(\frac{\text{L}\cdot\text{h}}{150\ \text{mg}}\right)\left(\frac{10^6\text{mg}}{1\ \text{kg}}\right)$$

$$= 1{,}071{,}212\ \text{L} = 1071\,\text{m}^3$$

Calculate the maximum liquid level and the mid-fill water depth as in Step 1.

$$\text{Maximum Liquid volume} = 1071\,\text{m}^3 + \left[\left(100\frac{\text{m}^3}{\text{d}}\right)\left(\frac{\text{d}}{3\ \text{cycles}}\right) + 200\frac{\text{m}^3}{\text{cycle}}\right] = 1304\ \text{m}^3$$

$$\text{Maximum sidewater depth} = 7\text{m}$$

$$\text{Surface area} = \frac{1304\ \text{m}^3}{7\ \text{m}} = 186.3\ \text{m}^2$$

$$\text{Minimum sidewater depth} = \frac{1071\,\text{m}^3}{186.3\ \text{m}^2} = 5.75\ \text{m}$$

$$\text{Average sidewater depth} = \frac{7\text{ m} + 5.75\text{ m}}{2} = 6.38\text{ m}$$

$$\text{Average diffuser submergence} = (6.38\text{ m} - 0.25\text{ m}) = 6.13\text{ m}$$

Apply Eq. (5-70) to calculate the AOTR to SOTR ratio. Because the conditions used in the application of Eq. (5-70) are identical to the nitrification-denitrification SBR, the values of the aeration parameters are the same as used above.

$$C^*_{s,T} = 7.05\text{ mg/L}$$

$$C^*_{\infty,20} = (9.08\text{ mg/L})\left[1 + 0.4\left(\frac{6.13\text{ m}}{10.33\text{ m}}\right)\right] = 11.24\text{ mg/L}$$

$$\Omega = 0.987$$

$$\tau = 0.776$$

$$\frac{\text{AOTR}}{\text{SOTR}} = \left[\frac{(0.776)(0.95)(0.987)(11.24) - 0.5}{11.24}\right]\left(1.024^{34-20}\right)(0.5)(0.85) = 0.405$$

Calculate the AOTR with the nitrogenous and carbonaceous oxygen demands calculated above.

$$\text{AOTR} = \frac{\left[(617.4\text{ kg O}_2)(0.9) + (18.9\text{ kg O}_2)(0.95)\right]}{3.96\text{ h}} = 144.9\text{ kg O}_2\text{/h}$$

Using the AOTR to SOTR ratio calculated above, the SOTR and standard air flow rate are calculated as follows.

$$\text{SOTR} = \frac{(144.9\text{ kg O}_2\text{/h})}{0.405} = 357.8\text{ kg O}_2\text{/h}$$

$$\text{Air flow rate} = \frac{(357.8\text{ kg O}_2\text{/h})}{\left[\left(\frac{0.06}{\text{m}}\right)(6.13\text{ m})\left(1.204\frac{\text{kg air}}{\text{m}^3}\right)\left(0.2318\frac{\text{kg O}_2}{\text{kg air}}\right)\right]}$$

$$= 3486\text{ m}^3\text{/h} = 0.968\text{ m}^3\text{/s}$$

The air blower power consumption rate is calculated with Eq. (5-77).

$$w = \left(0.968\ \text{m}^3/\text{s}\right)\left(1.204\ \text{kg air/m}^3\right) = 1.17\ \text{kg air/s}$$

$$\text{Average blower outlet pressure} = \left(\frac{6.13\ \text{m}}{10.33\ \text{m}}\right)\left(101.325\ \text{kPa}\right) + 12\ \text{kPa} + 99.97\ \text{kPa}$$
$$= 172.10\ \text{kPa}$$

$$P_w = \left[\frac{(1.17\ \text{kg/s})(8.314\ \text{kJ/kmole}\cdot\text{K})(273.15\text{K} + 20\text{K})}{(28.97)(0.283)(0.675)}\right]\left[\left(\frac{172.78}{98.27}\right)^{0.283} - 1\right]$$
$$= 88.6\ \text{kW}$$

$$\text{Aeration energy} = \left(88.6\text{kW}\right)\left(3.96\frac{\text{h}}{\text{cycle}}\right)\left(3\frac{\text{cycle}}{\text{d}}\right) = 1053\frac{\text{kW h}}{\text{d}}$$

The mixing energy is calculated at the maximum liquid depth for the anoxic periods.

$$\text{Mixing energy} = \frac{\left(4\ \text{W/m}^3\right)\left(1304\ \text{m}^3\right)\left(2.04\frac{\text{h}}{\text{cycle}}\right)\left(3\frac{\text{cycle}}{\text{d}}\right)\left(\frac{1\text{kW}}{1000\text{W}}\right)}{0.84} = 38\ \text{kWh/d}$$

3. Deammonification

The procedure for calculating aeration and mechanical mixing energy consumption rates for deammonification is identical to the procedure used above for the nitrification-denitrification and nitritation-denitritation operating conditions.

Calculate the nitrogenous and carbonaceous oxygen demands for the calculation of the minimum liquid depth.

$$\text{Nitrogenous Oxygen Demand} = \left(180\frac{\text{kg N}}{\text{cycle}}\right)\left(1.94\frac{\text{kg O}_2}{\text{kg N}}\right) = 349.2\frac{\text{kg O}_2}{\text{cycle}}$$

$$\text{Carbonaceous Oxygen Demand} = 18.9\frac{\text{kg O}_2}{\text{cycle}}$$

$$\text{Minimum liquid volume} = \left[349.2\frac{\text{kg O}_2}{\text{cycle}} + 18.9\frac{\text{kg O}_2}{\text{cycle}}\right]\left(\frac{\text{cycle}}{3.96\text{ h}}\right)\left(\frac{\text{L}\bullet\text{h}}{150\,\text{mg}}\right)\left(\frac{10^6\text{ mg}}{\text{kg}}\right)$$

$$= 619{,}697\text{ L} = 620\text{ m}^3$$

Calculate the maximum liquid level and the mid-fill water depth.

$$\text{Maximum liquid volume} = 620\,\text{m}^3 + 200\,\text{m}^3 = 820\,\text{m}^3$$

$$\text{Maximum sidewater depth} = 7\text{m}$$

$$\text{Surface area} = \frac{820\,\text{m}^3}{7\,\text{m}} = 117.1\text{m}^2$$

$$\text{Minimum sidewater depth} = \frac{620\,\text{m}^3}{117.1\text{m}^2} = 5.29\text{ m}$$

$$\text{Average sidewater depth} = \frac{7\text{ m} + 5.29\text{ m}}{2} = 6.15\text{ m}$$

$$\text{Average diffuser submergence} = (6.15\text{ m} - 0.25\text{ m}) = 5.90\text{ m}$$

Apply Eq. (5-70) to calculate the AOTR to SOTR ratio. Since the conditions used in the application of Eq. (5-70) are identical to the nitrification-denitrification and nitritation-denitritation SBR, the values of the aeration parameters are the same as used above.

$$C^*_{\infty,20} = (9.08\text{ mg/L})\left[1 + 0.4\left(\frac{5.9\text{ m}}{10.33\text{ m}}\right)\right] = 11.15\text{ mg/L}$$

$$\frac{\text{AOTR}}{\text{SOTR}} = \left[\frac{(0.776)(0.95)(0.987)(11.15) - 03}{(11.15)}\right](1.024^{34-20})(0.5)(0.85) = 0.415$$

$$\text{AOTR} = \frac{\left[(349.2\text{ kg O}_2)(0.9) + (18.9\text{ kg O}_2)(0.95)\right]}{3.96\text{ h}} = 83.9\text{ kg O}_2\text{/h}$$

Using the AOTR to SOTR ratio calculated above, the SOTR and standard air flow rate are calculated as follows.

$$\text{SOTR} = \frac{(83.9\text{ kg O}_2\text{/h})}{0.415} = 202.2\text{ kg O}_2\text{/h}$$

$$\text{Air flow rate} = \frac{(202.2\ \text{kg O}_2/\text{h})}{\left[\left(\frac{0.06}{\text{m}}\right)(5.9\ \text{m})\left(1.204\frac{\text{kg air}}{\text{m}^3}\right)\left(0.2318\frac{\text{kg O}_2}{\text{kg air}}\right)\right]}$$

$$= 2047\ \text{m}^3/\text{h} = 0.587\ \text{m}^3/\text{s}$$

The air blower power consumption rate is calculated with Eq. (5-77).

$$w = \left(0.587\ \text{m}^3/\text{s}\right)\left(1.204\ \text{kg air/m}^3\right) = 0.707\ \text{kg air/s}$$

$$\text{Average blower outlet pressure} = \left(\frac{5.9\ \text{m}}{10.33\ \text{m}}\right)(101.325\ \text{kPa}) + 12\ \text{kPa} + 99.97\ \text{kPa}$$

$$= 169.84\ \text{kPa}$$

$$P_w = \left[\frac{(0.707\ \text{kg/s})(8.314\ \text{kJ/kmole}\,^\circ\text{K})(273.15\text{K} + 20\text{K})}{(28.97)(0.283)(0.675)}\right]\left[\left(\frac{169.84}{98.27}\right)^{0.283} - 1\right]$$

$$= 51.9\ \text{kW}$$

$$\text{Aeration energy} = \left(51.9\ \text{kW}\right)\left(3.96\frac{\text{h}}{\text{cycle}}\right)\left(3\frac{\text{cycle}}{\text{d}}\right) = 617\frac{\text{kWh}}{\text{d}}$$

The mixing energy is calculated at the maximum liquid depth for the anoxic periods.

$$\text{Mixing energy} = \frac{\left(4\ \text{W/m}^3\right)\left(820\ \text{m}^3\right)\left(2.04\frac{\text{h}}{\text{cycle}}\right)\left(3\frac{\text{cycle}}{\text{d}}\right)\left(\frac{1\text{kW}}{1000\text{W}}\right)}{0.84} = 24\ \text{kWh/d}$$

Problem 15-7

Problem Statement—see text on page 1731-1732

Instructors Note: In addition to the information presented in the problem statement, the students should assume the pressate is not pretreated and the pressate, gravity thickener overflow and dissolved air flotation subnatant will be pumped to the inlet of the primary sedimentation tank. In the calculation of solids balances across the primary sedimentation tank, primary sludge gravity thickener, anaerobic digester and screw press, the contribution of pressate suspended solids is not included in the calculations presented below. For the purpose of estimating nutrient mass rates in the pressate and primary effluent, pressate solids can be excluded as the majority of the solids mass is considered inert and, therefore, will contribute to minimal additional ammonia and phosphate during anaerobic digestion. For the purpose of illustrating the impact of sidestream inert solids on the plant solids balance, the students may conduct an iterative calculation by including the pressate suspended solids mass load to the primary sedimentation tank and assume the solids capture efficiencies in the primary sedimentation tank and primary sludge gravity thickener apply. For the anaerobic digester, the solids contributed by the pressate are considered inert and would reduce the volatile solids destruction efficiency accordingly.

Solution

1. Calculate the flow and TSS concentration for gravity thickener overflow and dissolved air flotation subnatant.

   i. Gravity Thickener Overflow
   The first step in the calculation of the gravity thickener overflow flow rate and TSS concentration is to calculate the primary sludge flow and solids mass rate using the information provided in the problem statement.

$$\text{Primary influent TSS mass rate} = \left(26{,}500\ \text{m}^3/\text{d}\right)\left(290\ \text{mg/L}\right)\left(\frac{1\ \text{kg}}{10^6\ \text{mg}}\right)\left(\frac{10^3\ \text{L}}{1\ \text{m}^3}\right)$$

$$= 7685\ \text{kg TSS/d}$$

$$\text{TSS removal}\left(\text{primary sludge}\right) = \left(7685\ \text{kg TSS/d}\right)\left(0.6\right) = 4611\ \text{kg/d}$$

$$\text{Primary sludge flow} = \frac{(4611\ \text{kg/d})}{\left(0.01\right)\left(10^3\ \text{kg/m}^3\right)} = 461.1\ \text{m}^3/\text{d}$$

With the primary sludge flow and solids mass rate, the gravity thickener mass balance is conducted using the performance information provided in the problem statement.

$$\text{Gravity thickened primary sludge} = (4611\,\text{kg/d})(0.93) = 4288\,\text{kg/d}$$

$$\text{GTO TSS} = 4611\,\text{kg/d} - 4288\,\text{kg/d} = 323\,\text{kg TSS/d}$$

$$\text{Thickened primary sludge flow} = \frac{(4288\ \text{kg/d})}{(0.06)(10^3\,\text{kg}/\text{m}^3)} = 71.5\,\text{m}^3/\text{d}$$

Note: In the calculation of thickened primary sludge flow, a specific gravity is typically estimated for the anticipated solids concentration and applied in the flow calculation. For simplicity, a specific gravity of 1.0 is assumed.

$$\text{GTO Flow} = 461.1\,\text{m}^3/\text{d} - 71.5\,\text{m}^3/\text{d} = 389.6\,\text{m}^3/\text{d}$$

$$\text{GTO TSS concentration} = \left[\frac{(323\,\text{kg TSS/d})}{(389.6\ \text{m}^3/\text{d})}\right]\left(\frac{10^6\text{mg}}{1\text{kg}}\right)\left(\frac{1\text{m}^3}{10^3\,\text{L}}\right) = 829\,\text{mg/L}$$

ii. Dissolved air flotation (DAF)

The first step is to calculate the secondary sludge production rate:

cBOD removal in primary sedimentation tanks

$$= \left(26{,}500\,\frac{\text{m}^3}{\text{d}}\right)\left(275\,\frac{\text{mg cBOD}}{\text{L}}\right)\left(\frac{1\,\text{kg}}{10^6\,\text{mg}}\right)\left(\frac{1000\,\text{L}}{\text{m}^3}\right)(0.30)$$

$$= 2186\ \frac{\text{kg cBOD}}{\text{d}}$$

$$\text{Primary effluent cBOD mass rate} = \left(\frac{2186\ \text{kg cBOD/d}}{0.3}\right)(0.7) = 5101\ \text{kg/d}$$

$$\text{Secondary sludge production} = (5101\,\text{kg/d})\frac{(0.98)\left(0.55\,\frac{\text{kg VSS}}{\text{kg cBOD}}\right)}{\left(0.8\,\frac{\text{kg VSS}}{\text{kg TSS}}\right)} = 3437\,\text{kg/d}$$

$$\text{WAS flow} = \frac{(3437\,\text{kg/d})}{(7500\,\text{mg/L})\left(\frac{1\,\text{kg}}{10^6\text{mg}}\right)\left(\frac{10^3\,\text{L}}{\text{m}^3}\right)} = 458.3\,\text{m}^3/\text{d}$$

With the waste secondary solids flow and mass rate, the mass balance around the dissolved air flotation unit is performed as follows using the information in the problem statement:

$$\text{Thickened solids mass rate} = (3437\ \text{kg/d})(0.95) = 3265\ \text{kg/d}$$

$$\text{Subnatant solids mass rate} = 3437\ \text{kg/d} - 3265\ \text{kg/d} = 172\ \text{kg/d}$$

$$\text{Thickened solids flow} = \frac{(3265\ \text{kg/d})}{(0.05)(10^3\ \text{kg}/\text{m}^3)} = 65.3\ \text{m}^3/\text{d}$$

Note: In the calculation of thickened solids flow rate, a specific gravity should be estimated for this stream. For simplicity, the specific gravity is assumed to be 1.0.

$$\text{Subnatant flow} = 458.3\ \text{m}^3/\text{d} - 65.3\ \text{m}^3/\text{d} = 393\ \text{m}^3/\text{d}$$

$$\text{Subnatant TSS concentration} = \left[\frac{(172\ \text{kg/d})}{(393\ \text{m}^3/\text{d})}\right]\left(\frac{10^6\ \text{mg}}{1\,\text{kg}}\right)\left(\frac{1\ \text{m}^3}{10^3\ \text{L}}\right) = 438\ \text{mg/L}$$

2. Calculate pressate flow and concentrations of soluble TKN, TSS, and soluble phosphate.

   i. Anaerobic digester mass balances are conducted first to calculate the soluble TKN and soluble phosphorus concentrations in the digester, which will be equal to concentrations in the pressate from the screw press. The use of washwater in the screw press will impact the nutrient concentrations in the pressate if washwater is combined with the pressate. For simplicity, washwater is excluded from the mass balances conducted below.

   Combined thickened sludge flow to the anaerobic digester:

$$Q_T = 71.5\ \text{m}^3/\text{d} + 65.3\ \text{m}^3/\text{d} = 136.8\ \text{m}^3/\text{d}$$

   Solids balance across the anaerobic digester:

$$\text{Total solids mass rate} = 4288\ \text{kg/d} + 3437\ \text{kg/d} = 7725\ \text{kg/d}$$

$$\text{Volatile solids mass rate} = (4288\ \text{kg/d})\left[\frac{(226\ \text{mg/L})}{(290\ \text{mg/L})}\right] + (3437\ \text{kg/d})(0.8)$$

$$= 6091\,\text{kg/d}$$

$$\text{Fixed solids mass rate} = 7725\ \text{kg/d} - 6091\,\text{kg/d} = 1634\ \text{kg/d}$$

$$\text{Volatile solids destroyed} = 0.5\left(6091\,\text{kg/d}\right) = 3046\text{ kg/d}$$

$$\text{Digested solids mass rate} = 3046\text{ kg/d} + 1634\text{ kg/d} = 4680\text{ kg/d}$$

Nitrogen balance across the anaerobic digester:

$$\begin{aligned}\text{Organic-N mass rate} &= \left(4288\text{ kg/d}\right)\left[\frac{(226\text{ mg/L})}{(290\text{ mg/L})}\right]\left(0.04\right) + \left(3437\text{ kg/d}\right)\left(0.8\right)\left(0.095\right)\\ &= 395\text{ kg N/d}\end{aligned}$$

$$\text{Digested solids N mass rate} = 0.06\left(3046\text{ kg/d}\right) = 183\text{ kg/d}$$

$$\text{Soluble TKN generated} = 395\text{ kg N/d} - 183\text{ kg N/d} = 212\text{ kg N/d}$$

$$\begin{aligned}\text{Soluble TKN concentration} &= \left[\frac{(212\text{ kg N/d})}{(129{,}075\text{ kg H}_2\text{O/d})(1\text{L/kg})}\right]\left(\frac{10^6\text{mg}}{1\text{kg}}\right)\\ &= 1642\text{ mg/L}\end{aligned}$$

Phosphorus balance across the anaerobic digester:

$$\begin{aligned}\text{Organic P mass rate to digesters} &= \left(4288\text{ kg/d}\right)\left[\frac{(226\text{ mg/L})}{(290\text{ mg/L})}\right]\left(0.015\right)\\ &\quad + \left(3437\text{ kg/d}\right)\left(0.8\right)\left(0.02\right)\\ &= 105\text{ kg P/d}\end{aligned}$$

$$\begin{aligned}\text{Digested solids P mass rate} &= \left(3046\text{ kg VSS/d}\right)\left(0.018\text{ kg P/kg VSS}\right)\\ &= 55\text{ kg P/d}\end{aligned}$$

$$\text{P released to bulk water} = 105\text{ kg P/d} - 55\text{ kg P/d} = 50\text{ kg P/d}$$

$$\text{Soluble P concentration} = \left[\frac{(50\text{ kg P/d})}{(129{,}075\text{ kg H}_2\text{O/d})(1\text{ L/kg})}\right]\left(\frac{10^6\text{ mg}}{1\text{ kg}}\right) = 387\text{ mg/L}$$

ii. Screw press mass balances are conducted using the digester effluent mass rates calculated above to estimate pressate flow and TSS concentration:

$$\text{Screw press cake solids mass rate} = 0.95\left(4680\text{ kg/d}\right) = 4446\text{ kg/d}$$

$$\text{Pressate solids mass rate} = 4680\text{ kg/d} - 4446\text{ kg/d} = 234\text{ kg/d}$$

$$\text{Water to digester} = \left(136.8\text{ m}^3\text{/d}\right)\left(1000\text{ kg/m}^3\right) - 7725\text{ kg/d} = 129{,}075\text{ kg/d}$$

$$\text{Cake water mass rate} = \frac{(4446\text{ kg/d})}{0.25}(0.75) = 13{,}338\text{ kg/d}$$

$$\text{Pressate water mass rate} = 129{,}075\text{ kg/d} - 13{,}338\text{ kg/d} = 115{,}737\text{ kg/d}$$

$$\text{Pressate flow} = \frac{(115{,}737\text{ kg/d})}{(10^3\text{ kg/m}^3)} = 116\text{ m}^3\text{/d}$$

$$\text{Pressate TSS concentration} = \frac{\left[\dfrac{(234\text{ kg/d})}{(116\text{ m}^3\text{/d})}\right]\left(\dfrac{10^6\text{ mg}}{1\text{kg}}\right)}{\left(\dfrac{10^3\text{ L}}{1\text{m}^3}\right)} = 2017\text{ mg/L}$$

3. Contributions of pressate soluble TKN and P mass rates to the primary effluent nutrient mass rates, expressed as percentages, are calculated by conducting nutrient balances across the primary sedimentation tank for raw influent using the information presented in the problem statement. Once the “base load” of nutrients in the primary effluent are calculated, the soluble N and P mass loads are added to calculate their contribution the primary effluent nutrient mass rates. The contribution of pressate nutrients to the primary effluent is calculated based on the assumption that soluble constituents are not removed in the primary sedimentation tank, e.g. phosphate precipitation.

Primary sedimentation tank solids and flow balances:

$$\text{Primary effluent TSS mass rate} = 7685\text{ kg/d} - 4611\text{kg/d} = 3074\text{ kg/d}$$

$$\text{Primary effluent VSS mass rate} = (3074\text{ kg/d})\left[\frac{(226\text{ mg/L})}{(290\text{ mg/L})}\right] = 2396\text{ kg/d}$$

$$\text{Primary effluent Q} = 26{,}500\text{ m}^3\text{/d} - 461\text{m}^3\text{/d} = 26{,}039\text{ m}^3\text{/d}$$

Primary sedimentation tank TKN mass balance:

$$\text{Primary effluent particulate TKN mass rate} = (2396\text{ kg/d})(0.04) = 96\text{ kg/d}$$

$$\begin{aligned}\text{Primary influent sTKN concentration} &= 40\text{ mg/L} - (226\text{ mg VSS/L})(0.04)\\ &= 31\text{mg/L}\end{aligned}$$

Primary influent soluble TKN mass rate

$$= (26{,}039\ \text{m}^3/\text{d})(31\ \text{mg/L})\left(\frac{10^3\ \text{L}}{1\text{m}^3}\right)\left(\frac{1\ \text{kg}}{10^6\ \text{mg}}\right) = 807\ \text{kg/d}$$

$$\text{TKN mass rate} = 807\ \text{kg/d} + 96\ \text{kg/d} = 903\ \text{kg/d}$$

$$\text{Soluble P concentration} = 7\ \text{mg P/L} - (226\ \text{mg VSS/L})(0.015) = 3.6\ \text{mg P/L}$$

$$\text{Particulate P mass rate} = (2396\ \text{kg/d})(0.015) = 36\ \text{kg P/d}$$

$$\text{Total P mass rate} = (26{,}039\ \text{m}^3/\text{d})(3.6\ \text{mg P/L})\left(\frac{10^3\ \text{L}}{1\ \text{m}^3}\right)\left(\frac{1\ \text{kg}}{10^6\ \text{mg}}\right) + (36\ \text{kg P/d})$$

$$= 130\ \text{kg P/d}$$

From the pressate mass balance calculations:

$$\text{Pressate sTKN mass rate} = (116\ \text{m}^3/\text{d})(1642\ \text{mg/L})\left(\frac{10^3\ \text{L}}{1\text{m}^3}\right)\left(\frac{1\text{kg}}{10^6\ \text{mg}}\right)$$

$$= 190\ \text{kg N/d}$$

$$\text{Pressate soluble P mass rate} = (116\ \text{m}^3/\text{d})(387\ \text{mg/L})\left(\frac{10^3\ \text{L}}{1\text{m}^3}\right)\left(\frac{1\text{kg}}{10^6\ \text{mg}}\right)$$

$$= 45\ \text{kg P/d}$$

The contribution of the pressate soluble TKN and soluble phosphorus to the primary effluent mass rates, expressed in percent, are calculated as follows:

$$\text{N, \%} = \frac{(190\ \text{kg N/d})(100)}{(190\ \text{kg N/d}) + (903\ \text{kg N/d})} = 17.4$$

$$\text{P, \%} = \frac{(45\ \text{kg P/d})(100)}{(45\ \text{kg P/d}) + (130\ \text{kg P/d})} = 25.7$$

Problem 15-8
Problem Statement—see text on page 1733

Instructors Note: The referenced equations in the problem statement should be Eq. (7-126) in Sec. 15-8 and Eq. (15-12) in Sec. 15-9. The students should assume the net solids yield of 0.2 kg VSS / kg COD for both nitrification-denitrification and nitritation-denitritation.

Solution

The COD required to reduce 1 kg of NO_2-N is calculated with Eq. (15-12) using a net yield of 0.2 kg VSS / kg COD as follows.

$$\frac{\text{bsCOD}}{\text{NO}_2\text{-N}} = \frac{1.71}{1-(1.42)(0.2)} = 2.39\,\frac{\text{kg bsCOD}}{\text{kg NO}_2\text{-N}}$$

Similarly, the COD required to reduce 1 kg of NO3-N is calculated using Eq. (7-126) using a net yield of 0.2 kg VSS / kg COD as follows.

$$\frac{\text{bsCOD}}{\text{NO}_3\text{-N}} = \frac{2.86}{1-(1.42)(0.2)} = 3.99\,\frac{\text{kg bsCOD}}{\text{kg NO}_3\text{-N}}$$

Since both COD requirements as based on 1 kg of nitrogen, the two values are subtracted to obtain the COD reduction per kg of nitrogen reduced.

$$\text{Reduction in COD requirement} = 3.99 - 2.39 = 1.6\,\frac{\text{kg COD saved}}{\text{kg N reduced}}$$

Methanol is selected as the carbon source. The equivalent mass of methanol that is saved by operating the process in nitritation-denitritation mode is calculated as follows.

$$\text{Methanol mass savings per kg nitrogen reduced} = \frac{\left(1.6\ \dfrac{\text{kg COD saved}}{\text{kg N reduced}}\right)}{\left(1.5\ \dfrac{\text{kg COD}}{\text{kg methanol}}\right)}$$

$$= 1.1\,\frac{\text{kg methanol saved}}{\text{kg N reduced}}$$

Problem 15-9

Problem Statement—see text on page 1733

Solution

1. Estimate the sodium carbonate dosing rate required to achieve complete nitrification of the sidestream described in Problem 15-2.

From the Problem 15-2 statement:

Ammonia-N concentration = 1050 mg-N / L

From the solution to Problem 15-2:

Daily sidestream volume = 664 m^3 / d

With the concentration and flow rate, the ammonia mass rate is calculated.

$$\text{Ammonia}-\text{N mass rate} = \left(1050\ \frac{\text{mg N}}{\text{L}}\right)\left(\frac{10^3\ \text{L}}{\text{m}^3}\right)\left(\frac{1\ \text{kg}}{10^6\ \text{mg}}\right)\left(664\ \frac{\text{m}^3}{\text{d}}\right)$$

$$= 697\ \frac{\text{kg N}}{\text{d}}$$

As shown in Eq. (7-93) in Sec. 15-8, approximately 1.98 moles of bicarbonate are consumed per mole of ammonia-N that is oxidized when autotrophic cell mass synthesis is included in the mass balance. To account for the reduction in autotrophic yield due to decay, the selected alkalinity basis is 2 moles of bicarbonate per mole of ammonia-N or 7.14 grams of $CaCO_3$ per gram of ammonia-N oxidized. Using this value, the alkalinity consumed for complete oxidation of ammonia is calculated as follows.

$$\text{Alkalinity consumption rate} = (697 \text{ kg N/d})(7.14 \text{ kg CaCO}_3\text{/kg N})$$
$$= 4977 \text{ kg CaCO}_3\text{/d}$$

The mass of alkalinity required from an external source is the difference between the alkalinity consumption rate and the rate of alkalinity added to the reactor with the sidestream.

$$\text{Sidestream alkalinity mass rate} = (3750 \text{ mg CaCO}_3\text{/L})\left(\frac{10^3 \text{ L}}{1\text{m}^3}\right)\left(\frac{1\text{kg}}{10^6 \text{ mg}}\right)(664 \text{ m}^3\text{/d})$$
$$= 2490 \text{ kg CaCO}_3\text{/d}$$

$$\text{Alkalinity to be provided by external source} = 4977 \text{ kg CaCO}_3\text{/d} - 2490 \text{ kg CaCO}_3\text{/d}$$
$$= 2487 \text{ kg CaCO}_3\text{/d}$$

The mass of sodium carbonate required to supply the alkalinity is calculated as follows.

Calcium carbonate:

Molecular weight = 100 g/mole

1 mole = 2 eq

Therefore, 50 g of $CaCO_3$ = 1 equivalent

Sodium carbonate:

Molecular weight = 106 g/mole

1 mole = 2 equivalents

Therefore, 53 g of Na_2CO_3 = 1 equivalent

On a basis of equivalents:

53 grams of Na_2CO_3 = 50 g of $CaCO_3$

The mass rate of sodium carbonate is calculated as follows.

$$\text{Sodium carbonate mass rate} = (2487 \text{ kg CaCO}_3\text{/d})\left(\frac{53 \text{ kg Na}_2\text{CO}_3}{50 \text{ kg CaCO}_3}\right)$$
$$= 2636 \text{ kg NaCO}_3\text{/d}$$

2. Describe how the soda ash dosing requirement would change if the sidestream treatment process is modified from nitrification-denitrification to nitritation-denitritation.

Because the acidity generated during nitrification occurs during the oxidation of ammonia to nitrite, modifying the separate sidestream treatment process from nitrification-denitrification to nitritation-denitritation will not affect the soda ash dosing requirement. If autotrophic cell mass synthesis is considered in the mass balance, a small reduction in inorganic carbon would occur as nitrite oxidizing bacteria are not growing in the nitritation-denitritation process, but this reduction is negligible.

16

AIR EMISSIONS FROM WASTEWATER TREATMENT FACILITIES AND THEIR CONTROL

PROBLEM 16-1

Problem Statement - See text, page 1793

Instructors Note: The total alkalinity required should be 14.68 instead of 10.87 mg/L as $CaCO_3$.

Solution

1. The pertinent reaction for the destruction of H_2S with chlorine is:

$$\underset{34.06}{H_2S} + \underset{4 \times 70.91}{4Cl_2} + 4H_2O \rightarrow \underset{98.06}{H_2SO_4} + \underset{8 \times 36.5}{8HCl}$$

2. Determine the amount of H_2SO_4 and HCl formed for each mg/L of H_2S oxidized.

$$H_2SO_4 \text{ formed} = \frac{(98.06 \text{ g/mole})(1 \text{ mg/L})}{(34.06 \text{ g/mole})} = 2.88 \text{ mg/L}$$

$$\text{HCl formed} = \frac{8\ (36.5 \text{ g/mole})(1 \text{ mg/L})}{(34.06 \text{ g/mole})} = 8.57 \text{ mg/L}$$

3. The pertinent reactions for the amount of alkalinity expressed as $CaCO_3$ needed to neutralize the acid formed in the destruction of the H_2S are:

$$\underset{98.06}{H_2SO_4} + \underset{100 \text{ as } CaCO_3}{Ca(OH)_2} \rightarrow CaSO_4 + 2H_2O$$

$$\underset{8 \times 36.5}{8HCl} + \underset{4 \times 100 \text{ as } CaCO_3}{4Ca(OH)_2} \rightarrow 4CaCl_2 + 4CO_2 + 8H_2O$$

4. Determine the amount of alkalinity required as $CaCO_3$

   a. For the H_2SO_4

$$\text{Alkalinity for } H_2SO_4 = \frac{(100\ g/mole)(2.88\ mg/L)}{(98.06\ g/mole)} = 2.94\ mg/L \text{ as } CaCO_3$$

   b. For the HCl

$$\text{Alkalinity for HCl} = \frac{4(100\ g/mole)(8.57\ mg/L)}{8(36.5\ g/mole)} = 11.74\ mg/L \text{ as } CaCO_3$$

   c. Total alkalinity required = (2.94 + 11.74) mg/L = 14.68 mg/L as $CaCO_3$

PROBLEM 16-2

Problem Statement - See text, page 1793

Solution

1. The pertinent reaction for the destruction of H_2S with hydrogen peroxide is:

$$\underset{34.06}{H_2S} + \underset{34}{H_2O_2} \rightarrow S^o\downarrow + 2H_2O$$

2. Determine the amount of H_2O_2 needed for each mg/L of H_2S oxidized.

$$H_2O_2 \text{ needed} = \frac{(34\ g/mole)}{(34.06\ g/mole)} = \frac{(1\ mg/L\ H_2O_2)}{(1\ mg/L\ H_2S)}$$

PROBLEM 16-3

Problem Statement - See text, page 1793

Solution

1. Write the pertinent reaction for the destruction of H_2S with permanganate

$$\begin{array}{l} \quad 8\cdot(MnO_4^- + 4H^+ + 3e^- \rightarrow MnO_2(s) + 2H_2O) \\ + \quad 3\cdot(H_2S(g) + 4H_2O \rightarrow SO_4^{2-} + 10H^+ + 8e^-) \\ \hline 8MnO_4^- + 2H^+ + 3H_2S(g) \rightarrow 8MnO_2(s) + 4H_2O + 3SO_4^{2-} \\ (8\ x118.9) \qquad\qquad (3x34.1) \end{array}$$

2. Convert the gas concentration from ppm_v to g/m^3.

$$\text{H}_2\text{S(g) concentration} = \frac{(100\ \text{ppm}_\text{v})(34.1\ \text{g/mole})}{(10^6)(22.414 \cdot 10^{-3}\ \text{m}^3/\text{mole})} = 0.152\ \text{g/m}^3$$

3. Determine the amount of permanganate needed to oxidize 100 ppm_v of H_2S oxidized.

$$\text{MnO}_4^- \text{ needed} = \frac{8(118.9\ \text{g/mole})}{3(34.1\ \text{g/mole})} = \frac{(9.3\ \text{g/m}^3\ \text{MnO}_4^-)}{(1\ \text{g/m}^3\ \text{H}_2\text{S})}$$

4. Compute the amount of permanganate needed to oxidize 100 ppm_v H_2S with a gas flowrate of 1,500 m^3/min (2.16 x 10^6 m^3/d)

$$\text{MnO}_4^- \text{ needed} = \frac{(2.16 \cdot 10^6\ \text{m}^3/\text{d})(0.152\ \text{g/m}^3\ \text{H}_2\text{S})}{\left[\dfrac{(9.3\ \text{g/m}^3\ \text{MnO}_4^-)}{(1\ \text{g/m}^3\ \text{H}_2\text{S})}\right]\left(\dfrac{10^3\ \text{g}}{\text{kg}}\right)} = 35.3\ \text{kg MnO}_4^-/\text{d}$$

The amounts of permanganate needed for H_2S oxidation are summarized in the following table

Flowrate, m^3/d	Permanganate needed, kg/d
1500	35.3
1800	42.2
2000	47.1
2200	51.8

PROBLEM 16-4

Problem Statement - See text, page 1793

Solution

1. Write the pertinent reaction for the exchange reaction between H_2S and ferrous sulfide

$$\underset{(87.9)}{\text{FeS}} + \text{H}^+ \leftrightarrow \text{Fe}^{2+} + \underset{(34.1)}{\text{H}_2\text{S}}$$

2. Determine the amount of ferrous sulfate needed to remove 150 mg/L of H_2S.

$$\mathrm{FeSO_4} = \left[\frac{(87.9\ \mathrm{g/mole\ FeS})}{(34.1\ \mathrm{g/mole\ H_2S})}\right]\left[\frac{(151.9\ \mathrm{g/mole\ FeSO_4})}{(87.9\ \mathrm{g/mole\ FeS})}\right]$$

$$= \frac{(4.45\ \mathrm{mg/L\ FeSO_4})}{(1\ \mathrm{mg/L\ H_2S})}$$

The amount of $FeSO_4$ needed is (150)(4.45) = 667.5 mg/L

PROBLEM 16-5

Problem Statement - See text, page 1793

Solution

Determine the volume of gas occupied by one mole of a gas at a temperature of 28°C and a pressure of 1.0 atm using Eq. (2-44). The following solution is provided for **Plant 1**.

$$V = \frac{nRT}{P}$$

$$V = \frac{(1\ \mathrm{mole})(0.082057\ \mathrm{atm \cdot L / mole \cdot K})[(273.15 + 28)\mathrm{K}]}{1.0\ \mathrm{atm}} = 24.7\,\mathrm{L}$$

2. Estimate chlorine requirement.

   a. Determine the amount of H_2S that must be treated per day. Using Eq. (2-45), convert the H_2S concentration from $\mathrm{ppm_v}$ to $\mathrm{g/m^3}$

$$75\ \mathrm{ppm_v} = \left(\frac{75\ \mathrm{m^3}}{10^6\ \mathrm{m^3}}\right)\left[\frac{(34.08\ \mathrm{g/mole\,H_2S})}{(24.7\ \mathrm{x}10^{-3}\ \mathrm{m^3/mole\ of\ H_2S})}\right] = 0.103\ \mathrm{g/m^3}$$

$$(1000\ \mathrm{m^3/min})(0.103\ \mathrm{g/m^3})(1440\ \mathrm{min/d})(1\ \mathrm{kg}/10^3\ \mathrm{g}) = 148.9\ \mathrm{kg/d}$$

   b. Estimate the sodium hypochlorite dose. From Eq. (16-3), 8.74 mg/L of sodium hypochlorite are required per mg/L of sulfide, expressed as hydrogen sulfide.

NaOCl required per day = (148.9 kg/d) x (8.74) = 1301.4 kg/d

3. Estimate the water requirement for the scrubbing tower

    a. Determine the density of air at the given temperature using Appendix B-1 and B-3.

$$\rho_a = \frac{PM}{RT} = \frac{(101{,}325\ \mathrm{N/m^2})(28.97\ \mathrm{kg/kg\cdot mole})}{(8314\ \mathrm{N\cdot m/kg\cdot mole\cdot K})(273.15\mathrm{K}+28\mathrm{K})} = 1.1724\ \mathrm{kg/m^3}$$

    b. Determine the mass air flowrate

    (1000 m^3/min)(1.1724 kg/m^3) = 1172.4 kg/min

    c. Determine the water flowrate

    1172.4 kg/min x 1.85 = 2170 kg/min = 2.17 m^3/min

4. Determine the amount of sodium hydroxide (caustic) that must be added to replace the alkalinity consumed in the reaction.

    a. From the reaction given by Eq. (16-3), 2.35 mg/L of NaOH is required for each mg/L of H_2S removed.

    b. Determine the amount of NaOH required

    NaOH = 148.9 kg/d x 2.35 = 350 kg/d

    c. Determine the volume of NaOH required. The amount of caustic per liter is

    NaOH = 1.0 L x 1.52 kg/L x 0.50 = 0.76 kg/L

$$\text{Volume of NaOH} = \frac{(350\ \mathrm{kg/d})}{(0.76\mathrm{kg/L})} = 460.6\ \mathrm{L/d}$$

5. Summary of results from problem 16-5

	Chemical needs	
Plant	NaOCl, kg/d	NaOH, L/d
1	1301.8	460.6
2	1920.8	679.5
3	3586.4	1268.8
4	1104.5	390.8

PROBLEM 16-6

Problem Statement - See text, page 1793

Solution

1. Determine the air flow to be scrubbed **for a gas flowrate of 1500 m^3/min**

   Flow = 1500 m^3/min = 90,000 m^3/h

2. Select a surface loading rate from Table 16-11; use 90 $m^3/m^2 \bullet h$.

3. Select a filter bed depth from Table 16-11; use 1.0 m

4. Calculate the area needed for the filter bed.

   Area = gas flow/ loading rate

   Area = (90,000 m^3/h)/ (90 $m^3/m^2 \bullet h$)

   Area = 1000 m^2

5. Check the empty bed residence time using Eq. (16-13)

$$\text{EBRT} = \frac{V_f}{Q} = \frac{1000\ \text{m}^2}{90{,}000\ \text{m}^3/\text{h}} = 0.011\,\text{h} = 40\ \text{s}$$

6. Determine whether the volume of the biofilter determined in Step 5 is adequate to treat the H_2S.

a. Determine the concentration of H_2S in g/m^3 using Eq. (2-45). The volume of gas occupied by one mole of a gas at a temperature of 20°C and a pressure of 1.0 atm is 24.1 L. Thus, the concentration of H_2S is:

$$\text{g/m}^3 = \left(\frac{65\text{L}^3}{10^6\text{L}^3}\right)\left[\frac{(34.08\text{ g/mole H}_2\text{S})}{(24.1\times10^{-3}\text{ m}^3\text{/mole of H}_2\text{S})}\right] = 0.092\text{ g/m}^3$$

b. Determine the mass loading rate of S in g S/h

$$M_s = \left(\frac{90,000\text{ m}^3}{\text{h}}\right)\left(\frac{0.092\text{ g}}{\text{m}^3}\right)\left(\frac{32\text{ g}}{34.08\text{ g}}\right) = 7,768\text{ g S/h}$$

c. Determine the required volume assuming an elimination rate of 65 g S/m^3•h. The assume elimination rate is 50 percent of the maximum value reported on Page 1765.

$$V = \frac{(7768\text{ g S/h})}{(65\text{ g S/m}^3\bullet\text{h})} = 119.5\text{ m}^3$$

Because the volume of the bed (1000 m^3) is significantly greater than the required volume, the removal of H_2S will not be an issue.

7. Determine the mass of the buffer compound needed to neutralize the acid formed as a result of treatment within the filter

a. Determine the mass of H_2S in kg applied per year.

$$\text{H}_2\text{S, kg/y} = \frac{(90,000\text{ m}^3\text{/h})(0.092\text{ g/m}^3)(24\text{ h/d})(365\text{ d/y})}{(10^3\text{ g/kg})} = 72,533\text{ kg/y}$$

b. Determine the mass of buffer compound required. Assume the following equation applies.

$$\underset{34.06}{H_2S} + \underset{74.08}{Ca(OH)_2} + 2O_2 \rightarrow CaSO_4 + 2H_2O$$

Thus, about 2.05 kg of $Ca(OH)_2$ will be required per kg of H_2S. If the compost biofilter has a useful life of two years, then a total of 297,385 kg of $Ca(OH)_2$ equivalent will be required to be added to the bed.

kg of $Ca(OH)_2$ = 2 x (72,533 kg/y) (2.05) = 297,385

PROBLEM 16-7

Problem Statement - See text, page 1793

Instructors Note: The problem statement specified that average load by fuel oil is 35 percent. For the convenience of using the data from AP42, however, it should be corrected to 5 percent (to be consistent with the basis of emission factors presented in AP42.

The emission factors in Table 16-15 have errors for SI units (US customary units are correct). For the dual fuel engines, the emission factors for CO, NOx, and SO_2 are 0.58, 1.16, and $0.0216S_1+0.386S_2$, respectively.

Because the emission factors presented in Table 16-15 are based on the fuel input, assumptions must be made for the average output and the efficiency of the engine. In this solution, 38% efficiency for the reciprocating engine (electrical power output to fuel input). For SO_2, S_1 is weight percent of sulfur in the fuel oil, and S_2 is weight percent of sulfur in natural gas. In this solution, 1.0 percent for fuel oil and 0.00077 percent for natural gas are assumed. Instructor may provide these values, or students may be tasked to find out the typical values and state their assumptions.

Alternatively, the original AP42 document may be used to find the emission factors based on the power output.

Solution

The specified engine is categorized as a large diesel and dual fuel reciprocating engine. The emission factors for CO, NOx and SO_2 are, 0.58, 1.16, and $(0.0216S_1 + 0.386S_2)$ kg/GJ, respectively.

1. Determine the fuel consumption based on the assumed system efficiency and power output. (Assumed efficiency = 38 percent.)

   Annual output = (2386 kW)(8640 h/y) = 20,615,040 kWh/y

   Fuel input = (20,615,040 kWh/y)/0.38 = 54,250,105 kWh/y

   = (54,250,105 kWh/y)(1 GJ/277.8 kWh) = 195,285 GJ/y

2. Estimate the emissions based on the fuel input from Step 1.

   CO emission = (0.58 kg/GJ)(195,285 GJ/y) = 113,265 kg/y ≈ 113 tonne/y

   NOx emission = (1.16 kg/GJ)(195,285 GJ/y) = 226,531 kg/y ≈ 227 tonne/y

3. Determine the emission factor for SO_2.

   Assuming 1 and 0.00077 percent sulfur weight percent in fuel oil and natural gas, respectively, the emission factor is

   0.0216 x 1 + 0.386 x 0.00077 = 0.0219

4. Estimate the SO_2 emission based on the emission factor calculated in Step 3.

   SO_2 emission = (0.0219 kg/GJ)(195,285 GJ/y) = 4276 kg/y ≈ 4.3 tonne/y

Note: Emission factors based on the power output are also presented in AP42 (see Table 3.4-1). Using the emission factors based on the power output, the emissions are calculated as:

CO = (0.0075 lb/hp•h)(3200 bhp) = 24.0 lb/h = 94,058 kg/y ≈ 94 tonne/y

NOx = (0.018 lb/hp•h)(3200 bhp) = 57.6 lb/h = 225,739 kg/y ≈ 226 tonne/y

SO_2 = {[(0.000406)(1)+(0.00957)(0.00077)]lb/hp•h}(3200 bhp) = 1.32 lb/h = 5184 kg/y ≈ 5.2 tonne/y

As noted in AP42, the power output and fuel input values were averaged independently from each other because of the use of actual brake-specific fuel consumption (BSFC) values for each data point. The resulting emissions are somewhat similar in both calculations in this case, meaning the actual engines from which the data were collected had an average efficiency close to 38 percent.

PROBLEM 16-8

Problem Statement - See text, page 1794

Instructors Note: The reference to the example problem is to be corrected to Example 16-5. The available digester gas is more than the natural gas use in the existing condition from Example 16-5. The students may solve assuming only natural gas is replaced with the digester gas, or it can be assumed that the excess natural gas is used to generate electricity onsite, thereby reducing the purchase of electricity from the electrical grid. Both scenarios are presented in this solution.

Solution

1. Determine the energy content of digester gas flared and the reduction in natural gas use by using all natural gas for power generation.

   Energy content of digester gas = 0.0224 GJ/m^3

   Digester gas previously flared and vented = 290,500 + 2400 m^3/y
   = 292,900 m^3/y

   Additional energy obtained from the additional digester gas use

   = (0.0224 GJ/m^3)(290,500 m^3/y) = 6507.2 GJ/y

2. Determine the potential natural gas saving.

   Energy content of natural gas = 0.0383 GJ/m^3

   Natural gas saved = (6507.2 GJ/y)/(0.0383 GJ/m^3) = 169,901 m^3/y

The annual consumption of natural gas is 17,300 m^3/y, which is less than the amount unutilized digester gas could supplement. Therefore natural gas saving is 17,300 m^3/y.

3. Calculate the GHG emissions for the energy sources determined in Step 2.

   a. Determine the GHG emissions assuming that only natural gas use is replaced by the part of digester gas which was flared.

      i. Digester gas required to replace 17,300 m^3/y of natural gas

         = (17,300 m^3/y)/[(0.0383 GJ/m^3)/(0.0224 GJ/m^3)] = 10,118 m^3/y

      ii. Calculate the GHG emissions from the digester gas use and flare

         Digester gas used = 755,000 + 10,118 m^3/y = 765,118 m^3/y

         Digester gas flared = 290,500 – 10,118 m^3/y = 280,382 m^3/y

      iii. GHG emissions from digester gas used

      iv. GHG emissions from digester gas flared

      v. GHG emissions reduction by eliminating the natural gas use (from Step 1a of Example 16-5)

         GHG reduction = 33.3 tonne CO_2e/y

      Note: The GHG emissions from digester gas used and digester gas flared has a slightly different formula according to the LGO protocol but the resulting emissions are similar and the difference in the total emissions is negligible compared to the total emission.

   b. Determine the GHG emissions assuming that the remaining digester gas is used at an engine generator to generate electricity, thereby reducing the use of electricity from electrical grid.

i. Estimate electrical power generation from the use of remaining unused digester gas. In this solution, 38 percent efficiency (i.e., electricity output to digester gas energy input) is assumed.

Remaining digester gas = (290,500 + 2400 – 10,118) m^3/y
= 282,782 m^3/y

Energy content = (282,782 m^3/y)(0.0224 GJ/m^3) = 6334 GJ/y

At 38 percent efficiency, electrical power generated
= (6334 GJ/y)(277.8 kWh/1 GJ)(0.38) = 668,642 kWh/y

ii. Estimate the GHG emissions from the reduced use of electrical power from the grid

Electrical power usage from the grid = (14,100,000 – 668,642) kWh/y = 13,431,358 kWh/y

iii. Calculate the GHG emissions from the use of grid electricity

CO_2e emission
= (Electricity use, kWh/y)(emission factor, g CO_2e/kWh)(1 tonne/10^6 g)
= (13,431,358 kWh/y)(720 g/kWh)(1 tonne/10^6 g)
=9671 tonne/y

From Step 2 of Example 16-5, CO_2e emission from the use of electricity from power grid was 10,152 tonne/y.
CO_2e emission reduction = 10,152 – 9671 = 481 tonne/y

As mentioned in Step 3a, the GHG emissions from digester gas used and digester gas flared has a slightly different formula according to the LGO protocol but the resulting emissions are similar and the difference in the total emissions is negligible compared to the total emission.

c. Summary

GHG emissions reduction by replacing natural gas with digester gas
= 33.3 tonne CO_2e/y
(Available digester gas exceeds the total natural gas use)

GHG emissions reduction by generating electricity from remaining digester gas
= 481 tonne CO_2e/y

Note: Further to this analysis, waste heat from the engine generator could be used to replace the heat generated by boiler (with natural gas or digester gas), which will result in further reduction in the overall GHG emissions.

17

ENERGY CONSIDERATIONS IN WASTEWATER MANAGEMENT

PROBLEM 17-1

Instructors Note: The suggested articles in this solution are current as of September 2013. Instructors are advised to search for the latest articles at the time of the class.

Problem Statement – See text, page 1860

Solution

Examples of peer-reviewed articles that may be used include:

Blischke, J., A. Wong, and K. Matthews (2009) "Integrated Sustainable Solutions – Co-Diestion of Solid Waste at WWTPs and the BTA Process as a Pre-Treatment Step," *Proceedings of the Water Environment Federation 82nd Annual Conference and Exposition*, Orlando, FL.

Cabbai, V., M. Ballico, E. Aneggi, and D. Goi (2013) "BMP Tests of Source Selected OFMSW to Evaluate Anaerobic Codigestion with Sewage Sludge," *Waste Manag.*, **33**, 7, 1626-1632.

Kim, H.W., J.Y. Nam, and H.S. Shin (2011) "A Comparison Study on the High-Rate Co-Digestion of Sewage Sludge and Food Waste Using a Temperature-Phased Anaerobic Sequencing Batch Reactor System," *Bioresource Technol.*, **102**, 15, 7272-7279.

Krupp, M., J. Schubert, and R. Widmann (2005) "Feasibility Study for Co-Digestion of Sewage Sludge with OFMSW on Two Wastewater Treatment Plants in Germany," *Waste Manag*., **25**, 4, 393-399.

Iacovidou, E., D.G. Ohandja, and N. Voulvoulis (2012) "Food Waste Co-Digestion with Sewage Sludge – Realizing Its Potential in the UK," *J. Environ. Manag.*, **112**, 267-274.

Razaviarani, V., I.D. Buchanan, S. Malik, and H. Katalambula (2013) "Pilot-Scale Anaerobic Co-Digestion of Municipal Wastewater Sludge with Restaurant Grease Trap Waste," *J. Environ. Manag.*, **123**, 7, 26-33.

Zhou, P., E. Elbeshbishy, and G. Nakhla (2013) "Optimization of Biological Hydrogen Production for Anaerobic Co-Digestion of Food Waste and Wastewater Biosolids," *Bioresource Technol.*, **130**, 2, 710-718.

Zhu, H., W. Parker, D. Condidi, R. Bansar, and P. Seto (2011) "Eliminating Methanogenic Activity in Hydrogen Reactor to Improve Biogas Production in a Two-Stage Anaerobic Digestion Process Co-Digesting Municipal Food-Waste and Sewage Sludge," *Bioresource Technol.*, **102**, 14, 7086-7092.

The following publications are examples of reports that contain useful information about the implementation and operation of co-digestion facilities.

City of San Jose (2007) *Biomass-to-Energy Technology Evaluation*, Final Report, Prepared by CH2M-HILL, City of San Jose, Environmental Services Department.

City of San Rafael and Central Marin Sanitation Agency (2008) *Methane Capture Feasibility Study*, Prepared by Kennedy/Jenks Consultants.

WERF (2008) State of Science Report: Energy and Resource Recovery from Sludge, Prepared for the Global Water Research Coalition, Water Environment Research Foundation, Alexandria, VA.

WERF (2010) *Co-Digestion of Organic Waste Products with Wastewater Solids*, Interim Report, WERF OWSO5R07a, Water Environment Research Foundation, Alexandria, VA.

Zhang, R., R. Romano, X. Chen, and H.S. Kim (2007) *Anaerobic Digestion of Selected Food Waste Streams*, Research Report, Biological and Agricultural Engineering Department, University of California, Davis, Prepared for Sacramento Municipal Utility District.

PROBLEM 17-2

Instructors Note: If U.S. customary units are used, unit conversion between U.S. customary and SI units is not necessary. With U.S. customary units, use the exact equations as given in the original publication (AWWARF, 2007, see page 1863).

The following solution is for 60 percent use of produced digester gas.

Problem Statement – See text, page 1861

Solution – This solution is for **60 percent** use of produced digester gas.

1. Calculate the natural log of the source energy use value using Eq. (17–12) on page 1815 and the given data:

$$\begin{aligned}\ln(E_s, \text{kBtu/y}) = {} & 15.8741 \\ & +0.8944 \times \ln(\text{influent average Mgal/d}) \\ & +0.4510 \times \ln(\text{influent BOD mg/L}) \\ & -0.1943 \times \ln(\text{effluent BOD mg/L}) \\ & -0.4280 \times \ln(\text{influent average flow / influent design flow} \times 100) \\ & -0.3256 \times (\text{trickling filter? Yes-1, No-0}) \\ & +0.1774 \times (\text{nutrient removal? Yes-1, No-0})\end{aligned}$$

$$\begin{aligned}\ln(E_s \text{ kBtu / y}) = {} & 15.8741 \\ & +0.8944 \times \ln\{[24{,}000\ (\text{m}^3/\text{d})]/[3785\ (\text{m}^3/\text{Mgal})]\} \\ & +0.4510 \times \ln(120) \\ & -0.1943 \times \ln(6.2) \\ & -0.4280 \times \ln(24{,}000/30{,}000 \times 100) \\ & -0.3256 \times (0) \\ & +0.1774 \times (1) \\ = {} & 15.8741 + 1.6520 + 2.1592 - 0.3545 - 1.8755 - 0 + 0.1774 \\ = {} & 17.6327\end{aligned}$$

2. Calculate the adjustment factor from the value obtained in Step 1 using Eq. (17-13):

   Adjustment factor = 17.6327 / 17.8 = 0.9906

3. Calculate the natural log of the source energy use value using the energy usage data from the wastewater treatment plant and source energy factor in Table 17-6.

   a. Calculate actual source energy use for the energy from outside sources (not counting digester gas use) using Eq. (17-14).

   E_{as} (no digester gas) = (3,600,000 kWh/y)(11.1 kBtu/kWh)

   +(372,700 m^3/y)(35 MJ/m^3)(0.948 kBtu/MJ)

   = 39,960,000 + 12,366,186

   = 52,326,186 kBtu/y

4. Convert the source energy usage calculated in Step 3 to the natural log of the adjusted energy use using the adjustment factor from Step 2 and Eq. (17-15).

   a. Calculate $\ln(E_{adj})$ without digester gas usage

   $\ln(E_{adj})$ = ln(52,326,196 kBtu/y) / 0.9906 = 17.77 / 0.9906

   = 17.94

5. Using Fig. 17-5, find the benchmark score with and without digester gas usage.

   Score without counting the use of digester gas = 37

6. Calculate the reduction in natural gas usage when 60 percent of the digester gas is utilized to offset the natural gas usage.

   a. Calculate the natural gas saving.

   Assumed heating value for digester gas = 22 MJ/m^3

   = (22 MJ/m^3)(0.948 kBtu/MJ) = 20.85 kBtu/m^3

   60 percent of digester gas = (605,000 m^3/y)(0.6) = 363,000 m^3/y

   = 363,000 m^3/y)(20.85 kBtu/m^3) = 7,568,550 kBtu/y

   b. From Step 3, natural gas usage is 12,366,186 kBtu/y. Digester gas will substitute 7,568,550 kBtu/y of natural gas. Therefore natural gas use is 12,366,186 – 7,658,550 = 4,707,636 kBtu/y

7. Repeat the calculations in Steps 3 through 5 with the new natural gas usage.

a. Calculate actual source energy use for the energy from outside sources (not counting digester gas use) using Eq. (17-14).

E_{as} = 39,960,000 + 4,707,636

= 44,667,636 kBtu/y

b. Calculate ln(E_{adj}) without digester gas usage

ln(E_{adj}) = ln(44,667,636 kBtu/y) / 0.9906 = 17.61 / 0.9906

= 17.78

Score counting the use of digester gas = 52

PROBLEM 17-3

Problem Statement – See text, page 1861

Solution

1. As in Steps 1 and 2 of Example 17-5, ln(E_S) and the adjustment factor are 19.33 and 1.086, respectively.
2. Determine the potential electricity production from unused (flared + vented) digester gas.

Digester gas production = 1,047,900 m^3/y

Digester gas used = 755,000 m^3/y

Digester gas flared or vented = 292,900 m^3/y

Assumptions:

- Digester gas LHV = 22 MJ/m^3.
- From the data shown on Table 17-8, use 35 percent efficiency for electrical power generation and assume additional 35 percent of the energy is recovered (overall efficiency with CHP = 70 percent) as heat to lower the natural gas use.

a. Calculate the electrical power that can be generated by 292,900 m^3/y digester gas.

Power generation = (292,900 m^3/y)(22 MJ/m^3)(0.35) = 2,255,330 MJ/y

= (2,255,330 MJ/y) (1 kWh/3.6 MJ) = 626,481 kWh/y

3. Calculate the potential natural gas saving by using all digester gas generated and heat recovered.

   Assumptions:

   - Assume boiler efficiency = 85 percent
   - Natural gas LHV = 35.2 MJ/m^3.

   Heat recovered = (292,900 m^3/y)(22 MJ/m^3)(0.35) = 2,255,330 MJ/y

   Natural gas saving = $= \dfrac{(2{,}255{,}330\ \mathrm{MJ/y})}{(35.2\ \mathrm{MJ/m^3})(0.85)} = 75{,}379\ \mathrm{m^3/y}$

   Because annual natural gas consumption is 17,300 m^3/y, the heat recovered from engine generator is enough to offset all natural gas use. Note: In reality, natural gas use is seasonal and there may be periods when recovered heat from the engine generator is not sufficient and natural gas needs to be used to supplement the heat supply.

4. Calculate the natural log of the source energy use value using the energy usage data from the wastewater treatment plant and source energy factor in Table 17-6.

   a. Calculate actual source energy use for the energy from outside sources (no digester gas) using Eq. (17-14). As in Example 17-5

      E_{as} (no digester gas) = 156,510,000 + 626,135 + 14,528,358

      = 171,664,493 kBtu/y

   b. Calculate source energy use for the energy including digester gas usage.

      Electrical power consumption = (14,100,000 – 626,481) kWh/y

      = 13,473,519 kWh/y

      Natural gas consumption = 0 m^3/y

      Fuel oil consumption = 390 m^3/y

      E_{as} (without digester gas) = (13,473,519 kWh)(11.1 kBtu/kWh)

      + (0 m^3/y)(35.31 ft^3/1 m^3)(1.025 kBtu/ft^3)

      + (390 m^3/y)(264.2 gal)(141 kBtu/gal)

      = 149,556,061 + 0 + 14,528,358 kBtu/y

= 164,084,419 kBtu/y

E_{as} (with digester gas) = (13,473,519 kWh)(11.1 kBtu/kWh)

+ (0 m^3/y)(35.31 ft^3/1 m^3)(1.025 kBtu/ft^3)

+ (390 m^3/y)(264.2 gal)(141 kBtu/gal)

+ (1,047,900 m^3/y)(35.31 ft^3/1 m^3)(0.6 kBtu/ft^3)

= 149,556,061 + 0 + 14,528,358 + 22,200,809 kBtu/y

= 186,285,228 kBtu/y

5. Convert the source energy usage calculated in Step 4 to the natural log of the adjusted energy use using the adjustment factor from Step 1 and Eq. (17-15).
   a. Calculate $\ln(E_{adj})$ not including energy generated from digester gas.

      $\ln(E_{adj}) = \ln(164{,}084{,}419)/1.086 = 17.42$
   b. Calculate ln(Eadj) including energy generated from digester gas.

      $\ln(E_{adj}) = \ln(186{,}285{,}228)/1.086 = 17.53$
6. Using Fig. 17-5, find the benchmark score.

   Score not counting the use of energy generated from digester gas = 81

   Score counting the use of energy generated from digester gas = 73

PROBLEM 17-4

Problem Statement – See text, page 1861

Solution

1. From Figure 17-19, the recommended hydroturbine type is crossflow.
2. Using Eq. (17-8), calculate the hydraulic energy that can be recovered.

   $P_e = \rho Q g \Delta H \eta_t \eta_e$

   Total head ΔH= (2.5 bar)(10 m H_2O/1 bar) + $(1.5\ m/s)^2/(2 \cdot 9.81\ m/s^2)$

   = 25.1 m

Assuming $\eta_t\eta_e = 0.40$,

$$P_e = (1000\ \text{kg/m}^3)(7500\ \text{m}^3/\text{d})(9.81\ \text{m/s}^2)(25.1\ \text{m})(0.4)$$

$$= 738{,}693{,}000\ \text{kg}{\bullet}\text{m}^2/\text{s}^2{\bullet}\text{d}$$

$$= 738.7\ \text{MJ/d}$$

3. The two critical challenges of using raw wastewater for hydroturbine are (1) the variation in incoming flow, (2) debris in raw wastewater that may clog the turbine. Pelton type turbines are less susceptible to the abrasives and fibrous materials compared to other types of turbines but they typically require high net head [typically greater than 20m, see Fig. 17-19(b)].

PROBLEM 17-5

Problem Statement – See text, page 1861

Solution

1. Estimate the air requirement.

   a. Estimate the stoichiometric requirement to oxidize completely the sludge, assuming CO_2, H_2O, N_2, and SO_2 are the only combustion products. Set up a computation table to determine the moles of oxygen and kg of air required per kg of biosolids.

Component	Weight fraction	Atomic weight, kg/mole	Atomic weight units,[a] mole/kg	Moles O_2 required[b]	Combustion reaction and products	Product gas formed, mole/kg
Carbon	0.133	0.012	11.08	11.08	$C + O_2 \rightarrow CO_2$	11.83
Hydrogen	0.009	0.001	9.00	2.25	$4H + O_2 \rightarrow 2H_2O$	4.5
Oxygen	0.049	0.016	3.06	–1.53	$2O \rightarrow O_2$	0
Nitrogen	0.003	0.014	0.214	-	$2N \rightarrow N_2$	0.11
Sulfur	0.004	0.0321	0.125	0.062	$S + O_2 \rightarrow SO_2$	0.12
Water	0.719[c]	0.018			H_2O (vapor)	39.9
Inerts	0.083					
Total	1.000			11.86		56.46

[a] Atomic weight unit = weight fraction / atomic weight

[b] Moles required = atomic weight unit × mole of O_2 required per atom being oxidized based on the combustion reaction. For oxygen, O_2 saved due to oxygen in the biosolids is recorded, indicated with a negative sign.

[c] in the problem statement, the rounded value of 72 percent, was used for water. The value 0.719 is used in this solution so the total is 100.0 percent.

From the calculations above, 1 kg of biosolids will require 11.9 moles of O_2. Oxygen content in the air = 20.7 percent by volume at 20ºC and 50 percent humidity, and assuming mole fraction = volume fraction, moles of air required is:

Air required = 11.93/0.207 = 57.6 mole air/kg biosolids

b. Determine the amount of gas generated from combustion of 1 kg biosoloids.

For CO_2, 1 mole C is converted to 1 mole CO_2. From the summary above, CO_2 formed is 11.08 mole/kg biosolids (assuming complete combustion). Similarly, H_2O from hydrogen, N_2 from nitrogen, and SO_2 from sulfur are calculated and summarized in the table. Note that the water content in biosolids (72 percent) also becomes water vapor.

2. Develop a heat balance for a unit mass of biosolids. Ignore SO_2 for the rest of the calculations.

a. Determine air flows.

From Step 1, stoichiometric air requirement is 57.6 mole/kg biosolids

b. Determine heat content of added air.

From air composition and enthalpy data given in Example 17-6, heat content of added air at 20ºC without excess air is:

H = [(8.53×0.771 + 8.54×0.207 + (9.18×0.0004) + 9.74×0.0117 (kJ/mole)](57.6 mole air/kg biosolids) = 487 kJ/kg biosolids = 0.487 MJ/kg biosolids

c. Determine the heat content in biosolids at 20ºC

Solid content of biosolids is 28.1 percent and specific heat of dry biosolids is given in the problem statement. Thus the heat content is (0.281)(1.26)(20) = 7.08 kJ/kg biosolids. Water content of biosolids is 71.9 percent. Thus, the heat content is (0.719)(4.19)(20) = 60.25 kJ/kg biosolids. Total heat content is 7.08 + 60.25 = 67.3 kJ/kg biosolids =0.067 MJ/kg biosolids

d. Determine the flue gas composition and calculate heat content at 850ºC.

  i. Determine gas composition

  N_2: (N_2 from N in biosolids) + (N_2 in the air) = 0.11 (mole/kg biosolids) + 57.6 (mole air/kg biosolids)(0.771) = 44.5 mole/kg biosolids

  O_2: With no excess air, all oxygen in the air is used. For 1 kg of biosolids, 11.9 moles of oxygen is used

  CO_2: 11.08 (mole/kg biosolids) + 57.6 (mole air/kg biosolids)(0.0004) = 11.1 mole/kg-biosolids

  H_2O: [4.50 +39.9 (mole/kg biosolids)] + 57.6 (mole air/kg biosolids) × 0.011 = 45.1 (mole/kg biosolids)

  ii. Calculate the heat content using the data given in the problem statement

  N_2: 44.5 × 34.2 = 1522 kJ/kg biosolids

  O_2: 0 × 35.7 = 0 kJ/kg biosolids

  CO_2: 11.1 × 49.6 = 550 kJ/kg biosolids

  H_2O: 45.1 × 41.1 = 1853 kJ/kg biosolids

  Total = 1522 + 0 + 550 + 1853 = 3925 kJ/kg biosolids = 3.925 MJ/kg biosolids

e. Calculate the heat content remaining in the ash

Assuming complete combustion, ash = inert. Heat content is:

(0.083)(1.05)(850) = 74.1 kJ/kg biosolids = 0.074 MJ/kg biosolids

f. Estimate the heat released from combustion of biosolids, assuming complete combustion.

Using Eq. (2–66) and elemental analysis data given in the problem statement, estimate the heat contents of the solids:

HHV (MJ/kg) = 34.91 C + 117.83 H - 10.34 O - 1.51 N + 10.05 S - 2.11A

$$
\begin{aligned}
\text{HHV (MJ/kg)} &= (34.91\times 0.133)+(117.83\times 0.009)-(10.34\times 0.049)\\
&\quad -(1.51\times 0.003)+(10.05\times 0.004)-(2.11\times 0.083+\\
&= 5.057\ \text{(MJ/kg-biosolids)}
\end{aligned}
$$

g. Estimate evaporative cooling from the vaporization of water in biosolids and water formed by combustion of biosolids

From 1 kg of biosolids, 4.5 + 39.9 = 44.4 moles of water is formed. Latent heat of vaporization is 2257 kJ/kg. Therefore, latent heat of vaporization associated with every kg of biosolids is:

[(44.4 × 18)/1000](2257) = 1806 kJ/kg-biosolids = 1.806 MJ/kg-biosolids.

h. Estimate the heat loss. Assume 0.5 percent of gross heat input.

Gross heat input = (heat of biosolids) + (heat of inlet air) + (heat of combustion) – (heat loss from evaporation). Note that latent heat of vaporization should be subtracted from the gross heat input as the heat of combustion calculated in Step f above is HHV.

Gross heat loss = (0.487 + 0.067 + 5.057 – 1.806)(0.005) = 0.019 MJ/kg-biosolids

3. Evaluate the heat balance to determine if the system can maintain the operating temperature at 850ºC.

From the summary table below, energy balance is slightly negative with stoichiometric air flow. Therefore, to maintain 850 ºC operating temperature, water contents of the biosolids needs to be lowered, or temperature of incoming air raised. In this case, preheating of inlet air may be sufficient as the energy balance is close to zero.

Item	Unit	Stoichiometric air flow
Air added	mole/kg biosolids	57.6
Flue gas composition		
N_2	mole/kg biosolids	44.5
O_2	mole/kg biosolids	0
CO_2	mole/kg biosolids	11.1
H_2O	mole/kg biosolids	45.1

Heat content of added air at 20C	MJ/kg biosolids	0.487
Heat content of biosolids at 20C	MJ/kg biosolids	0.067
Flue gas heat content at 850C	MJ/kg biosolids	3.925
Ash heat content at 850C	MJ/kg biosolids	0.074
Energy released from combustion	MJ/kg biosolids	5.057
Heat loss by evaporation of water	MJ/kg biosolids	1.806
System heat loss	MJ/kg biosolids	0.019
Net energy balance		–0.212

Note: Because values presented in the table were calculated on a spreadsheet and rounded, some values may not match exactly with manual calculations.

PROBLEM 17-6

Problem Statement – See text, page 1862

Solution – for Heating requirement = 200 kW and total power requirement for pumps = 40 kW

1. Calculate the COP for the heat pump.

   Power input = 0.24 kW per 1 kW of output

   $$\mathrm{COP} = \frac{1.0}{0.24} = 4.2$$

   Heat output = 200 kW × 4.2/(4.2–1) = 263 kW

   Power input = 263 kW/4.2 = 62.5 kW

2. Calculate the COP for the entire system

   $$\mathrm{COP} = \frac{263\ \mathrm{kW}}{(62.5\ \mathrm{kW} + 40\ \mathrm{kW})}$$
   $$= 2.6$$

3. Calculate the wastewater flowrate to be transferred to the heat pump system.

   Heating requirement = 200 kW

   COP = 2.6

   Heat to be extracted from water = 200 – (200/2.6) = 123 kW

   123 kW = 123 kJ/s

Specific heat of water = 4.2 kJ/kg•°C

Assume density of water = 1.0

$$\text{Wastewater flow required} = \frac{(123\ \text{kJ/s})}{(4.2\ \text{kJ/kg}\cdot{}^\circ\text{C})(10^3\ \text{kg/m}^3)(4\ {}^\circ\text{C})}$$

$$= \frac{123}{4.2 \cdot 10^3 \cdot 4} = 0.00732\ \text{m}^3/\text{s}$$

$$= (0.00732\ \text{m}^3/\text{s})(3600\ \text{s}/1\,\text{h}) = 26\ \ \text{m}^3/\text{h}$$

PROBLEM 17-7

Problem Statement – See text, page 1862

Solution

Discussion points include:

1. Location of heat source and the point of use:

   Heat in raw wastewater may be extracted at the location along the wastewater collection system, where extracted heat could be utilized or added to an existing district heating system.

2. Quality of raw wastewater:

   Due to solid contents, debris, and oil, fat and grease, design of heat exchanger between raw wastewater and the intermediate heating medium requires careful considerations to prevent malfunction of the heat exchangers. The structure to extract wastewater and discharge the cooled wastewater back to the collection system should not create stagnant raw wastewater, which could become septic quickly. If heat extraction is seasonal, there must be a mechanism to flush out raw wastewater before the heat extraction is ceased and the heat exchanger maintained when it is off-line to prevent deterioration of the system such as corrosion.

3. Temperature of wastewater influent:

   Depending on the wastewater temperature and the amount of heat extracted, it is possible especially in the cold seasons that incoming wastewater temperature at the wastewater treatment facility may become lower than it is designed to maintain biological treatment in the optimal conditions.

PROBLEM 17-8

Instructors Note: The problem statement did not provide the reduction in TSS and VSS. Students are asked to estimate the TSS and VSS reduction from the given information. The most logical approach is to assume that the reduction of BOD and COD is only on particulate matters, and estimate other parameters, as presented in this solution.
There is an error in the first print in page 1855. The discharge pressure should be corrected from 121.5 to 156.5 kPa.

Assumed blower efficiency should be added to the table in Example 17-10. Blower efficiency was assumed to be 85 percent. Correction is to be made to the table.

Using these corrected values, the air requirements and energy requirements for the DO set point of 3.5 mg/L and 2.0 mg/L are 117.7 kg/min and 57.7 kW, and 98.6 kg/min and 74.0 kW, respectively.

The solution presented below is based on the corrected values.

Problem Statement – See text, page 1862

Solution – for 20 percent reduction

1. Estimate the characteristics of wastewater entering the activated sludge process after filtration. Assume all reduction of BOD is from the removal of particulate matter, and percent reduction in VSS is same as the percent reduction in particulate BOD.
   a. Before filtration,

      BOD = 140 g/m^3, sBOD = 70 mg/L

      COD = 300 mg/L, sCOD = 132 g/m^3

      pBOD = BOD – sBOD = (140 – 70) g/m^3 = 70 g/m^3

      pCOD = COD – sCOD = (300 – 132) g/m^3 = 168 g/m^3

pCOD/pBOD = 168/70 = 2.4

TSS = 70 g/m^3

VSS = 60 g/m^3

b. After filtration,

BOD = (140 g/m^3)(0.8) = 112 g/m^3

sBOD = 70 g/m^3

pBOD = (112 – 70) g/m^3 = 42 g/m^3

Assume pCOD/pBOD ratio remains the same after filtration.

pCOD = (42 g/m^3)(2.4) = 100.8 g/m^3

sCOD = 132 g/m^3

COD = pCOD + sCOD = 100.8 + 132 = 232.8 g/m^3

Recuction in pBOD = 70 – 42 = 28 g/m^3, or 40 percent.

Assume VSS percent reduction = pBOD percent reduction = 40 percent, and TSS/VSS ratio remains the same.

VSS = (60 g/m^3)(1– 0.4) = 36 g/m^3

TSS = (36 g/m^3)(70/60) = 42 g/m^3

2. Develop the wastewater characteristics needed for design.

a. Find bCOD.

bCOD = 1.6(BOD) = 1.6(112 g/m^3) = 179.2 g/m^3

b. Find nbCOD using Eq. (8-12).

nbCOD = COD – bCOD = (232.8 – 179.2) g/m^3 = 53.6 g/m^3

c. Find effluent nonbiodegradable sCOD.

nbsCODe = sCOD – 1.6sBOD

= (132 g/m^3) – (1.6)(70 g/m^3) = 20 g/m^3

d. Find nbVSS using Eqs. (8-7, 8-8, and 8-9).

nbpCOD = TCOD – bCOD – nbsCOD$_e$

= (232.8 – 179.2 – 20) g/m^3 = 33.6 g/m^3

$$\mathrm{VSS_{COD}} = \frac{\mathrm{TCOD - sCOD}}{\mathrm{VSS}}$$

$$= \frac{[(232.8 - 132)\ \mathrm{g/m^3}]}{(36\ \mathrm{g/m^3})} = 2.8\ \mathrm{g\ COD/g\ VSS}$$

$$\mathrm{nbVSS} = \frac{\mathrm{nbpCOD}}{\mathrm{VSS_{COD}}}$$

$$= \frac{(33.6\ \mathrm{g/m^3})}{(2.8\ \mathrm{g\ COD/g\ VSS})} = 12\ \mathrm{g\ nbVSS/m^3}$$

e. Find iTSS.

iTSS = TSS – VSS = 42 – 36 = 6 g/m^3

3. Design suspended growth system for BOD removal only.

a. Define biomass production using Eq. (8-20) in Table 8-10.

$$P_{X,Bio} = \frac{QY_H(S_o - S)}{1 + b_H(SRT)} + \frac{(f_d)(b_H)QY_H(S_o - S)SRT}{1 + b_H(SRT)}$$

Q = 22,700 m^3/d

S_o = 179.2 g/m^3

Y_H = 0.45 g VSS/g bCOD

f_d = 0.15

b. Determine S from Eq. (7-46) in Table 8-10.

$$S = \frac{K_s[1 + b_H(SRT)]}{SRT(\mu_{max} - b_H) - 1}$$

From Table 8-14, at 20°C,

μ_{max} = 6.0 g VSS/g VSS•d

b_H = 0.12 g VSS/g VSS•d

K_s = 8.0 g/m^3

At 12°C, using Eq. (1-44),

$$\mu_{m,T} = \mu_{max}\theta^{(T-20)}$$

$$= 6.0(1.07)^{(12-20)} = 3.5\ \mathrm{g/g{\bullet}d}$$

$$b_{H,T} = b_{H,20}\theta^{(T-20)}$$

$$= (0.12\ \text{g/g}\cdot\text{d})(1.04)^{(12-20)} = 0.088\ \text{g/g}\cdot\text{d}$$

$$S = \frac{(8.0\ \text{g/m}^3)[1 + 0(0.088\ \text{g/g}\cdot\text{d})(5\ \text{d})]}{(5\ \text{d})(3.5\ \text{g/g}\cdot\text{d} - 0.088\ \text{g/g}\cdot\text{d}) - 1} = 0.7\ \text{g bCOD/m}^3$$

c. Substitute the above values in the expression given above and solve for $P_{X,bio}$.

$$P_{X,Bio} = \frac{QY_H(S_o - S)}{1 + b_H(SRT)} + \frac{(f_d)(b_H)QY_H(S_o - S)SRT}{1 + b_H(SRT)}$$

$$= \frac{(22{,}700\ \text{m}^3/\text{d})(0.45\ \text{g/g})[(179.2 - 0.7)\ \text{g/m}^3](1\ \text{kg}/10^3\ \text{g})}{1 + (0.088\ \text{g/g}\cdot\text{d})(5\ \text{d})}$$

$$+ \frac{(0.15\ \text{g/g})(0.088\ \text{g/g}\cdot\text{d})(22{,}700\ \text{m}^3/\text{d})(0.45\ \text{g/g})[(179.2 - 0.7)\ \text{g/m}^3](5\ \text{d})(1\ \text{kg}/10^3\ \text{g})}{1 + (0.088\ \text{g/g}\cdot\text{d})(5\ \text{d})}$$

$$P_{X,bio} = (1266.2 + 83.6)\ \text{kg/d} = 1349.8\ \text{kg/d}$$

4. Determine the mass in terms of VSS and TSS in the aeration basin. Te mass of VSS and TSS can be determined using Eqs. (8-20), (8-21), and (7-57) in Table 8-10.

   Mass = P_X(SRT)

   a. Determine $P_{X,VSS}$ and $P_{X,TSS}$ using Eq. (8-20) and (8-21) including parts A, B and D. Part C = 0 because there is no nitrification.

      From Eq. (8-20), $P_{X,VSS}$ is

$$P_{X,VSS} = P_{X,bio} + Q(nbVSS)$$

$$P_{X,VSS} = 1349.8\ \text{kg/d} + (22{,}700\ \text{m}^3/\text{d})(12\ \text{g/m}^3)(1\ \text{kg}/10^3\ \text{g})$$

$$= (1349.8 + 272.4)\ \text{kg/d} = 1622.2\ \text{kg/d}$$

From Eq. (8-21), $P_{X,TSS}$ is

$$P_{X,TSS} = \frac{QY_H(S_o - S)(1\ \text{kg}/10^3\ \text{g})}{0.85[1 + b_H(SRT)]} + \frac{(f_d)(b_H)QY_H(S_o - S)SRT(1\ \text{kg}/10^3\ \text{g})}{0.85[1 + b_H(SRT)]}$$

$$+ Q(nbVSS)(1\ \text{kg}/10^3\ \text{g}) + Q(TSS_o - VSS_o)(1\ \text{kg}/10^3\ \text{g})$$

$$\begin{aligned}P_{X,TSS} &= \frac{(1266.2\ \mathrm{kg/d})}{0.85} + \frac{(83.6\ \mathrm{kg/d})}{0.85}\\ &\qquad + (22{,}700\ \mathrm{m^3/d})(12\ \mathrm{g/m^3})(1\,\mathrm{kg}/10^3\ \mathrm{g})\\ &\qquad + (22{,}700\ \mathrm{m^3/d})[(42-36)\ \mathrm{g/m^3}](1\,\mathrm{kg}/10^3\ \mathrm{g})\\ &= (1489.6 + 98.4 + 272.4 + 136.2)\,\mathrm{kg/d}\end{aligned}$$

$$P_{X,TSS} = 1996.6\ \mathrm{kg/d}$$

b. Calculate the mass of VSS and TSS in the aeration basin.

i. Mass of MLVSS using Eq. (7-57) in Table 8-10

$$\begin{aligned}(X_{VSS})(V) &= (P_{X,VSS})\mathrm{SRT}\\ &= (1622.2\ \mathrm{kg/d})(5\ \mathrm{d}) = 8111\,\mathrm{kg}\end{aligned}$$

ii. Mass of MLSS using Eq. (7-57) in Table 8-10

$$\begin{aligned}(X_{TSS})(V) &= (P_{X,TSS})\mathrm{SRT}\\ &= (1996.6\ \mathrm{kg/d})(5\ \mathrm{d}) = 9983\ \mathrm{kg}\end{aligned}$$

Note: the size of reactor has been set at 4445.7 m^3. Therefore MLSS concentration will be 2246 mg/L when SRT is maintained at 5 d.

5. Calculate the O_2 demand using Eq. (8-23) in Table 8-10.

$$\mathrm{Ro} = Q(S_o - S) - 1.42P_{X,bio} + 4.57(Q)\mathrm{NOx}$$

$$= (22{,}700\ \mathrm{m^3/d})[(179.2-0.7)\,\mathrm{g/m^3}](1\,\mathrm{kg}/10^3\ \mathrm{g}) - 1.42(1349.8\ \mathrm{kg/d})$$

$$= (4052.0 - 1916.7)\ \mathrm{kg/d} = (2135.3\ \mathrm{kg/d})(1\,\mathrm{d}/24\ \mathrm{h}) = 89.0\ \mathrm{kg/h}$$

6. Determine the air flowrate using the information from above calculations and information given in Example 8-3.

Parameter	Unit	Value
Required oxygen transfer rate, OTR_f	kg/h	89.0
α	-	0.50
F	-	0.90
β	-	0.95
Dissolved oxygen surface saturation concentration at 12°C, C_{st}	mg/L	10.78
Dissolved oxygen surface saturation concentration at standard temperature (20°C), C^*_{s20}	mg/L	9.09
Pressure correction factor, P_b/P_s		0.94
Steady-state DO saturation concentration, $C^*_{\infty 20}$		10.64
Empirical temperature correction factor, θ		1.024

Temperature of mixed liquor	°C	12
Ambient temperature	°C	15
Oxygen in the air	kg/kg air	0.232
Oxygen transfer efficiency, OTE	%	25
Universal gas constant	kJ/kmole	8.314
Blower inlet absolute pressure	kPa	101.3
Compressor efficiency		0.85
Blower discharge absolute pressure	kPa	156.5

a. Determine the SOTR for DO in aeration basin = 2.0 using Eq. (5-70).

$$\mathrm{SOTR} = \left[\frac{\mathrm{OTR_f}}{(\alpha)(\mathrm{F})}\right]\left[\frac{C^*_{\infty 20}}{(\beta)(C_{st}/C^*_{s20})(P_b/P_s)(C^*_{\infty 20}) - C}\right]\left[(1.024)^{20-t}\right]$$

Using the data given above, SOTR is calculated as

$$\mathrm{SOTR} = \left[\frac{(89.0\ \mathrm{kg/h})}{(0.50)(0.90)}\right]\left\{\frac{10.64}{\left[0.95\left(\dfrac{10.78}{9.09}\right)(0.94)(10.64) - 2.0\right]}\right\}\left(1.024^{20-12}\right) = 274.5\ \mathrm{kg/h}$$

b. Determine air flowrate in terms of kg/min.

$$\text{Air flowrate, kg/min} = \frac{(\mathrm{SOTR\ kg/h})}{[(\mathrm{E})(60\ \mathrm{min/h})(0.232\ \mathrm{kg\ O_2/kg\ air})]}$$

$$= \frac{274.5}{(0.25)(60)(0.232)} = 78.9\ \mathrm{kg/min}$$

c. Calculate an estimated power requirement using Eq. (5-77a) in Chap. 5.

$$P_w = \frac{wRT_1}{28.97\ n\ e}\left[\left(\frac{p_2}{p_1}\right)^n - 1\right]$$

Using the data give above, P_w is calculated as

$$P_w, \mathrm{kW} = \left\{\frac{(78.9\ \mathrm{kg/min})(1\ \mathrm{min}/60\ \mathrm{s})(8.314\ \mathrm{J/mole}\ ^\circ\mathrm{K})[(273.15+15)\mathrm{K}]}{(28.97\ \mathrm{g/mole})(0.283)(0.85)}\right\}\left[\left(\frac{156.5\ \mathrm{kPa}}{101.3\ \mathrm{kPa}}\right)^{0.283} - 1\right]$$

$$= 59.2\ \mathrm{kW}$$

7. Compare the energy demand.

Compared to the result of Example 17-10, the oxygen requirement was reduced from 98.6 kg/min to 78.9 kg/min. Energy demand was reduced from 74.0 kW to 59.2 kW. The reduction is about 25 percent. The energy requirements presented in Example 17-10 and this problem are significantly lower than the typical energy requirement for aeration presented in Table 17-3.

The energy requirement calculated in this problem does not include air requirements for other parts of the treatment facility such as aerated grit chamber, return sludge aeration, etc., and assumed relatively high efficiency for new equipment. In existing facilities, the mechanical equipment generally operates at lower efficiencies, and there are other causes of inefficiencies such as leaks. The reduction in aeration energy requirement by reducing particulate BOD in the primary effluent is significant based on the calculations in this problem. The cost and added energy requirement for removing particulate BOD, and potential increase in the energy production from increased recovery of biodegradable particulate for anaerobic digestion should be assessed to determine if the use of primary effluent filtration is cost effective.

PROBLEM 17-9

Instructors Note: Similar to Problem 17-8, students are asked to estimate the wastewater characteristics based on limited information provided in the problem statement. For the 60 percent loading condition, assume the flowrate and mass loadings of all constituents are 60 percent of the values given in Example 8-3 (i.e., concentrations are same). After implementation of the food garbage grinders, the flowrate will remain the same, but the organic concentration will increase. In this problem, only COD removal is considered in the activated sludge process and it is not necessary to estimate the increase in nitrogen and phosphorus.

The problem statement in the first printing did not specify the temperature to be assumed to calculate the energy requirements. An assumed average wastewater temperature of 20°C and ambient temperature of 18°C are used in this solution.

Problem Statement – See text, page 1862

Solution – for 600 kg/d increase in biodegradable COD

1. Determine the characteristics of wastewater entering the activated sludge process.
   a. Before implementation of food waste grinders,

      Flowrate = (22,700 m^3/d)(0.6) = 13,620 m^3/d

      BOD = 140 g/m^3, sBOD = 70 mg/L

      COD = 300 mg/L, sCOD = 132 g/m^3

      pBOD = BOD – sBOD = (140 – 70) g/m^3 = 70 g/m^3

      pCOD = COD – sCOD = (300 – 132) g/m^3 = 168 g/m^3

      bCOD = 1.6 (BOD) = 1.6 (140 g/m^3) = 224 g/m^3

      pCOD/pBOD = 168/70 = 2.4

      TSS = 70 g/m^3

      VSS = 60 g/m^3

   b. After implementation of food waste grinders,

      The increase in bCOD in raw wastewater = 600 kg/d, of which 75 percent is removed by primary settling.

      i. Increase in bCOD in primary effluent = (600 kg/d)(1 – 0.75) = 150 kg/d

         = 150,000 g/d

      ii. Increase in organic loading to the digester due to increased primary sludge = (600 – 150) kg/d = 450 kg bCOD/d.

      iii. Flowrate = 13,620 m^3/d (assume flowrate stays the same)

iv. bCOD in primary effluent = [(13,620 m^3/d)(224 g/m^3)

+ (150,000 g/d)]/(13,620 m^3/d)

= 235.0 g/m^3

v. Assume the BOD to COD ratio and the ratio of particulate to soluble BOD remain the same,

BOD = (235.0 g/m^3)/1.6 = 146.9 g/m^3

sBOD = (146.9 g/m^3)(70/140) = 73.4 g/m^3

pBOD = 73.4 g/m^3

vi. Assume pCOD/pBOD ratio remains the same.

pCOD = (73.4 g/m^3)(2.4) = 176.2 g/m^3

Increase in pCOD = 176.2 – 168 = 8.2 g/m^3, or 4.9 percent.

vii. Assume percent increase in VSS = percent increase in pCOD and TSS/VSS ratio remains the same.

VSS = (60 g/m^3)(1+ 0.049) = 62.9 g/m^3

TSS = (62.9 g/m^3)(70/60) = 73.4 g/m^3

2. Develop the wastewater characteristics needed for the estimate of aeration requirement for the wastewater with food waste grinders.

a. Find nbCOD.

Assuming the same biodegradable fraction, total COD after implementation of food waste grinders is:

COD = 235.0(300/224) g/m^3 = 314.7 g/m^3

nbCOD = COD – bCOD = (314.7 – 235.0) g/m^3 = 79.7 g/m^3

c. Find effluent nonbiodegradable sCOD.

sCOD = COD – pCOD = (314.7 – 176.2) g/m^3 = 138.5 g/m^3

$nbsCOD_e$ = sCOD – 1.6sBOD

= (138.5 g/m^3) – (1.6)(73.4 g/m^3) = 21.1 g/m^3

d. Find nbVSS using Eqs. (8-7, 8-8, and 8-9).

nbpCOD = TCOD – bCOD – $nbsCOD_e$

$= (314.7 - 235.0 - 21.1)\ \text{g/m}^3 = 58.6\ \text{g/m}^3$

$$\text{VSS}_{\text{COD}} = \frac{\text{TCOD} - \text{sCOD}}{\text{VSS}}$$

$$= \frac{[(314.7 - 138.5)\ \text{g}/\text{m}^3]}{(62.9\ \text{g}/\text{m}^3)} = 2.8\ \text{g COD}/\text{g VSS}$$

$$\text{nbVSS} = \frac{\text{nbpCOD}}{\text{VSS}_{\text{COD}}}$$

$$= \frac{(58.6\ \text{g}/\text{m}^3)}{(2.8\ \text{g COD}/\text{g VSS})} = 20.9\ \text{g nbVSS}/\text{m}^3$$

e. Find iTSS.

iTSS = TSS – VSS = 73.4 – 62.9 = 10.5 g/m^3

3. Determine the biomass production at 60 percent loading without food waste grinder.

a. Define biomass production using Eq. (8-20) in Table 8-10.

$$P_{X,\text{Bio}} = \frac{QY_H(S_o - S)}{1 + b_H(\text{SRT})} + \frac{(f_d)(b_H)QY_H(S_o - S)\text{SRT}}{1 + b_H(\text{SRT})}$$

$Q = 13{,}620\ \text{m}^3/\text{d}$

$S_o = 224\ \text{g/m}^3$

$Y_H = 0.45$ g VSS/g bCOD

$f_d = 0.15$

b. Determine S from Eq. (7-46) in Table 8-10.

$$S = \frac{K_s[1 + b_H(\text{SRT})]}{\text{SRT}(\mu_{\max} - b_H) - 1}$$

From Table 8-14, at 20°C,

$\mu_{\max} = 6.0$ g VSS/g VSS•d

$b_{H,20} = 0.12$ g VSS/g VSS•d

$K_s = 8.0\ \text{g/m}^3$

$$S = \frac{(8.0\ \text{g}/\text{m}^3)[1 + (0.12\ \text{g}/\text{g} \circlearrowright \text{d})(5\ \text{d})]}{(5\ \text{d})[(6.0\ \text{g}/\text{g} \circlearrowright \text{d}) - (0.12\ \text{g}/\text{g} \circlearrowright \text{d})] - 1} = 0.45\ \text{g bCOD}/\text{m}^3$$

c. Substitute the above values in the expression given above and solve for $P_{X,bio}$.

$$P_{X,Bio} = \frac{QY_H(S_o - S)}{1 + b_H(SRT)} + \frac{(f_d)(b_H)QY_H(S_o - S)SRT}{1 + b_H(SRT)}$$

$$= \frac{(13{,}620\ m^3/d)(0.45\ g/g)[(224 - 0.45)\ g/m^3](1\ kg/10^3\ g)}{1 + (0.12\ g/g{\bullet}d)(5\ d)}$$

$$+ \frac{(0.15\ g/g)(0.12\ g/g{\bullet}d)(13{,}620\ m^3/d)(0.45\ g/g)[(224 - 0.45)\ g/m^3](5\ d)(1\ kg/10^3\ g)}{1 + (0.12\ g/g{\bullet}d)(5\ d)}$$

$$P_{X,bio} = (856.3 + 77.1)\ kg/d = 933.4\ kg/d$$

4. Calculate the O_2 demand using Eq. (8-23) in Table 8-10.

$$Ro = Q(S_o - S) - 1.42P_{X,bio} + 4.57(Q)NOx$$

$$= (13{,}620\ m^3/d)[(224 - 0.45)\ g/m^3](1\ kg/10^3\ g) - 1.42(933.4\ kg/d) + 0$$

$$= (3044.8 - 1325.4)\ kg/d = (1719.4\ kg/d)(1\ d/24\ h) = 71.6\ kg/h$$

5. Determine the air flowrate using the information from above calculations and information given in Example 8-3.

Parameter	Unit	Value
Required oxygen transfer rate, OTR_f	kg/h	89.0
α	-	0.50
F	-	0.90
β	-	0.95
Dissolved oxygen surface saturation concentration at 20°C, C_{st}	mg/L	10.78
Dissolved oxygen surface saturation concentration at standard temperature (20°C), C^*_{s20}	mg/L	9.09
Pressure correction factor, P_b/P_s		0.94
Steady-state DO saturation concentration, $C^*_{\infty 20}$		10.64
Empirical temperature correction factor, θ		1.024
Temperature of mixed liquor	°C	20
Ambient temperature	°C	18
Oxygen in the air	kg/kg air	0.232
Oxygen transfer efficiency, OTE	%	25
Universal gas constant	kJ/kmole	8.314
Blower inlet absolute pressure	kPa	101.3
Blower discharge absolute pressure	kPa	156.5

a. Determine the SOTR for DO in aeration basin = 2.0 using Eq. (5-70).

$$\text{SOTR} = \left[\frac{\text{OTR}_f}{(\alpha)(\text{F})}\right]\left[\frac{C^*_{\infty 20}}{(\beta)(C_{st}/C^*_{s20})(P_b/P_s)(C^*_{\infty 20}) - C}\right][(1.024)^{20-t}]$$

Using the data given above, SOTR is calculated as

$$\text{SOTR}=\left[\frac{(71.6\text{ kg/h})}{(0.50)(0.90)}\right]\left\{\frac{10.64}{\left[0.95\left(\frac{9.09}{9.09}\right)(0.94)(10.64)-2.0\right]}\right\}\left(1.024^{20-20}\right) = 225.7\text{ kg/h}$$

b. Determine air flowrate in terms of kg/min.

$$\text{Air flowrate, kg/min} = \frac{(\text{SOTR kg/h})}{[(\text{E})(60\text{ min/h})(0.232\text{ kg O}_2/\text{kg air})]}$$

$$= \frac{225.7}{(0.25)(60)(0.232)} = 64.8\text{ kg/min}$$

c. Calculate an estimated power requirement using Eq. (5-77a) in Chap. 5.

$$P_w = \frac{wRT_1}{28.97\,n\,e}\left[\left(\frac{p_2}{p_1}\right)^n - 1\right]$$

Using the data give above, P_w is calculated as

$$P_w,\text{kW} = \left\{\frac{(64.8\text{ kg/min})(1\text{ min/60 s})(8.314\text{ J/mole}\cdot\text{K})[(273.15+18)\text{K}]}{(28.97\text{ g/mole})(0.283)(0.85)}\right\}\left[\left(\frac{156.5\text{ atm}}{101.3\text{ atm}}\right)^{0.283} - 1\right]$$

$$= 49.1\,\text{kW}$$

6. Determine the biomass production at 60 percent loading with food waste grinder.

   a. Define biomass production using Eq. (8-20) in Table 8-10.

$$P_{X,Bio} = \frac{QY_H(S_o - S)}{1 + b_H(\text{SRT})} + \frac{(f_d)(b_H)QY_H(S_o - S)\text{SRT}}{1 + b_H(\text{SRT})}$$

$Q = 13{,}620\text{ m}^3/\text{d}$

$S_o = 235\text{ g/m}^3$

$Y_H = 0.45$ g VSS/g bCOD

$f_d = 0.15$

b. Determine S from Eq. (7-46) in Table 8-10.

$$S = \frac{K_s[1 + b_H(SRT)]}{SRT(\mu_{max} - b_H) - 1}$$

From Table 8-14, at 20°C,

μ_{max} = 6.0 g VSS/g VSS•d

$b_{H,20}$ = 0.12 g VSS/g VSS•d

K_s = 8.0 g/m^3

$$S = \frac{(8.0\text{ g/m}^3)[1 + (0.12\text{ g/g•d})(5\text{ d})]}{(5\text{ d})[(6.0\text{ g/g•d}) - (0.12\text{ g/g•d})] - 1} = 0.45\text{ g bCOD/m}^3$$

c. Substitute the above values in the expression given above and solve for $P_{X,bio}$.

$$P_{X,Bio} = \frac{QY_H(S_o - S)}{1 + b_H(SRT)} + \frac{(f_d)(b_H)QY_H(S_o - S)SRT}{1 + b_H(SRT)}$$

$$= \frac{(13,620\text{ m}^3\text{/d})(0.45\text{ g/g})[(235 - 0.45)\text{ g/m}^3](1\text{ kg}/10^3\text{ g})}{1 + (0.12\text{ g/g•d})(5\text{ d})}$$

$$+ \frac{(0.15\text{ g/g})(0.12\text{ g/g•d})(13,620\text{ m}^3\text{/d})(0.45\text{ g/g})[(235 - 0.45)\text{ g/m}^3](5\text{ d})(1\text{ kg}/10^3\text{ g})}{1 + (0.12\text{ g/g•d})(5\text{ d})}$$

$$P_{X,bio} = (898.5 + 80.8)\text{ kg/d} = 979.3\text{ kg/d}$$

7. Calculate the O_2 demand using Eq. (8-23) in Table 8-10.

$$Ro = Q(S_o - S) - 1.42P_{X,bio} + 4.57(Q)NOx$$

$$= (13,620\text{ m}^3\text{/d})[(235 - 0.45)\text{ g/m}^3](1\text{ kg}/10^3\text{ g}) - 1.42(979.3\text{ kg/d}) + 0$$

$$= (3194.6 - 1390.6)\text{ kg/d} = (1804\text{ kg/d})(1\text{ d}/24\text{ h}) = 75.2\text{ kg/h}$$

8. Determine the air flowrate using the information from above calculations and information given in Example 8-3, and calculate the increase in energy demand.

a. Determine the SOTR for DO in aeration basin = 2.0 using Eq. (5-70).

$$SOTR = \left[\frac{OTR_f}{(\alpha)(F)}\right]\left[\frac{C^*_{\infty 20}}{(\beta)(C_{st}/C^*_{s20})(P_b/P_s)(C^*_{\infty 20}) - C}\right][(1.024)^{20-t}]$$

Using the data given above, SOTR is calculated as

$$\text{SOTR}=\left[\frac{(75.2\ \text{kg/h})}{(0.50)(0.90)}\right]\left\{\frac{10.64}{\left[0.95\left(\frac{9.09}{9.09}\right)(0.94)(10.64)-2.0\right]}\right\}\left(1.024^{20-20}\right)=237.0\ \text{kg/h}$$

b. Determine air flowrate in terms of kg/min.

$$\text{Air flowrate, kg/min}=\frac{(\text{SOTR kg/h})}{[(\text{E})(60\ \text{min/h})(0.232\ \text{kg}\ \text{O}_2/\text{kg air})]}$$

$$=\frac{237.0}{(0.25)(60)(0.232)}=68.1\ \text{kg/min}$$

c. Calculate an estimated power requirement using Eq. (5-77a) in Chap. 5.

$$P_w=\frac{wRT_1}{28.97\ n\ e}\left[\left(\frac{p_2}{p_1}\right)^n-1\right]$$

Using the data give above, P_w is calculated as

$$P_w,\text{kW}=\left\{\frac{(68.1\text{kg}/\text{min})(1\text{min}/\ 60\ \text{s})(8.314\ \text{J}/\text{mole}\ ^\circ\text{K})[(273.15+18)\text{K}]}{(28.97\ \text{g}/\text{mole})(0.283)(0.85)}\right\}\left[\left(\frac{156.5\ \text{atm}}{101.3\ \text{atm}}\right)^{0.283}-1\right]$$

$$=51.6\ \text{kW}$$

The increase in power requirement as a result of food waste grinder is (51.6 – 49.1) kW = 2.5 kW, or (2.5 kW)(24 h/1 d) = 60 kWh/d

9. Determine the increase in biogas production.
   a. Increase in bCOD to the digester = 450 kg/d
   b. From Eq. (7-142), 64g of bCOD is converted to one mole of CH_4 by anaerobic digestion, or 0.35 m^3 CH_4/kg COD at standard conditions (0°C at 1atm). Assuming 50 percent of the bCOD introduced to the digester from the food waste grinder is converted to CH_4, the amount of CH_4 produced is

      $$CH_4\ \text{produced}=(450\ \text{kg COD}/\text{d})(0.35\ \text{m}^3/\text{kg COD})=157.5\ \text{kg}/\text{d}$$

   c. Using the heating value for methane at 35,846 kJ/m^3, the energy in the produced methane is

Energy content in produced CH_4 (kJ/d)

$$= (157.5\ m^3/d)(35{,}846\ kJ/m^3)$$

$$= 5{,}645{,}745\ kJ/d = 5.6\ GJ/d$$

10. Estimate the increased energy production from the increased biogas production.

    From Table 17-8, assume typical efficiency of reciprocating engine of 35 percent.

    Energy recovered from the increased methane production

    = 0.35(5.6 GJ/d) = 2.0 GJ/d.

    Convert the unit to compare with the increased energy consumption for aeration

    2.0 GJ/d = (2.0 GJ/d)(277.8 kWh/GJ) = 555.6 kWh/d

Comment

Based on this assessment, theoretically, the use of food waste grinder can result in a significant increase in the energy production, while only 60 kWh/d increase in the aeration energy requirement. It should be noted this assessment did not count for the increased energy requirements for other parts of wastewater treatment facility.

PROBLEM 17-10

Problem Statement – See text, page 1862

Solution

The use of on/off control results in a varied wet well water depth, and therefore a varied head to the operating pumps. The use of VFD with a set wet-well level will allow the pumps to be operated at constant head which will allow operation of the pumps at an efficient point of the pump curve.

18

WASTEWATER MANAGEMENT: FUTURE CHALLENGES AND OPPORTUNITIES

PROBLEM 18-1

Problem Statement - See text, page 1899

Solution

1. Some possible sources of information are:

www.epa.gov/ogwdw/smallsystems/pdfs/guide_smallsystems_asset_mgmnt.pdf

http://www.epa.gov/owm/assetmanage/assets_training.htm

www.epa.gov/cupss/index.html

www.epa.gov/npdes/pubs/assetmanagement.pdf

http://208.88.129.72/wil.aspx?ekmensel=c57dfa7b_82_0_154_1

Old Forge Wastewater Treatment Plant and NYSDEC (2008) *Wastewater Infrastructure Asset Management Plan Village of Old Forge*, Albany, NY.

PROBLEM 18-2

Problem Statement - See text, page 1899

Solution

1. Some advantages and disadvantages, in no special order, are:

Advantages	Disadvantages
• Treated effluent could be used locally. • Sludge could be transported to larger downstream plant for processing similar to what occurs in the Los Angeles area (see Fig. 18-3). • Small footprint if sludge is processed at larger downstream plant. • Savings in pumping costs if purified wastewater is to be used for direct potable reuse	• More personnel are required for two plants as compared to one large plant. • Less opportunity to reap benefits of economy of scale. • More costly to build and operate two separate treatment plants.

PROBLEM 18-3

Problem Statement - See text, page 1899

Solution

1. Investigate whether the collection system has any storage capacity. If excess capacity is available in gravity flow collection system, determine if excess capacity can be utilized by installing control structures (e.g. dams and weirs). If the collection system contains pump stations, it may be possible to sequence the pumps so that the storage capacity in the collection system can be utilized.
2. Investigate whether any unused tankage is available at the wastewater treatment plant, and whether it could be utilized for peak flow equalization.
3. Investigate whether all of the secondary clarifiers are being utilized. Any unused clarifiers should be brought online during storm events.
4. Investigate whether some of the primary sedimentation tanks could be converted to secondary clarifiers during storm events.
5. Consider installation of tunnel storage (see Table 18-7) within the collection system.
6. Consider installation of online or offline flow equalization on or near wastewater treatment plant.
7. If a conventional plug-flow activated sludge process is used, consider converting it to step feed prior to and during storm events.

PROBLEM 18-4

Problem Statement - See text, page 1899

Solution

1. Some advantages and disadvantages, in no special order, are:

Advantages	Disadvantages
• Improved treatment can be provided for wastewater and stormwater. • The cost of treating of stormwater with complete secondary treatment can be reduced. • A higher level of treatment could be provided for the smaller wastewater flowrate.	• Enormously expensive. • Disruptive to the public for extended period of time that would be needed for the construction of the separate stormwater collections system. • Because of reduced flowrates, solids deposition may occur in the wastewater collection system, which would reqire periodic flushing. • Right of way may be difficult to obtain. • More personnel would be required to manage the separate wastewater and stormwater treatment plants. • Securing appropriate rights of way easements may be difficult and costly

PROBLEM 18-5

Problem Statement - See text, page 1899

Solution

1. Some advantages and disadvantages, in no special order, are:

Advantages	Disadvantages
• A single treatment facility could be operated. • Untreated stormwater discharges could potentially be eliminated.	• Depending of the rainfall pattern, excess plant capacity would not be utilized during extended periods of the year. • Disruptive to the public for extended period of time that would be needed to construction a combined collection system. • Serious operational problems can occur in a plant subject to peak storm events if flow equalization is not available.

PROBLEM 18-6

Problem Statement - See text, page 1899

Solution

1. Some benefits and drawbacks, in no special order, are:

Benefits	Drawbacks
Separate collection systems (Problem 18-4)	
• Smaller treatment facility for the treatment of wastewater system.	• Two different agencies or departments may be responsible for operation and management functions. • Because more staff are required, a larger supervisory staff would be required. • Enormously expensive to construct separate collection system. Beyond the financial, means of most communities.
Combined collection system (Problem 18-5)	
• Centralized agency responsible for management of both wastewater and stormwater • Potentially improved treatment of stormwater.	• New rate structure must be developed to deal with combined flows • Enormously expensive to construct combined collection system to handle both wastewater and stormwater. Beyond the financial, means of most communities