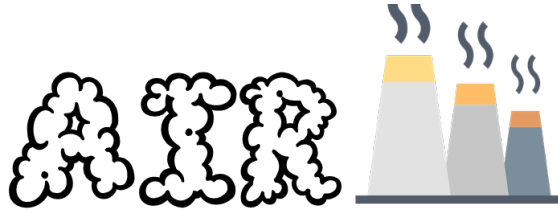


Montogue

Quiz EV101



POLLUTION

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► PROBLEMS

► Conversation Starter

About 95 percent of anthropogenic nitrogen oxide emissions are in the form of a single molecule. Which of the following is it?

- A) NO
- B) NO₂
- C) N₂O
- D) N₂O₅

→ Problem 2.1

An air sample contains 11 ppm CO (8-hour average), 320 $\mu\text{g}/\text{m}^3$ PM-10 (24-hour average), and 0.12 ppm SO₂ (24-hour average). Compute the Air Quality Index (AQI) for this air.

- A) AQI = 142
- B) AQI = 161
- C) AQI = 183
- D) AQI = 215

→ Problem 2.2

An air sample contains 0.14 ppm O₃ (1-hour average), 11.5 ppm CO (8-hour average), and 0.08 ppm SO₂ (24-hour average). Compute the Air Quality Index (AQI) for this air.

- A) AQI = 120
- B) AQI = 135
- C) AQI = 155
- D) AQI = 165

► Problem 3

Concerning various aspects of air pollution science, true or false?

1. () Although essentially inert, carbon monoxide can bind to blood hemoglobin and reduce oxygen concentration in the body. This effect is particularly harmful for individuals with some pre-existing form of oxygen deficiency, including anemia, various types of lung disease, or simply the condition of living in high altitudes.
2. () Otherwise healthy individuals exposed to sulfur oxides may experience irritation and reduction of the air passages, coughing, and breathing difficulties. The main source of sulfur oxide emissions in the United States, by far, is fossil fuel combustion for electric power generation.
3. () One precombustion technique used to reduce sulfur emissions in coal processing is *coal cleaning*. Sulfur in coal is either bound into organic coal molecules themselves, in which case precleaning would require chemical or biological treatment, or it can be in the form of inorganic pyrite, FeS₂, which can be readily separated using physical treatment. Physical cleaning of pyrite not only reduces the sulfur content of the coal, it also reduces ash content and increases the energy per unit weight of fuel, which can reduce coal transportation and pulverization costs.

- 4.()** Long term exposure to nitrous dioxide may cause adverse effects on humans, including pulmonary edema and bronchitis. Research carried out since the 1960s has demonstrated that plants, especially gymnosperms and broad-leaved eudicots, can withstand high levels of NO₂ for long periods without being damaged.
- 5.()** In the atmosphere, ozone is produced by a complex network of photochemical reactions involving volatile organic compounds (VOCs), nitrogen oxides, and other substances. A primary pollutant, ozone is a potent eye, throat and nose irritant.
- 6.()** Carbon monoxide is not a direct participant in the majority of reactions producing ozone in the atmosphere.
- 7.()** Per the Clean Air Act, there are six criteria pollutants, which may be compared with the so-called hazardous air pollutants. One immediate distinction between the two groups is that criteria pollutants bioaccumulate in tissues, whereas most studied hazardous air pollutants do not.
- 8.()** Unlike other criteria air pollutants, which produce primarily respiratory-system-related adverse effects, prolonged exposure to lead produces an array of additional consequences, most of which are neurologic in nature – behavioral changes, loss of muscle control, learning difficulties. In addition, prolonged exposure to substantial levels of airborne lead may cause anemia.
- 9.()** One of the main features of the 1990 amendments to the US' Clean Air Act was the creation of the Acid Rain Program, a policy designated to address atmospheric acid deposition. Rather innovative for its time, the program was based on the implementation of a market-based cap-and-trade system to control emissions. The system went into effect in 1995 and has since produced mediocre results, with most power plant operators preferring to exceed their pollution allowances and pay the additional costs instead of curtailing acidogenic emissions.
- 10.()** The United Nations Economic Council for Europe (UNECE) has established a committee to investigate transnational air pollution. For use in mapping the most significant sources of rising ozone concentration in the troposphere and the increasingly more frequent episodes of photochemical smog, the committee applies factors that, for each individual compound, express the potential contribution to ozone formation; these are the so-called Photochemical Ozone Creation Potentials (POCPs). The POCPs express the ozone formation potential as an equivalent emission relatively to a reference substance, namely ethane (C₂H₆).
- 11.()** The 1-hour National Air Quality Standard (NAAQS) for carbon monoxide is 35 ppm. Noting that the molar volume of an ideal gas at 25°C and 1 atm is about 24.5 m³/mol, we may convert this NAAQS to concentration units under these conditions and obtain a result greater than 50 mg/m³.
- 12.()** The mass concentration of particulate matter in a certain region is 10,800 μg/m³. Assuming the particles are spherical with 0.5 μm diameter and have the density of water (1 g/cm³), we may surmise that the number concentration (No. particles/cm³) of particles is greater than 150,000 particles/cm³.
- 13.()** A particulate matter particle has a diameter of 10 μm. Assuming the particle settles from the height of a stratus cloud at 2600 m above ground and the settling velocity is uniform as the particle settles from the sky to the ground, we may surmise that the particle requires more than 3 days to settle. In your analysis of this statement, take 2650 kg/m³ as the particle density and 1.8×10⁻⁵ Pa·s as the viscosity of air.
- 14.()** A solid waste incinerator has an emissions factor for the release of mercury equal to 0.12 lb per ton incinerated. The incinerator steadily processes 2.5×10⁶ lbs of solid waste per year. Accordingly, we may surmise that the incinerator emits more than 0.4 lb of mercury per day.
- 15.()** A company applies 40 liters of a coating every day that contains three volatile organic compounds: 0.15 kg of xylene per liter of coating, 0.11 kg of *n*-butyl alcohol per liter of coating, and 0.09 kg of ethyl benzene per liter of coating. It is known that 8% of the applied VOC is retained in a liquid wastestream and is discharged to the wastewater treatment plant; moreover,

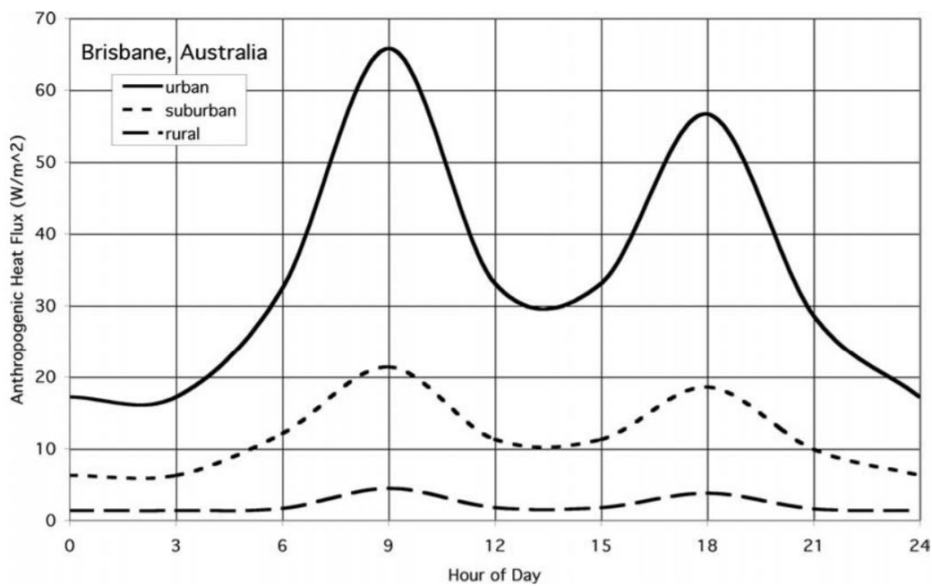
the company has implemented a pollution control equipment that reduces air emissions by 40%. In this case, we may surmise that the total amount of VOCs emitted by this operation over the course of a year is greater than 3000 kg.

16.() Many factors influence the dispersion of pollutants from a chimney, including the pollutants' temperature and exit velocity, wind speed and direction, and the chimney's height. Overall, taller chimneys, greater wind speeds, and higher exit velocities result in a lower concentration of pollutants.



17.() Airborne pollutant transport can be modeled by Lagrangian or Eulerian methods. Lagrangian models have the inherent disadvantage of requiring much greater computation times than, for the same situation, an unsteady Eulerian approach with a fine grid.

18.() In addition to the factors mentioned in Problem 4 (see below), heat islands may be compounded by anthropogenic heat release. As an example, the following graph illustrates daily anthropogenic heat flux generated in urban, suburban, and rural Brisbane, Australia, in December 1996. Clearly, anthropogenic heat flux in urban Brisbane at 9:00 h (9 AM) is over 4 times greater than the AHF in a suburban area at the same time.



► Problem 4

Regarding heat islands, which of the following is *false*?

- A) Heat islands are caused by reduced evaporation.
- B) Heat islands are caused by decreased heat radiation.
- C) Heat islands are caused by reduced convection.
- D) Heat islands are caused by increased heat storage.

► Problem 5 (Modified from Mihelcic and Zimmerman, 2014, w/ permission)

A baghouse that employs a shaker collection method is being designed to remove 99.75 percent of an incoming stream of rock dust particles stemming from a nearby mining facility. The baghouse treats 16,200 ft³ of polluted air per minute. How many bags are required if the bags are cylindrical and are 6 inches in diameter and 15 ft long?

Hint: Take a gas-to-cloth ratio from Table 3.

- A) $n_{bags} = 85$ bags
- B) $n_{bags} = 134$ bags
- C) $n_{bags} = 229$ bags
- D) $n_{bags} = 310$ bags

► Problem 6 (Modified from Masters and Ela, 2014, w/ permission)

An electrostatic precipitator with 4000 m² of collector plate area is 95 percent efficient in treating 145 m³/s of flue gas from a power plant operating at 200 MW. Find the surface area required for the same device to achieve 97 percent efficiency.

- A) $A_{97} = 4320$ m²
- B) $A_{97} = 4660$ m²
- C) $A_{97} = 4990$ m²
- D) $A_{97} = 5200$ m²

► **Problem 7** (Modified from Mihelcic and Zimmerman, 2014, w/ permission)

A thermal oxidizer incinerator operates as a plug flow reactor at a temperature of 300°C. The pollutant treated in the operation is vinyl chloride, which enters the incinerator at a rate of 3750 m³/min. The first-order rate constant for vinyl chloride removal is 36 sec⁻¹ and the inside diameter of the incinerator (which is shaped like a cylinder) is 1.2 m. If a 99.9% removal is desired, what should the length of the incinerator be?

- A) $L = 3.89$ m
- B) $L = 5.41$ m
- C) $L = 7.02$ m
- D) $L = 10.6$ m

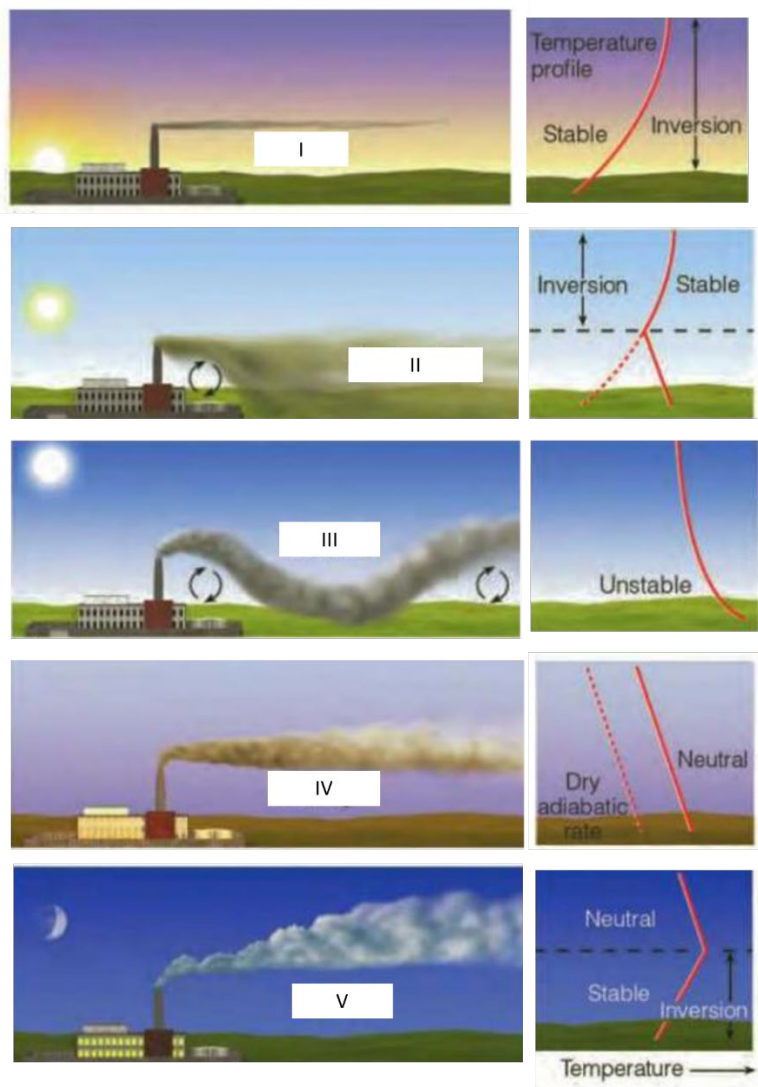
► **Problem 8** (Modified from Cooper and Alley, 2011)

Assume that equation 3 is valid for ambient particulate concentrations in a certain urban area, with $a = -2.4 \times 10^{-2}$ km⁻¹ and $b = 3.2 \times 10^{-3}$ m³/km-μg. Also assume that the absorption coefficient σ_a is due to particulates alone and equals the scattering coefficient σ_s . Estimate the limit of visibility in air that contains 170 μg/m³ of total suspended particles (TSP).

- A) $d_v = 3.76$ km
- B) $d_v = 5.54$ km
- C) $d_v = 7.11$ km
- D) $d_v = 8.55$ km

► **Problem 9** (Modified from Ahrens, 2019, w/ permission)

As the vertical temperature profile changes during the course of a day, the pattern of smoke emitted from a smokestack changes as well. The following figure illustrates the five smokestack plume behaviors that occur in succession over the course of a day. Choose the alternative that correctly identifies smoke plume (SP) patterns I to V.



- A) I. Coning SP; II. Lofting SP; III. Fumigation; IV. Fanning SP; V. Looping SP;
- B) I. Fanning SP; II. Lofting SP; III. Looping SP; IV. Coning SP; V. Fumigation;
- C) I. Fanning SP; II. Fumigation; III. Looping SP; IV. Lofting SP; V. Coning SP;
- D) I. Fanning SP; II. Fumigation; III. Looping SP; IV. Coning SP; V. Lofting SP;

→ **Problem 10.1** (Modified from Masters and Ela, 2014, w/ permission)

A localized fire, modeled as a stationary point source, emits carbon monoxide at a rate of 24 g/s on a clear night with the wind blowing at 4 m/s. The effective stack height of the fire is 7 m. Determine the ground-level CO concentration at 500 m downwind.

- A) $C = 4.67 \text{ mg/m}^3$
- B) $C = 8.11 \text{ mg/m}^3$
- C) $C = 10.4 \text{ mg/m}^3$
- D) $C = 11.9 \text{ mg/m}^3$

→ **Problem 10.2**

Estimate the maximum ground-level concentration.

- A) $C_{max} = 13.5 \text{ mg/m}^3$
- B) $C_{max} = 18.0 \text{ mg/m}^3$
- C) $C_{max} = 21.1 \text{ mg/m}^3$
- D) $C_{max} = 26.7 \text{ mg/m}^3$

▶ **Problem 11** (Modified from Masters and Ela, 2014, w/ permission)

A coal-fired power plant with effective stack height of 70 m emits 0.8 g/s of SO₂ per megawatt of power delivered. If winds are assumed to be 4 m/s at the stack height and approximately 3 m/s at 10 m, estimate how large (MW) the plant should be without having the ground level SO₂ exceed 315 μg/m³.

Hint: First decide which stability classification leads to the worst conditions.

- A) $\Pi = 18.5 \text{ MW}$
- B) $\Pi = 36.5 \text{ MW}$
- C) $\Pi = 52.5 \text{ MW}$
- D) $\Pi = 70.5 \text{ MW}$

→ **Problem 12.1** (Modified from Masters and Ela, 2014, w/ permission)

A stack emits 30 g/s of NO has an effective stack height of 50 m. The windspeed is 2.5 m/s at 10 m, and it is a somewhat cloudy day with moderate insolation. Estimate the ground-level NO concentration directly downwind at a distance of 2 km. If necessary, consider the terrain to be rough.

- A) $C = 43.3 \text{ } \mu\text{g/m}^3$
- B) $C = 69.7 \text{ } \mu\text{g/m}^3$
- C) $C = 85.8 \text{ } \mu\text{g/m}^3$
- D) $C = 101 \text{ } \mu\text{g/m}^3$

→ **Problem 12.2**

Estimate the ground-level NO concentration at the point downwind where NO is a maximum.

- A) $C_{max} = 305 \text{ } \mu\text{g/m}^3$
- B) $C_{max} = 566 \text{ } \mu\text{g/m}^3$
- C) $C_{max} = 750 \text{ } \mu\text{g/m}^3$
- D) $C_{max} = 911 \text{ } \mu\text{g/m}^3$

→ **Problem 12.3**

Estimate the concentration of NO at a point located 2 km downwind and 200 m off the downwind axis.

- A) $C = 6.82 \text{ } \mu\text{g/m}^3$
- B) $C = 11.1 \text{ } \mu\text{g/m}^3$
- C) $C = 20.2 \text{ } \mu\text{g/m}^3$
- D) $C = 34.1 \text{ } \mu\text{g/m}^3$

→ **Problem 13.1** (Modified from Masters and Ela, 2014, w/ permission)

A stack stands 200 m high and has an inner diameter at the top of 10 m. If 140°C gases exit the stack at 18 m/s while the ambient temperature is 15°C and the winds at stack height have a speed of 7 m/s, use the Briggs equation to estimate the effective stack height. The atmospheric stability category at the stack site is C.

- A) $H = 502 \text{ m}$
- B) $H = 618 \text{ m}$
- C) $H = 712 \text{ m}$
- D) $H = 801 \text{ m}$

→ **Problem 13.2**

Repeat the previous problem for a stable, isothermal atmosphere (no temperature change with altitude).

- A) $H = 280$ m
- B) $H = 322$ m
- C) $H = 414$ m
- D) $H = 491$ m

► **Problem 14** (Modified from Masters and Ela, 2014, w/ permission)

A 130-MW power plant has a 85-m stack with inner radius 2 m, flue gas exit velocity 14 m/s, and gas exit temperature 125°C. The ambient temperature is 18°C, windspeed at the stack is 4 m/s, and the atmosphere is stable, class E, with a lapse rate of 5°C/km. If the plant emits 200 g SO₂/s, estimate the concentration at ground level at a distance of 10 km directly downwind.

- A) $C = 23.1 \mu\text{g}/\text{m}^3$
- B) $C = 36.1 \mu\text{g}/\text{m}^3$
- C) $C = 49.2 \mu\text{g}/\text{m}^3$
- D) $C = 62.2 \mu\text{g}/\text{m}^3$

►► **ADDITIONAL INFORMATION**

Table 1 Air Quality Index (AQI)

<i>I</i> value	8-hr O ₃ (ppm)	1-hr O ₃ (ppm)	24-hr PM-2.5 (μg/m ³)	24-hr PM-10 (μg/m ³)	8-hr CO (ppm)	24-hr SO ₂ (ppm)
0	0	–	0	0	0	0
50	0.059	–	15.4	54	4.4	0.034
100	0.075	0.124	40.4	154	9.4	0.144
150	0.095	0.164	65.4	254	12.4	0.224
200	0.115	0.194	150.4	354	15.4	0.304
300	0.374	0.404	250.4	424	30.4	0.604
400	(*)	0.504	350.4	504	40.4	0.804
500	(*)	0.604	500.4	604	50.4	1.004

Table 2 Air Quality Index severity scale

Air quality index (AQI)	Designation	Interpretation
0 – 50	Good	Air pollution poses little or no health risk to the general population
51 – 100	Moderate	Air quality is acceptable; unusually sensitive people may be at some risk
101 – 150	Unhealthy for sensitive groups	Members of sensitive groups may experience health effects
151 – 200	Unhealthy	Everyone, especially members of sensitive groups, may experience health effects
201 – 300	Very unhealthy	Health warnings of emergency conditions; the entire population is likely to be affected
301 – 500	Hazardous	Health alert; everyone may experience more serious health effects

Table 3 Gas-to-cloth ratios (ft/min) for baghouse design

Material being removed in filters	Fabric type and method of particle removal from bags	
	Shaker/woven fabric; Reverse air/woven fabric	Pulsejet/felt fabric; Reverse air/felt fabric
Cement	2.0	8.0
Coal	2.5	8.0
Fly ash	2.5	5.0
Lime	2.5	10.0
Rock dust	3.0	9.0
Sawdust	3.5	12.0

Table 4 Values of constants a , c , d and f for use with equations _ and _

Stability	a	$x \leq 1$ km			$x \geq 1$ km		
		c	d	f	c	d	f
A	213	440.8	1.941	9.27	459.7	2.094	-9.6
B	156	106.6	1.149	3.3	108.2	1.098	2.0
C	104	61.0	0.911	0	61.0	0.911	0
D	68	33.2	0.725	-1.7	44.5	0.516	-13.0
E	50.5	22.8	0.678	-1.3	55.4	0.305	-34.0
F	34	14.35	0.740	-0.35	62.6	0.180	-48.6

Table 5 Atmospheric stability classifications

Surface windspeed ^a (m/s)	Day solar insolation			Night cloudiness ^e	
	Strong ^b	Moderate ^c	Slight ^d	Cloudy ($\geq 4/8$)	Clear ($\leq 3/8$)
< 2	A	A - B ^f	B	E	F
2 - 3	A - B	B	C	E	F
3 - 5	B	B - C	C	D	E
5 - 6	C	C - D	D	D	D
> 6	C	D	D	D	D

A → Very unstable
 B → Moderately unstable
 C → Slightly unstable
 D → Neutral
 E → Slightly stable
 F → Stable

a → Surface windspeed is measured 10 m above ground;
 b → Corresponds to a clear summer day with sun higher than 60° above the horizon;
 c → Corresponds to a summer day with a few broken clouds, or a clear day with sun 35 - 60° above the horizon;
 d → Corresponds to a fall afternoon, or a cloudy summer day, or clear summer day with the sun 15 - 35° above the horizon;
 e → Cloudiness is defined as the fraction of sky covered by clouds;
 f → For stability categories A - B, B - C, or C - D conditions, average the values obtained for each;

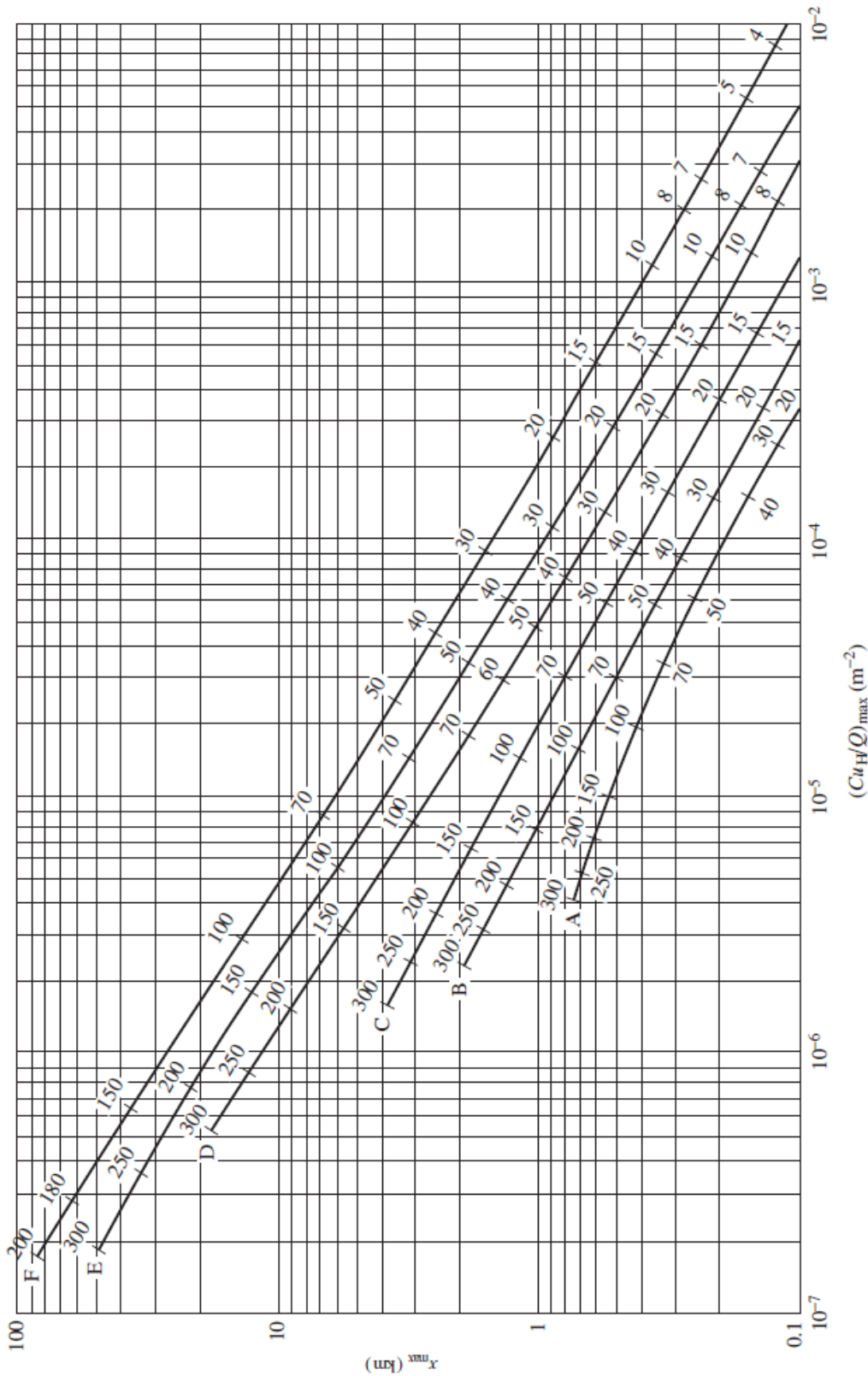
Table 6 Wind profile exponent for use with equation 6 - rough terrain*

Stability class	Exponent p
A	0.15
B	0.15
C	0.20
D	0.25
E	0.40
F	0.60

*For smooth terrain, multiply p by 0.6;

Figure 1 Turner's chart for downwind concentration peak

To find the downwind concentration peak, enter the graph at the appropriate stability class and effective stack height (numbers on the graph, in meters) and then project horizontally to find the distance to the peak, or vertically to find parameter $(Cu_H/Q)_{max}$, from which the peak concentration can be determined (equation 5).



→ Equations

Equation 1: Deutsch-Anderson equation for electrostatic precipitators

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

where η is fractional collection efficiency, A is the total area of collection plates, Q is the volumetric flow rate of gas through the precipitator, and w is the effective drift velocity (the terminal speed at which particles approach the collection plate under the influence of the electric field).

Equation 2: Equation for incinerators as plug flow reactors

$$\frac{C_{out}}{C_{in}} = e^{(-kV/Q)}$$

where C_{in} is the inlet concentration, C_{out} is the outlet concentration, k is the rate constant, V is reactor volume, and Q is flow rate. Ratio V/Q is the so-called residence time.

Equation 3: Limit of visibility

$$d_v = \frac{3.91}{\sigma_e}$$

where d_v is the visibility in kilometers and σ_e is the extinction coefficient in km^{-1} . The extinction coefficient equals the sum of the scattering coefficient σ_s and the absorption coefficient σ_a , which are often taken to be equal, i.e., $\sigma_s = \sigma_a$. The scattering coefficient is a function of TSP mass concentration, and can be approximated by the linear equation

$$\sigma_s = a + bC$$

where σ_s is given in km^{-1} , C is the TSP mass concentration in $\mu\text{g}/\text{m}^3$, and a and b are coefficients.

Equation 4: Gaussian plume model

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

where C is pollutant concentration, x is the distance directly downwind, y is the horizontal distance from the plume centerline, Q is the emission rate of pollutant, u_H is the average wind speed at the effective height of the stack, H is the effective stack height ($H = h + \Delta h$, where h is actual stack height and Δh is plume rise), and σ_y and σ_z are dispersion coefficients in the horizontal and vertical directions, respectively. The dispersion coefficients may be estimated from the equations

$$\sigma_y = ax^{0.894}$$

and

$$\sigma_z = cx^d + f$$

where parameters a , c , d and f may be read from Table 4. Bear in mind that, in these equations, x is entered in kilometers and σ_y and σ_z are returned in meters.

Equation 5: Peak downwind concentration

$$C_{\max} = \frac{Q}{u_H} \left(\frac{Cu_H}{Q} \right)_{\max}$$

where C_{\max} is the peak downwind concentration, Q is the emission rate of pollutant, u_H is the wind speed at elevation H , and $(Cu_H/Q)_{\max}$ is a parameter read from Turner's chart (Figure 1).

Equation 6: Wind speed at a certain height

$$u_H = u_a \left(\frac{H}{z_a} \right)^p$$

where u_H is the wind speed at height H , u_a is the wind speed at anemometer height, z_a is anemometer height (usually 10 m), and p is an exponent read from Table 6.

Equation 7: Plume rise – Stable atmosphere (categories E and F)

$$\Delta h = 2.6 \left(\frac{F}{u_h S} \right)^{1/3}$$

where Δh is plume rise in m, u_h is the wind speed at the height of the stack, F is the buoyancy flux parameter, and S is the stability parameter. The value of F (units: m^4/s^3) is

$$F = v_s g r^2 \left(1 - \frac{T_a}{T_s} \right)$$

where $g = 9.81 \text{ m/s}^2$, v_s is the stack exit gas velocity, r is the inside radius of the stack, T_a is the ambient temperature, and T_s is the stack gas temperature. The value of S (units: sec^{-2}) is

$$S = \frac{g}{T_a} \left(\frac{\Delta T_a}{\Delta z} + 0.01^\circ \text{C/m} \right)$$

where $\Delta T_a/\Delta z$ is the actual rate of change of ambient temperature with altitude in °C/m; a positive value of $\Delta T_a/\Delta z$ indicates that ambient temperature is increasing with altitude.

Equation 8: Plume rise – Neutral or unstable atmosphere (categories A – D)

$$\Delta h = 1.6 \frac{F^{1/3} x_f^{2/3}}{u_h}$$

where Δh is plume rise in m, F is the buoyancy flux parameter (see equation 7), u_h is the wind speed at the height of the stack, and x_f is the distance downwind to point of final plume rise. x_f is a function of F and may be computed as

$$x_f = 120F^{0.4} ; F \geq 55 \text{ m}^4/\text{s}^3$$

$$x_f = 50F^{5/8} ; F < 55 \text{ m}^4/\text{s}^3$$

► SOLUTIONS

P.CS → Solution

Most nitrogen oxides emitted by human activity come in the form of NO, a colorless gas that has no known adverse health effects at concentrations found in the atmosphere. However, nitric oxide readily oxidizes to NO₂, which is a potent irritant and may cause bronchitis, pneumonia, or lower resistance to respiratory infections.

♦ The correct answer is **A**.

P.2 → Solution

Part 1: Inspecting Table 1, it is easy to see that a 24-h average PM-10 concentration of 320 $\mu\text{g}/\text{m}^3$ corresponds to a subindex between 150 and 200. A 8-h average concentration of CO equal to 11 ppm, in turn, is associated with a subindex between 100 and 150. Likewise, a 24-h average concentration of SO₂ equal to 0.12 ppm also corresponds to a subindex between 50 and 100. The final AQI is based only on the pollutant with the greatest subindex – in this case, PM-10. By interpolation, we have

$$AQI = \frac{200 - 150}{354 - 254} \times (320 - 254) + 150 = \boxed{183}$$

Per Table 2, this AQI corresponds to a ‘unhealthy’ description.

♦ The correct answer is **C**.

Part 2: We may proceed as we did in Problem 2.1. For a 1-hour average O₃ concentration equal to 0.14 ppm, the subindex should be between 100 and 150. For an 8-hour average CO concentration of 11.5 ppm, the subindex should likewise be between 100 and 150. For a 24-hour average SO₂ concentration of 0.08 ppm, the subindex should be between 50 and 100. The AQI is determined with respect to the greatest subindex, which in this case may be associated with the 1-h avg. O₃ concentration or the 8-h avg. CO concentration. Interpolating with the ozone concentration, we obtain

$$I_{O_3} = \frac{150 - 100}{0.164 - 0.124} \times (0.14 - 0.124) + 100 = 120$$

As for the carbon monoxide concentration, we have

$$I_{CO} = \frac{150 - 100}{12.4 - 9.4} \times (11.5 - 9.4) + 100 = 135$$

The greatest subindex prevails, and hence we take $AQI = I_{CO} = 135$; per Table 2, this corresponds to a ‘unhealthy for sensitive groups’ description.

♦ The correct answer is **B**.

P.3 → Solution

1. True. Individuals with preexisting respiratory conditions and those living in high altitudes are in fact more vulnerable to high concentrations of atmospheric CO.

2. True. Indeed, emissions of SO_x in the US are primarily attributed to fossil fuel combustion, although certain industrial processes such as petroleum

refining and nonferrous metal smelting also play an important role in some locations. The primary oxide produced by these activities is sulfur dioxide, SO₂, but appreciable amounts of SO₃ may also be produced in furnaces. In the atmosphere, SO₂ is slowly oxidized to SO₃, which is why some authors consider sulfur trioxide to be a secondary pollutant.

3. True. Pyrite has a specific gravity that is 3.6 times greater than coal, and plant operators can take advantage of this difference to separate the two via successive “washing” steps. Physical cleaning of coal not only reduces the sulfur content of coal, it also reduces the ash content, increases the energy per unit weight of fuel (which reduces coal transportation and pulverization costs), and creates more uniform coal characteristics that can increase boiler efficiency. These benefits can offset much of the cost of coal cleaning. It has been estimated that this fairly simple coal cleaning procedure can reduce sulfur emissions by 10 percent.

Reference: MASTERS, G. and ELA, W. (2014). Introduction to Environmental Engineering and Science. 3rd edition. Upper Saddle River: Pearson.

4. False. Broad-leaved plants show necrosis at 2 to 10 ppm of NO₂, and retardation of growth can occur at concentrations as low as 0.5 ppm.

5. False. Since ozone is usually produced in the atmosphere by photochemical reactions instead of being directly emitted by pollution sources, it is classified as a secondary pollutant, not a primary pollutant. Nonetheless, it is true that ozone is a powerful irritant; eye irritation is an effect of exposure to concentrations as low as 100 ppb, and severe coughing ensues at 2.0 ppm. Chronic exposures to elevated ozone levels are responsible for losses in immune system functions, accelerated aging, and increased susceptibility to other infections.

6. True. Unlike, say, nitrogen dioxide, CO competes with ozone by reacting with OH free radicals to produce a free hydrogen atom. This hydrogen atom then rapidly reacts with oxygen to form the hydroperoxy free radical (HO₂), which may subsequently participate in the formation of ozone. Carbon monoxide oxidation is a slow process and the lifetime of CO in the atmosphere is of the order of several years.

7. False. In actuality, the criteria pollutants generally do not bioaccumulate, whereas hazardous air pollutants do. For that reason, HAPs may have significant effects on long-term health. Other generic distinctions between criteria pollutants and HAPs are listed below.

Criteria air pollutants*	Hazardous air pollutants
Few (6)	Many
Concentrations usually measured in ppm	Concentrations usually measured in ppb
Not bioaccumulated	Bioaccumulated
Lung is primary target organ (except CO)	Many target organs
Human health effects readily available	Human dose-response data rarely available
Effects generally occur in minutes to months	Effects generally occur after long latent periods (years)
Primarily acute effects	Primarily chronic effects
*As regulated under the Clean Air Act, except lead.	

8. True. Anemia is one of the main effects of prolonged exposure to lead in children and adults. There is also evidence for damage to the kidneys, liver and heart, indicating that lead may have a broader toxicological profile than other criteria air pollutants.

9. False. Since the Acid Rain Program went into effect, power plant emissions of sulfur dioxide and nitrogen oxides have declined over 93% and 86%, respectively. The EPA also observes that wet sulfate deposition, a common indicator of acid rain, dropped by 70% in the 2016 – 2018 period relatively to 1989 – 1991. Polluters have given rise to these results by simple yet effective measures such as switching to lower-sulfur coal and adoption of scrubbers. The ARP was anything but mediocre.

10. False. The POCPs are based on the contribution to photochemical ozone formation afforded by ethylene, C₂H₄. The following table lists POCP factors for

some hydrocarbons and aromatics, calculated for a time of 4 – 5 days for areas with high and low background concentrations of NO_x (defined as oxide concentrations above and below 10 ppbv or 0.02 mg/m³ over rural areas).

Substance	POCP	
	Low NO _x (g C ₂ H ₄)/(g gas)	High NO _x (g C ₂ H ₄)/(g gas)
Methane	0.007	0.007
Ethane	0.1	0.1
Propane	0.5	0.4
<i>n</i> -butane	0.5	0.4
Isobutane	0.4	0.3
Ethylene	1.0	1.0
Propylene	0.6	1.0
Acetylene	0.4	0.2
Benzene	0.4	0.2
Toluene	0.5	0.6
Ethylbenzene	0.5	0.6

11. False. The molar mass of CO is 12 + 16 = 28 g/mol. The concentration of CO that corresponds to a NAAQS of 35 ppm follows as

$$[\text{CO}] = \frac{35 \times 10^{-6} \frac{\text{m}^3(\text{CO})}{\text{m}^3(\text{air})} \times 28 \frac{\text{g}}{\text{mol}}}{24.5 \times 10^{-3} \frac{\text{m}^3}{\text{mol}}} = 0.04 \text{ g/m}^3 = \boxed{40 \text{ mg/m}^3}$$

12. True. All we have to do is perform some quick unit conversions,

$$10,800 \frac{\mu\text{g}}{\text{m}^3} \times \frac{1}{10^6} \frac{\text{g}}{\mu\text{g}} \times \frac{1}{1 \frac{\text{g}}{\text{cm}^3}} \times \frac{(10^4 \mu\text{m})^3}{(1 \text{cm})^3} \times \frac{\# \text{particles}}{\frac{4}{3} \pi \left(\frac{0.5 \mu\text{m}}{2}\right)^3} = 1.65 \times 10^{11} \frac{\text{particles}}{\text{m}^3}$$

$$\therefore 1.65 \times 10^{11} \frac{\text{particles}}{\text{m}^3} \times \frac{(1 \text{m})^3}{(100 \text{cm})^3} = \boxed{165,000 \text{ particles/cm}^3}$$

13. True. The settling velocity is given by Stokes' law,

$$v = \frac{\rho g d^2}{18\eta} = \frac{2650 \times 9.81 \times (10 \times 10^{-6})^2}{18 \times (1.8 \times 10^{-5})} = 8.02 \times 10^{-3} \text{ m/s}$$

The time required for the particle to settle is then

$$t = \frac{h}{v} = \frac{2650}{8.02 \times 10^{-3}} = 330,424 \text{ s} = \boxed{3.82 \text{ days}}$$

The particle should settle within 3 days and 20 hours. Needless to say, this problem is an oversimplification of atmospheric particle settlement. One important limitation is the adoption of a constant dynamic viscosity; in reality, as the atmospheric temperature increases from about -1°C at 2600 m to ambient temperature at sea level, the viscosity of air should decrease correspondingly.

14. True. The amount of mercury emitted over the course of a year is

$$E_{\text{Hg}} = 2.5 \times 10^6 \frac{\text{lb}}{\text{yr}} \times \frac{1 \text{ ton}}{2000 \text{ lb}} \times \frac{0.12 \text{ lb Hg}}{1 \text{ ton}} = 150 \text{ lb Hg/yr}$$

or, on a daily basis,

$$E_{\text{Hg}} = \frac{150 \text{ lb Hg/yr}}{365} = \boxed{0.411 \frac{\text{lb Hg}}{\text{day}}}$$

15. False. The operation applies 40 × 365 = 14,600 liters of coating every year, and 0.15 + 0.11 + 0.09 = 0.35 kg VOC per liter of coating. The amount of VOCs produced per year is then 14,600 × 0.35 = 5110 kg. Since 8% of these emissions are retained in a liquid wastestream and 40% are removed by pollution control, the amount of VOCs sent to the atmosphere follows as

$$\dot{m} = 5110 \times 0.92 \times 0.6 = \boxed{2820 \text{ kg VOC/yr}}$$

16. True. Indeed, a tall chimney, a fast wind field, and a high exit velocity leads to increased dispersion and a lower concentration of pollutants.

17. False. A Eulerian model with many closely-spaced nodes (i.e., a fine grid) and unsteady (i.e. time-varying) conditions generally requires much more processing power than a Lagrangian model under the same conditions.

18. False. By inspection, we see that anthropogenic heat flux in an urban environment at 9:00 h is about 65 W/m², while the AHF in a suburban setting at the same time is about 21 W/m²; accordingly, the AHF in the former is about 3.1 times greater than the latter.

P.4 → **Solution**

Statement B is false, in that *increased* heat radiation is an intensifier of heat islands. Increased heat radiation is caused by increased levels of air pollution, the inherently lower solar reflectance of urban materials, and use of urban geometries that trap heat. The other three statements indicate factors that lead to heat islands. Reduced evaporation comes in the form of lack of vegetative cover and widespread use of impermeable surfaces; reduced convection is primarily a consequence of urban designs that slow wind speeds; increased heat storage may be attributed to the high thermal diffusivity of urban materials.

♦ The false statement is **B**.

P.5 → **Solution**

Referring to Table 3, the gas-to-cloth ratio for a shaker baghouse collecting rock dust is 3.0. The total fabric area is then

$$\text{Total fabric area} = \frac{\text{Inlet flow rate}}{\text{Gas-to-cloth ratio}} = \frac{16,200 \text{ ft}^3/\text{min}}{3.0 \text{ ft/min}} = 5400 \text{ ft}^2$$

The surface area of a single bag is $\pi \times d \times h = \pi \times 0.5 \times 15 = 23.6 \text{ ft}^2$, so the number of bags required follows as

$$n_{\text{bags}} = \frac{5400 \text{ ft}^2}{23.6 \frac{\text{ft}^2}{\text{bag}}} = \boxed{229 \text{ bags}}$$

♦ The correct answer is **C**.

P.6 → **Solution**

Area requirements increases nonlinearly with collection efficiency in accordance with the Deutsch-Anderson equation (equation 1),

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

Solving for effective drift velocity gives

$$w = -\frac{Q}{A} \ln(1 - \eta) = -\frac{145}{4000} \times \ln(1 - 0.95) = 0.109 \text{ m/s}$$

To achieve 97 percent efficiency, the collector plate area must be

$$A_{97} = -\frac{Q}{w} \ln(1 - \eta) = -\frac{145}{0.109} \ln(1 - 0.97) = \boxed{4660 \text{ m}^2}$$

Raising the efficiency from 95 to 97 percent requires the plate area to increase about 16.5 percent.

♦ The correct answer is **B**.

P.7 → **Solution**

This is a straightforward application of equation 2,

$$C_{\text{out}} = C_{\text{in}} \exp\left(-\frac{kV}{Q}\right)$$

Applying logarithms and solving for residence time $t = V/Q$, we have

$$C_{\text{out}} = C_{\text{in}} \exp\left(-\frac{kV}{Q}\right) \rightarrow \frac{C_{\text{out}}}{C_{\text{in}}} = \exp\left(-\frac{kV}{Q}\right)$$

$$\therefore \ln\left(\frac{C_{\text{out}}}{C_{\text{in}}}\right) = \ln\left[\exp\left(-\frac{kV}{Q}\right)\right]$$

$$\therefore \ln\left(\frac{1-0.999}{1}\right) = \ln[\exp(-k \times t)]$$

$$\therefore t = \frac{\ln\left(\frac{1-0.999}{1}\right)}{-36} = 0.192 \text{ sec}$$

Appealing to the definition of residence time, we solve for volume to obtain

$$t = \frac{V}{Q} \rightarrow V = Q \times t$$

$$\therefore V = \left(3750 \frac{\text{m}^3}{\text{min}} \times \frac{1 \text{ min}}{60 \text{ sec}}\right) \times 0.192 \text{ sec} = 12 \text{ m}^3$$

This volume corresponds to a length L such that

$$V = \frac{\pi D^2 L}{4} \rightarrow L = \frac{4V}{\pi D^2}$$

$$\therefore L = \frac{4V}{\pi D^2} = \frac{4 \times 12}{\pi \times 1.2^2} = \boxed{10.6 \text{ m}}$$

◆ The correct answer is **D**.

P.8 → Solution

Using equation 3, we can estimate the scattering coefficient,

$$\sigma_s = a + bC = -2.4 \times 10^{-2} + 3.2 \times 10^{-3} C$$

$$\therefore \sigma_s = -2.4 \times 10^{-2} + 3.2 \times 10^{-3} \times 170 = 0.520 \text{ km}^{-1}$$

The extinction coefficient σ_e equals the sum of scattering and absorption coefficients; since $\sigma_s = \sigma_a$, we have $\sigma_e = 0.52 + 0.52 = 1.04 \text{ km}^{-1}$. The limit of visibility is then

$$d_v = \frac{3.91}{\sigma_e} = \frac{3.91}{1.04} = \boxed{3.76 \text{ km}}$$

◆ The correct answer is **B**.

P.9 → Solution

In illustration I, it is early morning, the winds are light, and a radiation inversion extends from the surface to well above the height of the smokestack. There is little up-and-down motion and the plume spreads horizontally; this is a *fanning smoke plume*.

In illustration II, it is later in the morning and the surface air warms quickly and destabilizes as the radiation inversion gradually disappears from the surface upward. However, the air above the chimney is still stable, as indicated by the presence of the inversion. Consequently, vertical motions are confined to the region near the surface. Hence, the smoke mixes downwind, increasing the concentration of pollution at the surface – sometimes to dangerously high levels. This phenomenon is called *fumigation*.

In illustration III, if daytime heating of the ground continues, the depth of atmospheric instability increases. Notice in the illustration that the inversion has completely disappeared. Light-to-moderate winds combine with rising and sinking air to cause the smoke to move up and down in a wavy pattern, producing a *looping smoke plume*.

In illustration IV, the continued rising of warm air and sinking of cool air can cause the temperature profile to equal that of the dry adiabatic rate. In this neutral atmosphere, vertical and horizontal motions are about equal, and the smoke from the stack takes the shape of a cone, forming a *coning smoke plume*.

Finally, in illustration V the sun has set, the ground cools rapidly and the radiation inversion reappears. When the top of the inversion extends upward to slightly above the stack, stable air is near the ground with neutral air above. Because the stable air in the inversion prevents the smoke from mixing downward, the smoke is carried upward, producing a *lofting smoke plume*.

These observations show that smoke plumes provide a clue to the stability of the atmosphere, and knowing the stability yields important information about the dispersion of pollutants.

Reference: AHRENS, C. and HENSON, R. (2019). *Meteorology Today*. 12th edition. Stamford: Cengage Learning.

◆ The correct answer is **D**.

P.10 → Solution

Part 1: Referring to Table 5, for a clear night and a 4-m/s wind, we read an atmospheric stability classification *E*. The next step is to read coefficients from Table 4; for stability *E* and $x \leq 1$ km, we get $a = 50.5$, $c = 22.8$, $d = 0.678$, and $f = -1.3$. Noting that the dispersion coefficients in equations 4 are given in meters when x is in kilometers, we compute the dispersion coefficients

$$\sigma_y = ax^{0.894} = 50.5 \times 0.5^{0.894} = 27.2 \text{ m}$$

and

$$\sigma_z = cx^d + f = 22.8x^{0.678} - 1.3$$

$$\therefore \sigma_z = 22.8 \times 0.5^{0.678} - 1.3 = 13.0 \text{ m}$$

In addition, we have $Q = 24 \text{ g/s} = 24 \times 10^6 \text{ } \mu\text{g/s}$, $u = 4 \text{ m/s}$, and $H = 7 \text{ m}$, so that, substituting in equation 4,

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

$$\therefore C = \frac{(24 \times 10^6)}{\pi \times 4 \times 27.2 \times 13.0} \exp\left(-\frac{7^2}{2 \times 13.0^2}\right) = 4670 \text{ } \mu\text{g/m}^3$$

$$\therefore \boxed{C = 4.67 \text{ mg/m}^3}$$

◆ The correct answer is **A**.

Part 2: Mapping stability = *E* and stack height = 7 m onto Figure 1, we read $(Cu_H/Q)_{\max} \approx 3 \times 10^{-2} \text{ m}^{-2}$. Substituting in equation 5 brings to

$$C_{\max} = \frac{Q}{u_H} \left(\frac{Cu_H}{Q} \right)_{\max} = \frac{24 \times 10^3 \text{ mg/s}}{4 \text{ m/s}} \times (3 \times 10^{-3}) \text{ m}^{-2} = \boxed{18 \text{ mg/m}^3}$$

◆ The correct answer is **B**.

P.11 → Solution

Refer to Table 5. The more unstable the atmosphere, the higher the peak downwind concentration. For wind $\geq 3 \text{ m/s}$, *B* is the most unstable rating and hence should lead to the highest concentration. Mapping this stability rating along with $H = 70 \text{ m}$ onto Figure 1, we read $x_{\max} = 0.6 \text{ km}$ and $(Cu_H/Q)_{\max} \approx 3 \times 10^{-5} \text{ m}^{-2}$. Substituting into equation 5 brings to

$$C_{\max} = \frac{Q}{u_H} \left(\frac{Cu_H}{Q} \right)_{\max} \rightarrow 315 \times 10^{-6} = \frac{Q}{4} \times (3 \times 10^{-5})$$

$$\therefore Q = \frac{4 \times (315 \times 10^{-6})}{3 \times 10^{-5}} = 42 \text{ g/s}$$

For the ground level SO₂ to be maintained below 315 μg/m³, the plant should emit sulfur dioxide at a rate no greater than 42 g/s. Since the plant emits 0.8 g SO₂ per MW of power delivered, the corresponding size must be, at most,

$$\text{Maximum power plant size} = \Pi = 42 \text{ g/s} \times \frac{1 \text{ MW}}{0.8 \text{ g/s}} = \boxed{52.5 \text{ MW}}$$

♦ The correct answer is **C**.

P.12 → Solution

Part 1: For a wind speed of 2.5 m/s and moderate insolation, atmospheric stability is category B (Table 5). Before anything else, we must estimate the wind speed at the effective stack height. Noting from Table 6 that exponent $p = 0.15$ for stability class B in rough terrain, we obtain

$$u_H = u_a \left(\frac{H}{z_a} \right)^p = 2.5 \times \left(\frac{50}{10} \right)^{0.15} = 3.18 \text{ m/s}$$

The next step is to determine the dispersion coefficients. Mapping stability = B and $x = 2$ km onto Table 4, we read coefficients $a = 156$, $c = 108.2$, $d = 1.098$, and $f = 2.0$. Appealing to equations 4, we compute dispersion coefficients

$$\sigma_y = ax^{0.894} = 156 \times 2^{0.894} = 290 \text{ m}$$

and

$$\sigma_z = cx^d + f = 108.2 \times 2^{1.098} + 2.0 = 234 \text{ m}$$

At this point, we evoke the Gaussian plume model,

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

$$\therefore C = \frac{30 \times 10^6}{\pi \times 3.18 \times 290 \times 234} \exp\left(-\frac{50^2}{2 \times 234^2}\right) = \boxed{43.3 \text{ } \mu\text{g/m}^3}$$

♦ The correct answer is **A**.

Part 2: With a stability class B and an effective height of 50 m, we read $x_{max} = 0.55$ km and $(Cu_H/Q)_{max} \approx 6 \times 10^{-5} \text{ m}^{-2}$ from Figure 1. The maximum concentration is then

$$C_{max} = \frac{Q}{u_H} \left(\frac{Cu_H}{Q} \right)_{max} = \frac{30 \times 10^6}{3.18} \times (6 \times 10^{-5}) = \boxed{566 \text{ } \mu\text{g/m}^3}$$

♦ The correct answer is **B**.

Part 3: To compute the concentration of NO at a position different from $y = 0$, we need the complete version of equation 4, namely

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

$$\therefore C(2000,200) = \underbrace{\frac{30 \times 10^6}{\pi \times 3.18 \times 290 \times 234} \exp\left(-\frac{50^2}{2 \times 234^2}\right)}_{=43.3} \times \exp\left(-\frac{200^2}{2 \times 290^2}\right)$$

$$\therefore C(2000,200) = \boxed{34.1 \text{ } \mu\text{g/m}^3}$$

♦ The correct answer is **D**.

P.13 → Solution

Part 1: To begin, we estimate the buoyancy flux parameter,

$$F = v_s g r^2 \left(1 - \frac{T_a}{T_s} \right) = 18 \times 9.81 \times \left(\frac{10}{2} \right)^2 \times \left(1 - \frac{15 + 273}{140 + 273} \right) = 1340 \text{ m}^4/\text{s}^3$$

Since $F > 55 \text{ m}^4/\text{s}^3$, the distance downwind to final plume rise, x_f , is given by

$$x_f = 120F^{0.4} = 120 \times 1340^{0.4} = 2140$$

For neutral/unstable atmospheric conditions, the plume rise may be estimated with equation 8,

$$\Delta h = \frac{1.6F^{1/3}x_f^{2/3}}{u_h} = \frac{1.6 \times 1340^{1/3} \times 2140^{2/3}}{7} = 418 \text{ m}$$

The effective stack height is the sum of plume rise Δh and stack height, that is,

$$H = h + \Delta h = 200 + 418 = \boxed{618 \text{ m}}$$

♦ The correct answer is **B**.

Part 2: For a stable atmosphere, the plume rise is given by equation 7, namely

$$\Delta h = 2.6 \left(\frac{F}{u_h S} \right)^{1/3}$$

In addition to $F = 1340 \text{ m}^4/\text{s}^3$ and $u_h = 7 \text{ m/s}$, we also require parameter S ,

$$S = \frac{g}{T_a} \left(\frac{\Delta T_a}{\Delta z} + 0.01 \right) = \frac{9.81}{15 + 273} \times (0 + 0.01) = 3.41 \times 10^{-4} \text{ s}^{-2}$$

so that

$$\Delta h = 2.6 \times \left[\frac{1340}{7 \times (3.41 \times 10^{-4})} \right]^{1/3} = 214 \text{ m}$$

It remains to compute the effective stack height,

$$H = h + \Delta h = 200 + 214 = \boxed{414 \text{ m}}$$

Notice how the effective stack height for a stable adiabatic atmosphere (414 m) is appreciably lower than the ESH for an unstable atmosphere (618 m).

♦ The correct answer is **C**.

P.14 → **Solution**

The concentration at ground level, x downwind from the source, is given by equation 4, namely

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

Before anything else, we need the effective height H . To determine this quantity, we begin by computing the buoyancy flux parameter F ,

$$F = v_s g r^2 \left(1 - \frac{T_a}{T_x} \right) = 14 \times 9.81 \times 2^2 \times \left(1 - \frac{18 + 273}{125 + 273} \right) = 148 \text{ m}^4/\text{s}^3$$

and parameter S ,

$$S = \frac{g}{T_a} \left(\frac{\Delta T_a}{\Delta z} + 0.01 \right) = \frac{9.81}{18 + 273} \left(\frac{5}{1000} + 0.01 \right) = 5.06 \times 10^{-4} \text{ s}^{-2}$$

The plume rise for a stable atmosphere is given by equation 7,

$$\Delta h = 2.6 \left(\frac{F}{u_h S} \right)^{1/3} = 2.6 \times \left[\frac{148}{4 \times (5.06 \times 10^{-4})} \right]^{1/3} = 109 \text{ m}$$

The effective height is $H = h + \Delta h = 85 + 109 = 194 \text{ m}$. To compute the concentration in question, we also need dispersion coefficients σ_y and σ_z . For a

stability class E and $x \geq 1$ km, we refer to Table 4 and read coefficients $a = 50.5$, $c = 55.4$, $d = 0.305$, and $f = -34.0$. The dispersion coefficients are determined as

$$\sigma_y = ax^{0.894} = 50.5 \times 10^{0.894} = 396 \text{ m}$$

and

$$\sigma_z = cx^d + f = 55.4 \times 10^{0.305} - 34.0 = 77.8 \text{ m}$$

It remains to compute the concentration 10 km downwind of the plant,

$$C = \frac{200 \times 10^6}{\pi \times 4 \times 396 \times 77.8} \times \exp\left(-\frac{194^2}{2 \times 77.8^2}\right) = \boxed{23.1 \mu\text{g}/\text{m}^3}$$

◆ The correct answer is **A**.

➤ ANSWER SUMMARY

Problem CS		A
Problem 2	2.1	C
	2.2	B
Problem 3		T/F
Problem 4		B
Problem 5		C
Problem 6		B
Problem 7		D
Problem 8		A
Problem 9		D
Problem 10	10.1	A
	10.2	B
Problem 11		C
Problem 12	12.1	A
	12.2	B
	12.3	D
Problem 13	13.1	B
	13.2	C
Problem 14		A

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