

Environmental Engineering FE CBT Exam

Knowledge: Solid and Hazardous Waste with 15 Example Problems

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1 Exam Framework and Waste-Management Hierarchy

The FE scope treats solid and hazardous waste as an engineering system: material is generated, collected, transported, processed, recovered, treated, and ultimately disposed. A useful organizational idea is the **waste-management hierarchy**: source reduction and reuse are preferred, followed by recycling/composting, then energy recovery, with treatment and disposal used for material that cannot be beneficially managed upstream.

Why the hierarchy matters on the FE exam

Questions often ask you to compare alternatives using mass, volume, energy, or contaminant balances. Start by defining the system boundary. A general steady-state balance is

$$\text{Input} + \text{Generation} = \text{Output} + \text{Consumption}.$$

For a conserved material with no generation or consumption,

$$\dot{m}_{\text{in}} = \dot{m}_{\text{out}}.$$

For a component or contaminant,

$$\dot{m} = QC,$$

provided the units of flow and concentration are compatible.

FE categories to recognize

- **Solid waste management:** collection, transfer, transportation, storage, composting, recycling, energy recovery.
- **Solid waste disposal:** landfill capacity, compaction, liner performance, leachate, gas collection.
- **Hazardous waste:** incompatibility, ignitability, corrosivity, reactivity, toxicity, and treatment selection.
- **Site characterization:** sampling, monitoring, background comparison, remedial investigation.
- **Radioactive waste:** half-life, effective half-life, daughter products, shielding/distance concepts.

Exam habit: Before calculating, write one line stating the basis: for example, “per day,” “per ton of incoming waste,” or “per acre of landfill.” A consistent basis prevents most unit errors.

Reference cue: FE Environmental specification; FE Reference Handbook environmental engineering section.

2 Solid-Waste Mass Balances

Mass balances are central because recovery, diversion, treatment, and disposal are all fractions of an incoming stream. For a facility receiving total mass rate $\dot{m}_0$, with recovered fraction f_r , treatment residue fraction f_s , and direct disposal fraction f_d , the fractions must be consistent with the process definition.

For a simple two-way split,

$$\dot{m}_0 = \dot{m}_r + \dot{m}_d, \quad f_r = \frac{\dot{m}_r}{\dot{m}_0}, \quad f_d = 1 - f_r.$$

A percent recovery is

$$\% \text{ recovery} = 100 \frac{\dot{m}_r}{\dot{m}_0}.$$

If a recovered stream has contamination or process losses, distinguish **gross recovered mass** from **saleable recovered product**. For product yield Y ,

$$\dot{m}_{\text{product}} = Y \dot{m}_{\text{feed to recovery}}.$$

Moisture and dry-solids basis

For wet mass M_w and moisture fraction x_w on a wet basis,

$$M_{\text{water}} = x_w M_w, \quad M_{\text{dry}} = (1 - x_w) M_w.$$

If moisture is removed without losing dry solids, the dry-solids mass is conserved. This is especially useful for composting, drying, sludge-like wastes, and combustion calculations.

Common FE traps

- Confusing a percentage of the original feed with a percentage of an intermediate stream.
- Mixing mass fractions and percentages.
- Applying a volume reduction directly to mass; compaction changes volume, not dry mass.
- Forgetting that residue from recycling or treatment can still require disposal.

Fast setup: Draw one box around the process, label all streams with $\dot{m}$, and write one balance before touching the calculator.

2.1 Waste Properties: Density, Moisture, and Composition

Waste-property questions typically involve converting between mass and volume or using a weighted composition. The FE Reference Handbook provides representative densities and moisture contents for several source-separated and municipal-solid-waste components.

The basic mass-volume relation is

$$\rho_b = \frac{M}{V}, \quad V = \frac{M}{\rho_b},$$

where ρ_b is bulk density. Keep track of whether a density is for loose, compacted, crushed, or baled material.

Weighted average property

For a mixture with mass fractions w_i and component property P_i , a mass-weighted average is

$$\bar{P} = \sum_i w_i P_i, \quad \sum_i w_i = 1.$$

This approach is used for moisture content, heating value, ash content, or other composition-dependent properties when the basis is mass.

Moisture accounting

If component i has wet mass M_i and wet-basis moisture $x_{w,i}$,

$$M_{\text{water}} = \sum_i M_i x_{w,i}, \quad M_{\text{dry}} = \sum_i M_i (1 - x_{w,i}).$$

Overall wet-basis moisture is then

$$\bar{x}_w = \frac{M_{\text{water}}}{\sum_i M_i}.$$

When a table gives a range and a typical value, use the value specified by the question. If none is specified, the exam question will normally provide enough data or point you to the needed table entry.

Practical interpretation

High-moisture waste generally increases mass to be transported and reduces the net useful energy available during combustion because more energy is required to evaporate water. Low bulk density increases required storage and transport volume.

3 Collection and Storage

The FE specification explicitly includes collection, transportation, and storage. These questions are usually balance or capacity calculations rather than detailed route optimization.

Container sizing

For waste generation rate G (mass/time), collection interval Δt , and loose bulk density ρ_b , the uncompacted storage volume is

$$V_{\text{req}} = \frac{G \Delta t}{\rho_b}.$$

If a safety or peak factor F_p is specified,

$$V_{\text{design}} = F_p V_{\text{req}}.$$

If storage uses a compaction factor $CF = V_f/V_i$, then

$$V_f = CF V_i.$$

Collection productivity

A collection system may be separated conceptually into pickup time, travel time, unloading time, and nonproductive delay. A daily mass capacity can be represented as

$$M_{\text{day}} = N_{\text{trips}} M_{\text{trip}}.$$

If a truck is volume-limited,

$$M_{\text{trip}} = \rho_b V_{\text{truck}}.$$

If it is weight-limited, use the allowable payload instead. The controlling capacity is the smaller of the volume-based and weight-based values.

Storage considerations for hazardous materials

The source materials emphasize compatibility. Storage decisions therefore begin with chemical grouping and segregation. Waste streams that can generate heat, fire, toxic gas, flammable gas, explosive reactions, or polymerization when mixed should not be combined.

A compatibility question is not solved by assuming dilution makes mixing safe. Use the compatibility information supplied in the NCEES reference or the problem statement.

3.1 Transfer Stations and Transportation

Transfer stations consolidate waste from smaller collection vehicles into larger transport units. FE questions typically ask for throughput, vehicle counts, or mass/volume conversions.

For a transfer station receiving average flow M_d tons/day and operating H hours/day, average hourly throughput is

$$\dot{M}_h = \frac{M_d}{H}.$$

If each transfer vehicle carries payload M_p , the theoretical number of loads per day is

$$N = \frac{M_d}{M_p}.$$

Round up when a whole number of loads is required.

Volume-limited versus mass-limited transport

If vehicle volume is V_t , then the mass that physically fits is

$$M_v = \rho_b V_t.$$

The actual payload is

$$M_{\text{actual}} = \min(M_v, M_{\text{legal payload}}).$$

Why compaction affects transportation

Compaction does not destroy mass, but it can allow more mass to fit in a fixed-volume vehicle. If incoming waste is loose and the truck compacts it, a useful volume relation is

$$V_f = CF V_i,$$

with $CF < 1$ for volume reduction. Because exam conventions can differ, check the exact definition supplied in the reference or question.

Transportation workflow: (1) compute waste mass generated, (2) convert to volume if needed, (3) compare truck volume and payload constraints, (4) calculate whole trips, and (5) check the time basis.

3.2 Recycling and Materials Recovery

The FE specification includes recycling. Most quantitative questions can be handled using recovery fractions, processing efficiencies, and residue balances.

For incoming mass M_0 , targeted material fraction x_t , and recovery efficiency η_r ,

$$M_{\text{recovered}} = M_0 x_t \eta_r.$$

If the recovered product must meet a purity p , distinguish product mass from contaminant mass. If contamination is expressed as a mass fraction x_c ,

$$p = 1 - x_c.$$

Diversion rate

A common performance measure is

$$\text{Diversion fraction} = \frac{M_{\text{recycled}} + M_{\text{composted}} + M_{\text{other diverted}}}{M_{\text{generated}}}.$$

The landfill disposal rate is the generated mass minus all legitimate diverted outputs and other non-landfilled dispositions.

Density matters

The FE handbook includes typical densities of separated paper, glass, metal cans, and plastics. Densification by crushing, flattening, or baling can dramatically reduce transport and storage volume even though mass remains essentially unchanged.

For a recycling problem with several materials, compute each recovered mass separately and sum the results. Avoid applying one recovery percentage to the entire waste stream unless the problem states that it is an overall facility recovery.

Mass-balance check

At the end of any materials-recovery calculation,

$$M_{\text{feed}} = M_{\text{product}} + M_{\text{residue}} + M_{\text{other losses}}.$$

If the terms do not close, re-check bases and percentages.

3.3 Composting and Biological Stabilization

Composting appears explicitly in the FE Solid and Hazardous Waste specification. The source materials describe composting as biological conversion of organic waste into useful material for land application. FE calculations are most naturally handled with mass, moisture, and solids balances.

Suppose incoming wet feed is M_0 with moisture fraction $x_{w,0}$. Initial dry solids are

$$M_{s,0} = M_0(1 - x_{w,0}).$$

If a fraction f_d of dry solids remains after biological conversion,

$$M_{s,f} = f_d M_{s,0}.$$

If final product moisture is $x_{w,f}$, then final wet product mass is

$$M_f = \frac{M_{s,f}}{1 - x_{w,f}}.$$

Interpretation

Mass decreases can arise from water loss and conversion of degradable organic matter to gases. Because the FE specification is broad, a problem may provide a degradation fraction, moisture target, or product yield rather than asking for biological kinetics.

Material suitability

Keep the exam emphasis on the engineering balance: determine the organic fraction, account for contaminants or rejects, and track water if required. If the question provides a recycle stream or bulking material, place it explicitly in the balance.

Composting calculation pattern: wet feed $\rightarrow$ dry-solids basis $\rightarrow$ biodegradation/yield $\rightarrow$ final moisture $\rightarrow$ wet product mass.

3.4 Waste-to-Energy and Energy Balances

The FE specification includes waste-to-energy. Energy-recovery questions usually combine mass flow, heating value, and conversion efficiency.

If a waste stream has mass flow $\dot{m}$ and heating value HV , thermal input is

$$\dot{Q}_{\text{in}} = \dot{m} HV.$$

If net electrical conversion efficiency is η_e ,

$$P_e = \eta_e \dot{Q}_{\text{in}}.$$

Use consistent units. For example, convert Btu/hr to kW or MJ/day to kW before comparing power values.

For a mixed waste stream with mass fractions w_i ,

$$HV_{\text{mix}} = \sum_i w_i HV_i.$$

Residuals

Energy recovery reduces waste volume but does not make the mass balance disappear. Ash and other residues remain and may require disposal or further treatment. If the ash fraction on a feed-mass basis is x_a ,

$$M_a = x_a M_0.$$

Excess air and combustion data

The supplied references contain useful relationships and typical heating values. When the exam question provides stoichiometric or excess-air data, separate the **mass balance** from the **energy balance**; do not combine them prematurely.

A quick reasonableness check: electrical output must be less than thermal input when efficiency is below 100%. If the calculated power exceeds the incoming thermal power, a unit conversion is wrong.

3.5 Heating Value, Moisture, and Combustion

The NCEES solid-waste references distinguish higher heating value (HHV) and lower heating value (LHV). A reference relationship is

$$\text{LHV} = \text{HHV} - (\Delta H_v)(9H),$$

where H is the hydrogen content of the combusted material and ΔH_v is the heat of vaporization of water on the stated basis.

Weighted heating value

For a mixture,

$$\text{HHV}_{\text{mix}} = \sum_i w_i \text{HHV}_i.$$

If moisture is included in the given component heating values, use those values directly. If the problem explicitly separates dry heating value and moisture, follow the stated basis carefully.

Combustion-air concepts

The reference materials include stoichiometric-air and combustion-product relationships for representative solid waste. FE problems may provide a heating value, excess-air percentage, or product-gas information. A general excess-air relation is

$$\dot{m}_{\text{air,actual}} = (1 + EA)\dot{m}_{\text{air,stoich}},$$

where EA is decimal excess air.

Energy efficiency

If useful energy recovered is E_u from input energy E_{in} ,

$$\eta = \frac{E_u}{E_{in}}.$$

Do not mix HHV and LHV in the same efficiency calculation unless the problem explicitly converts one basis to the other.

4 Landfill Systems Overview

Landfills appear directly in the FE specification, including leachate and gas collection. The FE Reference Handbook provides formulas for liner breakthrough, overburden effects, gas flux, cover water balance, and compaction.

A landfill system can be viewed as several interacting controls:

- **Waste placement and compaction** control consumed airspace.
- **Liner and leachate collection** control downward liquid migration.
- **Cover systems** control infiltration, runoff, evapotranspiration, and gas migration.
- **Gas collection** controls methane and other landfill-gas movement.
- **Monitoring** checks groundwater, gas, and other environmental performance.

Airspace and mass

If available landfill volume is V_L and average in-place waste density is ρ_L , the nominal waste mass capacity is

$$M_{\text{cap}} = \rho_L V_L.$$

If daily disposed mass is M_d , an idealized service life is

$$T = \frac{M_{\text{cap}}}{M_d}.$$

Convert the time basis as needed.

System perspective

Landfill questions frequently combine multiple topics: a cover water balance may determine percolation, while a liner formula addresses travel time, and compaction determines capacity. Keep each subproblem separate, then combine only at the end.

Search terms to know: “Landfill,” “Break-Through Time,” “Gas Flux,” “Soil Landfill Cover Water Balance,” and “Compaction.”

4.1 Landfill Capacity and Compaction

The FE Reference Handbook gives volume reduction due to compaction as

$$\% \text{ Volume Reduction} = 100 \left(\frac{V_i - V_f}{V_i} \right),$$

where V_i and V_f are initial and final waste volumes.

A compaction factor may be defined as

$$CF = \frac{V_f}{V_i}.$$

Therefore,

$$V_f = CF V_i, \quad \% \text{ reduction} = 100(1 - CF).$$

A compaction ratio is sometimes expressed as the reciprocal, so always check the definition in the question or table.

Capacity from geometry

For a simple rectangular cell,

$$V = LWH.$$

For more complex shapes, use the geometric data provided. When a fraction f_c of total cell volume is occupied by cover or infrastructure rather than waste,

$$V_{\text{waste}} = (1 - f_c)V_{\text{gross}}.$$

Mass life of a landfill

With average in-place density ρ ,

$$M_{\text{cap}} = \rho V_{\text{waste}}.$$

If incoming waste is diverted at fraction f_d , disposed mass is

$$M_{\text{disposed}} = (1 - f_d)M_{\text{generated}}.$$

Capacity questions often hide the critical step in one word: *generated*, *collected*, *diverted*, or *disposed*. Use the correct mass stream for landfill life.

4.2 Clay Liner Breakthrough

The FE Reference Handbook provides an expression for the breakthrough time for leachate to penetrate a clay liner:

$$t = \frac{d^2 \eta}{K(d + h)},$$

where d is liner thickness, η is porosity, K is hydraulic conductivity, and h is hydraulic head above the liner, using compatible units.

Parameter effects

The equation reveals several useful trends:

- Increasing liner thickness d generally increases breakthrough time strongly because d^2 appears in the numerator.
- Increasing hydraulic conductivity K decreases breakthrough time.
- Increasing head h increases the driving force and decreases breakthrough time.
- Increasing porosity η increases the pore volume to be traversed and increases breakthrough time in this model.

Unit discipline

If K is in ft/yr and lengths are in ft, t is in years. If conductivity is given in cm/s, convert it before inserting into a formula using feet and years.

A dimensional check is useful:

$$\frac{\text{ft}^2}{(\text{ft/yr})(\text{ft})} = \text{yr}.$$

Exam shortcut: Write the units beside K first. Most mistakes in liner problems are time-unit or length-unit conversions, not algebra.

4.3 Landfill Cover Water Balance and Leachate

The FE Reference Handbook expresses the landfill-cover water balance as

$$\Delta S_{LC} = P - R - ET - PER_{sw},$$

where P is precipitation, R is runoff, ET is evapotranspiration, and PER_{sw} is percolation into the compacted waste. Rearranging,

$$PER_{sw} = P - R - ET - \Delta S_{LC}.$$

For a long-term period where net cover storage change is negligible,

$$PER_{sw} \approx P - R - ET.$$

Convert depth to volume

If percolation depth is d_p over area A , leachate volume is

$$V_L = Ad_p,$$

after converting the depth to the same length unit used for area. For acres and inches, converting to cubic feet or gallons is often required.

Interpretation

- More runoff reduces infiltration available for percolation.
- Greater evapotranspiration reduces water remaining to percolate.
- Positive ΔS_{LC} means the cover retained water during the accounting period.
- Negative ΔS_{LC} means stored water decreased and can contribute to outflow.

Water-balance signs matter. Use the exact NCEES convention: precipitation is an input; runoff, evapotranspiration, and percolation are outputs from cover storage.

4.4 Landfill Gas Generation and Composition

The NCEES solid-waste reference describes anaerobic conversion of organic matter in landfills as producing new biomass, resistant organic matter, carbon dioxide, methane, ammonia, hydrogen sulfide, and heat. A representative landfill gas is dominated by methane and carbon dioxide.

Gas mass or volume balances

If total gas production is Q_g and methane dry-volume fraction is y_{CH_4} ,

$$Q_{CH_4} = y_{CH_4} Q_g.$$

Likewise,

$$Q_{CO_2} = y_{CO_2} Q_g.$$

For a collection efficiency η_c , recovered gas is

$$Q_{g,\text{collected}} = \eta_c Q_g.$$

Energy recovery from methane

If a problem gives methane heating value HV_{CH_4} , recovered thermal power can be calculated from the methane flow after converting to compatible units:

$$\dot{Q}_{\text{thermal}} = Q_{CH_4,\text{collected}} HV_{CH_4}.$$

Then electrical output is

$$P_e = \eta_e \dot{Q}_{\text{thermal}}.$$

Safety perspective

Landfill gas is not just an energy resource. Methane migration and hydrogen sulfide are safety and environmental concerns. The engineering objective is controlled collection and management rather than uncontrolled migration.

Keep dry-volume fraction, wet-gas flow, and standard-volume conditions consistent with the problem statement.

4.5 Landfill Gas Migration and Diffusive Flux

The FE Reference Handbook provides a gas-flux relation through landfill cover of the form

$$N_A = \frac{D \eta_{gas}^{4/3}}{L \eta^2} (C_{A,fill} - C_{A,atm}),$$

with the exact notation and units given in the reference. Here D is a diffusion coefficient, L is cover thickness, η_{gas} is gas-filled porosity, η is total porosity, and the concentration difference drives diffusion.

How to read the equation

- Flux increases as the internal-to-atmospheric concentration difference increases.
- Flux decreases as cover thickness increases.
- Flux increases as diffusion coefficient increases.
- Porosity terms can strongly affect flux because of the exponent on gas-filled porosity.

If flux N_A is mass per area per time and landfill-cover area is A , total emission rate is

$$\dot{M}_A = N_A A.$$

Direction and sign

Use the concentration order that corresponds to outward flux. If a raw calculation produces a negative sign, interpret it using the concentration gradient and the sign convention in the supplied formula.

Do not confuse **flux** with **total rate**. Flux is normalized by area. Multiply by emitting area only if the question requests a total mass or molar emission rate.

5 Hazardous-Waste Characteristics

The NCEES references summarize the characteristic hazardous-waste framework: **ignitability**, **corrosivity**, **reactivity**, and **toxicity**. These are commonly associated with waste codes D001, D002, D003, and D004–D043, respectively.

Ignitability

A key liquid criterion given in the source is a flash point below 60°C, subject to the stated regulatory details and exceptions.

Corrosivity

For aqueous wastes, the source identifies corrosivity at

$$pH \leq 2.0 \quad \text{or} \quad pH \geq 12.5,$$

and also includes a steel-corrosion-rate criterion for liquids.

Reactivity

Reactive wastes can be unstable, react violently with water, form explosive mixtures, generate dangerous gases, or detonate under specified conditions. Reactivity questions are usually qualitative and depend on the stated behavior.

Toxicity

The source describes use of the Toxicity Characteristic Leaching Procedure (TCLP), comparing extract concentrations with regulatory levels for listed contaminants.

For classification questions, use the exact threshold and conditions supplied by the reference or problem. Do not classify a waste solely from intuition about whether the material seems “dangerous.”

5.1 Hazardous-Waste Compatibility

The FE specification explicitly names hazardous-waste compatibility. The NCEES reference includes a compatibility chart organized by reactivity groups and consequence codes. Possible consequences include heat generation, fire, non-flammable gas generation, toxic gas generation, flammable gas generation, explosion, polymerization, and solubilization of toxic material.

How to solve a compatibility question

1. Identify the reactivity group for Waste A.
2. Identify the reactivity group for Waste B.
3. Locate the pair in the compatibility matrix.
4. Interpret the consequence code using the chart key.
5. Choose the answer that matches the indicated hazard or required segregation.

Engineering meaning

Compatibility is a storage, transfer, and treatment issue. Two wastes that are individually manageable may become dangerous when mixed. Therefore, a process-flow question may require separate tanks, separate feed lines, or sequential treatment.

Mass-balance caution

Never combine streams in a balance until compatibility is established. If two streams must remain segregated, solve their treatment and storage requirements separately.

Search term: “Chemical Compatibility Chart” or “Hazardous Waste Compatibility.” This is a classic handbook-lookup item rather than a memorization item.

6 Site Characterization and Remedial Investigation

Site characterization is explicitly listed in the FE specification under Solid and Hazardous Waste. The objective is to define the nature and extent of contamination using a defensible sampling and monitoring program.

Conceptual sequence

1. Establish investigation objectives.
2. Identify media and locations to be sampled.
3. Define background/reference conditions.
4. Select sample type, frequency, and analytical parameters.
5. Compare measured results with the decision criterion.
6. Refine the investigation if uncertainty remains too large.

Data quality

The FE Reference Handbook includes data-quality objectives for soil and solids investigations using confidence level $(1 - \alpha)$, statistical power $(1 - \beta)$, and minimum detectable relative difference.

Background comparison can be expressed as a relative increase:

$$\text{Relative increase (\%)} = 100 \frac{\mu_S - \mu_B}{\mu_B},$$

where μ_S is the site mean and μ_B is the background mean.

Monitoring logic

A monitoring network should answer the decision question, not merely generate data. For FE purposes, expect questions on statistical variability, sample number, detection goals, or interpretation of site versus background results.

Sampling questions are often probability/statistics questions in environmental clothing. Reuse the same confidence, power, mean, and standard-deviation concepts studied elsewhere on the FE exam.

6.1 Sampling Statistics and Data Quality Objectives

The FE Reference Handbook gives the coefficient of variation as

$$CV = 100 \frac{s}{\bar{x}},$$

where s is sample standard deviation and $\bar{x}$ is the sample average.

A lower CV indicates less relative variability. Higher variability generally requires more samples to detect a specified difference with the same confidence and power.

Confidence and power

- Confidence level: $1 - \alpha$, related to Type I error probability α .
- Power: $1 - \beta$, related to Type II error probability β .
- Minimum detectable relative difference: the smallest relative increase over background the design is intended to detect with the stated power.

Using the NCEES sample-size table

When the question gives CV , confidence level, power, and minimum detectable relative difference, use the provided table rather than deriving the one-sided t -test sample size from scratch. Read the row and column carefully.

Simple variability check

If $\bar{x} = 40$ mg/kg and $s = 8$ mg/kg,

$$CV = 100 \frac{8}{40} = 20\%.$$

Exam habit: Determine whether the question asks for a calculated statistic (such as CV) or a handbook table lookup (sample count). Those are two different tasks.

7 Physical Treatment of Hazardous Waste

The FE specification lists physical treatment as one category of hazardous-waste treatment and disposal. On the exam, physical treatment is best viewed as separation or phase-management that does not depend primarily on chemical transformation.

Common engineering functions include separating solids from liquids, concentrating a waste stream, removing suspended matter, or transferring a contaminant between phases when the problem states an applicable physical process.

Mass-separation framework

For feed mass M_F , recovered/concentrated stream M_R , and residual stream M_S ,

$$M_F = M_R + M_S.$$

For contaminant mass fraction x ,

$$M_F x_F = M_R x_R + M_S x_S.$$

These two equations can solve many separator-style problems.

Removal efficiency

If influent and effluent contaminant loads are L_{in} and L_{out} ,

$$\eta = \frac{L_{in} - L_{out}}{L_{in}}.$$

If flow is constant, concentration can replace load in the ratio.

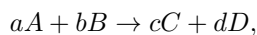
Physical treatment changes where the contaminant is; it does not automatically destroy it. If a concentrated residual is created, that residual still requires management.

7.1 Chemical Treatment of Hazardous Waste

Chemical treatment is another category explicitly included in the FE specification. The exam may combine hazardous-waste context with chemistry concepts such as neutralization, precipitation, oxidation-reduction, or stoichiometry.

Stoichiometric basis

For a reaction



the stoichiometric reagent requirement is obtained from molar ratios:

$$\frac{n_B}{n_A} = \frac{b}{a}.$$

Then convert moles to mass using molecular weight.

Neutralization logic

When an acidic or basic hazardous waste is treated, the question may ask for reagent quantity or final loading. Keep the equivalent or molar basis consistent with the chemistry information supplied.

Precipitation and separation

Chemical conversion can transform a dissolved contaminant into a solid phase, but the new solid must then be separated and managed. Thus, chemical and physical treatment are often sequential.

Compatibility first

Before assuming two chemical streams can be mixed for treatment, verify that the combination is allowed by the compatibility information in the problem or reference.

Do not invent a reaction. FE questions that require a specific reaction will normally provide the needed chemistry or make it accessible elsewhere in the reference handbook.

7.2 Biological Treatment of Hazardous Waste

Biological treatment is included in the FE hazardous-waste scope. The source materials elsewhere in the FE Reference Handbook provide reactor and first-order decay relationships that can be applied when the problem supplies a biological rate constant.

For first-order decay in a batch or ideal plug-flow setting,

$$C_t = C_0 e^{-kt}.$$

The first-order half-life is

$$t_{1/2} = \frac{0.693}{k}.$$

For a completely mixed steady-state reactor with first-order decay, a common reference form is

$$C_e = \frac{C_0}{1 + k\theta},$$

where θ is mean retention time.

What the FE question is testing

Expect to identify the kinetic model, calculate a concentration or required time, and interpret whether the target is met. The hazardous-waste context does not change the mathematics of the reactor model.

Mass balance

At steady state,

$$\text{Input} - \text{Output} - \text{Reaction} = 0.$$

Cross-topic connection: Hazardous-waste biological treatment may use formulas found in the general reactor or environmental-engineering sections of the FE handbook, not only in the solid-waste pages.

7.3 Thermal Treatment and Incineration

Thermal treatment is explicitly included in the FE specification. The NCEES solid-waste material also includes heating-value concepts and incineration relationships. FE problems are likely to emphasize energy balance, residence time if given, residual ash, or gas-flow calculations.

Thermal input

$$\dot{Q}_{in} = \dot{m} HV.$$

If supplemental fuel adds heat,

$$\dot{Q}_{total} = \dot{m}_w HV_w + \dot{m}_f HV_f.$$

Useful recovered energy

$$\dot{Q}_{useful} = \eta \dot{Q}_{total}.$$

Mass residual

If noncombustible ash fraction is x_a ,

$$\dot{m}_{ash} = x_a \dot{m}_w.$$

Kiln retention time

The supplemental NCEES environmental reference provides a kiln mean-residence-time relationship of the form

$$t = \frac{0.228(L/D)}{SN},$$

where the exact variable definitions and unit conventions are given in that reference. If such a relationship appears in an exam problem, use it exactly as supplied.

Separate four quantities: waste mass, combustion air, energy, and residue. They are related but have different units and balances.

7.4 Radioactive Waste: Half-Life, Effective Half-Life, and Disposal

Radioactive waste appears explicitly in the FE specification, and the FE Reference Handbook includes radiation formulas.

Radioactive decay

$$N = N_0 e^{-0.693t/\tau} = N_0 \left(\frac{1}{2}\right)^{t/\tau},$$

where τ is half-life.

Effective half-life

When both radioactive decay and biological removal apply,

$$\frac{1}{\tau_e} = \frac{1}{\tau_r} + \frac{1}{\tau_b}.$$

Therefore,

$$\tau_e = \frac{\tau_r \tau_b}{\tau_r + \tau_b}.$$

The effective half-life is less than either individual half-life.

Inverse-square law

For a point-source geometry,

$$\frac{I_2}{I_1} = \left(\frac{R_1}{R_2}\right)^2.$$

Doubling the distance reduces intensity to one-fourth.

First-order rate constant

$$k = \frac{0.693}{t_{1/2}}.$$

Fast check: after one half-life, 50% remains; after two, 25%; after three, 12.5%. This catches calculator-entry errors quickly.

8 Integrated Review and Formula Map

Use this page as a final checklist before moving to the worked problems.

Core equations

Mass balance: $\text{In} + \text{Generation} = \text{Out} + \text{Consumption}$

Bulk density: $\rho_b = \frac{M}{V}$

Compaction reduction: $\%VR = 100 \frac{V_i - V_f}{V_i}$

Cover water balance: $\Delta S_{LC} = P - R - ET - PER_{sw}$

Clay-liner breakthrough: $t = \frac{d^2 \eta}{K(d + h)}$

Thermal input: $\dot{Q} = \dot{m} HV$

Weighted heating value: $HV_{mix} = \sum_i w_i HV_i$

Coefficient of variation: $CV = 100 \frac{s}{\bar{x}}$

Radioactive decay: $N = N_0 (0.5)^{t/\tau}$

Effective half-life: $\frac{1}{\tau_e} = \frac{1}{\tau_r} + \frac{1}{\tau_b}$

Inverse square: $\frac{I_2}{I_1} = \left(\frac{R_1}{R_2} \right)^2$

Conceptual lookups

- Hazardous-waste characteristics: ignitable, corrosive, reactive, toxic.
- Compatibility matrix: identify pairwise reaction consequence.
- Sample-size table: use CV , confidence, power, and detectable difference.
- Waste density/moisture tables: use the stated material and physical condition.

Final exam rule: Let the reference handbook control the equation form and variable definition. Many mistakes come from remembering a similar formula with a different convention.

9 15 Example Problems

Example Problem 1: Recycling Mass Balance

A municipal facility receives 180 tons/day of mixed waste. Paper is 28% of the incoming mass. A sorting system recovers 82% of the paper. Of the gross recovered paper, 6% is rejected as paper process loss and sent to disposal. Determine (a) saleable recovered paper and (b) total paper sent to disposal.

Solution

Incoming paper:

$$M_p = (180)(0.28) = 50.4 \text{ tons/day.}$$

Gross recovered paper:

$$M_{r,g} = (50.4)(0.82) = 41.328 \text{ tons/day.}$$

Saleable paper:

$$M_{sale} = (41.328)(1 - 0.06) = 38.85 \text{ tons/day.}$$

Paper not recovered initially:

$$M_{unrec} = 50.4 - 41.328 = 9.072 \text{ tons/day.}$$

Paper process rejects from recovered stream:

$$M_{rej} = (41.328)(0.06) = 2.480 \text{ tons/day.}$$

Total paper sent to disposal:

$$M_{disp} = 9.072 + 2.480 = 11.55 \text{ tons/day.}$$

Answer: Mass-balance check: $38.848 + 9.072 + 2.480 = 50.400$ tons/day.
Saleable paper = 38.85 tons/day; paper to disposal = 11.55 tons/day.

Example Problem 2: Compaction and Volume Reduction

A waste stream occupies 1,250 yd³ before compaction and 475 yd³ afterward. Determine the percent volume reduction and the compaction factor $CF = V_f/V_i$.

Solution

$$\%VR = 100 \left(\frac{1250 - 475}{1250} \right) = 100(0.62) = 62.0\%.$$

$$CF = \frac{475}{1250} = 0.380.$$

Answer: volume reduction = 62.0%; compaction factor = 0.380.

Check

$$100(1 - CF) = 100(1 - 0.380) = 62.0\%.$$

Example Problem 3: Landfill Service Life

A landfill has 2.40×10^6 yd³ of gross remaining airspace. Daily/intermediate cover and infrastructure consume 18% of gross airspace. Average in-place waste density is 1,450 lb/yd³. The community generates 620 tons/day, of which 35% is diverted. Estimate landfill service life in years using 365 days/year.

Solution

Waste airspace:

$$V_w = (1 - 0.18)(2.40 \times 10^6) = 1.968 \times 10^6 \text{ yd}^3.$$

Mass capacity:

$$M_{cap} = \frac{(1.968 \times 10^6)(1450)}{2000} = 1.4268 \times 10^6 \text{ tons.}$$

Disposed mass rate:

$$M_d = (620)(1 - 0.35) = 403 \text{ tons/day.}$$

Service life:

$$T = \frac{1.4268 \times 10^6}{403 \times 365} = 9.70 \text{ yr.}$$

Answer: approximately 9.7 years.

Example Problem 4: Landfill Cover Water Balance

During one year, a landfill cover receives 46 in. of precipitation. Runoff is 12 in., evapotranspiration is 25 in., and cover storage increases by 2 in. Determine annual percolation into the waste. If the active area is 18 acres, estimate annual percolation volume in acre-ft.

Solution

Use

$$\Delta S_{LC} = P - R - ET - PER_{sw}.$$

Solve for percolation:

$$PER_{sw} = 46 - 12 - 25 - 2 = 7 \text{ in./yr.}$$

Convert to feet:

$$7 \text{ in.} \left(\frac{1 \text{ ft}}{12 \text{ in.}} \right) = 0.5833 \text{ ft.}$$

Volume:

$$V = (18 \text{ ac})(0.5833 \text{ ft}) = 10.50 \text{ acre-ft/yr.}$$

Answer: 7.0 in./yr of percolation, or about 10.5 acre-ft/yr.

Example Problem 5: Clay-Liner Breakthrough Time

A compacted clay liner is 3.0 ft thick with porosity $\eta = 0.22$. Hydraulic conductivity is 0.015 ft/yr, and leachate head above the liner is 1.5 ft. Estimate breakthrough time using

$$t = \frac{d^2 \eta}{K(d + h)}.$$

Solution

$$t = \frac{(3.0)^2(0.22)}{(0.015)(3.0 + 1.5)} = \frac{1.98}{0.0675} = 29.33 \text{ yr.}$$

Answer: approximately 29.3 years.

Reasonableness

Increasing K or head would decrease this time; increasing thickness would generally increase it.

Example Problem 6: Landfill Gas Diffusive Flux

Use the simplified handbook-form relation

$$N_A = \frac{D\eta_{gas}^{4/3}}{L\eta^2}(C_{fill} - C_{atm}).$$

Let $D = 0.20 \text{ cm}^2/\text{s}$, $\eta_{gas} = 0.18$, $\eta = 0.35$, $L = 60 \text{ cm}$, and $C_{fill} - C_{atm} = 1.8 \times 10^{-4} \text{ g/cm}^3$. Calculate N_A .

Solution

First,

$$\eta_{gas}^{4/3} = (0.18)^{4/3} \approx 0.1017.$$

Then

$$N_A = \frac{(0.20)(0.1017)}{(60)(0.35)^2}(1.8 \times 10^{-4}).$$

$$N_A \approx 4.98 \times 10^{-7} \text{ g/(cm}^2\text{s)}.$$

Answer: $N_A \approx 5.0 \times 10^{-7} \text{ g/(cm}^2\text{s)}.$

Example Problem 7: Weighted Heating Value

A dry combustible waste blend is 35% paper at 7,200 Btu/lb, 25% cardboard at 7,000 Btu/lb, 20% plastics at 14,000 Btu/lb, and 20% wood at 8,000 Btu/lb. Estimate the mixture heating value.

Solution

$$HV_{mix} = \sum w_i HV_i.$$

$$\begin{aligned} HV_{mix} &= 0.35(7200) + 0.25(7000) \\ &\quad + 0.20(14000) + 0.20(8000) \\ &= 2520 + 1750 + 2800 + 1600 \\ &= 8670 \text{ Btu/lb.} \end{aligned}$$

Answer: 8,670 Btu/lb.

Example Problem 8: Waste-to-Energy Power Output

A facility burns 500 tons/day of waste with a lower heating value of 8,500 Btu/lb. Net electrical conversion efficiency is 24%. Estimate average electrical power output in MW. Use 1 kWh = 3413 Btu.

Solution

Daily waste mass:

$$M = (500)(2000) = 1.00 \times 10^6 \text{ lb/day.}$$

Thermal energy:

$$E_{th} = (1.00 \times 10^6)(8500) = 8.50 \times 10^9 \text{ Btu/day.}$$

Electrical energy:

$$E_e = 0.24(8.50 \times 10^9) = 2.04 \times 10^9 \text{ Btu/day.}$$

Convert to kWh/day:

$$E_e = \frac{2.04 \times 10^9}{3413} = 5.977 \times 10^5 \text{ kWh/day.}$$

Average power:

$$P = \frac{5.977 \times 10^5}{24} = 2.49 \times 10^4 \text{ kW} = 24.9 \text{ MW.}$$

Answer: approximately 24.9 MW.

Example Problem 9: Hazardous-Waste Characteristic Classification

Three aqueous wastes have the following properties: Waste A has pH 1.7; Waste B has pH 7.1 and a flash point of 72°C; Waste C has pH 13.1. Based only on the corrosivity pH criterion in the NCEES source, identify which wastes meet that criterion.

Solution

The source criterion is

$$pH \leq 2.0 \quad \text{or} \quad pH \geq 12.5.$$

Waste A:

$$1.7 \leq 2.0 \quad \Rightarrow \quad \text{meets pH corrosivity criterion.}$$

Waste B:

$$2.0 < 7.1 < 12.5 \quad \Rightarrow \quad \text{does not meet pH criterion.}$$

Waste C:

$$13.1 \geq 12.5 \quad \Rightarrow \quad \text{meets pH corrosivity criterion.}$$

Answer: Wastes A and C meet the stated corrosivity pH criterion.

Example Problem 10: Compatibility Interpretation

A compatibility chart lookup for two waste groups returns the code *GT*, and the chart key defines *GT* as toxic gas generation. What is the appropriate engineering interpretation for a storage or transfer design?

Solution

The pairwise chart result indicates that mixing the wastes can generate toxic gas. Therefore, they should not be intentionally combined in a common storage or transfer vessel unless a specifically designed treatment process and hazard-control strategy is provided by the problem.

For a routine FE design-selection question, the appropriate choice is to **segregate the streams** and prevent accidental mixing.

Answer: Keep the wastes segregated; the chart predicts toxic-gas generation on mixing.

Why this is an FE question

The calculation is not numerical; it tests correct use of the supplied compatibility matrix and consequence key.

Example Problem 11: Coefficient of Variation for Site Sampling

A set of soil samples has mean contaminant concentration $\bar{x} = 52$ mg/kg and standard deviation $s = 10.4$ mg/kg. Calculate the coefficient of variation.

Solution

$$CV = 100 \frac{s}{\bar{x}} = 100 \frac{10.4}{52} = 20.0\%.$$

Answer: $CV = 20.0\%$.

Exam follow-up

If the question then provides confidence, power, and minimum detectable relative difference, use $CV = 20\%$ to enter the NCEES sample-size table.

Example Problem 12: Effective Half-Life

A radionuclide has radioactive half-life $\tau_r = 18$ years and biological half-life $\tau_b = 6$ years. Determine the effective half-life.

Solution

$$\frac{1}{\tau_e} = \frac{1}{18} + \frac{1}{6} = \frac{1}{18} + \frac{3}{18} = \frac{4}{18}.$$

Therefore,

$$\tau_e = \frac{18}{4} = 4.50 \text{ years.}$$

Answer: $\tau_e = 4.50$ years.

Check

The effective half-life is smaller than both 18 years and 6 years, as expected for two simultaneous removal mechanisms.

Example Problem 13: Radioactive Decay

An activity is initially 160 units. The radionuclide half-life is 12 years. Determine the activity after 30 years.

Solution

$$N = N_0 \left(\frac{1}{2} \right)^{t/\tau}.$$

$$N = 160 \left(\frac{1}{2} \right)^{30/12} = 160(0.5)^{2.5}.$$

Since

$$(0.5)^{2.5} \approx 0.17678,$$

$$N \approx 160(0.17678) = 28.28.$$

Answer: approximately 28.3 activity units remain.

Example Problem 14: Inverse-Square Radiation Intensity

Radiation intensity is $I_1 = 36 \mu\text{Sv/h}$ at $R_1 = 2.0 \text{ m}$ from a point source. Estimate the intensity at $R_2 = 6.0 \text{ m}$.

Solution

$$\frac{I_2}{I_1} = \left(\frac{R_1}{R_2} \right)^2$$
$$I_2 = 36 \left(\frac{2}{6} \right)^2 = 36 \left(\frac{1}{3} \right)^2 = 36 \left(\frac{1}{9} \right) = 4.0 \mu\text{Sv/h}.$$

Answer: $4.0 \mu\text{Sv/h}$.

Example Problem 15: Integrated Disposal and Leachate Calculation

A city generates 420 tons/day of municipal solid waste. Recycling and composting together divert 32%. The landfill has 1.10 million yd³ of usable waste airspace and an average in-place density of 1,300 lb/yd³. The active cover area averages 14 acres. Annual precipitation is 48 in., runoff is 13 in., evapotranspiration is 27 in., and annual change in cover storage is +1 in. Determine (a) landfill service life and (b) annual percolation volume in acre-ft.

Solution

Disposed mass rate:

$$M_d = 420(1 - 0.32) = 285.6 \text{ tons/day.}$$

Landfill mass capacity:

$$M_{cap} = \frac{(1.10 \times 10^6)(1300)}{2000} = 715,000 \text{ tons.}$$

Service life:

$$T = \frac{715000}{285.6 \times 365} = 6.86 \text{ yr.}$$

Percolation depth:

$$PER_{sw} = 48 - 13 - 27 - 1 = 7 \text{ in.} = 0.5833 \text{ ft.}$$

Percolation volume:

$$V = (14)(0.5833) = 8.17 \text{ acre-ft/yr.}$$

Answer: landfill service life ≈ 6.86 years; annual percolation ≈ 8.17 acre-ft/yr.

References and Alignment

- National Council of Examiners for Engineering and Surveying (NCEES), *FE Reference Handbook*, Version 10.6, eighth printing April 2026. Relevant environmental-engineering pages include the landfill, radiation, and sampling/-monitoring material.
- NCEES, *Fundamentals of Engineering (FE) Environmental CBT Exam Specifications*, effective beginning with the July 2020 examinations. Solid and Hazardous Waste: 7–11 questions; topics A–F used as the organizational scope of this guide.
- NCEES, *PE Environmental Reference Handbook*, Version 2.0 (2025), used only as a supplemental technical cross-check for solid/hazardous-waste equations and terminology that complement the FE handbook.

The CBT electronic reference is periodically updated. During preparation, practice searching the exact edition that NCEES identifies for your exam administration.