

Environmental Engineering FE CBT Exam

Knowledge: Fundamental Principles with 15 Example Problems

Contents

1 Quick-Reference Fundamental Principles Equation Matrix	2
2 Population Projections and Resource Demand Calculations	2
2.1 Population Growth Models	2
2.1.1 Linear (Arithmetic) Growth Model	2
2.1.2 Geometric (Exponential) Growth Model	2
2.1.3 Decreasing Rate of Increase Model	3
2.1.4 Logistic (S-Curve) Growth Model	3
2.2 Water Demand Calculations	3
2.2.1 Municipal Water Demand Components	3
2.2.2 Insurance Services Office (ISO) Fire Flow Formula	3
2.3 Wastewater Generation and Flow Calculations	4
2.3.1 Sanitary Wastewater Flow Components	4
2.3.2 Peaking Factors for Sewer Design	4
2.4 Solid Waste Generation and Landfill Airspace Sizing	4
2.5 Energy Demand Calculations	4
3 Reactors, Reaction Kinetics, and Mass Balances	5
3.1 Chemical and Biological Reaction Kinetics	5
3.1.1 Reaction Rates and Reaction Orders	5
3.1.2 Temperature Dependence of Reaction Rates	5
3.2 Reactor Models and Mass Balances	5
3.2.1 Ideal Batch Reactor	5
3.2.2 Continuous Stirred Tank Reactor (CSTR / CMFR)	5
3.2.3 CSTRs in Series	6
3.2.4 Plug Flow Reactor (PFR)	6
3.3 Non-Ideal Reactors and Tracer Studies	6
3.3.1 Residence Time Distribution (RTD)	6
4 Materials Science, Environmental Compatibility, and Corrosion	7
4.1 Mechanical Properties and Stress-Strain Behavior	7
4.1.1 Stress-Strain Concepts	7
4.2 Material Selection for Environmental Infrastructure	7
4.3 Corrosion Mechanisms and Protection	7
4.3.1 Electrochemistry of Corrosion	7
4.3.2 Nernst Equation for Electrochemical Potential	7
4.3.3 Cathodic Protection Systems	8
5 Overview of 15 FE-Style Practice Problems	9
6 15 Example Problems	10

1 Quick-Reference Fundamental Principles Equation Matrix

Topic	Primary Mathematical Equation / Formulation	Key Parameters & Notes
Linear Growth	$P_t = P_0 + K_a \cdot t$	$K_a = \Delta P / \Delta t$ (constant rate)
Geometric Growth	$P_t = P_0 e^{K_g t} \implies K_g = \frac{\ln(P_t/P_0)}{t}$	Exponential growth rate
Declining Growth	$P_t = P_0 + (S - P_0)(1 - e^{-K_d t})$	S = saturation population
Logistic Growth	$P_t = \frac{S}{1 + e^{a+b \cdot t}}$	$S = \frac{2P_0 P_1 P_2 - P_1^2 (P_0 + P_2)}{P_0 P_2 - P_1^2}$
Fire Flow	$F = 18C\sqrt{A}$	F in gpm, A in ft^2 , C coef.
Babbitt Peaking	$M = \frac{5}{P^{0.2}}$	P in thousands
Harmon Peaking	$M = 1 + \frac{14}{4 + \sqrt{P}}$	P in thousands
Landfill Volume	$V_{\text{landfill}} = \sum \frac{P_t \cdot G \cdot 365 \cdot (1 + R_{\text{cover}})}{\rho_{\text{lf}}}$	Compacted MSW airspace
First-Order Decay	$C_t = C_0 e^{-kt}$, $t_{1/2} = \frac{\ln 2}{k} = \frac{0.693}{k}$	Batch / PFR kinetics
CSTR Balance	$V \frac{dC}{dt} = QC_0 - QC + r_A V \implies C = \frac{C_0}{1 + k\tau}$	Steady-state first-order
CSTRs in Series	$C_n = \frac{C_0}{(1 + k\tau_i)^n}$, $\tau_i = \frac{V_{\text{total}}}{nQ}$	Equal volume tanks
Arrhenius Rate	$k_T = k_{20} \cdot \theta^{(T-20)}$	$\theta = 1.047$ (BOD decay)
Tracer Mean HRT	$\bar{t} = \frac{\int_0^\infty t C(t) dt}{\int_0^\infty C(t) dt} \approx \frac{\sum t_i C_i \Delta t_i}{\sum C_i \Delta t_i}$	Experimental residence time
Hooke's Law	$\sigma = E \cdot \epsilon$, $\sigma = \frac{P}{A_0}$, $\epsilon = \frac{\Delta L}{L_0}$	Tensile stress & strain
Hoop Stress	$\sigma_h = \frac{P \cdot D}{2t}$	Thin-walled pressure pipe
Nernst Equation	$E = E^\circ - \frac{RT}{nF} \ln Q = E^\circ - \frac{0.05916}{n} \log_{10} Q$	Cell potential at 25°C
Faraday's Law	$m = \frac{I \cdot t \cdot MW}{n \cdot F}$	$F = 96,485$ C/eq

2 Population Projections and Resource Demand Calculations

2.1 Population Growth Models

Population forecasting forms the fundamental basis for sizing water supply networks, wastewater treatment facilities, municipal solid waste landfills, and power utilities. Engineers evaluate census data to select the most appropriate growth model based on community maturity and land availability.

2.1.1 Linear (Arithmetic) Growth Model

The linear model assumes that population increases at a constant absolute rate per unit time ($dP/dt = K_a$):

$$P_t = P_0 + K_a \cdot t \quad (1)$$

where P_0 is the base population, P_t is the projected population at time t , and K_a is the arithmetic growth constant:

$$K_a = \frac{P_2 - P_1}{t_2 - t_1} \quad \left[\frac{\text{persons}}{\text{year}} \right] \quad (2)$$

Application: Mature, fully developed urban areas with constrained boundary limits.

2.1.2 Geometric (Exponential) Growth Model

The geometric model assumes that population growth is proportional to the current population size ($dP/dt = K_g P$):

$$P_t = P_0 e^{K_g t} \implies \ln P_t = \ln P_0 + K_g t \quad (3)$$

The compound growth rate K_g is determined from historical endpoints:

$$K_g = \frac{\ln(P_2/P_1)}{t_2 - t_1} \quad [\text{year}^{-1}] \quad (4)$$

Application: Young, rapidly expanding suburban communities with abundant land and economic growth.

2.1.3 Decreasing Rate of Increase Model

This model assumes that the rate of population growth is proportional to the remaining unallocated capacity ($S - P_t$), where S is the ultimate saturation population:

$$\frac{dP}{dt} = K_d(S - P_t) \implies P_t = P_0 + (S - P_0)(1 - e^{-K_d t}) \quad (5)$$

where K_d is the declining rate constant:

$$K_d = -\frac{1}{\Delta t} \ln \left(\frac{S - P_2}{S - P_1} \right) \quad (6)$$

2.1.4 Logistic (S-Curve) Growth Model

The logistic model accounts for initial lag, rapid exponential growth, and eventual asymptotic leveling off as saturation S is approached:

$$P_t = \frac{S}{1 + e^{a+b \cdot t}} \quad (7)$$

where S , a , and b are calculated from three equally spaced census records (P_0, P_1, P_2 at time t_0, t_1, t_2 with interval n years):

$$S = \frac{2P_0P_1P_2 - P_1^2(P_0 + P_2)}{P_0P_2 - P_1^2} \quad (8)$$

$$a = \ln \left(\frac{S - P_0}{P_0} \right), \quad b = \frac{1}{n} \ln \left[\frac{P_0(S - P_1)}{P_1(S - P_0)} \right] \quad (9)$$

2.2 Water Demand Calculations

2.2.1 Municipal Water Demand Components

Water distribution networks are designed to deliver water under peak demand scenarios while maintaining fire protection pressures (≥ 20 psi):

- **Average Daily Demand (ADD):** $ADD = P_t \times q_{\text{per capita}}$ (typically 100–150 gpcd or 380–570 L/capita/day).
- **Maximum Daily Demand (MDD):** $MDD = 1.8 \times ADD$. Used to size water treatment plants, clearwells, and high-service pumps.
- **Maximum Hourly Demand (MHD):** $MHD = 3.0 \times ADD$. Used to size distribution mains and localized storage tanks.
- **Design Coincident Peak Demand:** Design Demand = $\max(MHD, MDD + \text{Fire Flow})$.

2.2.2 Insurance Services Office (ISO) Fire Flow Formula

The required fire flow F (in gallons per minute, gpm) for a building is governed by construction type and structural area:

$$F = 18 C \sqrt{A} \quad (10)$$

where A is the total effective floor area (ft^2), and C is the structural construction coefficient:

- $C = 1.5$ for wood frame construction.
- $C = 1.0$ for ordinary masonry construction.
- $C = 0.8$ for non-combustible steel construction.
- $C = 0.6$ for fire-resistive reinforced concrete construction.

Required fire flow durations range from 2 hours ($F \leq 500$ gpm) to 4 hours ($F \geq 500$ gpm).

2.3 Wastewater Generation and Flow Calculations

2.3.1 Sanitary Wastewater Flow Components

Sanitary wastewater generation is estimated as 70% to 85% of average daily domestic water supply ($q_{\text{sanitary}} \approx 0.70 - 0.85 \times \text{ADD}$). Typical per capita domestic wastewater generation ranges from 60 to 100 gpcd (230 – 380 L/cap/day).

2.3.2 Peaking Factors for Sewer Design

Peak dry-weather wastewater flow accounts for diurnal human activity variations. Collection basins use peaking factor formulas:

- **Babbitt Formula:** $M = \frac{5}{P^{0.2}}$ (P = population in thousands, max $M = 5.0$)
- **Harmon Formula:** $M = 1 + \frac{14}{4 + \sqrt{P}}$ (P = population in thousands)

Design Peak Flow = $M \times Q_{\text{avg}} + Q_{\text{Infiltration/Inflow (I/I)}}$.

2.4 Solid Waste Generation and Landfill Airspace Sizing

Landfill capacity design requires projecting municipal solid waste (MSW) generation and compacted volume over the operating life:

$$V_{\text{landfill}} = \sum_{t=1}^N \frac{P_t \cdot G \cdot 365 \cdot (1 + R_{\text{cover}})}{\rho_{\text{lf}}} \quad (11)$$

where P_t is population in year t , G is waste generation rate (lb/capita/day), R_{cover} is daily cover volume ratio (0.20 – 0.25), and ρ_{lf} is compacted in-place landfill density (1,000 – 1,400 lb/yd³).

2.5 Energy Demand Calculations

Energy requirements in water treatment rely on motor power equations for pumping and aeration:

$$P_{\text{water}} = \frac{\gamma \cdot Q \cdot H}{550} \quad [\text{Water HP}], \quad P_{\text{brake}} = \frac{P_{\text{water}}}{\eta_{\text{pump}}} \quad [\text{Brake HP}], \quad P_{\text{electrical}} = \frac{P_{\text{brake}}}{\eta_{\text{motor}}} \times 0.7457 \quad [\text{kW}] \quad (12)$$

where $\gamma = 62.4 \text{ lb/ft}^3$, Q is flow (ft³/s), H is total dynamic head (ft), and η is efficiency.

3 Reactors, Reaction Kinetics, and Mass Balances

3.1 Chemical and Biological Reaction Kinetics

3.1.1 Reaction Rates and Reaction Orders

The reaction rate r_A represents the change in mass concentration of species A per unit volume per unit time ($r_A = dC_A/dt$).

Order (n)	Differential Law	Integrated Rate Law	Half-Life ($t_{1/2}$)	Units of k
Zero ($n = 0$)	$\frac{dC_A}{dt} = -k$	$C_t = C_0 - kt$	$t_{1/2} = \frac{C_0}{2k}$	mg/(L · time)
First ($n = 1$)	$\frac{dC_A}{dt} = -kC_A$	$C_t = C_0 e^{-kt}$	$t_{1/2} = \frac{\ln 2}{k} = \frac{0.693}{k}$	time ⁻¹
Second ($n = 2$)	$\frac{dC_A}{dt} = -kC_A^2$	$\frac{1}{C_t} = \frac{1}{C_0} + kt$	$t_{1/2} = \frac{1}{kC_0}$	L/(mg · time)

3.1.2 Temperature Dependence of Reaction Rates

Reaction rate constants vary with temperature according to the Arrhenius equation:

$$k = Ae^{-E_a/(RT)} \implies \ln\left(\frac{k_2}{k_1}\right) = \frac{E_a}{R} \left(\frac{1}{T_1} - \frac{1}{T_2}\right) \quad (13)$$

where E_a is activation energy (J/mol), $R = 8.314$ J/(mol · K), and T is in Kelvin. In environmental biological applications (e.g., BOD decay, activated sludge), the modified Streeter-Phelps temperature formula is used:

$$k_T = k_{20} \cdot \theta^{(T-20)} \quad (14)$$

where $\theta = 1.047$ for BOD decay in standard municipal wastewater (20°C to 30°C).

3.2 Reactor Models and Mass Balances

The general control-volume mass balance equation for any reactor is:

$$[\text{Accumulation Rate}] = [\text{Input Rate}] - [\text{Output Rate}] \pm [\text{Reaction Rate}] \quad (15)$$

$$V \frac{dC}{dt} = Q \cdot C_{\text{in}} - Q \cdot C_{\text{out}} + r_A \cdot V \quad (16)$$

3.2.1 Ideal Batch Reactor

No flow enters or leaves the reactor ($Q = 0$). Mass balance for constant volume V :

$$V \frac{dC}{dt} = r_A V \implies \frac{dC}{dt} = r_A \quad (17)$$

For first-order decay ($r_A = -kC$), the required reaction time to achieve conversion $X = (C_0 - C_t)/C_0$ is:

$$t = \frac{1}{k} \ln\left(\frac{C_0}{C_t}\right) = \frac{1}{k} \ln\left(\frac{1}{1-X}\right) \quad (18)$$

3.2.2 Continuous Stirred Tank Reactor (CSTR / CMFR)

An ideal CSTR features complete uniform mixing; effluent concentration equals the reactor internal concentration ($C_{\text{out}} = C$). At steady state ($dC/dt = 0$):

$$0 = QC_0 - QC + r_A V \implies Q(C_0 - C) = -r_A V \quad (19)$$

Defining hydraulic retention time $\tau = V/Q$:

$$\tau = \frac{C_0 - C}{-r_A} \quad (20)$$

For a first-order decay reaction ($r_A = -kC$):

$$QC_0 - QC - kCV = 0 \implies C = \frac{C_0}{1 + k\tau} = \frac{C_0}{1 + k(V/Q)} \quad (21)$$

3.2.3 CSTRs in Series

When n equal-volume CSTRs each with volume $V_i = V_{\text{total}}/n$ and HRT $\tau_i = \tau_{\text{total}}/n$ are connected in series, the effluent concentration from tank n for first-order decay is:

$$C_n = \frac{C_0}{(1 + k\tau_i)^n} = \frac{C_0}{(1 + k\frac{\tau_{\text{total}}}{n})^n} \quad (22)$$

As $n \rightarrow \infty$, the performance of CSTRs in series approaches that of an ideal Plug Flow Reactor (PFR).

3.2.4 Plug Flow Reactor (PFR)

Fluid flows as discrete packets along the longitudinal axis with zero axial mixing. Each plug acts as a mini-batch reactor:

$$\tau_{\text{PFR}} = \frac{V}{Q} = \int_{C_{\text{out}}}^{C_0} \frac{dC}{-r_A} \quad (23)$$

For first-order decay ($r_A = -kC$):

$$C_{\text{out}} = C_0 e^{-k\tau_{\text{PFR}}} \implies \tau_{\text{PFR}} = \frac{1}{k} \ln \left(\frac{C_0}{C_{\text{out}}} \right) \quad (24)$$

Comparison: For any positive reaction order ($n > 0$), $V_{\text{CSTR}} > V_{\text{PFR}}$ to achieve the same removal efficiency.

3.3 Non-Ideal Reactors and Tracer Studies

3.3.1 Residence Time Distribution (RTD)

Real reactors experience short-circuiting, dead zones, and axial dispersion. Tracer injection studies characterize hydrodynamics:

$$E(t) = \frac{C(t)}{\int_0^\infty C(t) dt} \approx \frac{C(t)}{\sum C_i \Delta t_i} \quad (25)$$

Experimental mean residence time $\bar{t}$:

$$\bar{t} = \int_0^\infty t E(t) dt \approx \frac{\sum t_i C_i \Delta t_i}{\sum C_i \Delta t_i} \quad (26)$$

Volumetric Efficiency: $\eta_v = \frac{\bar{t}}{\tau_{\text{theoretical}}} = \frac{V_{\text{active}}}{V_{\text{total}}}$. Dead volume fraction = $1 - \eta_v$.

4 Materials Science, Environmental Compatibility, and Corrosion

4.1 Mechanical Properties and Stress-Strain Behavior

4.1.1 Stress-Strain Concepts

Environmental materials (piping, geomembranes, concrete tanks, structural steel) must withstand mechanical loads:

- **Normal Stress (σ):** $\sigma = \frac{P}{A_0}$ [psi or MPa].
- **Normal Strain (ϵ):** $\epsilon = \frac{\Delta L}{L_0}$ [in/in or mm/mm].
- **Hooke's Law (Elastic Region):** $\sigma = E \cdot \epsilon$, where E is Young's Modulus of Elasticity (psi or GPa).
- **Poisson's Ratio (ν):** $\nu = -\frac{\epsilon_{\text{lateral}}}{\epsilon_{\text{axial}}}$ (typically 0.25 – 0.35 for metals, 0.40 – 0.45 for polymers).
- **Hoop Stress in Pressurized Pipes:** $\sigma_h = \frac{P \cdot D}{2t}$ (where P is internal pressure, D is pipe diameter, t is wall thickness).

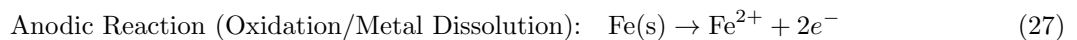
4.2 Material Selection for Environmental Infrastructure

- **HDPE (High-Density Polyethylene):** Excellent chemical resistance, flexible, zero corrosion, preferred for landfill geomembranes and sewer force mains.
- **Ductile Iron Pipe (DIP):** High tensile strength, requires external polyethylene encasement in corrosive soils.
- **Stainless Steel (316 SS):** Molybdenum-bearing alloy resistant to chloride pitting in marine and chemical environments.

4.3 Corrosion Mechanisms and Protection

4.3.1 Electrochemistry of Corrosion

Corrosion is an electrochemical process requiring an anode, cathode, metallic pathway, and electrolyte:



4.3.2 Nernst Equation for Electrochemical Potential

The cell potential under non-standard conditions is calculated as:

$$E = E^\circ - \frac{RT}{nF} \ln Q = E^\circ - \frac{0.05916}{n} \log_{10} Q \quad [\text{at } 25^\circ\text{C}] \quad (30)$$

Faraday's Law determines the mass rate of metal loss m :

$$m = \frac{I \cdot t \cdot MW}{n \cdot F} \quad (31)$$

where I is corrosion current (Amperes), t is time (seconds), MW is molecular weight, n is valence, and $F = 96,485 \text{ C/eq}$.

4.3.3 Cathodic Protection Systems

To prevent infrastructure corrosion:

- **Sacrificial Anode System:** Attach a more active metal (Magnesium, Zinc) with a more negative reduction potential to serve as the anode and protect the steel structure.
- **Impressed Current Cathodic Protection (ICCP):** Apply an external DC power supply connecting an inert anode (titanium/graphite) to drive electrons into the protected pipe.

5 Overview of 15 FE-Style Practice Problems

No.	Problem Topic & Scenario Description	Key Formula Tested	Page
1	Linear vs. Geometric Population Projection	$P_t = P_0 e^{K_g t}$ vs $P_t = P_0 + K_a t$	10
2	Logistic S-Curve Growth Saturation Limit	$S = \frac{2P_0 P_1 P_2 - P_1^2 (P_0 + P_2)}{P_0 P_2 - P_1^2}$	10
3	Municipal Water Demand & ISO Fire Flow	$F = 18C\sqrt{A}$	12
4	Wastewater Peaking Factor & Combined Sewer Flow	Harmon Formula $M = 1 + \frac{14}{4 + \sqrt{P}}$	12
5	MSW Compaction & Landfill Airspace Volume	$V = \frac{\sum P_t \cdot G \cdot 365(1+R)}{\rho}$	13
6	Arrhenius Reaction Rate Temperature Adjustment	$\ln(k_2/k_1) = \frac{E_a}{R} (1/T_1 - 1/T_2)$	14
7	Ideal Batch Reactor Degradation Time	$t = \frac{1}{k} \ln(C_0/C_t)$	14
8	CSTR Volume Sizing for Industrial Wastewater	$V = \frac{Q(C_0 - C)}{kC}$	14
9	Equal-Volume CSTRs in Series Performance	$C_n = \frac{C_0}{(1 + k\tau_i)^n}$	16
10	Plug Flow Reactor vs. CSTR Volume Comparison	$V_{\text{CSTR}}/V_{\text{PFR}}$ ratio	16
11	Non-Ideal Reactor Tracer Analysis & Dead Space	$\bar{t} = \frac{\sum t_i C_i \Delta t}{\sum C_i \Delta t}$	17
12	Tensile Stress and Hooke's Law in HDPE Pipe	$\sigma = E\epsilon, \quad \sigma_h = \frac{PD}{2t}$	17
13	Galvanic Cell Potential & Nernst Equation	$E = E^\circ - \frac{0.05916}{n} \log Q$	18
14	Microbiologically Induced Corrosion (MIC) in Sewers	$H_2S + 2O_2 \rightarrow H_2SO_4$ acid mass	18
15	Sacrificial Magnesium Anode Cathodic Protection	$m = \frac{I \cdot t \cdot MW}{n \cdot F}$	19

6 15 Example Problems

Example Problem 1: Arithmetic vs. Geometric Population Projection

A municipality had a population of 45,000 in 2010 and 60,000 in 2020. Assuming the community follows a geometric (exponential) growth model, what is the projected population for the year 2035?

Select the correct answer:

- (A) 78,750
- (B) 85,500
- (C) 92,300
- (D) 103,900

Solution

Step 1: Calculate geometric growth rate K_g .

$$P_t = P_0 e^{K_g t} \Rightarrow K_g = \frac{\ln(P_{2020}/P_{2010})}{\Delta t} = \frac{\ln(60,000/45,000)}{10 \text{ years}} = \frac{\ln(1.3333)}{10} = 0.02877 \text{ year}^{-1} \quad (32)$$

Step 2: Project population to 2035 ($t = 2035 - 2010 = 25$ years).

$$P_{2035} = 45,000 \times e^{(0.02877 \times 25)} = 45,000 \times e^{0.7192} = 45,000 \times 2.0528 = 92,376 \approx 92,300 \quad (33)$$

Correct Choice: (C)

Example Problem 2: Logistic S-Curve Growth Saturation Limit

A growing suburb recorded census populations of 12,000 in 2000, 20,000 in 2010, and 28,000 in 2020. What is the ultimate saturation population S predicted by the logistic growth model?

Select the correct answer:

- (A) 36,000
- (B) 40,000
- (C) 48,000
- (D) 56,000

Solution

Step 1: Apply the saturation population formula for equal time intervals ($n = 10$ years). Given $P_0 = 12,000$, $P_1 = 20,000$, $P_2 = 28,000$:

$$S = \frac{2P_0P_1P_2 - P_1^2(P_0 + P_2)}{P_0P_2 - P_1^2} \quad (34)$$

Numerator:

$$2(12,000)(20,000)(28,000) - (20,000)^2(12,000 + 28,000) = 1.344 \times 10^{13} - (4.0 \times 10^8)(40,000) = 1.344 \times 10^{13} - 1.60 \times 10^{13}$$

Numerator = $-2,560 \times 10^9$.

Denominator:

$$P_0P_2 - P_1^2 = (12,000)(28,000) - (20,000)^2 = 3.36 \times 10^8 - 4.0 \times 10^8 = -0.64 \times 10^8 \quad (36)$$

Divide:

$$S = \frac{-2,560 \times 10^9}{-0.064 \times 10^9} = 40,000 \quad (37)$$

Correct Choice: (B)

Example Problem 3: Municipal Water Demand & ISO Fire Flow

A commercial complex of ordinary masonry construction ($C = 1.0$) has a total effective floor area of 36,000 ft². What is the required ISO fire flow rate?

Select the correct answer:

- (A) 1,800 gpm
- (B) 2,400 gpm
- (C) 3,420 gpm
- (D) 4,100 gpm

Solution

Step 1: Apply ISO Fire Flow formula.

$$F = 18 C \sqrt{A} = 18(1.0) \sqrt{36,000} = 18 \times 189.736 = 3,415.2 \approx 3,420 \text{ gpm} \quad (38)$$

Correct Choice: (C)

Example Problem 4: Wastewater Peaking Factor Sewer Sizing

A collection basin serves a population of 16,000 people generating an average domestic wastewater flow of 80 gpcd. Using the Harmon formula, what is the design peak hourly wastewater flow rate (excluding I/I)?

Select the correct answer:

- (A) 1.28 MGD
- (B) 3.52 MGD
- (C) 4.80 MGD
- (D) 6.40 MGD

Solution

Step 1: Calculate Average Daily Flow (Q_{avg}).

$$Q_{\text{avg}} = 16,000 \text{ people} \times 80 \text{ gpcd} = 1,280,000 \text{ gpd} = 1.28 \text{ MGD} \quad (39)$$

Step 2: Calculate Harmon Peaking Factor M ($P = 16.0$ thousands).

$$M = 1 + \frac{14}{4 + \sqrt{P}} = 1 + \frac{14}{4 + \sqrt{16}} = 1 + \frac{14}{4 + 4} = 1 + 1.75 = 2.75 \quad (40)$$

Step 3: Calculate Design Peak Flow.

$$Q_{\text{peak}} = M \times Q_{\text{avg}} = 2.75 \times 1.28 \text{ MGD} = 3.52 \text{ MGD} \quad (41)$$

Correct Choice: (B)

Example Problem 5: MSW Compaction and Landfill Airspace Volume

A community of 50,000 residents generates solid waste at a rate of 4.5 lb/capita/day. The waste is compacted in a landfill to an in-place density of 1,200 lb/yd³. Daily soil cover adds 20% to the compacted waste volume ($R_{\text{cover}} = 0.20$). What is the total landfill volume required for 1 year of operation?

Select the correct answer:

- (A) 57,000 yd³
- (B) 68,400 yd³
- (C) 82,100 yd³
- (D) 102,500 yd³

Solution

Step 1: Calculate total annual raw MSW mass.

$$W_{\text{annual}} = 50,000 \text{ people} \times 4.5 \text{ lb/cap/day} \times 365 \text{ days/yr} = 82,125,000 \text{ lb/yr} \quad (42)$$

Step 2: Calculate compacted MSW volume without cover.

$$V_{\text{waste}} = \frac{82,125,000 \text{ lb}}{1,200 \text{ lb/yd}^3} = 68,437.5 \text{ yd}^3 \quad (43)$$

Step 3: Add 20% daily cover ($R_{\text{cover}} = 0.20$).

$$V_{\text{total}} = V_{\text{waste}} \times (1 + 0.20) = 68,437.5 \times 1.20 = 82,125 \approx 82,100 \text{ yd}^3 \quad (44)$$

Correct Choice: (C)

Example Problem 6: Arrhenius Reaction Rate Temperature Adjustment

A biological BOD degradation rate constant is measured as $k_1 = 0.23 \text{ day}^{-1}$ at 20°C . Assuming a modified Streeter-Phelps temperature coefficient of $\theta = 1.047$, what is the reaction rate constant at 30°C ?

Select the correct answer:

- (A) 0.28 day^{-1}
- (B) 0.36 day^{-1}
- (C) 0.44 day^{-1}
- (D) 0.52 day^{-1}

Solution

Step 1: Apply temperature correction equation.

$$k_{30} = k_{20} \cdot \theta^{(30-20)} = 0.23 \times (1.047)^{10} = 0.23 \times 1.5829 = 0.364 \approx 0.36 \text{ day}^{-1} \quad (45)$$

Correct Choice: (B)

Example Problem 7: Ideal Batch Reactor Degradation Time

An industrial batch reactor treats a toxic organic pollutant subject to first-order decay with rate constant $k = 0.15 \text{ hr}^{-1}$. How long must the batch reaction proceed to achieve 95% pollutant removal?

Select the correct answer:

- (A) 13.3 hours
- (B) 20.0 hours
- (C) 26.6 hours
- (D) 32.1 hours

Solution

Step 1: Calculate C_t/C_0 for 95% removal.

$$X = 0.95 \implies \frac{C_t}{C_0} = 1 - 0.95 = 0.05 \quad (46)$$

Step 2: Solve integrated first-order batch rate equation.

$$t = \frac{1}{k} \ln \left(\frac{C_0}{C_t} \right) = \frac{1}{0.15 \text{ hr}^{-1}} \ln \left(\frac{1}{0.05} \right) = \frac{\ln(20)}{0.15} = \frac{2.9957}{0.15} = 19.97 \approx 20.0 \text{ hours} \quad (47)$$

Correct Choice: (B)

Example Problem 8: CSTR Volume Sizing for Industrial Wastewater

A CSTR treats an industrial wastewater stream flowing at $Q = 2.0 \text{ MGD}$ with an influent contaminant concentration of $C_0 = 300 \text{ mg/L}$. The first-order decay rate constant is $k = 0.50 \text{ hr}^{-1}$. What reactor volume (in gallons) is required to achieve an effluent concentration of $C = 30 \text{ mg/L}$?

Select the correct answer:

300,000 gal

750,000 gal

1,500,000 gal

2,250,000 gal

Solution

Step 1: Convert flow rate Q to gallons per hour (gph).

$$Q = \frac{2,000,000 \text{ gal/day}}{24 \text{ hr/day}} = 83,333.3 \text{ gph} \quad (48)$$

Step 2: Apply steady-state CSTR mass balance equation.

$$C = \frac{C_0}{1 + k\tau} \implies 30 = \frac{300}{1 + 0.50 \cdot \tau} \implies 1 + 0.50\tau = 10 \implies 0.50\tau = 9 \implies \tau = 18 \text{ hours} \quad (49)$$

Step 3: Calculate required reactor volume V .

$$V = Q \times \tau = 83,333.3 \text{ gph} \times 18 \text{ hr} = 1,500,000 \text{ gallons} \quad (50)$$

Correct Choice: (C)

Example Problem 9: Equal-Volume CSTRs in Series Performance

An influent stream with $C_0 = 200$ mg/L passes through three equal-volume CSTRs connected in series ($n = 3$). The total system hydraulic retention time is $\tau_{\text{total}} = 12$ hours, and the first-order reaction rate constant is $k = 0.25 \text{ hr}^{-1}$. What is the final effluent concentration from the 3rd reactor?

Select the correct answer:

- (A) 25.0 mg/L
- (B) 40.0 mg/L
- (C) 65.0 mg/L
- (D) 80.0 mg/L

Solution

Step 1: Calculate HRT per individual tank (τ_i).

$$\tau_i = \frac{\tau_{\text{total}}}{n} = \frac{12 \text{ hours}}{3} = 4.0 \text{ hours} \quad (51)$$

Step 2: Apply CSTRs in series formula for $n = 3$.

$$C_3 = \frac{C_0}{(1 + k\tau_i)^3} = \frac{200}{(1 + 0.25 \times 4.0)^3} = \frac{200}{(1 + 1.0)^3} = \frac{200}{2^3} = \frac{200}{8} = 25.0 \text{ mg/L} \quad (52)$$

Correct Choice: (A)

Example Problem 10: CSTR vs. Plug Flow Reactor Volume Ratio

A water treatment plant must achieve 90% removal ($X = 0.90$) of a dissolved contaminant undergoing first-order decay. What is the ratio of required CSTR volume to PFR volume ($V_{\text{CSTR}}/V_{\text{PFR}}$)?

Select the correct answer:

- (A) 1.91
- (B) 2.75
- (C) 3.91
- (D) 4.50

Solution

Step 1: Calculate dimensionless CSTR retention time ($k\tau_{\text{CSTR}}$) for $C/C_0 = 0.10$.

$$\frac{C}{C_0} = 0.10 = \frac{1}{1 + k\tau_{\text{CSTR}}} \implies 1 + k\tau_{\text{CSTR}} = 10 \implies k\tau_{\text{CSTR}} = 9.0 \quad (53)$$

Step 2: Calculate dimensionless PFR retention time ($k\tau_{\text{PFR}}$).

$$\frac{C}{C_0} = 0.10 = e^{-k\tau_{\text{PFR}}} \implies k\tau_{\text{PFR}} = \ln\left(\frac{1}{0.10}\right) = \ln(10) = 2.3026 \quad (54)$$

Step 3: Calculate volume ratio $V_{\text{CSTR}}/V_{\text{PFR}}$. Since Q and k are identical:

$$\frac{V_{\text{CSTR}}}{V_{\text{PFR}}} = \frac{\tau_{\text{CSTR}}}{\tau_{\text{PFR}}} = \frac{9.0}{2.3026} = 3.9088 \approx 3.91 \quad (55)$$

Correct Choice: (C)

Example Problem 11: Non-Ideal Reactor Tracer Analysis Dead Volume

A pulse tracer study conducted on a contact basin with theoretical HRT $\tau_{\text{theoretical}} = 4.0$ hours yielded an experimental mean residence time of $\bar{t} = 3.2$ hours. What is the percentage of dead volume (stagnant zone) in the basin?

Select the correct answer:

- (A) 10%
- (B) 20%
- (C) 25%
- (D) 30%

Solution

Step 1: Calculate active volumetric efficiency η_v .

$$\eta_v = \frac{\bar{t}}{\tau_{\text{theoretical}}} = \frac{3.2 \text{ hours}}{4.0 \text{ hours}} = 0.80 = 80\% \quad (56)$$

Step 2: Calculate dead volume percentage.

$$\text{Dead Volume Fraction} = 1 - \eta_v = 1 - 0.80 = 0.20 = 20\% \quad (57)$$

Correct Choice: (B)

Example Problem 12: Tensile Stress and Hooke's Law in HDPE Pipe

An HDPE water pipe with inside diameter $D = 12.0$ in and wall thickness $t = 0.75$ in operates under an internal water pressure of $P = 100$ psi. If the modulus of elasticity of HDPE is $E = 120,000$ psi, what is the circumferential (hoop) strain in the pipe wall?

Select the correct answer:

- 0.0033 in/in
- 0.0067 in/in
- 0.0100 in/in
- 0.0133 in/in

Solution

Step 1: Calculate hoop stress σ_h .

$$\sigma_h = \frac{P \cdot D}{2t} = \frac{100 \text{ psi} \times 12.0 \text{ in}}{2 \times 0.75 \text{ in}} = \frac{1,200}{1.50} = 800 \text{ psi} \quad (58)$$

Step 2: Apply Hooke's Law to find strain ϵ .

$$\sigma_h = E \cdot \epsilon \implies \epsilon = \frac{\sigma_h}{E} = \frac{800 \text{ psi}}{120,000 \text{ psi}} = 0.00667 \approx 0.0067 \text{ in/in} \quad (59)$$

Correct Choice: (B)

Example Problem 13: Galvanic Cell Potential Nernst Equation

A electrochemical cell consists of an iron anode ($\text{Fe}^{2+} + 2e^- \rightleftharpoons \text{Fe(s)}$, $E^\circ = -0.44 \text{ V}$) and a copper cathode ($\text{Cu}^{2+} + 2e^- \rightleftharpoons \text{Cu(s)}$, $E^\circ = +0.34 \text{ V}$) operating at 25°C . If $[\text{Fe}^{2+}] = 0.10 \text{ M}$ and $[\text{Cu}^{2+}] = 0.001 \text{ M}$, what is the cell potential E_{cell} ?

Select the correct answer:

- (A) 0.72 V
- (B) 0.78 V
- (C) 0.84 V
- (D) 0.90 V

Solution

Step 1: Calculate standard cell potential E_{cell}° .

$$E_{\text{cell}}^\circ = E_{\text{cathode}}^\circ - E_{\text{anode}}^\circ = +0.34 \text{ V} - (-0.44 \text{ V}) = +0.78 \text{ V} \quad (60)$$

Step 2: Write cell reaction and reaction quotient Q .

$$\text{Fe(s)} + \text{Cu}^{2+} \rightleftharpoons \text{Fe}^{2+} + \text{Cu(s)} \implies Q = \frac{[\text{Fe}^{2+}]}{[\text{Cu}^{2+}]} = \frac{0.10}{0.001} = 100 \quad (61)$$

Step 3: Apply Nernst equation ($n = 2$ electrons transferred).

$$E_{\text{cell}} = E_{\text{cell}}^\circ - \frac{0.05916}{2} \log_{10}(Q) = 0.78 - 0.02958 \log_{10}(100) = 0.78 - 0.02958(2) = 0.78 - 0.05916 = 0.7208 \approx 0.72 \text{ V} \quad (62)$$

Correct Choice: (A)

Example Problem 14: Microbiologically Induced Corrosion (MIC) in Sewers

Sulfate-reducing bacteria in anaerobic wastewater produce H_2S gas. Autotrophic bacteria oxidize H_2S to sulfuric acid (H_2SO_4) according to $\text{H}_2\text{S} + 2\text{O}_2 \rightarrow \text{H}_2\text{SO}_4$. If 5.0 kg/day of H_2S is oxidized, what mass of pure concrete matrix (CaCO_3) is dissolved per year ($\text{H}_2\text{SO}_4 + \text{CaCO}_3 \rightarrow \text{CaSO}_4 + \text{H}_2\text{O} + \text{CO}_2$)?

Select the correct answer:

- (A) 1,825 kg/yr
- (B) 5,360 kg/yr
- (C) 7,240 kg/yr
- (D) 9,800 kg/yr

Solution

Step 1: Determine molar mass ratios ($\text{MW}_{\text{H}_2\text{S}} = 34.08 \text{ g/mol}$, $\text{MW}_{\text{CaCO}_3} = 100.09 \text{ g/mol}$). 1 mole of H_2S yields 1 mole of H_2SO_4 , which neutralizes 1 mole of CaCO_3 .

Step 2: Calculate daily CaCO_3 dissolution mass.

$$\text{Mass}_{\text{CaCO}_3/\text{day}} = 5.0 \text{ kg H}_2\text{S/day} \times \left(\frac{100.09 \text{ g/mol CaCO}_3}{34.08 \text{ g/mol H}_2\text{S}} \right) = 5.0 \times 2.9369 = 14.685 \text{ kg/day} \quad (63)$$

Step 3: Calculate annual mass loss.

$$\text{Annual Mass} = 14.685 \text{ kg/day} \times 365 \text{ days/yr} = 5,360 \text{ kg/yr} \quad (64)$$

Correct Choice: (B)

Example Problem 15: Sacrificial Magnesium Anode Cathodic Protection Sizing

A buried steel pipeline requires a continuous protective cathodic protection current of $I = 0.50$ Amperes. A magnesium sacrificial anode ($\text{Mg} \rightarrow \text{Mg}^{2+} + 2e^-$, $MW = 24.31$ g/mol) is installed. Assuming 100% anode current efficiency, what mass of magnesium is consumed over a 10-year design life?

Select the correct answer:

- 19.8 kg
- 39.8 kg
- 79.6 kg
- 119.4 kg

Solution

Step 1: Calculate total charge Q_{total} in Coulombs over 10 years.

$$t = 10 \text{ years} \times 365 \text{ days/yr} \times 86,400 \text{ s/day} = 315,360,000 \text{ seconds} \quad (65)$$

$$Q_{\text{total}} = I \times t = 0.50 \text{ A} \times 315,360,000 \text{ s} = 157,680,000 \text{ Coulombs} \quad (66)$$

Step 2: Apply Faraday's Law of Electrolysis ($n = 2$ eq/mol, $F = 96,485$ C/eq).

$$m = \frac{Q_{\text{total}} \cdot MW}{n \cdot F} = \frac{157,680,000 \text{ C} \times 24.31 \text{ g/mol}}{2 \times 96,485 \text{ C/eq}} = \frac{3,833,200,800}{192,970} = 19,864 \text{ grams} \approx 19.86 \text{ kg} \approx 19.8 \text{ kg} \quad (67)$$

Correct Choice: (A)