FE Review Manual

Rapid Preparation for the General Fundamentals of Engineering Exam

Second Edition

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Professional Publications, Inc. • Belmont, California

them than among those used for pharmaceutical purposes. The typical wastewater processing units are described in this chapter.

ENVIRONMENTAL MICROBIOLOGY

Microorganisms play an important role in the biological treatment of wastewater. They are useful for the removal of organic matter, colloids, and nitrogen and phosphorus compounds.

The important microorganisms in wastewater treatment are bacteria. Bacteria are single-celled organisms that survive within a narrow range of pH and temperature. Their size varies from 0.5 μm to 1 μm, and they generally reproduce by fission (division). (Fungi are aerobic organisms, multicellular in nature, that can survive in a low-pH environment. Protozoa are generally unicellular organisms, aerobic in nature, that consume bacteria.)

Bacteria placed in a vessel in a nutrient medium go through five growth phases; Fig. 33.3 shows the progression in graph form.

BOD Exertion

A laboratory analysis of organic matter in water often includes a biochemical oxygen demand (BOD) test. Most water quality laboratories have a ready supply of water that is saturated with oxygen, obtained by sparging air overnight through the water. To measure BOD, a sample of wastewater is diluted with oxygen-saturated water. A small amount of bacteria is fed to the sample. Oxygen concentrations are measured at the beginning of the test and also on a daily basis. The difference between the oxygen concentrations at the initial time and at time t gives a measure of the concentration of organic compounds in the water and is called the BOD exerted at time t. In this way, BOD provides a measure of the concentration of organic compounds in water without the complexity of analyzing the different compounds.

If the biological depletion of organic compounds in wastewater can be assumed to be an approximately first-order reaction and L corresponds to BOD remaining, then

$$-\frac{dL}{dt} = kL \qquad 36.1$$

Integrating between the limits of $(t = 0,\ L = L)$ to $(t = t,\ L = L_t)$ gives

$$\frac{L_t}{L} = e^{-kt} \qquad 36.2$$

The value $(L - L_t)$ is called y_t, the amount of BOD exerted at time t. Therefore,

$$y_t = L(1 - e^{-kt}) \qquad 36.3$$

Monod Kinetics

Mathematically, in a batch reactor, the rate of growth of bacteria is given by

$$\frac{dX}{dt} = \mu X \qquad 36.4$$

The value of μ is given by

$$\mu = \mu_{\max}\frac{S}{K_S + S} \qquad 36.5$$

Half-Life of a Biologically Degraded Contaminant, Assuming a First-Order Rate Constant

The half-life of a reaction is the time taken to reduce the concentration (in this case, the organic compound) to half of its initial amount. The differential equation for a first-order reaction is shown as Eq. 36.1.

Integrating between the limits of $(t = 0,\ L = L)$ to $(t = t_{1/2},\ L = 0.5L)$ gives

$$0.5 = e^{kt_{1/2}} \qquad 36.6$$

Solving for k gives

$$k = \frac{\ln 2}{t_{1/2}} = \frac{0.693}{t_{1/2}} \qquad 36.7$$

ACTIVATED SLUDGE

The activated sludge process in its simplest form, as shown in the Fig. 36.1, consists of a mixing/aeration tank followed by a settler/clarifier. Mathematical analysis of the entire process is done by means of material balances on the different components and also by using the Monod kinetic model.

The results of the analysis for the reactor/aerator give a formula for the biomass concentration in the aerator, as well as the sludge flow rate and the solids residence time. The formulas for the organic loading rates are given. The biomass concentration in the aeration tank is

$$X_A = \frac{\theta_c Y(S_o - S_e)}{\theta(1 + k_d\theta_c)} \qquad 36.8$$

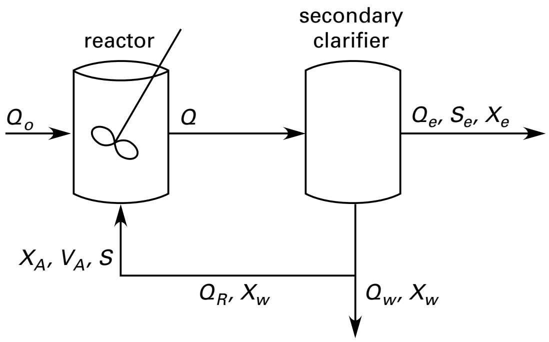
The *yield coefficient* is

$$Y = \frac{\text{mass of biomass}}{\text{mass of BOD consumed}} \qquad 36.9$$

The *hydraulic residence time* is

$$\theta = \frac{V}{Q} \qquad 36.10$$

Figure 36.1 Activated Sludge Process



The *solids residence time* is

$$\theta_c = \frac{V_A X_A}{Q_w X_w + Q_e X_e} \qquad 36.11$$

The *sludge volume* per day is

$$Q_s = \frac{100M}{\rho_s(\%\ \text{solids})} \qquad 36.12$$

$$\textit{Solids loading rate} = \frac{QX}{A} \qquad 36.13$$

For an activated sludge secondary clarifier,

$$Q = Q_\text{o} + Q_R \qquad 36.14$$

$$\textit{Organic loading rate}\ (\text{volumetric}) = \frac{Q_\text{o} S_\text{o}}{V} \qquad 36.15$$

$$\textit{Organic loading rate}\ (\text{F:M}) = \frac{Q_\text{o} S_\text{o}}{V_A X_A} \qquad 36.16$$

$$\textit{Organic loading rate}\ (\text{surface area}) = \frac{Q_\text{o} S_\text{o}}{A_M} \qquad 36.17$$

$$\text{SVI} = \frac{\text{sludge volume after settling}_{(\text{mL/L})(1000)}}{\text{MLSS}_{\text{mg/L}}} \qquad 36.18$$

The steady-state mass balance for a secondary clarifier is

$$(Q_\text{o} + Q_R)X_A = Q_e X_e + Q_R X_w + Q_w X_w \qquad 36.19$$

The *recycle ratio* is

$$R = \frac{Q_R}{Q_\text{o}} \qquad 36.20$$

The *recycle flow rate* is

$$Q_R = Q_\text{o} R \qquad 36.21$$

Design and operational parameters for activated-sludge treatment of municipal wastewater are given in Table 36.1.

FACULTATIVE POND

Facultative ponds, where the waste is kept in an open pond, are also called stabilization ponds. In these ponds, aerobic bacteria degrade the top layer, anaerobic bacteria degrade the bottom layer, and both aerobic and anaerobic bacteria degrade the middle layer.

Table 36.1 Design and Operational Parameters for Activated-Sludge Treatment of Municipal Wastewater

type of process	mean-cell residence time, θ_c (d)	food-to mass ratio (kg BOD_5/kg MLSS)	volumetric loading (V_L, kg BOD_5/m^3	hydraulic residence time in aeration basin, θ (h)	mixed liquor suspended solids, MLSS (mg/L)	recycle ratio (Q_r/Q)	flow regime*	BOD_5 removal efficiency (%)	air supplied m^3/kg BOD_5)
tapered aeration	5–15	0.2–0.4	0.3–0.6	4–8	1500–3000	0.25–0.5	PF	85–95	45–90
conventional	4–15	0.2–0.4	0.3–0.6	4–8	1500–3000	0.25–0.5	PF	85–95	45–90
step aeration	4–15	0.2–0.4	0.6–1.0	3–5	2000–3500	0.25–0.75	PF	85–95	45–90
completely mixed	4–15	0.2–0.4	0.8–2.0	3–5	3000–6000	0.25–1.0	CM	85–95	45–90
contact stabilization	4–15	0.2–0.6	1.0–1.2	–	–	0.25–1.0	–	–	45–90
contact basin	–	–	–	0.5–1.0	1000–3000	–	PF	80–90	–
stabilization basin	–	–	–	4–6	4000–10 000	–	PF	–	–
high-rate aeration	4–15	0.4–1.5	1.6–16	0.5–2.0	4000–10 000	1.0–5.0	CM	75–90	25–45
pure oxygen	8–20	0.2–1.0	1.6–4	1–3	6000–8000	0.25–0.5	CM	85–95	–
extended aeration	20–30	0.05–0.15	0.16–0.40	18–24	3000–6000	0.75–1.50	CM	75–90	90–125

BOD Loading

$$\text{mass} = \text{flow} \times \text{concentration} \qquad 36.22$$

A typical facultative pond system can process 35 lbm or less of BOD_5/ac/d. A system contains a minimum of three ponds, which are 3 ft to 8 ft deep. The minimum residence time is 90–120 days.

BIOTOWER

Also called a trickling filter, a biotower operates by having the wastewater fall through a packed bed or tower filled with permeable packing. The packing has both aerobic and anaerobic microorganisms attached to it. Material balance equations can be formulated using the flux from both the connective and diffusive processes. The rate of reaction is formulated by using the Monod kinetic model. The biotowers can be operated either with or without recycling.

Fixed-Film Equation without Recycle

$$\frac{S_e}{S_o} = e^{-kD/q^n} \qquad 36.23$$

Fixed-Film Equation with Recycle

$$\frac{S_e}{S_a} = \frac{e^{-kD/q^n}}{(1+R) - R(e^{-kD/q^n})} \qquad 36.24$$

$$S_a = \frac{S_o + RS_e}{1+R} \qquad 36.25$$

Hydraulic loading with recycle is

$$q = \frac{Q_o + RQ_o}{A_{\text{plan}}} \qquad 36.26$$

The *treatability constant*, k, is given by Eq. 36.27, where the temperature, T, is in °C.

$$k_T = k_{20}(1.035)^{T-20} \qquad 36.27$$

As with activated sludge, the recycle ratio is

$$R = \frac{Q_o}{Q_R} \qquad 36.28$$

ANAEROBIC DIGESTER

The sludge from the primary settlers and the biological treatment processes can be treated to obtain methane, carbon dioxide, and other products. In the standard-rate digester, the digester is unmixed and not externally heated; in the high-rate digester, there is external heating and stirring of the contents.

Standard Rate

A standard rate digester must be sized to accommodate the raw sludge input, V_1, and the digested sludge accumulation, V_2, for the time for the sludge to digest and thicken (i.e., for the *residence time*, t_r) as well as to hold the accumulation for the period it is stored, t_s.

$$\text{Reactor volume} = \left(\frac{V_1 + V_2}{2}\right) t_r + V_2 t_s \qquad 36.29$$

High Rate

The first-stage reactor volume is selected to hold the raw sludge for as long as it takes for digestion to occur.

$$\text{Reactor volume} = V_1 t_r \qquad 36.30$$

The second-stage reactor volume is selected based on the time it takes for thickening to occur, t_t.

$$\text{Reactor volume} = \left(\frac{V_1 + V_2}{2}\right) t_t + V_2 t_s \qquad 36.31$$

AEROBIC DIGESTION

The aerobic digestion process is similar to the activated sludge process. Aeration is accomplished by means of diffusing equipment. The process can be either batch or continuous.

For a continuous process, the tank volume is

$$V = \frac{Q_i(X_i + FS_i)}{X_d\left(K_d P_v + \frac{1}{\theta_c}\right)} \qquad 36.32$$

SAMPLE PROBLEMS

Problem 1

Sludge is digested after being removed from a secondary treatment tank. During the digestion process, the gas that is produced is

(A) carbon dioxide
(B) methane
(C) nitrogen oxide
(D) hydrogen sulfide

Solution

The gas produced is primarily methane.

Answer is B.

Problem 2

Because of intermolecular forces, every kilogram of solids that enters a petroleum refinery's wastewater treatment system results in 10 kg of oily sludge. Oil that enters the wastewater treatment system and that is not entrained in oily sludge is recovered and processed into saleable product. After recovery and reprocessing, the recovered oil has an average value of \$0.20/L and an average density of 0.8 g/mL. For this refinery, the sludge is composed of 10% solids, 40% oil, and 50% water (by mass). It is suggested that 50 kg/d of solids be prevented from entering the wastewater treatment system by sweeping refinery areas and instituting erosion control measures. If these measures were taken, how much would sales increase due to the increased recovery of oil solids?

(A) \$4000/yr
(B) \$12,000/yr
(C) \$18,000/yr
(D) \$27,000/yr

Solution

For every kilogram of solids that is prevented from going to wastewater treatment, 4 kg of oil are allowed to be recovered.

$$\begin{aligned}\text{sales} &= \left(50\ \frac{\text{kg solids}}{\text{d}}\right)\left(4\ \frac{\text{kg oil}}{\text{kg solids}}\right)\left(0.20\ \frac{\$}{\text{L oil}}\right) \\ &\quad \times \left(\frac{1\ \text{mL}}{0.8\ \text{g}}\right)\left(\frac{1\ \text{L}}{1000\ \text{mL}}\right)\left(365\ \frac{\text{d}}{\text{yr}}\right) \\ &\quad \times \left(1000\ \frac{\text{g}}{\text{kg}}\right) \\ &= \$18{,}250 \quad (\$18\,000/\text{yr})\end{aligned}$$

Answer is C.

FE-STYLE EXAM PROBLEMS

1. An aerobic digester has an inflow of 2.8 m^3/d. The influent 5 day BOD is 200 mg/L, while the influent suspended solids is 5 mg/L. The digester suspended solids concentration is 10 mg/L. The reaction rate constant is 0.50/d. The volatile fraction is 0.1. The solids retention time is 2 d. The fraction of influent 5 day BOD consisting of raw sewage is 0.5. Under these conditions, the volume of the aerobic digester in cubic feet is most nearly

(A) 5.6 m^3
(B) 28 m^3
(C) 34 m^3
(D) 53 m^3

2. A sample of wastewater is diluted by a factor of 10. The diluted wastewater has an initial dissolved oxygen concentration of 7.0 mg/L. After 5 days the dissolved oxygen concentration is 3.0 mg/L. The 5 day BOD of the initial undiluted wastewater is most nearly

(A) 3 mg/L
(B) 4 mg/L
(C) 7 mg/L
(D) 40 mg/L

3. A sample of wastewater has a kinetic rate constant of 0.1/d. The initial dissolved oxygen concentration is 8.0 mg/L. The concentration after 2 days without any additional oxygen being added is 6.0 mg/L. The ultimate BOD is most nearly

(A) 2.0 mg/L
(B) 9.0 mg/L
(C) 11 mg/L
(D) 21 mg/L

4. For a sample of wastewater, the BOD exerted in 5 days is 100 mg/L, and the reaction rate constant is 0.1 d^{-1}. The value of the ultimate BOD is most nearly

(A) 100 mg/L
(B) 200 mg/L
(C) 250 mg/L
(D) 280 mg/L

5. The half-life of a biologically degraded contaminant is 1 h. The kinetic constant of the degradation reaction is most nearly

(A) 17/d
(B) 24/d
(C) 73/d
(D) 96/d

6. The overall nitrification reaction when ammonia is released to water is approximated by

$$\begin{aligned}&NH_4^+ + 1.731O_2 + 1.962HCO_3^- \\ &\quad \rightarrow 0.038C_5H_7NO_2 + 0.962NO_3^- \\ &\qquad + 1.077H_2O + 1.769H_2CO_3\end{aligned}$$

In this equation, $C_5H_7NO_2$ represents bacterial cells. If this is the sole removal process when 30 kg of ammonia is released from a livestock operation to a stream, the amount of oxygen consumed will most nearly be

(A) 2.9 kg O_2
(B) 52 kg O_2
(C) 76 kg O_2
(D) 92 kg O_2

SOLUTIONS TO FE-STYLE EXAM PROBLEMS

1. Use aerobic digester tank volume given by the formula in the NCEES Handbook.

$$V = \frac{Q_i(X_i + FS)}{X_d\left(K_d P_v + \frac{1}{\theta_c}\right)}$$

$$= \frac{\left(2.8\ \frac{\text{m}^3}{\text{d}}\right)\left(5\ \frac{\text{mg}}{\text{L}} + (0.5)\left(200\ \frac{\text{mg}}{\text{L}}\right)\right)}{\left(10\ \frac{\text{mg}}{\text{L}}\right)\left(\left(0.5\ \frac{1}{\text{d}}\right)(0.1) + \frac{1}{2\ \text{d}}\right)}$$

$$= 53.45\ \text{m}^3 \quad (53\ \text{m}^3)$$

Answer is D.

2. The 5 d BOD of the diluted wastewater is

$$\text{initial BOD} - \text{BOD}_5 = 7.0\ \frac{\text{mg}}{\text{L}} - 3.0\ \frac{\text{mg}}{\text{L}} = 4\ \text{mg/L}$$

Since the sample is diluted by a factor of 10, the original wastewater has a BOD_5 of

$$\text{BOD}_5 = (\text{dilution factor})(\text{BOD of diluted water}) = (10)\left(4\ \frac{\text{mg}}{\text{L}}\right) = 40\ \text{mg/L}$$

Answer is D.

3. The dissolved oxygen demand is

$$y_t = \text{DO}_\text{o} - \text{DO}_t = L(1 - e^{-kt})$$

Therefore,

$$y_{2\ \text{d}} = \text{DO}_\text{o} - \text{DO}_{2\ \text{d}} = 8\ \frac{\text{mg}}{\text{L}} - 6\ \frac{\text{mg}}{\text{L}} = 2\ \text{mg/L}$$

$$2\ \frac{\text{mg}}{\text{L}} = L\left(1 - e^{-\left(0.1\ \frac{1}{\text{d}}\right)(2\ \text{d})}\right)$$

Solve for L.

$$L = \frac{2\ \frac{\text{mg}}{\text{L}}}{1 - e^{-0.2}} = 11.03\ \text{mg/L} \quad (11\ \text{mg/L})$$

Answer is C.

4. The dissolved oxygen demand is

$$y_t = L\left(1 - e^{-kt}\right)$$

Solve for the ultimate BOD, L.

$$L = \frac{y_t}{1 - e^{-kt}} = \frac{100\ \frac{\text{mg}}{\text{L}}}{1 - e^{-\left(0.1\ \frac{1}{\text{d}}\right)(5\ \text{d})}} = 254\ \text{mg/L} \quad (250\ \text{mg/L})$$

Answer is C.

5. The half-life is equal to

$$\tau = \frac{1\ \text{h}}{24\ \frac{\text{h}}{\text{d}}} = \frac{1}{24}\ \text{d}$$

The biological reaction is a Michelis-Menten type reaction which can be modeled as a first order reaction. For a first order reaction, the kinetic constant

$$k = \frac{0.693}{\tau} = \frac{0.693}{\frac{1}{24}\ \text{d}} = 16.6/\text{day} \quad (17/\text{day})$$

Answer is A.

6. The molecular weight of ammonia, NH_3, is

$$(1)\left(14\ \frac{\text{g}}{\text{mol}}\right) + (4)\left(1\ \frac{\text{g}}{\text{mol}}\right) = 18\ \text{g/mol}$$

The molecular weight of oxygen is

$$(2)\left(16\ \frac{\text{g}}{\text{mol}}\right) = 32\ \text{g/mol}$$

From the chemical equation, for every mole of ammonia, 1.731 moles of oxygen are consumed. Thus, the amount of oxygen consumed when 30 kg of ammonia are released is

$$(30\ \text{kg})\left(\frac{1\ \text{mol NH}_4}{18\ \text{g NH}_4}\right)\left(1.731\ \frac{\text{mol O}_2}{\text{mol NH}_4}\right) \times \left(32\ \frac{\text{g O}_2}{\text{mol O}_2}\right) = 92.3\ \text{kg O}_2 \quad (92\ \text{kg O}_2)$$

Answer is D.