

Environmental Engineering FE CBT Exam

Knowledge: Air Quality and Control with 15 Example Problems

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1 Exam Scope and Air-Pollution Framework

The FE Environmental specification assigns **8–12 questions** to Air Quality and Control. The tested scope spans seven connected areas: ambient and indoor air quality; mass and energy balances; emissions; atmospheric modeling and meteorology; gas treatment; particle treatment; and indoor-air modeling and control.

1.1 Source-to-receptor framework

Most air problems can be organized as a chain:

Source → Emission rate → Transport/dispersion → Receptor concentration → Control

A source generates pollutants. An exhaust system carries them. Atmospheric processes dilute and transport them. A receptor experiences a concentration or dose. Control equipment changes the emission rate before release.

1.2 Pollutant categories

Category	What to recognize on the exam
Criteria pollutants	Common ambient pollutants regulated through air-quality standards; know the distinction between concentration-based ambient limits and source emission limits.
Hazardous/toxic pollutants	Compounds of concern because of toxicity, carcinogenicity, or other health effects; often controlled by technology or risk-based requirements.
Particulate matter	Suspended solid or liquid particles; behavior depends strongly on aerodynamic size.
Gaseous pollutants	Examples include sulfur compounds, nitrogen oxides, carbon monoxide, volatile organics, and acid gases.
Secondary pollutants	Form in the atmosphere from precursor reactions rather than being emitted entirely in final form.

1.3 Engineering quantities

The most common quantitative outputs are **mass rate** (e.g., kg/h), **concentration** (e.g., mg/m³, ppmv), **fractional efficiency**, and **volumetric flow**.

Exam Tip. Before calculating, identify whether the problem asks for a source rate, stack concentration, ambient concentration, or control-device performance. These quantities are related but not interchangeable.

2 Ambient Air, Indoor Air, and Pollutant Classification

2.1 Ambient versus indoor air

Ambient air refers to the outdoor atmosphere at receptors. **Indoor air** is treated as a control-volume problem in which sources, ventilation, and removal determine concentration.

2.2 Primary and secondary pollutants

A **primary pollutant** is emitted directly. A **secondary pollutant** forms through atmospheric reactions. The distinction matters because controlling a secondary pollutant may require controlling one or more precursors.

2.3 Concentration versus exposure

Air-quality engineering problems usually quantify concentration. Health-risk problems may combine concentration with exposure time, inhalation rate, and toxicity information. Do not substitute exposure metrics for ambient concentration unless the problem explicitly asks for risk.

2.4 Useful classifications for control selection

Property	Examples of engineering relevance	Likely control implication
Particle size	coarse, fine, submicron	settling, impaction, filtration, electrostatic collection
Solubility	soluble gas or acid gas	absorption/wet scrubbing may be effective
Volatility	VOC in a gas stream	adsorption, condensation, oxidation
Combustibility	oxidizable organics	thermal or catalytic oxidation
Biodegradability	biodegradable vapor	biofilter/biotrickling concepts
Electrical behavior	chargeable aerosol	electrostatic precipitation

2.5 Control hierarchy mindset

Source reduction and process modification can reduce the load before end-of-pipe treatment. For an FE calculation, however, control performance is usually expressed by a mass balance across a device.

$$\eta = \frac{\dot{m}_{in} - \dot{m}_{out}}{\dot{m}_{in}} \quad \text{or} \quad \dot{m}_{out} = (1 - \eta)\dot{m}_{in}$$

Exam Tip. If several devices are in series and each has an independent fractional efficiency, multiply the penetration fractions: $P_{overall} = \prod_i (1 - \eta_i)$.

3 Gas Concentration Units: ppm, ppb, and Mass per Volume

Gas concentrations frequently appear as ppmv or ppbv and must be converted to mass concentration.

3.1 Ideal-gas relationship

For an ideal gas,

$$PV = nRT.$$

At a specified temperature and pressure, one mole occupies a molar volume $V_m = RT/P$.

3.2 ppmv to mg/m³

Because 1 ppmv = 10^{-6} mole fraction,

$$C_{mg/m^3} = \text{ppmv} \left(\frac{MW P}{RT} \right) \text{ when units are chosen consistently.}$$

A widely used shortcut near 25°C and 1 atm is

$$C_{mg/m^3} \approx \text{ppmv} \frac{MW}{24.45}.$$

For ppbv, first convert ppbv to ppmv by dividing by 1000.

3.3 Dimensional check

With MW in g/mol and molar volume in L/mol,

$$\frac{\text{g/mol}}{\text{L/mol}} = \text{g/L} = \text{mg/m}^3.$$

Thus the numerical units align conveniently.

3.4 Common errors

- Using °C instead of absolute temperature in gas-law equations.
- Treating ppmv as mg/L without molecular-weight and molar-volume conversion.
- Forgetting that a fixed ppmv corresponds to different mg/m³ at different T and P .

Exam Tip. Write the gas basis beside every concentration: wet/dry, actual/standard, and oxygen reference if one is specified. Many stack problems are basis-conversion problems rather than difficult air-pollution problems.

4 Standard Conditions and Stack-Gas Basis Corrections

Stack data are often measured at actual temperature and pressure but reported at a reference condition.

4.1 Temperature and pressure

For a fixed molar flow, the ideal-gas relation gives

$$\frac{Q_1 P_1}{T_1} = \frac{Q_2 P_2}{T_2}.$$

If converting a concentration to a reference condition, concentration changes inversely with gas volume.

$$C_2 = C_1 \left(\frac{P_2}{P_1} \right) \left(\frac{T_1}{T_2} \right) \text{ for the same pollutant molar flow.}$$

4.2 Wet to dry basis

If the wet gas contains water vapor fraction y_{H_2O} ,

$$C_{dry} = \frac{C_{wet}}{1 - y_{H_2O}}.$$

If moisture is given in percent, $y_{H_2O} = \%H_2O/100$.

4.3 Oxygen correction concept

Combustion-source concentrations may be normalized to a reference oxygen content because excess combustion air dilutes measured pollutants. Use the exact relation supplied in the reference/problem statement and keep measured and reference oxygen on the same dry/wet basis.

4.4 Actual versus standard volumetric flow

Standard flow is not a new mass flow. It is the gas volume the same moles would occupy at standard conditions:

$$Q_s = Q_a \left(\frac{P_a}{P_s} \right) \left(\frac{T_s}{T_a} \right).$$

Exam Tip. A mass emission rate should remain invariant under a correct basis conversion: $\dot{m} = C_a Q_a = C_s Q_s$ when units and wet/dry definitions are consistent.

5 Air-Stream Mass Balances and Loading Rates

5.1 General steady-state pollutant balance

For a control volume at steady state with no accumulation,

$$\sum \dot{m}_{in} + \dot{m}_{gen} = \sum \dot{m}_{out} + \dot{m}_{destroyed}.$$

For a single air stream with no reaction,

$$\dot{m} = CQ.$$

Here C is mass per gas volume and Q is gas volume per time on the same basis.

5.2 Control-device efficiency

$$\eta = 1 - \frac{\dot{m}_{out}}{\dot{m}_{in}}$$

If inlet and outlet gas flows are approximately equal,

$$\eta \approx 1 - \frac{C_{out}}{C_{in}}.$$

If gas flow changes substantially, use mass rates instead of concentration ratios.

5.3 Devices in series

For two devices,

$$\dot{m}_2 = (1 - \eta_2)(1 - \eta_1)\dot{m}_0,$$

so

$$\eta_{overall} = 1 - (1 - \eta_1)(1 - \eta_2).$$

5.4 Loading terminology

- **Inlet loading:** pollutant mass rate or concentration entering a device.
- **Outlet loading:** residual pollutant rate after treatment.
- **Collected rate:** $\dot{m}_{in} - \dot{m}_{out}$.
- **Specific loading:** mass rate normalized by gas volume, fuel use, production, or area.

Exam Tip. When a problem provides concentration and flow, convert both to compatible time and volume units before multiplying.

6 Energy Balances, Heating Values, and Combustion Basics

Air-control devices such as thermal oxidizers and incinerators require energy balances in addition to pollutant balances.

6.1 Heating value

A fuel heating value is energy released per unit fuel mass or volume. The heat-release rate is

$$\dot{Q}_{fuel} = \dot{m}_f HV.$$

If thermal efficiency η_T is specified,

$$\dot{Q}_{useful} = \eta_T \dot{m}_f HV.$$

6.2 Sensible heating of gas

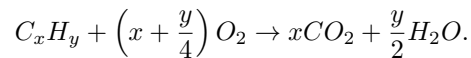
For a gas stream with approximately constant heat capacity,

$$\dot{Q} = \dot{m}_g c_p (T_{out} - T_{in})$$

This is often used to estimate supplemental fuel for an oxidizer.

6.3 Combustion stoichiometry

Complete hydrocarbon combustion follows the pattern



Air contains mostly nitrogen, so actual flue gas includes substantial N_2 . Excess air increases flue-gas volume and can lower pollutant concentration without changing pollutant mass rate.

6.4 Combustion efficiency indicator

A common combustion-efficiency expression uses measured dry CO_2 and CO:

$$CE = 100 \frac{CO_2}{CO_2 + CO}.$$

Use consistent concentration units for both gases.

Exam Tip. Distinguish destruction efficiency of an organic pollutant from combustion efficiency based on CO_2/CO . They are not the same metric.

7 Emission Factors and Emission Inventories

7.1 Emission-factor method

An emission factor links activity to pollutant generation:

$$E = A EF (1 - \eta_c)$$

where E is emission rate, A is activity rate, EF is pollutant mass per activity unit, and η_c is overall control efficiency if the factor is uncontrolled.

7.2 Typical activity bases

- fuel burned: kg pollutant per Mg fuel or lb/MMBtu;
- material processed: kg pollutant per Mg product;
- solvent used: mass VOC per mass solvent;
- distance or throughput: mass per vehicle-distance or production unit.

7.3 Inventory workflow

1. Select time basis: hour, day, or year.
2. Convert each source activity to that basis.
3. Apply the appropriate emission factor.
4. Apply control efficiency only once.
5. Sum sources by pollutant.

7.4 Mass-rate to concentration

If the exhaust flow Q is known,

$$C = \frac{E}{Q}.$$

This conversion requires the emission rate and gas flow to refer to the same actual/standard and wet/dry basis.

Exam Tip. Watch whether an emission factor is pre-control or post-control. Applying a control efficiency to an already controlled factor double-counts removal.

8 Atmospheric Transport and Meteorology

The atmosphere transports and dilutes emissions. FE questions emphasize qualitative stability concepts and Gaussian-plume calculations.

8.1 Wind speed

Increasing wind speed generally lowers centerline concentrations in the basic Gaussian model because the same emission rate is carried through a larger air volume per unit time.

8.2 Mechanical and thermal turbulence

- **Mechanical turbulence:** generated by surface roughness, buildings, terrain, and wind shear.
- **Thermal turbulence:** generated by buoyant convection when the surface warms the air above it.

8.3 Atmospheric stability

Stability describes resistance to vertical motion. Unstable air promotes vigorous vertical mixing; stable air suppresses it. Neutral conditions lie between.

Condition	Mixing	Typical concentration tendency
Unstable	strong vertical mixing	faster dilution, broader plume
Neutral	moderate mixing	intermediate dispersion
Stable	weak vertical mixing	narrow plume, potentially higher downwind centerline concentrations

8.4 Effective stack height

$$H = h + \Delta h,$$

where h is physical stack height and Δh is plume rise.

Exam Tip. Gaussian-plume questions are most error-prone when coordinates are misread. Always identify x (downwind), y (crosswind), and z (height above ground).

9 Lapse Rates and Stability Classes

9.1 Environmental lapse rate

The environmental lapse rate describes the actual vertical temperature gradient in the atmosphere. Compare it with the dry adiabatic lapse rate to infer whether displaced air parcels tend to continue moving or return toward their original level.

The FE Reference Handbook lists the dry adiabatic lapse rate approximately as

$$\Gamma_{AD} \approx 0.98^{\circ}\text{C}/100\text{ m}.$$

9.2 Temperature inversion

An inversion occurs when temperature increases with height over a layer. It suppresses vertical mixing and can trap pollutants near the ground or below an elevated inversion lid.

9.3 Pasquill-type stability classes

Stability classes are conventionally labeled A through F:

- A extremely unstable
- B moderately unstable
- C slightly unstable
- D neutral
- E slightly stable
- F moderately stable

9.4 What controls stability?

Strong daytime solar heating with light wind favors instability. Cloudy or windy conditions tend toward neutral. Clear nights with light winds favor stable conditions.

Exam Tip. Do not memorize a full stability-class lookup table unless provided in your study source. Focus on the physical direction: stronger surface heating → less stable; strong nighttime radiational cooling → more stable.

10 Gaussian Plume Equation

For a continuous point source under steady conditions, the Gaussian plume equation estimates concentration at (x, y, z) .

$$C(x, y, z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \left[\exp\left(-\frac{(z-H)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+H)^2}{2\sigma_z^2}\right) \right]$$

10.1 Variables

Q	pollutant emission rate
u	average wind speed at stack height
σ_y	horizontal dispersion parameter
σ_z	vertical dispersion parameter
H	effective stack height
x, y, z	downwind, crosswind, and vertical receptor coordinates

The second vertical exponential accounts for an image source that represents reflection at the ground.

10.2 Centerline ground-level receptor

At $y = 0$ and $z = 0$,

$$C(x, 0, 0) = \frac{Q}{\pi u \sigma_y \sigma_z} \exp\left(-\frac{H^2}{2\sigma_z^2}\right).$$

The dispersion parameters depend on downwind distance and atmospheric stability.

Exam Tip. Use a consistent mass unit for Q and the desired concentration. If Q is in $\mu\text{g/s}$ and distances are in m, the result is $\mu\text{g/m}^3$.

11 Ground-Level Maximum and Plume Behavior

11.1 Why the maximum is not at the stack

For an elevated source, the plume centerline initially lies above ground. As σ_z increases downwind, more of the plume reaches ground level. Farther downwind, dilution eventually dominates. This creates a maximum ground-level concentration at some intermediate distance.

11.2 Centerline expression

At $y = z = 0$,

$$C = \frac{Q}{\pi u \sigma_y \sigma_z} \exp\left(-\frac{H^2}{2\sigma_z^2}\right).$$

This expression shows three competing effects:

- Larger Q increases C linearly.
- Larger u decreases C inversely.
- Larger H tends to decrease nearby ground-level concentration.

11.3 Role of dispersion parameters

Near the source, small σ_z may keep the plume aloft. At larger distance, increasing $\sigma_y \sigma_z$ increases dilution.

11.4 Crosswind concentration

At a fixed x, z , concentration decreases away from the plume centerline according to

$$\frac{C(y)}{C(0)} = \exp\left(-\frac{y^2}{2\sigma_y^2}\right).$$

At $y = \sigma_y$, the crosswind factor is $e^{-1/2} \approx 0.607$.

Exam Tip. If a problem asks only for a ratio of concentrations, many terms cancel. Look for opportunities to avoid unnecessary calculation.

12 Plume Rise, Stack Effects, and Building Downwash

12.1 Physical versus effective stack height

$$H = h + \Delta h.$$

Plume rise Δh results from momentum and buoyancy of the exhaust. Hot, fast exhaust tends to rise more before behaving like a passive plume.

12.2 Qualitative factors increasing plume rise

- greater exhaust temperature relative to ambient;
- greater stack exit velocity;
- larger stack diameter at comparable velocity;
- lower opposing wind speed, all else equal.

12.3 Building downwash

Nearby buildings disturb airflow and can pull a plume downward into a recirculation zone. The practical consequence is that a physically tall stack may have less effective dispersion than an isolated-stack calculation suggests.

12.4 Stack exit velocity and volumetric flow

For a circular stack,

$$A = \frac{\pi D^2}{4}, \quad v_e = \frac{Q_g}{A}.$$

These relations may be used before a plume-rise correlation when flow and diameter are given.

12.5 Exam approach

If a plume-rise correlation is supplied, identify whether it returns Δh or H . Do not add the physical stack height twice.

Exam Tip. Atmospheric-dispersion equations are extremely sensitive to units of distance. Keep all stack heights, σ values, and receptor coordinates in the same length unit.

13 Particulate Matter and Collection Mechanisms

Particle-control selection depends primarily on particle size, density, gas conditions, and required efficiency.

13.1 Particle-size effects

Large particles have greater inertia and settle or impact more readily. Fine particles follow gas streamlines more closely and may require filtration, electrostatic forces, or diffusional mechanisms.

13.2 Collection mechanisms

Mechanism	Meaning
Gravitational settling	particle falls relative to gas under gravity
Inertial impaction	particle cannot follow a rapidly turning gas streamline
Interception	particle following a streamline contacts a surface because of finite radius
Diffusion	very small particles undergo Brownian motion and contact collection surfaces
Electrostatic attraction	charged particles migrate toward oppositely charged collection plates
Filtration	gas passes through porous media while particles are captured in/on a cake

13.3 Fractional efficiency

A device can have a different efficiency for each particle-size interval. Overall efficiency must be mass weighted:

$$\eta_T = \sum_i f_i \eta_i,$$

where f_i is the inlet mass fraction in size class i .

Exam Tip. A high overall efficiency can hide poor performance for the smallest particle fraction. If size-bin data are given, use a weighted efficiency rather than a single nominal value.

14 Cyclones

Cyclones remove particles by forcing the gas into a rotating flow field; particle inertia drives particles toward the wall.

14.1 Fractional efficiency model

The FE reference provides a relation of the form

$$\eta = \frac{1}{1 + (d_{pc}/d_p)^2}$$

where d_{pc} is the particle diameter collected at 50% efficiency and d_p is particle diameter.

Checks:

- If $d_p = d_{pc}$, then $\eta = 0.50$.
- If $d_p \gg d_{pc}$, $\eta \rightarrow 1$.
- If $d_p \ll d_{pc}$, $\eta \rightarrow 0$.

14.2 Cut diameter

The 50% cut diameter decreases when particle separation becomes easier. A common relation has

$$d_{pc} \propto \left[\frac{\mu W}{N_e V_i (\rho_p - \rho_g)} \right]^{1/2}.$$

Thus increasing inlet velocity, particle density, or effective turns generally improves collection of smaller particles, while higher gas viscosity makes separation harder.

14.3 Cyclone strengths and limits

Cyclones are simple, rugged, and useful for coarse particles and pretreatment. They are generally less effective for very fine particles than baghouses or ESPs.

Exam Tip. For cyclone equations, convert micrometers to meters when using SI physical-property formulas:
 $1 \mu\text{m} = 10^{-6} \text{ m}$.

15 Fabric Filters (Baghouses)

A baghouse passes particulate-laden gas through fabric. A dust cake forms and often becomes the dominant filtering layer.

15.1 Air-to-cloth ratio

$$V_f = \frac{Q}{A_c}$$

where V_f is superficial filtering velocity, Q is gas flow rate, and A_c is total active cloth area. Rearranging,

$$A_c = \frac{Q}{V_f}.$$

15.2 Pressure drop

Total pressure drop includes contributions from clean fabric, dust cake, and structure:

$$\Delta P_T = \Delta P_f + \Delta P_p + \Delta P_s.$$

As dust accumulates, resistance and pressure drop increase; periodic cleaning restores permeability.

15.3 Compartment operation

If one compartment is offline for cleaning, the remaining compartments must carry the gas. This increases instantaneous air-to-cloth ratio unless the design includes sufficient reserve area.

15.4 Design logic

Given gas flow and an allowable air-to-cloth ratio, cloth area is usually the first calculation. If a bag diameter and length are provided, bag area is approximately

$$A_{bag} = \pi DL$$

for the cylindrical side surface, so the required number of bags is $N = A_c/A_{bag}$, rounded up.

Exam Tip. Do not use stack cross-sectional area as baghouse cloth area. Cloth area is the sum of the filtering surface areas of all bags.

16 Electrostatic Precipitators

An electrostatic precipitator (ESP) charges particles and drives them toward collection surfaces under an electric field.

16.1 Deutsch-Anderson equation

$$\eta = 1 - \exp\left(-\frac{WA}{Q}\right)$$

where W is effective migration (drift) velocity, A is total collection area, and Q is gas volumetric flow rate.

16.2 Design rearrangements

Required area for a target efficiency:

$$A = -\frac{Q}{W} \ln(1 - \eta).$$

Required migration velocity:

$$W = -\frac{Q}{A} \ln(1 - \eta).$$

16.3 Sensitivity

Because the relation is exponential, approaching very high collection efficiencies requires increasingly large WA/Q .

16.4 Physical interpretation

A/Q is a gas residence-area measure; multiplying by migration velocity creates a dimensionless collection parameter. Consistent units are essential: if W is m/s, A is m², and Q is m³/s, then WA/Q is dimensionless.

Exam Tip. Use fractional efficiency inside the logarithm. For 99.5%, use $\eta = 0.995$, not 99.5.

17 Wet Scrubbers and Absorption

Wet scrubbers contact a gas with liquid droplets or films. They may remove particles, soluble gases, or both depending on design.

17.1 Gas absorption

For a soluble gas, transfer proceeds from gas to liquid because of a concentration or partial-pressure driving force. Reactive absorption can enhance removal by consuming dissolved pollutant in the liquid phase.

17.2 Overall mass balance

For pollutant A ,

$$\dot{m}_{A,in} = \dot{m}_{A,out} + \dot{m}_{A,liquid}.$$

With removal efficiency η ,

$$\dot{m}_{A,liquid} = \eta \dot{m}_{A,in}.$$

17.3 Liquid-to-gas ratio

A common operating variable is L/G , the liquid flow relative to gas flow. Higher liquid rate can improve contact but increases pumping and wastewater generation.

17.4 Particle scrubbing

Fine particle capture in high-energy scrubbers relies on relative motion between particles and droplets. Greater pressure drop often corresponds to greater energy input and higher particle collection performance.

17.5 Advantages and tradeoffs

Wet systems can cool hot gas and handle sticky material, but they transfer pollutants to a liquid residual stream that must be treated or managed.

Exam Tip. When a scrubber removes a gas by reaction, check whether the problem asks for pollutant mass removed, reagent demand, or outlet concentration; these require different balances.

18 Adsorption for VOC and Gas Control

Adsorption accumulates molecules on a solid surface, commonly activated carbon or another porous sorbent.

18.1 Adsorption capacity

If equilibrium capacity is expressed as

$$q = \frac{m_{\text{adsorbate}}}{m_{\text{sorbent}}},$$

then a first sizing estimate is

$$m_{\text{sorbent}} = \frac{m_{\text{adsorbate}}}{q_{\text{usable}}}.$$

Use a working capacity smaller than ideal equilibrium capacity when a safety factor or breakthrough margin is specified.

18.2 Bed service time

For a constant captured pollutant rate $\dot{m}_c$,

$$t_{\text{service}} = \frac{m_{\text{sorbent}} q_{\text{usable}}}{\dot{m}_c}.$$

18.3 What favors adsorption?

Adsorption is often favored by higher pollutant concentration, lower temperature, and compounds with stronger affinity for the sorbent. Humidity and competing compounds can reduce effective capacity.

18.4 Regeneration versus disposal

Spent sorbent can be regenerated or replaced. Regeneration creates a smaller, more concentrated pollutant stream that may be recovered or destroyed.

Exam Tip. Adsorption transfers pollutant from gas to solid; it does not inherently destroy the pollutant. Distinguish removal from destruction.

19 Biofiltration and Biological Gas Treatment

Biofilters and related biological gas-treatment systems use microorganisms to degrade biodegradable gas-phase contaminants after mass transfer into a moist biofilm.

19.1 Conceptual sequence

gas pollutant → mass transfer to moisture/biofilm → biodegradation → products

19.2 Loading and removal

A volumetric loading can be defined as

$$L_v = \frac{QC_{in}}{V_{media}}.$$

An elimination capacity is

$$EC = \frac{Q(C_{in} - C_{out})}{V_{media}}.$$

Both must use consistent concentration and flow units.

19.3 Empty-bed contact time

$$EBCT = \frac{V_{media}}{Q}$$

EBCT is a hydraulic-style nominal contact time; it is not the exact residence time of every gas molecule.

19.4 Operating factors

Moisture, temperature, pH, nutrient availability, pollutant biodegradability, and excessive loading can affect performance.

19.5 Technology comparison

Biofiltration destroys biodegradable contaminants biologically; adsorption transfers them to a sorbent; absorption transfers them to liquid; oxidation destroys combustible contaminants thermally or catalytically.

Exam Tip. If the question emphasizes biodegradable dilute VOCs and moderate gas conditions, biological treatment may be conceptually favored over high-temperature oxidation.

20 Thermal Oxidation and Incineration

Thermal oxidation destroys combustible organic pollutants by oxidation at elevated temperature.

20.1 Destruction and removal efficiency

$$DRE = 100 \left(\frac{W_{in} - W_{out}}{W_{in}} \right)$$

where W_{in} and W_{out} are mass rates of the same target contaminant.

20.2 Three design concepts

- **Temperature:** sufficiently high for rapid oxidation.
- **Time:** sufficient gas residence time at reaction temperature.
- **Mixing:** contact with adequate oxygen and uniform temperature.

20.3 Thermal versus catalytic oxidation

Catalysts can lower required oxidation temperature, reducing fuel demand, but catalysts may be poisoned or fouled by contaminants.

20.4 Heat recovery

A recuperative or regenerative heat exchanger can preheat incoming contaminated gas using hot clean exhaust, lowering supplemental fuel demand.

20.5 Combustion efficiency

When dry CO_2 and CO are given in the same units,

$$CE = 100 \frac{CO_2}{CO_2 + CO}.$$

Exam Tip. A high DRE for a target VOC does not by itself prove complete combustion. Carbon monoxide or other products of incomplete combustion may still be relevant.

21 Sulfur, Nitrogen Oxides, and Catalytic Reduction

21.1 Sulfur oxide control

Sulfur dioxide can be reduced by fuel sulfur reduction, sorbent addition, or flue-gas desulfurization. Wet systems often use alkaline reagents; the design basis is a stoichiometric or excess reagent requirement tied to sulfur or SO_2 loading.

21.2 Nitrogen oxide formation

NO_x can form through high-temperature oxidation of atmospheric nitrogen and from nitrogen in fuel. Combustion modification aims to limit formation; post-combustion systems convert NO_x after it forms.

21.3 Selective catalytic reduction concept

A reducing agent reacts with NO_x in the presence of a catalyst. A problem may provide stoichiometry and ask for reagent rate or percent removal.

21.4 Stoichiometric engineering

For any supplied reaction,

$$\dot{n}_i = \frac{\dot{m}_i}{MW_i}$$

and stoichiometric coefficients relate molar consumption and production. Convert back to mass only after the mole ratio is applied.

21.5 Excess reagent

If theoretical reagent demand is $\dot{m}_{th}$ and an excess fraction e is specified,

$$\dot{m}_{actual} = (1 + e)\dot{m}_{th}.$$

Exam Tip. For gas-control chemistry, work in moles first. Mass ratios are usually wrong unless molecular weights happen to cancel.

22 Indoor Air Quality: Steady-State Mass Balance

Treat a room as a well-mixed control volume of volume V . Let Q be ventilation rate, C_o outdoor concentration, S indoor source rate, C indoor concentration, and k a first-order removal constant.

22.1 Dynamic balance

$$V \frac{dC}{dt} = QC_o + S - QC - kVC$$

22.2 Steady state

At steady state, $dC/dt = 0$:

$$C_{ss} = \frac{QC_o + S}{Q + kV}.$$

Define air exchange rate $A = Q/V$:

$$C_{ss} = \frac{AC_o + S/V}{A + k}.$$

22.3 Special case: no reaction/removal

If $k = 0$,

$$C_{ss} = C_o + \frac{S}{Q}.$$

This directly shows that increasing ventilation reduces the source-induced concentration increment.

22.4 Units

If S is mg/h, Q is m³/h, and V is m³, then C is mg/m³ and k is h⁻¹.

Exam Tip. The source term S is mass/time, not concentration/time. Divide by volume only when rewriting the equation on a per-volume basis.

23 Indoor Air: Transient Response, ACH, and Tracer Decay

23.1 Time constant

For constant Q , V , and k ,

$$\tau = \frac{1}{Q/V + k} = \frac{1}{A + k}.$$

23.2 Transient concentration

If conditions change at $t = 0$ and the new steady concentration is C_{ss} ,

$$C(t) = C_{ss} + (C_0 - C_{ss})e^{-t/\tau}$$

After one time constant, 63.2% of the total change toward the new steady state has occurred.

23.3 Air changes per hour

$$ACH = A = \frac{Q}{V}.$$

Thus $Q = ACH \cdot V$.

23.4 Tracer-gas decay

With no internal source and negligible removal other than ventilation,

$$C(t) - C_o = (C_0 - C_o)e^{-At}.$$

Therefore,

$$A = \frac{1}{t} \ln \left(\frac{C_0 - C_o}{C(t) - C_o} \right).$$

23.5 Control interpretation

Ventilation dilutes indoor sources but may introduce outdoor contaminants. Filtration or first-order removal adds k to the decay rate.

Exam Tip. For transient equations, ensure t , A , and k use compatible time units before evaluating the exponential.

24 Control-Train Selection and Fan/Pressure-Drop Concepts

Real systems often use multiple devices in sequence. A coarse-particle precleaner may protect a high-efficiency device; gas cooling may precede adsorption; a scrubber may remove acid gas before another polishing step.

24.1 Series performance

$$\eta_{overall} = 1 - \prod_i (1 - \eta_i).$$

This formula applies when each device acts on the mass entering it and the stated efficiencies are independent for the pollutant of interest.

24.2 Pressure drop and fan power

Air-moving power increases with gas flow and system pressure drop. In U.S. customary ventilation work, air horsepower is proportional to

$$P_{air} \propto Q\Delta P.$$

Actual brake horsepower is larger because fan efficiency is less than one:

$$P_{brake} = \frac{P_{air}}{\eta_f}.$$

24.3 Tradeoff logic

Higher pressure drop	often greater energy demand; may improve capture in some devices
Higher removal efficiency	lower emissions but often greater area, energy, reagent, or capital requirement
Wet treatment	creates liquid residuals
Adsorption	creates spent sorbent/regeneration stream
Oxidation	destroys organics but consumes energy and may generate combustion products

Exam Tip. When comparing control trains, calculate final mass emissions first. Do not compare devices solely by percent efficiency if inlet loads differ.

25 Exam Formula Map and Problem-Solving Strategy

25.1 High-value equations

$$\begin{aligned}\dot{m} &= CQ \\ \eta &= 1 - \dot{m}_{out}/\dot{m}_{in} \\ E &= AEF(1 - \eta_c) \\ C_{mg/m^3} &\approx \text{ppmv } MW/24.45 \quad (25^\circ\text{C}, 1 \text{ atm}) \\ C(x, y, z) &= \frac{Q}{2\pi u \sigma_y \sigma_z} e^{-y^2/(2\sigma_y^2)} \left[e^{-(z-H)^2/(2\sigma_z^2)} + e^{-(z+H)^2/(2\sigma_z^2)} \right] \\ \eta_{cyclone} &= \frac{1}{1 + (d_{pc}/d_p)^2} \\ \eta_{ESP} &= 1 - e^{-WA/Q} \\ C_{ss, indoor} &= \frac{QC_o + S}{Q + kV} \\ \tau &= (Q/V + k)^{-1} \\ C(t) &= C_{ss} + (C_0 - C_{ss})e^{-t/\tau}\end{aligned}$$

25.2 Fast decision sequence

1. Identify the requested quantity and basis.
2. Sketch a control volume or source-to-receptor pathway.
3. Write the governing balance/equation symbolically.
4. Convert units before inserting numbers.
5. Perform a limiting check: should efficiency be between 0 and 1? should concentration fall after control? should higher ventilation lower indoor concentration?

25.3 Common FE traps

- percent versus fraction inside equations;
- ppm versus ppb and gas-law temperature units;
- wet versus dry gas basis;
- physical versus effective stack height;
- using concentration ratio instead of mass-rate ratio when gas flow changes;
- forgetting to round required equipment counts up.

Exam Tip. The fastest route is usually not more memorization; it is recognizing the problem family, finding the reference equation quickly, and keeping the basis and units consistent.

26 15 Example Problems

Example Problem 1: Convert ppbv to mg/m³

Problem. A sulfur dioxide concentration is 75 ppbv at 25°C and 1 atm. Estimate the mass concentration in mg/m³. Use $MW_{SO_2} = 64.07$ g/mol.

Solution

Convert ppbv to ppmv:

$$75 \text{ ppbv} = 0.075 \text{ ppmv}.$$

At 25°C and 1 atm, use $V_m \approx 24.45$ L/mol:

$$C = \text{ppmv} \frac{MW}{24.45}.$$

Substitute:

$$C = 0.075 \frac{64.07}{24.45} = 0.1965 \text{ mg/m}^3.$$

$C \approx 0.197 \text{ mg/m}^3$

Check. A sub-ppm concentration should usually correspond to a sub-mg/m³ mass concentration for a gas with molecular weight near 64 at room conditions.

FE takeaway. Convert ppb to ppm before using the room-temperature shortcut.

Example Problem 2: Emission factor with control

Problem. A process handles 120 Mg/day of material. The uncontrolled particulate emission factor is 1.8 kg/Mg. A control device removes 92% of the particulate. Determine the controlled particulate emission rate in kg/day.

Solution

Uncontrolled emissions:

$$E_u = (120 \text{ Mg/day})(1.8 \text{ kg/Mg}) = 216 \text{ kg/day}.$$

The penetration fraction is

$$1 - \eta = 1 - 0.92 = 0.08.$$

Controlled emissions:

$$E_c = 216(0.08) = 17.28 \text{ kg/day}.$$

$$E_c \approx 17.3 \text{ kg/day}$$

Collected mass:

$$216 - 17.28 = 198.72 \text{ kg/day}.$$

FE takeaway. A 92% efficient device does not emit 92%; it emits the 8% penetration.

Example Problem 3: Two control devices in series

Problem. A gas stream contains 50 kg/h of particulate. A cyclone removes 70%, followed by a baghouse that removes 99% of the particulate entering it. Determine the final emission rate and overall efficiency.

Solution

After cyclone:

$$\dot{m}_1 = (1 - 0.70)(50) = 15 \text{ kg/h.}$$

After baghouse:

$$\dot{m}_2 = (1 - 0.99)(15) = 0.15 \text{ kg/h.}$$

Overall efficiency:

$$\eta_o = 1 - \frac{0.15}{50} = 0.997.$$

$$\boxed{\dot{m}_{out} = 0.15 \text{ kg/h}}, \quad \boxed{\eta_o = 99.7\%}.$$

Alternative directly:

$$\eta_o = 1 - (0.30)(0.01) = 0.997.$$

FE takeaway. Multiply penetrations, not efficiencies, for devices in series.

Example Problem 4: Wet-basis to dry-basis concentration

Problem. A stack-gas pollutant concentration is measured as 180 mg/m³ on a wet basis. The gas contains 12% water vapor by volume. Determine the dry-basis concentration at the same temperature and pressure.

Solution

Dry gas occupies only

$$1 - y_{H_2O} = 1 - 0.12 = 0.88$$

of the wet gas volume after water is excluded. Therefore,

$$C_{dry} = \frac{C_{wet}}{1 - y_{H_2O}} = \frac{180}{0.88} = 204.55 \text{ mg/m}^3.$$

$$C_{dry} \approx 205 \text{ mg/m}^3$$

Reasonableness. Removing water vapor from the reporting basis reduces the reference gas volume, so dry-basis concentration must be higher than wet-basis concentration.

Example Problem 5: Actual flow to standard flow

Problem. A stack exhausts $18.0 \text{ m}^3/\text{s}$ at 150°C and 95 kPa . Determine the equivalent volumetric flow at 0°C and 101.325 kPa , assuming ideal-gas behavior and unchanged molar flow.

Solution

Use

$$Q_s = Q_a \left(\frac{P_a}{P_s} \right) \left(\frac{T_s}{T_a} \right).$$

Convert temperature to Kelvin:

$$T_a = 423.15 \text{ K}, \quad T_s = 273.15 \text{ K}.$$

Then

$$Q_s = 18.0 \left(\frac{95}{101.325} \right) \left(\frac{273.15}{423.15} \right) = 10.90 \text{ m}^3/\text{s}.$$

$$Q_s \approx 10.9 \text{ m}^3/\text{s}$$

FE takeaway. Cooling the same gas to standard temperature substantially decreases its reported volume.

Example Problem 6: Gaussian plume at ground-level centerline

Problem. A source emits 5.0 g/s of pollutant. At a receptor downwind, $u = 4.0$ m/s, $\sigma_y = 60$ m, $\sigma_z = 30$ m, and effective stack height $H = 40$ m. Find the ground-level centerline concentration.

Solution

At $y = 0$ and $z = 0$,

$$C = \frac{Q}{\pi u \sigma_y \sigma_z} \exp\left(-\frac{H^2}{2\sigma_z^2}\right).$$

Convert Q :

$$5.0 \text{ g/s} = 5.0 \times 10^6 \text{ } \mu\text{g/s}.$$

Substitute:

$$C = \frac{5.0 \times 10^6}{\pi(4)(60)(30)} \exp\left[-\frac{40^2}{2(30)^2}\right].$$

$$C = 90.9 \text{ } \mu\text{g/m}^3.$$

$$\boxed{C \approx 91 \text{ } \mu\text{g/m}^3}$$

FE takeaway. At ground-level centerline, the two reflected vertical Gaussian terms combine to remove the factor of 2 in the denominator.

Example Problem 7: Use lapse rate to assess stability tendency

Problem. The measured air temperature is 24.0°C at ground level and 20.0°C at 500 m. Compare the environmental lapse rate with the dry adiabatic lapse rate of 0.98°C per 100 m and identify the stability tendency.

Solution

Temperature decreases by

$$24.0 - 20.0 = 4.0^{\circ}\text{C}$$

over 500 m. Therefore,

$$\Gamma_e = \frac{4.0}{500}(100) = 0.80^{\circ}\text{C}/100 \text{ m}.$$

Compare:

$$\Gamma_e = 0.80 < \Gamma_{AD} = 0.98.$$

The atmosphere cools with height less rapidly than a rising dry parcel would cool. A displaced parcel tends to become cooler/denser than its environment and return toward its original level.

Stable tendency

FE takeaway. A smaller-magnitude environmental cooling rate than the dry adiabatic rate indicates resistance to vertical displacement.

Example Problem 8: Cyclone fractional efficiency

Problem. A cyclone has a 50% cut diameter $d_{pc} = 10 \mu\text{m}$. Estimate the collection efficiency for particles with $d_p = 15 \mu\text{m}$ using

$$\eta = \frac{1}{1 + (d_{pc}/d_p)^2}.$$

Solution

$$\frac{d_{pc}}{d_p} = \frac{10}{15} = 0.6667.$$

Then

$$\eta = \frac{1}{1 + (0.6667)^2} = 0.6923.$$

$$\boxed{\eta \approx 69.2\%}$$

Check. Because $d_p > d_{pc}$, the efficiency should exceed 50%, which it does.

Example Problem 9: Cyclone cut diameter from operating data

Problem. Estimate cyclone cut diameter from

$$d_{pc} = \left[\frac{9\mu W}{2\pi N_e V_i (\rho_p - \rho_g)} \right]^{1/2}$$

for $\mu = 1.8 \times 10^{-5}$ kg/(m·s), $W = 0.25$ m, $N_e = 5.0$, $V_i = 18$ m/s, $\rho_p = 1800$ kg/m³, and $\rho_g = 1.2$ kg/m³.

Solution

$$d_{pc} = \left[\frac{9(1.8 \times 10^{-5})(0.25)}{2\pi(5)(18)(1800 - 1.2)} \right]^{1/2}.$$

The quantity inside the square root is approximately 3.98×10^{-11} m², so

$$d_{pc} = 6.31 \times 10^{-6} \text{ m.}$$

$$\boxed{d_{pc} \approx 6.3 \text{ } \mu\text{m}}$$

FE takeaway. Convert the final meter value to micrometers only after evaluating the SI equation.

Example Problem 10: Baghouse cloth area and bag count

Problem. A baghouse must treat 24,000 m³/min. The selected air-to-cloth ratio is 2.0 m/min. Each cylindrical bag is **0.16 m in diameter and 6.0 m long. Estimate the required cloth area and minimum number of bags**

Solution

Required cloth area:

$$A_c = \frac{Q}{V_f} = \frac{24,000}{2.0} = 12,000 \text{ m}^2.$$

Area per bag (side area):

$$A_{bag} = \pi DL = \pi(0.16)(6.0) = 3.016 \text{ m}^2.$$

Number of bags:

$$N = \frac{12,000}{3.016} = 3978.9.$$

Round up:

$$\boxed{A_c = 12,000 \text{ m}^2}, \quad \boxed{N = 3979 \text{ bags minimum}}.$$

FE takeaway. Equipment counts are integers; always round up when sizing for minimum area.

Example Problem 11: ESP collection area

Problem. An ESP treats $Q = 80 \text{ m}^3/\text{s}$. The effective migration velocity is $W = 0.12 \text{ m/s}$. Determine the collection area required for 99.0% efficiency.

Solution

Use Deutsch-Anderson:

$$\eta = 1 - e^{-WA/Q}.$$

Rearrange:

$$A = -\frac{Q}{W} \ln(1 - \eta).$$

Substitute:

$$A = -\frac{80}{0.12} \ln(0.01).$$

Since $-\ln(0.01) = 4.6052$,

$$A = 3070 \text{ m}^2.$$

$A \approx 3.07 \times 10^3 \text{ m}^2$
--

FE takeaway. The logarithm uses the penetration fraction $1 - \eta$.

Example Problem 12: Wet scrubber pollutant removal

Problem. A scrubber receives 35,000 m³/h of gas containing 850 mg/m³ of a soluble pollutant. The scrubber removes 96%. Find the pollutant mass captured per hour and the outlet concentration, assuming gas flow is unchanged.

Solution

Inlet mass rate:

$$\dot{m}_{in} = CQ = (850)(35,000) = 2.975 \times 10^7 \text{ mg/h} = 29.75 \text{ kg/h.}$$

Captured mass:

$$\dot{m}_c = 0.96(29.75) = 28.56 \text{ kg/h.}$$

Outlet concentration:

$$C_{out} = (1 - 0.96)(850) = 34.0 \text{ mg/m}^3.$$

$$\boxed{\dot{m}_c \approx 28.6 \text{ kg/h}}, \quad \boxed{C_{out} = 34.0 \text{ mg/m}^3}.$$

Example Problem 13: Incinerator DRE and combustion efficiency

Problem. An incinerator receives 12.0 kg/h of a target organic compound and emits 0.018 kg/h of the same compound. The dry exhaust contains 9.2% CO₂ and 0.08% CO. Determine DRE and combustion efficiency.

Solution

DRE:

$$DRE = 100 \frac{12.0 - 0.018}{12.0} = 99.85\%.$$

Combustion efficiency:

$$CE = 100 \frac{CO_2}{CO_2 + CO} = 100 \frac{9.2}{9.2 + 0.08} = 99.14\%.$$

$$\boxed{DRE \approx 99.85\%}, \quad \boxed{CE \approx 99.14\%}.$$

FE takeaway. DRE tracks destruction/removal of the target compound; CE uses combustion gases. They answer different questions.

Example Problem 14: Indoor-air steady-state concentration

Problem. A 250 m³ room is ventilated at 500 m³/h. Outdoor pollutant concentration is 0.020 mg/m³. An indoor source emits 150 mg/h. The pollutant also decays at $k = 0.10 \text{ h}^{-1}$. Find the steady-state indoor concentration.

Solution

Use

$$C_{ss} = \frac{QC_o + S}{Q + kV}.$$

Numerator:

$$QC_o + S = (500)(0.020) + 150 = 160 \text{ mg/h.}$$

Denominator:

$$Q + kV = 500 + (0.10)(250) = 525 \text{ m}^3/\text{h.}$$

Thus

$$C_{ss} = \frac{160}{525} = 0.3048 \text{ mg/m}^3.$$

$$\boxed{C_{ss} \approx 0.305 \text{ mg/m}^3}$$

Example Problem 15: Indoor-air transient response

Problem. Use the room from Problem 14. At $t = 0$, the indoor concentration is $C_0 = 0.020 \text{ mg/m}^3$ and the 150 mg/h source turns on. Determine concentration after 1.0 h .

Solution

Air exchange rate:

$$A = \frac{Q}{V} = \frac{500}{250} = 2.0 \text{ h}^{-1}.$$

Time constant:

$$\tau = \frac{1}{A + k} = \frac{1}{2.0 + 0.10} = 0.4762 \text{ h}.$$

From Problem 14, $C_{ss} = 0.3048 \text{ mg/m}^3$. Use

$$C(t) = C_{ss} + (C_0 - C_{ss})e^{-t/\tau}.$$

At $t = 1.0 \text{ h}$:

$$C(1) = 0.3048 + (0.020 - 0.3048)e^{-1/0.4762}.$$

Since $e^{-2.10} = 0.1225$,

$$C(1) = 0.2699 \text{ mg/m}^3.$$

$$\boxed{C(1 \text{ h}) \approx 0.270 \text{ mg/m}^3}$$

Check. The value lies between the initial and steady-state concentrations, as required.

27 Reference and Scope Alignment

This guide is organized around the Air Quality and Control domain in the NCEES FE Environmental CBT Exam Specifications, which identifies 8–12 questions in the domain and lists the following areas: ambient and indoor air quality; mass and energy balances; emissions; atmospheric modeling and meteorology; gas treatment technologies; particle treatment technologies; and indoor air quality modeling and controls.

The equations and terminology used in this guide were aligned to the FE Reference Handbook, Version 10.6, especially the Environmental Engineering air-pollution material covering gas concentration conversion, Gaussian atmospheric dispersion, cyclone collection, baghouse concepts, electrostatic precipitator efficiency, incineration metrics, and indoor-air mass balances.

Primary source documents used for alignment

1. NCEES, *FE Reference Handbook*, Version 10.6, 2026 printing.
2. NCEES, *Fundamentals of Engineering (FE) Environmental CBT Exam Specifications*, effective beginning July 2020 examinations.

How to use this guide

Use the 25 study pages to build equation recognition and conceptual organization. Then work the 15 examples without looking at the solution, using the electronic reference as you would during the computer-based exam. Rework missed problems until you can identify the governing equation within about 30 seconds.