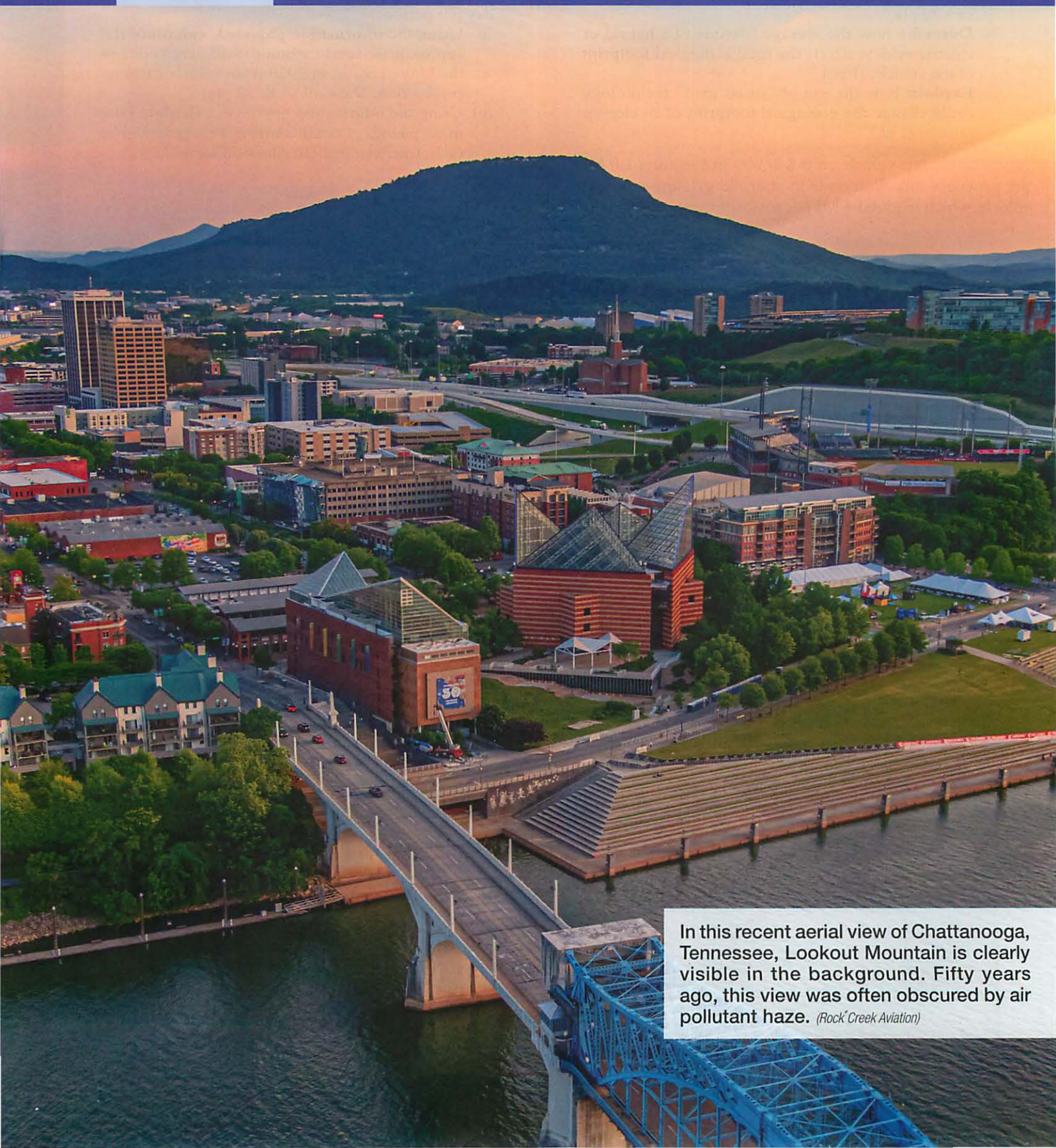
3. Although hybrid and electric vehicles release less carbon dioxide per distance traveled than internal combustion engine (gasoline-powered) vehicles, there remains some debate over whether hybrid vehicles are better for the environment and whether their overall efficiency is greater.
   (a) **Identify** TWO reasons why hybrid and electric vehicles might be less energy-efficient than gas-powered cars. (2 pts.)
   (b) **Describe** how the average lifetime of a hybrid or electric vehicle affects the total ecological footprint of the vehicle. (1 pt.)
   (c) **Explain** how the use of "smart grid" technology could change the ecological footprint of an electric vehicle. (1 pt.)

A new all-electric vehicle costs $40,000 and requires 1.5 MJ per passenger-mile. You trade in your old gasoline-powered vehicle, which required 4 MJ per passenger-mile, for $2,000.

   (d) If a gallon of gasoline contains 20 MJ and costs $4.00, **calculate** how many miles you must drive before your purchase becomes cost effective. Show all work. (2 pts.)
   (e) Burning a gallon of gasoline released 19 pounds of carbon dioxide into the atmosphere. In 2020, Americans burned approximately 123 billion gallons of gasoline in vehicles, or about 1.022 gallons per day per person.
      (i) Using the information provided, **calculate** the approximate total carbon dioxide emissions of the United States in 2020 from vehicle gasoline combustion. Show all work. (2 pts.)
      (ii) Using the information provided, **calculate** how many pounds of carbon dioxide were produced by each American in 2020. Show all work. (2 pts.)

UNIT 7

# Atmospheric Pollution



In this recent aerial view of Chattanooga, Tennessee, Lookout Mountain is clearly visible in the background. Fifty years ago, this view was often obscured by air pollutant haze. *(Rock Creek Aviation)*




MODULE 42 Introduction to Air Pollution
MODULE 43 Photochemical Smog, Thermal Inversions, Atmospheric $CO_2$ and Particulates
MODULE 44 Indoor Air Pollutants
MODULE 45 Reduction of Air Pollutants
MODULE 46 Acid Rain and Noise Pollution


# CASE STUDY

## Cleaning Up in Chattanooga

The fall of 2016 was not kind to Chattanooga, Tennessee. Nearby wildfires covered downtown Chattanooga with a smoky haze resulting in a number of poor air quality days in a city that is generally known for very good air quality. A few years earlier, dust storms in the West had also reduced the generally good air quality of the city. Protecting air quality in cities in the United States is something of a challenge. Regulators and government officials can impose standards, but a vast array of natural and human-caused regional and continental pollutants can conspire to cause local air pollution problems for any number of reasons. Local geography, direction of prevailing winds, the activities of other cities and sometimes other countries, and many other factors can affect air quality. Unfortunately, most of these factors are beyond the control of one city. The story of Chattanooga is representative of many cities in the United States and around the world.

Chattanooga sits along the Tennessee River in a natural basin formed by the Appalachian Mountains, one of which — Lookout Mountain — rises 600 m (1,970 feet) over the city. After the Civil War, foundries, textile mills, and other industrial plants were quickly built, and Chattanooga became one of the leading manufacturing centers in the nation.

The economic boom in Chattanooga had an environmental cost. Because it is surrounded by mountains, it traps pollutants that hover above the city. By 1957, Chattanooga had the third-worst particulate pollution in the country and rates of respiratory diseases were well above the national average. Over the next decade conditions worsened and by the 1960s, people were often unable to see Lookout Mountain even from a short distance of a quarter mile. In 1969, a U.S. survey of the nation's air quality confirmed what many Chattanooga residents suspected: Their city topped the list of the worst cities in the United States for particulate air pollution.

**By 1957, Chattanooga had the third-worst particulate pollution in the country and rates of respiratory diseases were well above the national average.**

Obviously, the poor quality of the air needed to be addressed. In 1969, Chattanooga and the county in which it is located created its own air pollution legislation by enacting the Air Pollution Control Ordinance. It controlled the emissions of sulfur oxides, allowed open burning by permit only, placed regulations on odors and dust, outlawed visible automobile emissions, capped the sulfur content of fuel at 4 percent, and limited visible emissions from industry. At the same time, the city and county governments implemented new pollution monitoring techniques to ensure that the ordinance was being followed.

The city and county governments, along with private industry, spent approximately $40 million on the cleanup effort. Actions to improve air quality did not hinder business, as some people feared, but created new industrial opportunities related to the cleanup effort, such as the establishment of a local manufacturer of smokestack scrubbers. As a result of all these measures, in 1972 — just 3 years after passage of the city ordinance and 2 years after the passage of the Federal Clean Air Act — Chattanooga achieved compliance with Clean Air Act air-quality standards.

The people of Chattanooga and the local governments recognized that keeping their air clean and maintaining economic sustainability would be an ongoing effort. To maintain their newly improved air quality, the city government and local businesses began several programs. One such program was a comprehensive recycling program,

chosen as an alternative to a waste incinerator that would have added more particulates to the air. Public and private sectors successfully partnered to achieve both environmental and economic sustainability in creating the largest municipal fleet of electric buses in the United States, manufactured by another local business.

Unfortunately, while Chattanooga's efforts dramatically reduced the levels of particulate pollutants, the concentration of ozone, mostly from automotive pollutant precursors within and beyond the city limits, continued to climb. Ozone concentrations exceeded the 1997 air quality standard of 0.08 parts per million by volume set by the Environmental Protection Agency. Chattanooga has responded to the new air pollution problem in the same way it faced the particulate pollutant problem of the 1960s — through a combined effort of government, public, and local industries. The city and county governments formed an Early Action Compact with the EPA, agreeing to improve ozone concentrations ahead of EPA requirements in return for not being labeled a "non-attainment area," a designation that can result in the loss of federal highway funds and create a negative image that makes industrial recruitment and economic development more difficult. Like the 1969 Air Pollution Control Ordinance, the new Early Action Compact called for a concerted effort by private and public sectors and included educating people on how they can take action to limit ozone production on high-ozone days.

Chattanooga attained the 0.08 parts per million standard in 2007, 2 years ahead of schedule. Then, national legislation again lowered the ozone standard, this time to 0.075 parts per million. By 2011, before the dust storms from the West and the local forest fires, Chattanooga had met the new, lower ozone standard. In 2017, the American Lung Association rated Chattanooga one of the cleanest cities in the United States and in 2020 it received its best rankings ever for ozone and particulate pollution. In 2022, massive fires in the western United States did not adversely impact Chattanooga. However, residents know that to achieve their goals of an economically vibrant city with clean air, they must continue to encourage cooperation among government, people, and business. They also need fewer dust storms from the West and fewer distant and nearby forest fires, which are, unfortunately, not in their control.

*Sources:* Chattanooga Area Chamber of Commerce, *Summary of the Chattanooga Area Chamber of Commerce's Position on Strengthening the National Ambient Air Quality Standard for Ozone*, 2010, www.chattanoogachamber.com; S. Johnson, Report: Chattanooga air quality among best in U.S., *Chattanooga Times Free Press*, April 19, 2017.

### Practice your science skills

1. **Concept Explanation:** By 1957, Chattanooga's pollution levels were some of the highest in the country and rates of respiratory diseases were well above the national average. The foundries, textile mills, and other industrial plants built after the Civil War released large amounts of air pollution. Describe the category of air pollutants that cause respiratory diseases in Chattanooga.
2. **Concept Explanation:** Chattanooga's efforts dramatically reduced the levels of particulate pollutants; but the concentration of ozone, mostly from automotive pollutant precursors within and beyond the city limits, continued to climb. Describe the environmental process of ozone formation.
3. **Concept Explanation:** The mountains surrounding Chattanooga trap hovering air pollutants produced by industry. Describe the atmospheric and geological conditions that would trap large amounts of pollution in the city.

Air pollution occurs over terrestrial, aquatic, and marine natural systems and it also occurs in human-made indoor systems. To understand air pollution and its effects, we need to examine the wide variety of air pollutants, where they come from, and the harm they cause after they are released into the air. In this unit we will identify the major air pollutants found around the globe and discuss the specific air pollution conditions that promote photochemical smog and thermal inversions. We will describe natural sources of carbon dioxide and particulates. We will identify indoor air pollutants and consider air pollution control measures currently used. And finally, we will conclude the unit with a discussion of acid rain and noise pollution. After reading the modules within this unit, you will be able to recognize the physical, chemical, and biological consequences of human activities on our atmosphere, and you will recognize that with appropriate measures, in many instances, improved air quality is achievable.

# Module 42



# Introduction to Air Pollution

**Air pollution** is defined as the introduction of chemicals, particulate matter, or microorganisms into the atmosphere at concentrations high enough to harm plants, animals, and materials such as buildings, or to alter ecosystems. Generally, the term air pollution refers to pollution in the troposphere, the first 16 km (10 miles) of the atmosphere above the surface of Earth. Tropospheric pollution is also sometimes called ground-level pollution. In this module we will examine the major air pollutants that occur in the troposphere and identify where they come from and what harm they cause. We will also distinguish between primary and secondary pollutants.

**Learning Goals**

After reading this module you should be able to

**42-1** identify the sources and effects of major air pollutants.

**42-2** describe primary and secondary pollutants and how they change over time.

**42-1** What are the sources and effects of major air pollutants?

## Air pollution sources are widespread and their effects vary

Since one of the major repositories for air pollutants is the atmosphere, which envelops the entire globe, we must think of the air pollution system as a global system. In fact, air pollution can travel from one side of the globe to the other. For example, in recent years, sulfur emissions in Asia have been responsible for acidic rainfall on the West Coast of the United States (**FIGURE 42.1**).

The air pollution system has many inputs, which are the sources of pollution. It also has many outputs, which are components of the atmosphere and biosphere that remove air pollutants. Air pollution inputs can come from automobiles on the ground, airplanes in the sky, or tree leaves that emit volatile gases. Similarly, air pollution can be removed or altered by plant surfaces, soil, and components of the atmosphere such as clouds, particles, or gases. As a starting point for understanding the global air pollution system, we will identify the major pollutants and where they come from.



**FIGURE 42.1 Air pollution and visibility.** Air pollutants can reduce visibility in cities, such as this location in China. Some of those same air pollutants can also be transported long distances and cause problems far from the source. Pollutants such as sulfur dioxide from China have been detected on the West Coast of the United States as acid deposition. *(Natalie Behring/Panos Pictures)*

### Classifying Pollutants

Even though air pollution has existed for millennia, both the specific definition of pollution and the classification of a substance as a pollutant have changed considerably in the

**Air pollution** The introduction of chemicals, particulate matter, or microorganisms into the atmosphere at concentrations high enough to harm plants, animals, and materials such as buildings, or to alter ecosystems.

last few decades. The atmosphere is a public resource—in effect, a global commons—and consequently the science of air pollution is closely intertwined with political and social perspectives. In formulating the U.S. Clean Air Act of 1970 and subsequent amendments, legislators used information from environmental scientists and human health scientists on the most important air pollutants to monitor and control. The original act identified six pollutants that significantly threaten human well-being, ecosystems, and structures: sulfur dioxide, nitrogen oxides, carbon monoxide, particulate matter, tropospheric ozone, and lead. These were called "criteria air pollutants" because under the Clean Air Act, the U.S. Environmental Protection Agency (EPA) uses allowable concentrations of each pollutant to set criteria for whether the air in a particular location should be considered "clean."

Although carbon dioxide was not included among the major air pollutants identified in the 1970s, today it is widely accepted that carbon dioxide is altering ecosystems in a substantial way. In 2007, the U.S. Supreme Court ruled that carbon dioxide should be considered an air pollutant under the Clean Air Act, and in 2012, a federal appeals court agreed that the EPA is required to impose limits on harmful greenhouse gas emissions, including carbon dioxide. In addition, volatile organic compounds and mercury, though not officially listed in the Clean Air Act, are commonly measured air pollutants that have the potential to be harmful. Traditionally, the six criteria air pollutants originally identified in the Clean Air Act of 1970 are the most commonly identified air pollutants. Carbon dioxide may or may not be considered an air pollutant, depending on the context of the statement or question.

## Coal and Oil

Different fuels are the sources of different types and amounts of air pollutants. In general, coal combustion releases the greatest amount of air pollutants per unit of energy obtained, including carbon dioxide, sulfur dioxide, toxic metals, and particulates. Oil releases somewhat fewer pollutants than coal. It will release less carbon dioxide per unit of energy released and less sulfur dioxide. Oil also releases fewer particulates and toxic metals than coal. Natural gas, as you might have guessed, is even cleaner. It releases half the carbon dioxide of coal per unit of energy obtained and relatively small amounts of sulfur dioxide, metals, and particulates. The combustion of all fuels in the atmosphere results in the release of nitrogen oxides, which contribute to ozone formation and acid rain. Combustion of fuels also results in release of carbon monoxide and hydrocarbons.

**Sulfur dioxide ($SO_2$)** A corrosive gas that comes primarily from combustion of fuels such as coal and oil, including diesel fuel from trucks.

The sources and effects of the major air pollutants, including the six criteria air pollutants, are summarized in **TABLE 42.1**. Let's take a closer look at each of these major air pollutants: sulfur dioxide, nitrogen oxides, carbon monoxide, carbon dioxide, particulate matter, photochemical oxidants, lead and other metals, and volatile organic compounds.

### Sulfur Dioxide

**Sulfur dioxide ($SO_2$)** is a corrosive gas that comes primarily from combustion of fuels such as coal and oil, including diesel fuel from trucks. Since 2010, diesel sold for on-road vehicles has been ultra-low sulfur diesel, so it contributes to less sulfur pollution than it used to. Sulfur dioxide emissions affect air quality in many ways: It is a respiratory irritant and can adversely affect plant tissue, and it also is a precursor to one component of acid rain. Because all plants and animals contain sulfur in varying amounts, the fossil fuels derived from their remains contain sulfur. When these fuels are combusted, the sulfur combines with oxygen to form sulfur dioxide. Sulfur dioxide is also released in large quantities from volcanoes during volcanic eruptions and can be released, though in much smaller quantities, during forest fires.

**AP® Exam Tip**

Always be as specific as you can when answering questions about air pollution. Give the specific pollutant name or compound rather than referring to "air pollution" broadly.

### Nitrogen Oxides

Nitrogen oxides are generically designated $NO_x$, with the X indicating that there may be either one or two oxygen atoms per nitrogen atom: nitrogen oxide (NO), a colorless, odorless gas; and nitrogen dioxide ($NO_2$), a pungent, reddish-brown gas, respectively. When we use the term nitrogen oxides in our discussion, we will be referring to either nitrogen oxide or nitrogen dioxide since they easily transform from one to the other in the atmosphere. The atmosphere is 78 percent nitrogen gas ($N_2$), and all combustion in the atmosphere leads to the formation of nitrogen oxides. Motor vehicles and stationary fossil fuel combustion are the primary anthropogenic sources of nitrogen oxides, which can transform to nitric acid and eventually acid rain. Natural sources of nitrogen oxides include forest fires, lightning, and microbial activity in soils. Atmospheric nitrogen oxides play a role in forming ozone and other components of smog. We will take a closer look at this process in Module 43.

**TABLE 42.1 Major air pollutants**

| Compound | Symbol | Human-derived sources | Effects/Impacts |
|---|---|---|---|
| **Criteria air pollutants** | | | |
| Sulfur dioxide | $SO_2$ | • Combustion of fuels that contain sulfur, including coal, oil, gasoline | • Respiratory irritant, can exacerbate asthma and other respiratory ailments<br>• $SO_2$ gas can harm stomata and other plant tissue<br>• Converts to sulfuric acid in atmosphere, which is harmful to aquatic life and some vegetation |
| Nitrogen oxides | $NO_x$ | • All combustion in the atmosphere including fossil fuel combustion, wood, and other biomass burning | • Respiratory irritant, increases susceptibility to respiratory infection<br>• An ozone precursor, leads to formation of photochemical smog<br>• Converts to nitric acid in atmosphere, which is harmful to aquatic life and some vegetation<br>• Contributes to over-fertilization of terrestrial and aquatic systems |
| Carbon monoxide | CO | • Incomplete combustion of any kind<br>• Malfunctioning exhaust systems and poorly ventilated cooking fires | • Bonds to hemoglobin, thereby interfering with oxygen transport in the bloodstream<br>• Causes headaches at low concentrations<br>• Can cause death with prolonged exposure at high concentrations |
| Particulate matter | $PM_{10}$ (smaller than 10 micrometers)<br>$PM_{2.5}$ (2.5 micrometers and smaller) | • Combustion of coal, oil, and diesel, and of biofuels such as manure and wood<br>• Agriculture, road construction, and other activities that mobilize soil, soot, and dust | • Can exacerbate respiratory and cardiovascular disease and reduce lung function<br>• May lead to premature death<br>• Reduces visibility and contributes to haze and smog; correlated with heart disease and higher incidence of lung cancer |
| Lead | Pb | • Gasoline additive, oil and gasoline, coal, old paint | • Impairs central nervous system<br>• At low concentrations, can have measurable effects on learning and ability to concentrate |
| Ozone | $O_3$ | • A secondary pollutant formed by the combination of sunlight, water, oxygen, VOCs, and $NO_x$ | • Reduces lung function and exacerbates respiratory symptoms<br>• Degrades plant surfaces<br>• Damages materials such as rubber and plastic |
| **Other air pollutants** | | | |
| Volatile organic compounds | VOC | • Evaporation of fuels, solvents, paints<br>• Improper combustion of fuels such as gasoline | • A precursor to ozone formation |
| Mercury | Hg | • Coal, oil, gold mining | • Impairs central nervous system<br>• Bioaccumulates in the food chain |
| Carbon dioxide | $CO_2$ | • Combustion of fossil fuels and clearing of land | • Affects climate and alters ecosystems by increasing greenhouse gas concentrations |

## Carbon Monoxide and Carbon Dioxide

As you first learned in Unit 6, Carbon monoxide (CO) is a colorless, odorless gas that is formed during incomplete combustion of all fuels including fossil fuels, and therefore is a common pollutant in vehicle exhaust and most other combustion processes. Carbon monoxide can be a significant component of air pollution in urban areas. It also can be a dangerous indoor air pollutant in developed countries when exhaust systems from natural gas heaters malfunction. Carbon monoxide is a particular problem in developing countries, where people may cook with manure, charcoal, or kerosene indoors.

Carbon dioxide ($CO_2$), as you learned in Unit 6, is a colorless, odorless gas that is formed during the complete combustion of matter, including fossil fuels and biomass. While it has not historically been considered an air pollutant, its classification as such is undergoing a transition. It is absorbed by plants during photosynthesis and is released during respiration.

In general, the complete combustion of matter that produces carbon dioxide is more desirable than the incomplete combustion that produces carbon monoxide and other pollutants. Burning fossil fuels has contributed additional carbon dioxide to the atmosphere and has led to it being considered a major pollutant. Carbon dioxide concentrations have been steadily increasing in conjunction with the increase in the use of fossil fuels, and in 2022, concentrations exceeded 415 parts per million. This topic will be covered in more detail later on in the textbook when we discuss greenhouse gases and climate change.

## Particulate Matter

Particulate matter (PM), also called particulates or particles, is solid or liquid particles suspended in air. It may also be referred to as "soot particles." Particulate matter comes from the combustion of wood, animal manure and other biofuels, coal, oil, and gasoline. In the developed world, it is most commonly known as a class of pollutants released from the combustion of fuels such as coal and oil. Diesel-powered vehicles give off more particulate matter, in the form of black soot particles, than do gasoline-powered vehicles. Particulate matter can also come from road dust and rock-crushing operations. Volcanoes, forest fires, and dust storms are important natural sources of particulate matter. Particulate matter contributes to **haze**, which is reduced visibility. We will discuss particulate matter in greater detail in Module 43.

## Photochemical Oxidants

Oxides are reactive compounds that remove electrons from other substances. **Photochemical oxidants** are a class of air pollutants formed as a result of sunlight (*photo*) acting on chemical compounds such as nitrogen oxides and sulfur dioxide. There are many photochemical oxidants, and they degrade plant tissue, human respiratory tissue, and construction materials such as brick and concrete. However, environmental scientists frequently focus on one particular photochemical oxidant: ozone. Ozone ($O_3$), as we first learned in Unit 4, is a secondary pollutant made up of three oxygen atoms bound together. It is harmful to both plants and animals and impairs respiratory function.

In the presence of sulfur and nitrogen oxides, photochemical oxidants can enhance the formation of certain particulate matter, which contributes to scattering light. The resulting mixture is called **smog**, a mixture of oxidants and particulate matter. We will examine smog in greater detail in the next module.

**Haze** Reduced visibility.

**Photochemical oxidant** A class of air pollutants formed as a result of sunlight acting on chemical compounds such as nitrogen oxides and sulfur dioxide.

**Smog** A type of air pollution that is a mixture of oxidants and particulate matter.

**Lead (Pb)** A trace metal that occurs naturally in rocks and soils, is present in small concentrations in coal and oil and is a neurotoxin.

**Hydrocarbons** Pollutant compounds that contain carbon-hydrogen bonds, such as gasoline and other fossil fuels, lighter fluid, dry-cleaning fluid, oil-based paints, and perfumes.

## Lead and Other Metals

**Lead (Pb)** is a trace metal that occurs naturally in rocks and soils, is present in small concentrations in fuels including oil and coal, and is a neurotoxin. Supplemental lead compounds were used as a gasoline additive for many years to improve vehicle performance. During that time, lead compounds released into the air traveled with the prevailing winds and were deposited on the ground by rain or snow. They became pervasive around the globe, including in polar regions far from combustion sources.

One provision of the Clean Air Act required that lead be phased out as a gasoline additive in the United States between 1975 and 1996, and since then its concentration in the air has dropped considerably. A campaign to phase out lead use in gasoline globally finally succeeded. In July 2021, the United Nations Environment Program announced that lead is no longer being added to gasoline anywhere in the world. Another persistent source of lead is lead-based paint in buildings constructed in the 1960s or earlier. When the paint peels off, the resulting dust or chips can be toxic to the central nervous system and can affect learning and intelligence, particularly for young children who may ingest the dust or chips.

Mercury (Hg), another trace metal, is also found in coal and oil and, like lead, is toxic to the central nervous system of humans and other organisms. Mercury emissions into the atmosphere in the United States is primarily from the combustion of fossil fuels, especially coal, and waste incineration. However, due to reductions in both coal combustion and waste incineration, the concentrations of mercury in both air and water have decreased in recent years. "Do the Math: Unleaded versus Leaded Gasoline" shows you how to calculate lead emissions from leaded and unleaded gasoline.

## Volatile Organic Compounds

Organic compounds that evaporate at typical atmospheric temperatures are called volatile organic compounds (VOCs). Many VOCs are **hydrocarbons**—pollutant compounds that contain carbon-hydrogen bonds—such as gasoline and other fossil fuels, lighter fluid, dry-cleaning fluid, oil-based paints, and perfumes. Compounds that give off a strong aroma are often VOCs since the fact that you can smell them indicates that the chemicals are easily released into the air. VOCs play an important role in the formation of photochemical oxidants such as ozone. VOCs are not necessarily hazardous; many, such as VOCs given off by conifer trees, cause no direct harm. VOCs are not currently

## DO THE MATH Unleaded versus Leaded Gasoline

Preparing for the AP® Exam

In 1970, when gasoline in the United States contained the additive tetra-ethyl lead, there was roughly 0.5 g of lead added to each liter of gasoline. How much lead was emitted to the air per year by one car if that car burned 2,000 liters of gasoline per year?

0.5 g lead/liter × 2,000 liters/year = 1,000 g of lead released in a year from one car in 1970

**YOUR TURN** Although lead is not added to gasoline today, gasoline typically contains about 0.01 g of lead per liter from lead that is in the petroleum before the gasoline is refined. How much lead is released from one car that burns 2,000 liters of unleaded gasoline per year?

considered a criteria air pollutant, but because they can lead to the formation of photochemical oxidants, they have the potential to be harmful and are therefore of concern to air pollution scientists. It is important to be aware that hydrocarbons such as gasoline become air pollutants when they evaporate and enter the air from usage and spillage. They also become air pollutants when they pass through the internal combustion engine and are emitted in a raw or partially combusted form. Small engines like lawn mowers are notorious for releasing through their exhaust system a large fraction of their fuel as raw, uncombusted hydrocarbons. Understanding what comes directly from an emission source and what undergoes transformations in the atmosphere after emission is the subject of the next section.

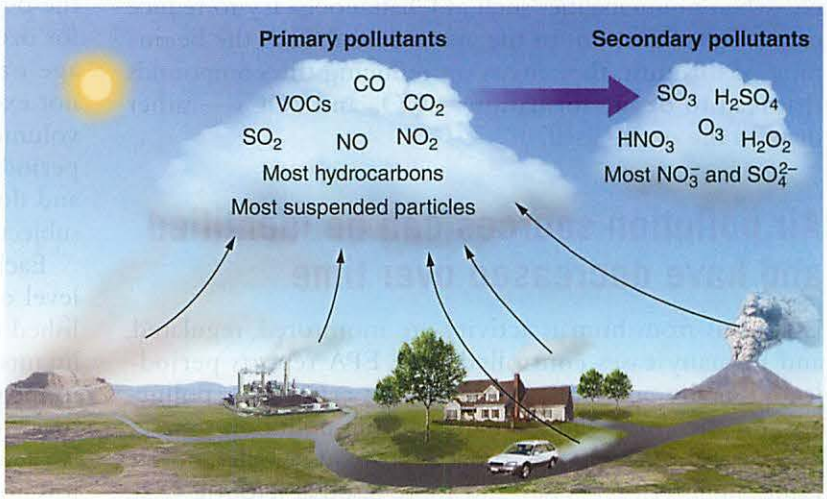



**FIGURE 42.2 Primary and secondary air pollutants.** The transformation from primary to secondary pollutants requires a number of factors including sunlight, water (clouds), and the appropriate temperature.

**42-2** What are primary and secondary pollutants and how do they change over time?

## Primary and secondary pollutants have decreased over time

When trying to understand pollution sources and effects, and when attempting to reduce pollution emissions, it is important to know if a particular pollutant is coming directly from an emission source such as a smokestack or tailpipe, or if it has undergone transformations in the atmosphere after emission. Depending on the source, pollutants in the air can be categorized as primary or secondary.

### AP® Exam Tip

Make sure that you know the difference between primary and secondary pollutants and can describe how each type of pollutant is formed.

### Primary Pollutants

**Primary pollutants** are polluting compounds that come directly out of a smokestack, exhaust pipe, or natural emission source. As you can see in FIGURE 42.2, they include CO, $CO_2$, $SO_2$, $NO_x$, and most suspended particulate matter. Many VOCs are also primary pollutants. For example, as gasoline is burned in a car, it volatilizes from a liquid to a vapor, some of which is emitted from the exhaust pipe in an uncombusted form. The effect is more pronounced if the car is not operating efficiently. The resulting VOC becomes a primary air pollutant.

### Secondary Pollutants

**Secondary pollutants** are primary pollutants that have undergone transformation in the presence of sunlight, water,

**Primary pollutant** A polluting compound that comes directly out of a smokestack, exhaust pipe, or natural emission source.

**Secondary pollutant** A primary pollutant that has undergone transformation in the presence of sunlight, water, oxygen, or other compounds.

oxygen, or other compounds. Because solar radiation provides energy for many of these transformations, and because water is usually involved, the conversion to secondary pollutants occurs more rapidly during the day and in wet environments.

Ozone is an example of a secondary pollutant. Ozone is formed in the atmosphere as a result of the emission of the primary air pollutants $NO_x$ and VOCs in the presence of sunlight. The main components of acid deposition—sulfate ($SO_4^{2-}$) and nitrate ($NO_3^-$)—are also secondary pollutants. These secondary pollutants will be discussed further in Module 43.

When trying to control secondary pollutants, it is necessary to consider the primary pollutants that create them, as well as factors that may lead to the formation, breakdown, or reduction in the secondary pollutants themselves. For example, when municipalities such as Chattanooga try to reduce ozone concentrations in the air, as described at the beginning of this unit, they focus on reducing the compounds that lead to ozone formation—$NO_x$ and VOCs—rather than on the ozone itself.

## Air pollution sources can be identified and have decreased over time

Emissions from human activity are monitored, regulated, and in many cases controlled. The EPA reports periodically on the emission sources of the criteria air pollutants for the entire United States, listing pollution sources in a variety of categories, such as on-road vehicles, power plants, industrial processes, and waste disposal (**FIGURE 42.3**). Highway vehicles are the largest sources of carbon monoxide and nitrogen oxides. Nonroad mobile sources such as farm equipment, airplanes, and boats are sources of carbon monoxide and nitrogen oxides as well. Electricity generation and other stationary sources of fuel combustion are the major sources of anthropogenic sulfur dioxide. A substantial amount of the sulfur dioxide emissions come from the 19 percent of electricity that is fueled by coal. Particulate matter comes from a variety of sources including stationary fuel combustion of coal and oil.

Through the National Ambient Air Quality Standards (NAAQS), the EPA specifies concentration limits for each air pollutant. The NAAQS notes a concentration for each pollutant that should not be exceeded over a specified time period. Our discussion of air pollution in Chattanooga at the beginning of this unit partially described the standard for ozone: For each locality in the United States, the average ozone concentration for any 8-hour period should not exceed 0.075 parts of ozone per million parts of air by volume more than 4 days per year, averaged over a 3-year period. If a locality violates the ozone air-quality standard and does not make an attempt to improve air quality, it is subject to penalties.

Each year, the EPA issues a report that shows the national level of the six criteria air pollutants relative to the published standards. **FIGURE 42.4** shows that all criteria air pollutants have decreased considerably in the United States in recent decades to well below published standards. Only ozone concentrations have been close to the NAAQS in the last few years. Lead has decreased most significantly because it is no longer added to gasoline.

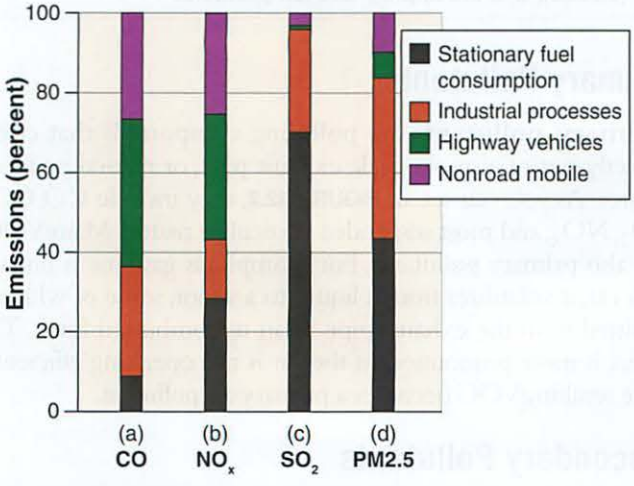



**FIGURE 42.3 Emission sources of criteria air pollutants for the United States in 2020.** Recent EPA data show that highway vehicles are the largest source of (a) carbon monoxide and (b) nitrogen oxides. The major sources of (c) anthropogenic sulfur dioxide and (d) particulate matter are stationary fuel combustion from industrial plants and power plants that generate electricity with coal. *(Data from Our Nation's Air USEPA 2020, https://gispub.epa.gov/air/trendsreport/2020)*

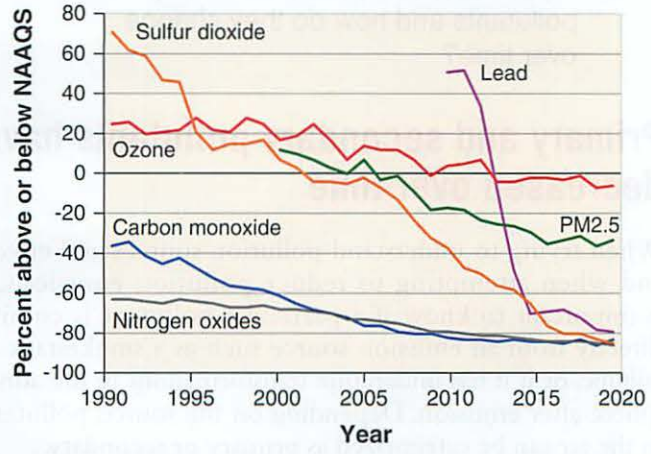



**FIGURE 42.4 Criteria air pollutant trends for the past 30 years.** Trends in the criteria air pollutants in the United States between 1990 through 2020 are shown. All criteria air pollutants have decreased during this time period. Note that data are shown as a percentage above or below the national air quality standard. Lead has shown the most substantial decrease of any pollutant in recent years. *(Data from EPA Our Nation's Air, Trends Through 2020, https://gispub.epa.gov/air/trendsreport/2021/#introduction)*

The situation is less positive in other parts of the world. Large areas in Germany, Poland, and the Czech Republic contain a great deal of "brown" coal or lignite that provides fuel for nearby coal-fired power plants and other industries. Emissions from combustion of this high-sulfur-content coal once caused this region to become one of the most polluted areas in the world. In addition to human health problems such as respiratory illnesses, forest ecosystems in this region have also been damaged in the last 40 years. In many parts of Asia, air quality has been so severely impaired by particulate matter and sulfates that visibility has been reduced, in some cases by more than 20 percent. Many of the most polluted cities in the world are in China and India.

In this module we identified the major air pollutants and described their sources and effects. The Clean Air Act identified six "criteria" air pollutants. Coal combustion releases the greatest amount of air pollutants per unit of energy obtained, including carbon dioxide, sulfur dioxide, toxic metals, and particulates. Oil releases fewer pollutants than coal. Air pollutants can be both primary, meaning directly emitted from pollution sources, or secondary, meaning they undergo transformations in the atmosphere. In the next module we will examine photochemical smog, inversions, particulates, and carbon dioxide more closely.

# Module 42 AP® Review

Preparing for the AP® Exam

## Learning Goals Revisited

### 42-1 What are the sources and effects of major air pollutants?

Air pollution occurs across the troposphere, the portion of the atmosphere closest to Earth's surface. Coal is the dirtiest fossil fuel and releases the greatest amount of carbon dioxide, sulfur dioxide, and particulates per unit of energy obtained. Oil emits fewer pollutants than coal and natural gas releases fewer pollutants than oil. Nitrogen oxides lead to ozone formation, smog, and acid rain. Lead concentrations in air have decreased considerably due to EPA regulations banning it as a gasoline additive.

### 42-2 What are primary and secondary pollutants and how do they change over time?

Primary pollutants are released directly from the emission source while secondary pollutants undergo transformations in the atmosphere in the presence of sunlight and water at the appropriate temperatures. Implementation of air quality standards has led to reductions in most air pollutants, especially lead.

## AP® Practice Questions

Preparing for the AP® Exam

### Multiple-Choice Questions

1. Which form of legislation is responsible for regulating lead in fuels, which ultimately ends up in the atmosphere?
   (a) Safe Drinking Water Act
   (b) Clean Air Act
   (c) Montreal Protocol
   (d) Clean Water Act

2. Secondary pollutants tend to be the result of a combination of a pollutant and _____.
   (a) water
   (b) soil
   (c) photochemical smog
   (d) ozone

3. Which is a major source of sulfur dioxide found in nature?
   (a) ruminant animals
   (b) lightning strikes
   (c) plant emissions
   (d) volcanoes

4. Carbon monoxide
   (a) increases lung cancer rates.
   (b) leads to the formation of photochemical smog.
   (c) is most problematic in rural areas.
   (d) is produced by incomplete combustion.

5. Which criteria air pollutant has seen the most substantial decrease in recent years?
   (a) carbon monoxide
   (b) nitrogen oxides
   (c) ozone
   (d) lead

*Use the passage below to answer questions 6 & 7:*

Air quality data were gathered near a downtown area at 5:00 PM, when most businesses close, and at 8:00 PM. Readings show a high concentration of volatile organic compounds (VOCs) at 5:00 PM, and a reduction of them at 8:00 PM. The same data also show low concentrations of ozone ($O_3$) at 5:00 PM, and an increase at 8:00 PM.

6. Which of the following explains the difference in concentrations of VOCs and Ozone at the two reading times?
   (a) The VOCs are a primary pollutant that react and are reduced in quantity.
   (b) Ozone comes from vehicle emissions that are used more in evenings.
   (c) VOCs are a secondary pollutant that peak in the afternoon.
   (d) Ozone is a primary pollutant that peaks in the evenings.

7. Which of the following claims is supported by the evidence in the paragraph?
   (a) Burning fossil fuels increases ozone levels.
   (b) Vehicle emissions cause VOCs to decrease.
   (c) Ozone forms as a secondary pollutant from VOCs.
   (d) Industrial processes are responsible for a drop in VOCs.

## Free-Response Question

There are a number of fossil fuel sources that provide energy.

| | Tons of pollutant per 1,000 tons of fuel | | |
|---|---|---|---|
| | $NO_2$ | $SO_2$ | Particulates |
| Natural gas | 3.5 | 0.0 | 0.0 |
| Bituminous Coal | 63.6 | 9.2 | 65.3 |
| Fuel oil | 5.2 | 35.3 | 0.3 |

(Data from https://www.researchgate.net/figure/Levels-of-emissions-of-pollutants-into-the-atmosphere-when-burning-various-types-of-fuel_tbl2_351818804)

(a) **Identify** the fuel that releases the least amount of overall pollutants into the atmosphere. (1 pt.)
(b) **Identify** the fuel source that releases the highest amount of overall pollutants into the atmosphere. (1 pt.)
(c) **Describe** why the fuel source in part (b) typically has more pollutants. (1 pt.)
(d) **Describe** which fuel source is used primarily for transportation purposes. (1 pt.)
(e) **Explain** which fuel source is more prevalent in powering homes. (1 pt.)
(f) **Describe** one environmental drawback, other than air pollution, of using bituminous coal as a fuel source. (1 pt.)
(g) A group of researchers gathered data on particulate matter at four different times of the day:

12:00 AM – 113 ppm
6:00 AM – 105 ppm
12:00 PM – 91 ppm
6:00 PM – 93 ppm

   (i) **Identify** two possible hypotheses for this investigation. (2 pts.)
   (ii) **Identify** the dependent variable for this investigation. (1 pt.)
   (iii) **Describe** a modification the researchers could do to improve the accuracy of their investigation. (1 pt.)

# Module 43



# Photochemical Smog, Thermal Inversions, Atmospheric $CO_2$, and Particulates

As we saw in the last module air quality in the United States has greatly improved in recent decades. However, some cities and regions of the United States continue to experience high air pollution events, often related to smog formation. In this module we will examine photochemical smog, which is a problem in the United States and elsewhere in the world, and thermal inversions that can lead to serious air pollution episodes and human health problems. We will also describe natural sources of $CO_2$ and particulates, the latter of which can contribute to photochemical smog.

**Learning Goals**

After reading this module you should be able to

- **43-1** explain photochemical smog and how to reduce it.
- **43-2** describe thermal inversions and how they relate to air pollution.
- **43-3** describe the natural sources of particulates and $CO_2$.

**43-1** What is photochemical smog and how can we reduce it?

## Photochemical smog is a complex combination of compounds and it can be reduced by decreasing emissions of its precursors

A recent news article stated that "More than 4 in 10 Americans live in counties where the air is unhealthy to breathe." You might think this was from a newspaper in the 1970s, before the Clean Air Act was fully in effect. But in *State of the Air 2021*, the American Lung Association reported that 40 percent of people in the United States—over 135 million people—were exposed to air that did not comply with the maximum allowable ozone concentration. An allowable ozone concentration is more than 75 parts of ozone per billion parts of air averaged over an 8-hour period. Although sulfur, nitrogen, and carbon monoxide pollution have been reduced well below the specified standards since the Clean Air Act was implemented, controlling the secondary pollutants photochemical smog and ozone have proven to be especially challenging. As we saw in Figure 42.4 in the previous module average ozone concentrations in 2020 were just below the Clean Air Act standards. For ozone, the average is taken over 8 hours during a day. If the average concentration is just below the standard, that means that shorter-term ozone concentrations, such as those measured hourly, are sometimes higher than the CAA standards. For example, in September 2020, Los Angeles, California, experienced its worst smog in 30 years. **FIGURE 43.1** shows the hourly ozone and nitrogen oxide concentrations during one day, September 4. As you can see, the ozone concentration

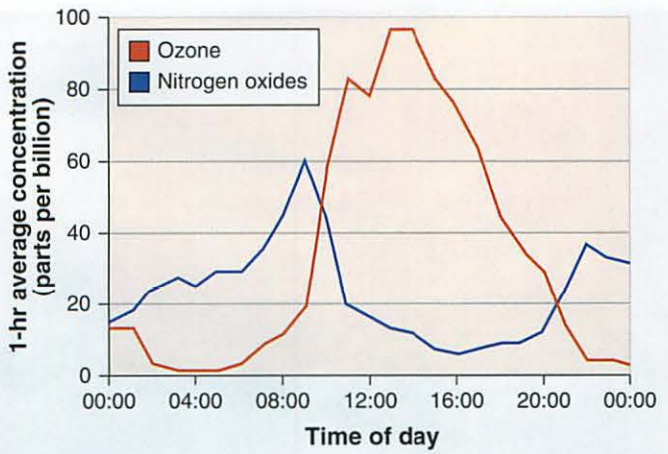



**FIGURE 43.1 Tropospheric ozone concentrations measured each hour in Los Angeles, California, on September 4, 2020.** In most cities, mid- to late-afternoon ozone concentrations are higher than the daily average as a result of an increase in nitrogen oxides in the early morning hours. *(Data from South Coast Air Quality Management District, http://www.aqmd.gov/)*

at 6 AM is less than 5 parts per billion (ppb) and at 2 PM it was more than 95 ppb. The reason for this large daytime increase lies in the chemistry of smog formation and the behavior of the atmosphere during changing weather conditions. These various environmental factors make smog formation complex and somewhat difficult to predict and even more difficult to reduce.

## Chemistry of Ozone and Photochemical Smog Formation

We defined smog in the last module as a combination of oxidants and particulate matter. The word smog was derived by combining smoke and fog. Smog is partly responsible for the hazy view and reduced sunlight observed in many cities. Smog can be divided into two categories: photochemical smog and sulfurous smog. **Photochemical smog** is dominated by oxidants such as ozone and is sometimes called **Los Angeles–type smog** or **brown smog**. FIGURE 43.2a shows Los Angeles during the September, 2020 smog event represented by the data in Figure 43.1. Nearby forest fires also contributed to the poor air quality during this time period. **Sulfurous smog** is dominated by sulfur dioxide, sulfate compounds, and particulate matter and is also called **London-type smog**, **gray smog**, or **industrial smog**. Figure 43.2b shows the city of London, England during a gray smog event.

**Photochemical smog** Smog that is dominated by oxidants such as ozone. *Also known as* **Los Angeles–type smog; brown smog.**

**Sulfurous smog** Smog dominated by sulfur dioxide, sulfate compounds, and particulate matter. *Also known as* **London-type smog; gray smog; industrial smog.**

### AP® Exam Tip

Remember that the prefix "photo" means light. You should be able to explain that photochemical smog is caused in part by the presence of sunlight. And on days when there are more hours of sunlight, if all other factors remain equal, there will be more photochemical smog.

In addition to human health problems, particulate matter and photochemical oxidants also cause economic harm, since poor visibility in popular vacation destinations can reduce tourism revenues for recreation areas, including lower incomes for hotels and restaurants in these areas.

Today, Los Angeles–type brown photochemical smog is still a problem in many U.S. cities. The formation of this photochemical smog is complex and still not well understood. A number of pollutants are involved, and they undergo a series of complex transformations in the atmosphere that involve both intensity and number of hours of sunlight as well as water and the presence of volatile organic compounds (VOCs).

FIGURE 43.3 shows a portion of the chemical process that creates photochemical smog. The first part of the process, shown in Figure 43.3a, takes place during the day, in the presence of sunlight, including ultraviolet energy from the Sun, which warms the atmosphere. When an abundance of nitrogen oxides is present in the atmosphere, with very few VOCs present, nitrogen dioxide ($NO_2$) splits to form nitrogen oxide (NO) and a free oxygen atom (O). In the presence of energy inputs from sunlight, this free oxygen atom combines with diatomic oxygen ($O_2$) to form ozone ($O_3$). When there is abundant nitrogen dioxide in the atmosphere and the Sun provides light and warms the atmosphere, ozone accumulates. Because of the dependence on sunlight and temperature, ozone concentrations are normally greatest in the early to middle

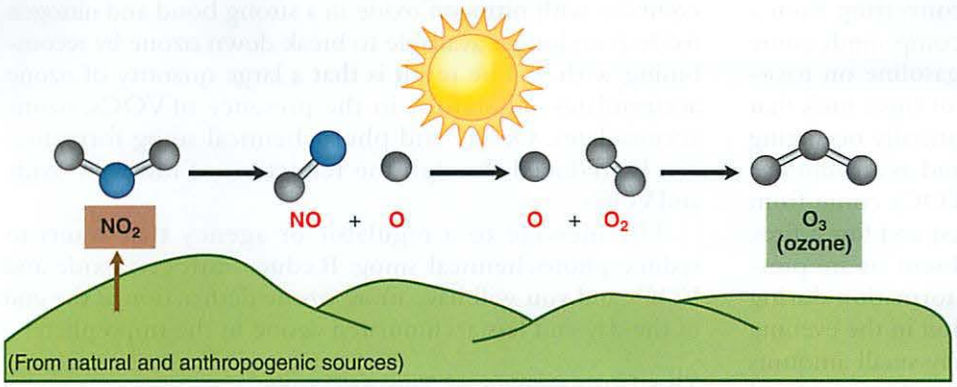


(a)

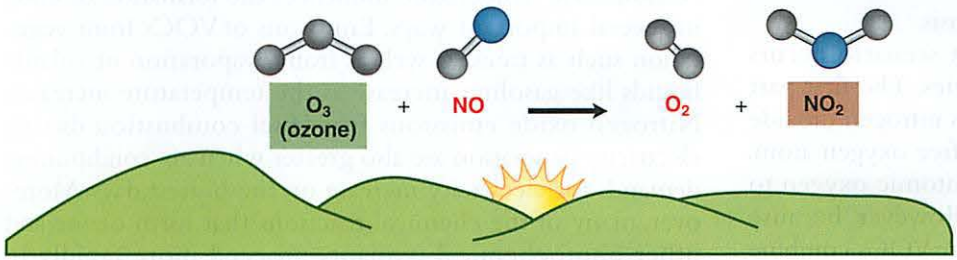


(b)

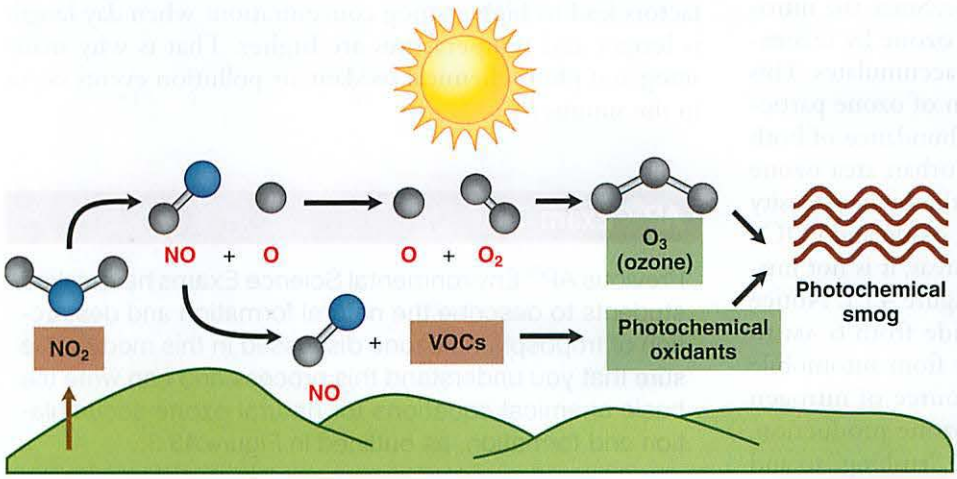
**FIGURE 43.2 There are two different types of smog.** (a) Los Angeles–type brown smog. The smog seen here, photographed in Los Angeles, September 2020, is also a result of nearby wildfires. (b) London-type smog, gray smog, also known as industrial smog. The smog seen here was photographed in 2014. *(a: Citizen of the Planet/Alamy Stock Photo; b: Dinendra Haria/Alamy Stock Photo)*




(a) Natural ozone accumulation




(b) Natural ozone destruction




(c) Buildup of photochemical smog

**FIGURE 43.3 Tropospheric ozone and photochemical smog formation.** (a) In the absence of VOCs, ozone will form during the daylight hours. (b) After sunset, the ozone will break down. (c) In the presence of VOCs, ozone will form during the daylight hours. The VOCs combine with nitrogen oxides to form photochemical oxidants, which reduce the amount of ozone that will break down later and contribute to prolonged periods of photochemical smog.

afternoon and they are also highest in the summer months, when there is the greatest number of hours of sunlight.

Figure 43.3b shows that a few hours later, when sunlight intensity decreases and nitrogen oxide is still present in the atmosphere, the ozone combines with nitrogen oxide (NO), and re-forms into $O_2$ + $NO_2$. This is referred to as ozone destruction and it is a natural process that happens in the latter part of every day and evening. But sometimes, there are compounds in the air that interfere with the natural ozone destruction that normally occurs in the latter part of the day as the Sun goes down.

In order to explore this further, we first need to discuss volatile organic compounds (VOCs). We described VOCs as having a strong aroma, stating that if you can smell them, this indicates that the chemicals within the VOC are easily released into the air. This means that the VOCs either **evaporate**, the process of converting from a liquid to a gas

**Evaporate** The process of converting from a liquid to a gas or vapor.

or vapor, or **sublimate**, the process of converting from a solid to a gas or vapor. Volatile organic compounds come from human activity such as spilling of gasoline on pavement. They also come from combustion of fossil fuels that release VOCs such as **formaldehyde**, a naturally occurring compound that is used as a preservative and as an adhesive in plywood and carpeting. In addition, VOCs come from natural sources such as tree leaves in a forest and forest fires. When volatile organic compounds are absent or are present in small amounts, the cycle of ozone formation during the day (Figure 43.3a) and ozone destruction in the evening (Figure 43.3b) occurs. As a result, relatively small amounts of photochemical smog accumulate. This can be considered the natural cycle of ozone formation and ozone destruction that occurs around the world on a daily basis.

As shown in Figure 43.3c, a different scenario occurs when VOCs are present in larger quantities. The first part of the process is the same: Sunlight causes nitrogen dioxide to break apart into nitrogen oxide and a free oxygen atom. The free oxygen atom combines with diatomic oxygen to form ozone. And ozone accumulates. However, because VOCs are present in larger quantities, more VOCs combine with nitrogen oxide in a strong bond and nitrogen oxide is no longer available to combine with ozone. Since the nitrogen oxide is not available to break down ozone by recombining with it, a larger amount of ozone accumulates. This explains, in part, the daytime accumulation of ozone particularly in urban areas that experience an abundance of both VOCs and nitrogen dioxide. Part of the urban area ozone accumulation problem occurs because of the higher density of automobiles that release both nitrogen oxide and VOCs. Although smog is associated with urban areas, it is not limited to such areas. Take another look at Figure 43.1. Notice that there is an increase in nitrogen oxide from 6 AM to 9 AM. The nitrogen oxide comes primarily from automobile exhaust during "rush hour," and is the source of nitrogen oxide needed in Figure 43.3a to cause ozone production. Rush hour is so named because people are "rushing" to and from work, so although rush hour time varies by city and by country, the approximate times of rush hour are from 7 AM to 9 AM and from 5 PM to 8 PM. To summarize this complex series of reactions in the atmosphere: Sunlight, including ultraviolet radiation from the Sun, causes nitrogen dioxide to break apart into nitrogen oxide and a free oxygen atom which combines with diatomic oxygen to form ozone. Ozone accumulates. In the absence of VOCs, the nitrogen oxide accumulates in the atmosphere and later in the day it contributes to ozone destruction. However, when air pollutant VOCs are present in large quantities, VOCs combine with nitrogen oxide in a strong bond and nitrogen oxide is no longer available to break down ozone by recombining with it. The result is that a large quantity of ozone accumulates. Therefore, in the presence of VOCs, ozone accumulates. Ozone and photochemical smog formation can be reduced through the reduction of nitrogen oxide and VOCs.

The message to a regulator or agency that wants to reduce photochemical smog: Reduce nitrogen oxide and VOCs and you will have more ozone destruction at the end of the day and less accumulated ozone in the troposphere!

**Sublimate** The process of converting from a solid to a gas or vapor.

**Formaldehyde** A naturally occurring compound that is used as a preservative and as an adhesive in plywood and carpeting.

## The Importance of Temperature

Atmospheric temperature influences the formation of smog in several important ways. Emissions of VOCs from vegetation such as trees, as well as from evaporation of volatile liquids like gasoline, increase as the temperature increases. Nitrogen oxide emissions from fuel combustion during electricity generation are also greater when air-conditioning demands for electricity increase on the hottest days. Moreover, many of the chemical reactions that form ozone and other photochemical oxidants proceed more rapidly in sunny conditions at higher temperatures. These and other factors lead to higher smog concentrations when day length is longer and temperatures are higher. That is why many smog and photochemical oxidant air pollution events occur in the summer.

### AP® Exam Tip

Previous AP® Environmental Science Exams have asked students to describe the natural formation and destruction of tropospheric ozone discussed in this module. Be sure that you understand this process and can write the basic chemical equations for natural ozone accumulation and formation, as outlined in Figure 43.3.

## Smog and Human Health

Secondary pollutants such as smog and photochemical oxidants, including ozone, can affect human health in a number of ways. They are responsible for burning and itchy eyes and can irritate the nose and throat, causing coughing and a scratchy, sore throat. They can make it harder to breathe deeply and cause pain when taking a deep breath. They can also inflame the air passageways and lungs, making them more susceptible to infection. And they aggravate existing lung conditions such as asthma (constriction and inflammation of the airway to the lungs), emphysema (a disease affecting the air sacs or alveoli in the lungs), and bronchitis (an inflammation of the bronchial tubes that transport air to the lungs). The U.S. Environmental Protection Agency reports that long-term exposure to ozone is possibly one of many factors that causes asthma to develop. The U.S.

Centers for Disease Control reports that smog is responsible for both decreased lung capacity and increased hospital admissions for asthma and causes some number of premature deaths each year. When smog levels are above a certain level, many public health officials recommend that people reduce or eliminate outdoor activity like cycling or going for a run. Most smart phone weather apps give an air quality index for cities susceptible to high concentrations of smog and inform residents when it is advisable to limit time outside. However, people in lower income groups who may be more dependent on public transportation may have no choice but to be outside, for example, while waiting for a bus, during poor air quality events.

### AP® Exam Tip

Remember to be specific when answering questions about air pollution effects on human health. You should provide more details than simply stating that air pollution causes respiratory problems. Identify specific pollutants such as sulfur dioxide and ozone and specific conditions such as asthma, bronchitis, and emphysema.

There is one more factor, a combination of air temperature and topography of an urban location and its surroundings, that can influence smog accumulation. This factor is called a thermal inversion.

**43-2** What are thermal inversions and how do they relate to air pollution?

## Thermal inversions trap air pollutants close to Earth's surface

Temperature also influences air pollution conditions in more complex ways. Normally, temperature decreases as altitude increases. As shown in **FIGURE 43.4a**, the warmest air is closest to Earth. This warm air, which is less dense than the colder air above it, can easily rise, dispersing pollutants into the upper atmosphere. This allows pollutants from the surface to be reduced or diluted by all of the atmosphere above. However, during a **thermal inversion**—shown in Figure 43.4b—the typical temperature gradient shown in Figure 43.4a is flipped: a relatively warm layer of air at mid-altitude covers a layer of cold, dense air below. This layer of warm air that traps emissions is known as an **inversion layer**. Because in a thermal inversion the air closest to the surface of Earth is denser than the air above it, the cool air and the pollutants within it do not rise. Thus, the inversion layer traps pollutants that accumulate beneath it close to the ground. These trapped emissions, mostly smog and particulates, can cause a severe pollution event. Thermal inversions that create pollution events are particularly common in certain cities, where high concentrations of vehicle exhaust and industrial emissions are easily trapped by the inversion layer.

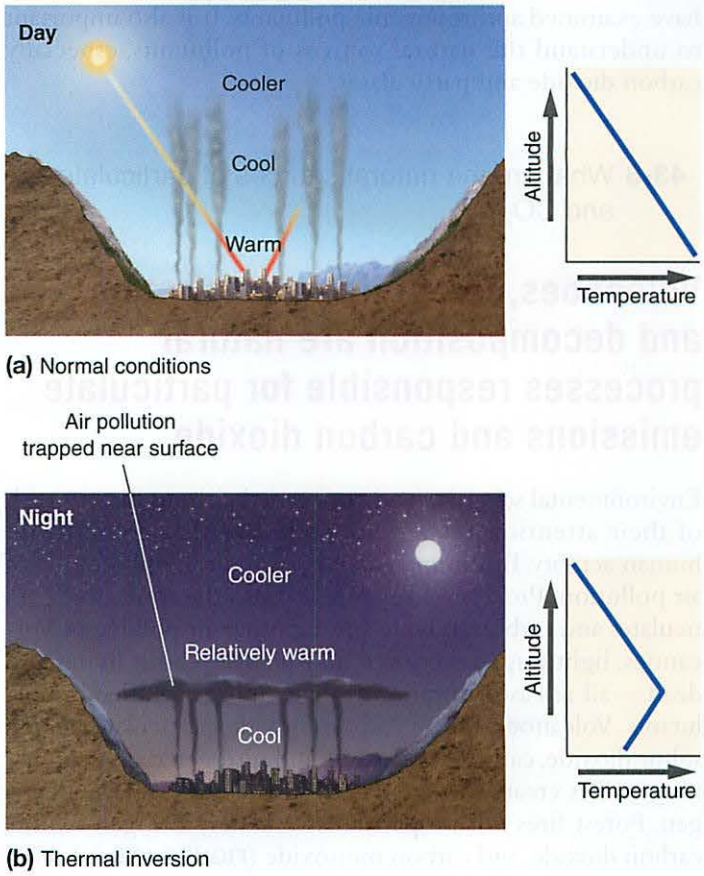



**FIGURE 43.4 A thermal inversion.** (a) Under normal conditions, where temperatures decrease with increasing altitude, emissions rise into the atmosphere. (b) When a mid-altitude, relatively warm inversion layer blankets a cooler layer, emissions are trapped and accumulate.

Thermal inversions can also lead to problems resulting from other forms of pollution. A striking example occurred in spring 1998 in the northern Chinese city of Tianjin. A cold spell that occurred after the city had shut off its district heating system for the season led many households to use individual coal-burning stoves for heat. A temperature inversion trapped the carbon monoxide and particulate matter from the coal used in these stoves and caused over 1,000 people to suffer carbon monoxide poisoning or respiratory ailments from the polluted air. Eleven people died. Inversions are a natural process although some researchers have begun to investigate whether climate change has led to an increase in the number of inversions that occur each year around the world. Here and in the previous module we

**Thermal inversion** An atmospheric condition in which a relatively warm layer of air at mid-altitude covers a layer of cold, dense air below.

**Inversion layer** The layer of warm air that traps emissions in a thermal inversion.

have examined anthropogenic pollutants. It is also important to understand the natural sources of pollutants, especially carbon dioxide and particulates.

**43-3** What are the natural sources of particulates and $CO_2$?

## Volcanoes, forest fires, respiration, and decomposition are natural processes responsible for particulate emissions and carbon dioxide

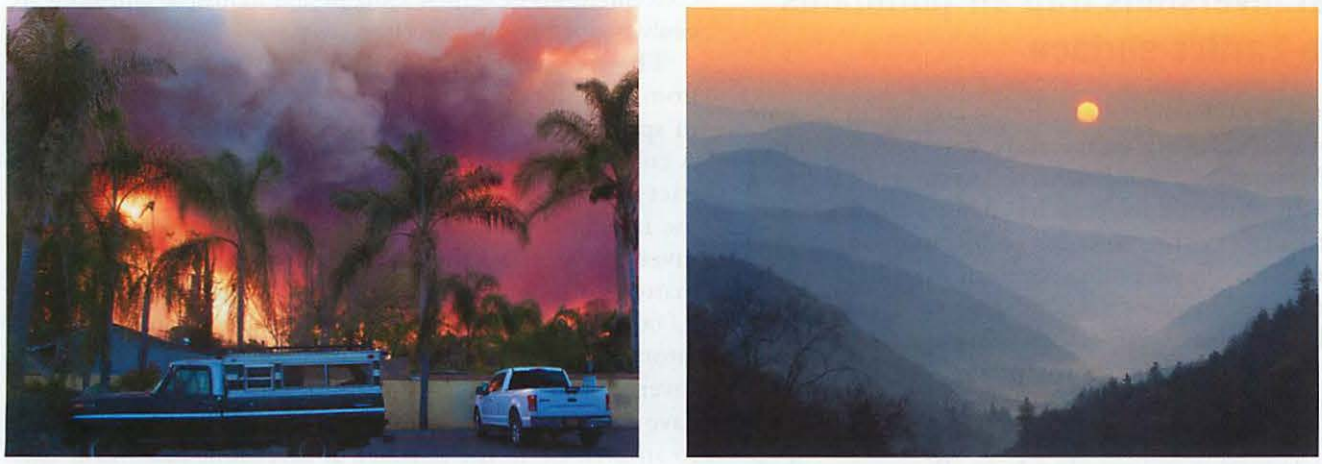
Environmental scientists and concerned citizens direct much of their attention toward air pollution that comes from human activity. But human activity is not the only source of air pollution. Processes in nature are also the sources of particulates and carbon dioxide among other air pollutants. Volcanoes, lightning, forest fires, and plants—both living and dead—all release compounds that can be classified as pollutants. Volcanoes release carbon dioxide, particulate matter, sulfur dioxide, carbon monoxide, and nitrogen oxides. Lightning strikes create nitrogen oxides from atmospheric nitrogen. Forest fires release particulate matter, nitrogen oxides, carbon dioxide, and carbon monoxide (**FIGURE 43.5a**). Living plants release a variety of VOCs, including terpenes. The fragrant smell from conifer trees such as pine and fir and the smell from citrus fruits are mostly from terpenes; though we enjoy their fragrance, they can be precursors to photochemical smog. Long before anthropogenic pollution was common, the natural VOCs from plants gave rise to smog and photochemical oxidant pollution—hence the names of the forested mountain ranges in the southeastern United States, the Blue Ridge and the Smoky Mountains, which were given their names by their indigenous residents who predated the use of modern combustion fuels (Figure 43.5b).

### Natural Sources of Particulates

Large nonindustrial areas such as agricultural fields can give rise to particulate matter when they are plowed, as happened in the Dust Bowl of the 1930s. Averaged globally, sulfur dioxide emissions are 30 percent natural, nitrogen oxide emissions are 44 percent natural, and volatile organic compound emissions are 89 percent natural. However, in certain locations, such as North America, the anthropogenic contribution is much greater, perhaps as much as 95 percent for nitrogen oxides and sulfur dioxide.

The effects of these various compounds, especially when major natural events occur, depend in part on natural conditions such as wind direction. In May 1980, the prevailing westerly winds carried volcanic emissions from a massive eruption of Mount St. Helens in Washington State and distributed particulate matter and sulfur oxides from the volcano across the United States. The rainfall pH was noticeably lower in the eastern United States that summer due to the sulfur oxides emitted by Mount St. Helens.

Particulate matter is a frequent pollutant from natural sources. Volcanoes, forest fires, and dust storms are all events that result in the release of particulate matter into the atmosphere. **FIGURE 43.6** shows the sources of particulate matter and its effects. Particulate matter ranges in size from 0.01 micrometer ($\mu$m) to 100 $\mu$m (1 micrometer = 0.000001 m). For comparison, a human hair has a diameter of roughly



(a) (b)

**FIGURE 43.5 Natural sources of air pollution.** There are many natural sources of air pollution, including volcanoes, lightning strikes, forest fires, and plants. (a) A forest fire in Ojai, California, produces air pollution. (b) The Great Smoky Mountains were named for the natural air pollutants that reduce visibility and give the landscape a smoky appearance. *(a: Bill Boch/Getty Images; b: Bill Lea/Dembinsky Photo Associates/Alamy)*

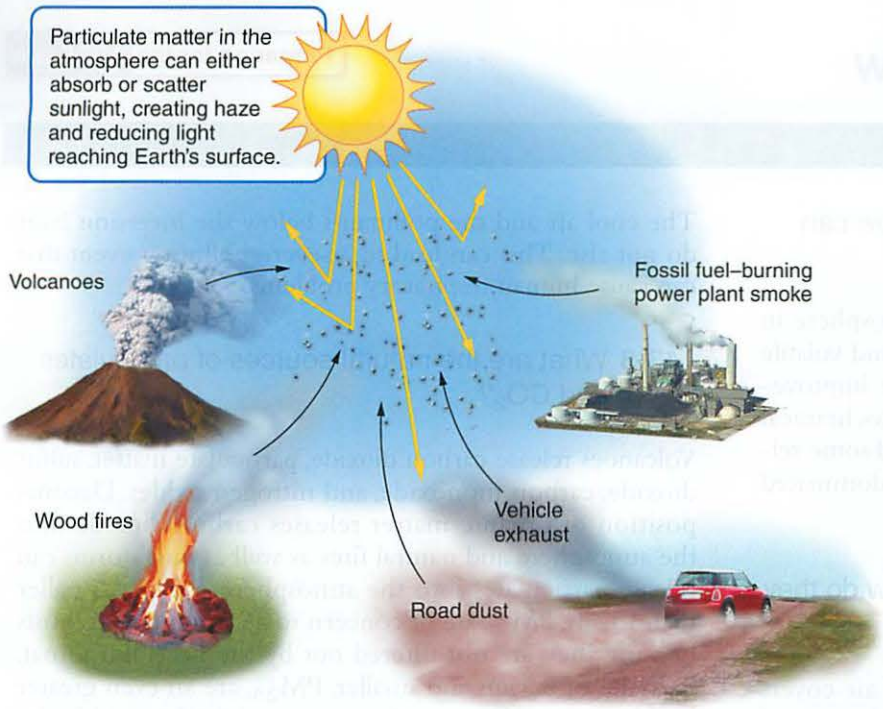



**FIGURE 43.6 The sources of particulate matter and its effects.** Particulate matter can be natural as well as anthropogenic. Particulate matter in the atmosphere ranges considerably in size and can absorb or scatter light, which creates a haze and reduces the light that reaches the surface of Earth.

50 to 100 $\mu$m. Particulate matter larger than 10 $\mu$m is usually filtered out by the nose and throat; particulate matter of this size is not regulated by the EPA. Particles smaller than 10 $\mu$m are called Particulate Matter-10, written as $\mathbf{PM_{10}}$, and are of concern to air pollution scientists because they are not filtered out by the nose and throat and can be deposited deep within the respiratory tract. Particles of 2.5 $\mu$m and smaller, called $\mathbf{PM_{2.5}}$, are an even greater health concern because they can travel further within the respiratory tract and they tend to be composed of more toxic substances than particles in larger size ranges. They are also associated with a higher incidence of lung cancer.

Particulate matter also scatters and absorbs sunlight. If the atmospheric concentration of particulate matter is high enough, as it would be immediately following a large forest fire or a volcanic eruption, incoming solar radiation in the region will be reduced enough to affect photosynthesis. This happened in 1816, a year after a large volcanic eruption in Java released more than 150 million metric tons of particles that slowly spread around the globe, reducing and scattering sunlight and creating haze. That year is commonly referred to as the year without a summer. Haze, which we described as reduced visibility in Module 42, occurs when particulate matter from air pollution scatters light. As we saw earlier in this module, ozone and photochemical oxidants can also play an important indirect role in the formation of haze.

## Natural Sources of Carbon Dioxide

We have referred to photosynthesis and respiration several times throughout this text. Carbon dioxide is a by-product of respiration, decomposition, and combustion. All three processes are similar in that they convert an energy source such as biomass or sugar into energy, water, and carbon dioxide. As we saw in Figure 6.1, respiration is the opposite of photosynthesis: Cells convert sugar and oxygen into energy, carbon dioxide, and water. So respiration is one natural source of carbon dioxide. We also learned in Module 6 that there are two types of respiration: aerobic, or with oxygen, and anaerobic, in the absence of oxygen. Both types of respiration result in producing carbon dioxide. Decomposition also occurs in the presence or absence of oxygen, and globally respiration and decomposition are important natural sources of carbon dioxide. Finally, combustion of biomass in fires also results in the release of carbon dioxide. The decomposition reactions can be represented by

Aerobic decomposition (oxygen present):
$C_6H_{12}O_6 + 6\,O_2 \rightarrow 6\,CO_2 + 6\,H_2O + \text{energy}$

For decomposition of organic matter in the absence of oxygen, we use the aerobic respiration formula that we presented in Module 6

Anaerobic decomposition (oxygen not present):
$C_6H_{12}O_6 \rightarrow 3\,CO_2 + 3\,CH_4 + \text{less energy}$

In this module we examined the conditions under which photochemical smog forms and is destroyed. We described the connection between nitrogen oxide, volatile organic compounds, and ozone formation, accumulation, and destruction. Thermal inversions occur when the air temperature at the surface of Earth is cooler than higher up. This will trap air pollutants close to Earth's surface, giving rise to harmful air pollution events. Carbon dioxide and particulate matter both have natural and human sources. In the next module we will examine indoor air pollutants, some of which are derived from outdoor pollutants.

**$PM_{10}$** Particles smaller than 10 $\mu$m are called Particulate Matter-10 and are not filtered out by the nose and throat and can be deposited deep within the respiratory tract.

**$PM_{2.5}$** Particles of size 2.5 $\mu$m and smaller can travel further within the respiratory tract and are of even greater health concern.

# Module 43 AP® Review

Preparing for the AP® Exam

## Learning Goals Revisited

### 43-1 What is photochemical smog and how can we reduce it?

Photochemical smog accumulates in the troposphere in the presence of sunlight when nitrogen oxides and volatile organic compounds are present. Despite many improvements in air quality in the United States, photochemical smog is still a problem in a number of urban and some relatively rural areas. Different types of smog are dominated by different compounds.

### 43-2 What are thermal inversions and how do they relate to air pollution?

During a thermal inversion, a warm layer of air covers a colder layer below it. The warm layer that is trapped between two cooler layers is known as an inversion layer. The cool air and the pollutants below the inversion layer do not rise. This can lead to a severe pollution event that can cause human respiratory problems.

### 43-3 What are the natural sources of particulates and $CO_2$?

Volcanoes release carbon dioxide, particulate matter, sulfur dioxide, carbon monoxide, and nitrogen oxides. Decomposition of organic matter releases carbon dioxide into the atmosphere and natural fires as well as dust storms can release particulates into the atmosphere. Particles smaller than 10 $\mu$m, $PM_{10}$, are of concern to air pollution scientists because they are not filtered out by the nose and throat. Particles of 2.5 $\mu$m and smaller, $PM_{2.5}$, are an even greater health concern because they can travel further within the respiratory tract and cause even greater harm.

## AP® Practice Questions

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### Multiple-Choice Questions

1. The data below show sulfur dioxide and nitrogen dioxide levels within an urban metro area. Which time of day would have the highest likelihood of photochemical smog formation?

| Time of day | $SO_2$ (PPM) | $NO_2$ (PPM) |
|---|---|---|
| 8:00 AM | 0.1 | 0.2 |
| 11:00 AM | 0.2 | 0.2 |
| 2:00 PM | 0.3 | 0.4 |
| 5:00 PM | 0.6 | 0.8 |

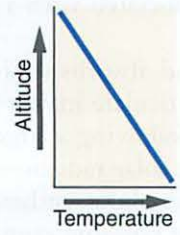
(a) 8:00 AM
(b) 11:00 AM
(c) 2:00 PM
(d) 5:00 PM

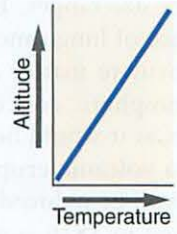
2. Thermal inversions
(a) increase the rate of smog formation.
(b) trap high concentrations of pollution at ground level.
(c) result in lower levels of particulate matter.
(d) are caused by high levels of precipitation.

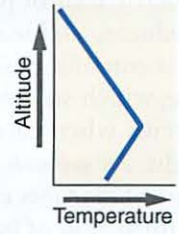
3. Which size of particulate matter causes the greatest health concern?
(a) $PM_{2.5}$
(b) $PM_{10}$
(c) $PM_{100}$
(d) $PM_{30}$

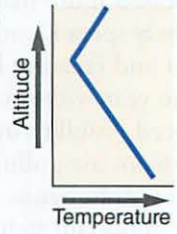
4. Which of the following is considered a natural source of carbon dioxide in the atmosphere?
(a) decomposition
(b) transportation
(c) agricultural practices
(d) energy generation

5. Which of the following best represents the atmospheric changes during a thermal inversion?

(a)


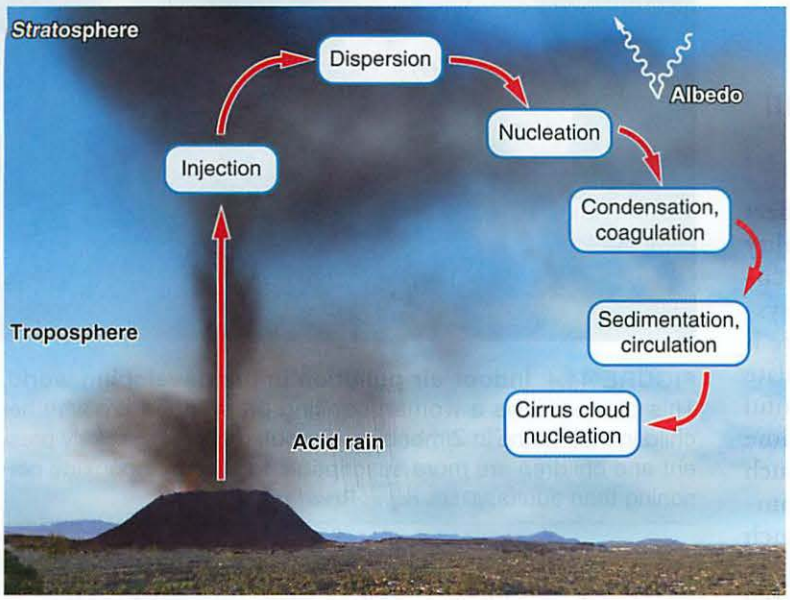

(c)



(b)



(d)


### Free-Response Question

The figure below shows a volcano eruption.




(a) **Identify** one pollutant that comes out of a volcano at an eruption. (1 pt.)
(b) **Describe** the class of pollutants identified in part (a). (1 pt.)
(c) Once the pollutants come out of the volcano, **explain** one way those pollutants change into secondary pollutants. (1 pt.)
(d) **Identify** one way that humans add more of the pollutant mentioned in part (a) into the environment. (1 pt.)
(e) **Explain** how the pollutant mentioned in part (a) can impact ecosystems. (1 pt.)
(f) While volcanoes are natural emitters of pollution, there are also natural ways to mitigate particulates and carbon dioxide emissions.
  (i) **Describe** a natural method to reduce carbon dioxide emissions. (1 pt.)
  (ii) **Identify** a potential drawback to the method described in part (i). (1 pt.)
  (iii) **Describe** an additional benefit of the solution proposed in part (i). (1 pt.)
(g) **Make a claim** as to whether natural emissions or anthropogenic emissions have a greater impact on ecosystems. (1 pt.)
(h) **Justify** the claim in part (g), using evidence. (1 pt.)

# Module 44





# Indoor Air Pollutants

When we think of air pollution, we usually don't associate it with air inside our buildings, but indoor air pollution causes more deaths each year than does outdoor air pollution. Sadly, most of these deaths occur in the developing world, but indoor air pollution is a significant hazard in both developing and developed countries. The quality of indoor air is highly variable and when polluting activities take place indoors, and time spent indoors is high, exposure to pollutants can be a significant health risk. In this module we will learn about the various types of indoor air pollutants, where they come from, what effects they have on human health, and how they differ around the world.

## Learning Goals

After reading this module you should be able to

**44-1** identify the major indoor air pollutants and where they come from.

**44-2** describe indoor air pollution differences in the developing and developed world.

**44-1** What are the major indoor air pollutants and where do they come from?

## Indoor air pollutants come from natural, human-made, and combustion sources

**Indoor air pollutants** are compounds that adversely affect the quality of air in buildings and structures. Air quality indoors influences both health and comfort of the occupants. Because a home or other building is a closed system with an abundance of manufactured materials, there is ample opportunity for indoor air pollutants to accumulate and for the occupants of that space to encounter harmful substances. Some indoor air pollutants are the exact same compounds of concern found in outdoor air pollution, such as carbon monoxide and particulates, while other compounds are only of concern when they are indoors, such as radon and asbestos. Sources of indoor air pollution are activities such as combustion within the building and the release of gases and compounds from materials within the building; other indoor air pollutants occur after transfer of gases and compounds from outside into the building. We will review the major indoor air pollutants and their effects.

### Carbon Monoxide

Carbon monoxide is perhaps the most dangerous indoor air pollutant because when concentrations are high enough, it can cause asphyxiation (oxygen deprivation) and death within minutes. We have already described carbon monoxide as an outdoor air pollutant, but it can be even more dangerous as an indoor air pollutant. In the human body, carbon monoxide binds with hemoglobin more efficiently than oxygen, essentially displacing oxygen from hemoglobin, thereby interfering with oxygen transport in the blood. Extended exposure to high concentrations of carbon monoxide in air can lead to oxygen deprivation in the brain and, ultimately, death. Lower exposures can lead to headache, dizziness, nausea, and loss of consciousness.

Carbon monoxide can come from urban outdoor air pollution that infiltrates a building or it can come from within the building. In the developed world, carbon monoxide exposure indoors occurs most often as a result of malfunctioning exhaust systems on household furnace heating systems, most commonly natural gas heaters. When the exhaust system in a natural gas heater malfunctions, exhaust air escapes into the living space of the house instead of being vented outside. Because natural gas burns relatively cleanly with little odor, a malfunctioning natural gas burner can cause the colorless, odorless carbon monoxide to accumulate in a house without the occupants noticing. This is especially problematic if the occupants are asleep. That is why carbon monoxide detectors are so important in homes and apartments and why they should be maintained and tested periodically.

**Indoor air pollutants** Compounds that adversely affect the quality of air in buildings and structures.



**FIGURE 44.1 Indoor air pollution in the developing world.** This photo shows a woman cooking on an open fire with her child in their home in Zimbabwe. Carbon monoxide is likely present and children are more susceptible to carbon monoxide poisoning than adults. *(Crispin Hughes/Panos Pictures)*

In the developing world, exhaust fans are not that common in homes, so cooking is done with little or no mechanical ventilation. As we discussed in Module 39, biomass is burned in open-pit fires that lack the proper mix of fuel and air to allow complete combustion. Usually, there is no exhaust system and little or no ventilation available in the home, which makes indoor air pollution from carbon monoxide, and also particulates, a hazard in developing countries (**FIGURE 44.1**). Children are at an even higher risk for carbon monoxide poisoning because their respiration rate is higher than adults.

### Particulates

As we know from Module 42, particulates are solid particles or particulate matter suspended in the air. Among indoor air pollutants, the most important particles are smoke, dust, and mold.

#### Smoke

Smoke and soot from fire, either from outside or from within the building, and from burning tobacco are sources of particulate matter in buildings. We described particulate matter in Modules 42 and 43 and the same principles and health concerns apply to indoor particulate matter. Respiratory infections, pneumonia, bronchitis, and even cancer can develop from prolonged exposure to indoor particulate matter. Obviously, a person smoking tobacco is going to be exposed to high concentrations of particulate matter but other people in the same building will likely be exposed to second-hand smoke, which is a source of particulate matter that can increase the likelihood of developing respiratory ailments and cancer.



**FIGURE 44.2 Dust mites in a pillow.** An entire ecosystem lives in a pillow. The energy source is dead human skin cells. These dust mites are approximately 250 microns in size and can cause respiratory and skin allergic reactions. *(selvanegra/Getty Images)*

## Dust and Mold

Both dust and molds are natural sources of indoor air pollutants. Dust is a combination of particulate matter, pollen, bacteria, and the waste product of an intricate ecosystem within all households. Humans shed millions of skin cells each day. Within each household, there is an entire ecosystem supported by the food energy of dead human skin cells including dust mites that live in our bedding, pillows, flooring, and carpeting (**FIGURE 44.2**). Dead human skin cells, the droppings from dust mites, and dust mite body fragments all become part of household dust. While household dust might seem like it is simply an inconvenience, it actually contributes to a variety of conditions including asthma and skin and respiratory allergic reactions. Particulate matter enters buildings from airborne particulates and from soil that is carried into the building on shoes and clothing. Pollen can enter buildings through open windows and clothing. Bacteria is introduced into buildings through just about anything that is brought inside. Mold, also known as mildew, is a fungal growth that can rapidly spread on damp organic matter. It occurs in homes, sometimes behind walls where it cannot be easily detected or seen. Molds can be introduced from outside and thrive in moist environments such as bathrooms, kitchens, and basements. Allergies, lung inflammation, and asthma are three conditions that can occur after exposure to damp conditions and mold.

## Asbestos

**Asbestos** is a long, thin, fibrous silicate mineral with insulating properties that can cause cancer when inhaled (**FIGURE 44.3a**). There are actually six different minerals that are classified as asbestos and all are harmful to the respiratory tract. It is found in metamorphic rocks and mined in many locations around the world. For many years it was used as an insulating material on steam and hot water pipes (Figure 44.3b) and in shingles for the siding of buildings. The greatest health risks from asbestos have been respiratory diseases such as asbestosis, a chronic lung condition, and mesothelioma, a form of lung cancer caused from exposure to asbestos. Both of these diseases occur at very high rates among workers who have mined asbestos. In manufactured form, asbestos is relatively stable and not dangerous until it is disturbed. When insulating materials become old or are damaged or disrupted, however, the fine fibers can become airborne within a building and can

**Asbestos** A long, thin, fibrous silicate mineral with insulating properties, which can cause cancer when inhaled.



(a)



(b)

**FIGURE 44.3 Asbestos insulation in a school** Asbestos mineral (a) is a good insulator and used to be installed on steam pipes in buildings. (b) It still remains in some older buildings. *(a: Education Images/Getty Images; b: Joe_Potato/Getty Images)*

enter the respiratory tract. In the United States, asbestos is no longer used as an insulating material, but it can still be found in older buildings, including schools. Removal of asbestos must be done under tightly controlled conditions so that the fibers, typically less than 10 microns in diameter, cannot contaminate air inside the building. Some studies have shown that when asbestos removal is complete, the concentration of asbestos fibers in the air of the remediated building is greater in the year after removal than during the year before removal. For this reason, it is absolutely necessary that asbestos removal be carefully done by qualified asbestos abatement personnel.

**AP® Exam Tip**

The AP® Environmental Science Exam may ask about solutions to challenges such as asbestos in a residence. Make certain you describe "professional removal" or "professional abatement." Merely stating "remove the asbestos" suggests removing it on your own, and improper removal can be more dangerous for the occupants of the building and those doing the removal than leaving it in place.

## Radon

**Radon-222**, a radioactive gas that occurs naturally from the decay of uranium, exists in granitic and some other rocks and soils in many parts of the world, and is an indoor air pollutant. The map in **FIGURE 44.4** shows areas for potential radon exposure in the United States. Humans can receive significant exposure to radon if it enters a building through cracks in the foundation from underlying rock or soil, or enters the house via groundwater that came from a well. Radon-222 decays within 4 days to a radioactive daughter product, polonium-210. Either the radon or the polonium can attach to dust and other particles in the air and then be inhaled by the inhabitants of the home. Exposure to radon can lead to lung cancer.

The EPA, the federal agency most responsible for identifying, measuring, and addressing environmental risks, estimates that about 21,000 people die each year from radon-induced lung cancer. This is 15 percent of yearly lung cancer deaths, and makes radon the second leading cause of lung cancer, after smoking. The EPA suggests that people test their homes for airborne radon. If radon air concentrations are determined to be high, it is important to increase ventilation in the home and ventilate the underground space below the house. These radon mitigation systems are highly successful at reducing indoor air radon concentrations. Other relatively inexpensive actions, such as sealing cracks in the basement, can be beneficial if radon is coming from underlying soil and bedrock. "Do the Math: Averaging Radon over Time" asks you to calculate radon concentrations in a home based on the readings of two radon collection devices.

**Radon-222** A radioactive gas that occurs naturally from the decay of uranium and is an indoor air pollutant.

**AP® Exam Tip**

Remember that it is not advisable to write a phrase such as "air pollution causes cancer." Be specific: radon, particulate matter (specifically $PM_{2.5}$ from diesel exhaust), and airborne asbestos are associated with lung cancer. But many air pollutants are not directly associated with lung cancer.

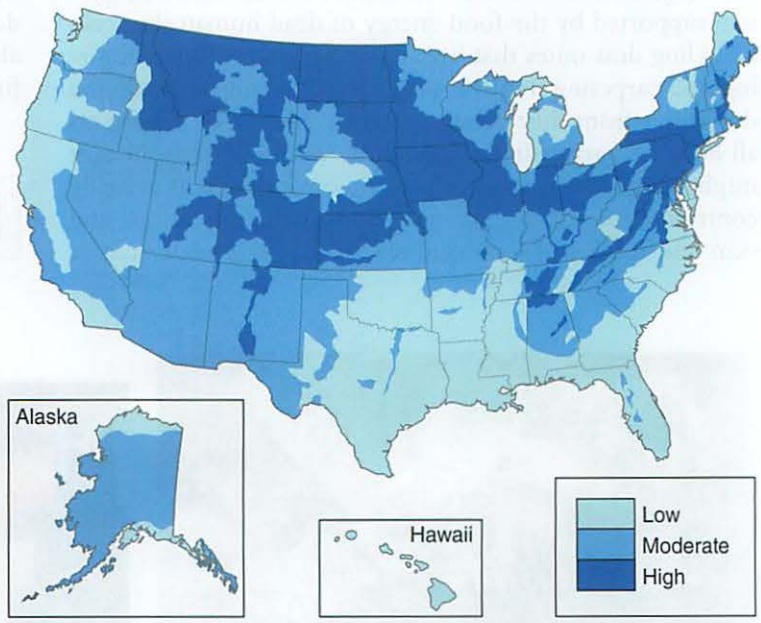



**FIGURE 44.4 Potential radon exposure in the United States.** Depending on the underlying bedrock and soils, the potential for exposure to radon exists in houses in certain parts of the United States. *(Data from U.S. Geological Survey and http://www.epa.gove/radon/zonemap.html)*

## DO THE MATH Averaging Radon over Time

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Since radon in homes is believed to cause approximately 21,000 lung cancer deaths in the United States each year, homeowners are encouraged to measure radon concentrations in their homes at least once. There are short-term (e.g., 4 day or 8 day measurements) and long-term (up to 1 year) radon collection devices available. Longer measurement times are likely to produce more accurate readings. After the designated collection time period, the device is mailed to a laboratory and the air concentration of radon is estimated from the collection device. The EPA has established an action level for home radon: If concentrations of 4.0 pCi/L (picoCuries per liter) or greater are found, the homeowner should install abatement equipment to lower radon concentrations in the home.

For one brand of a short-term collection device, the homeowner should place two devices within 1 meter (3 feet) of each other and leave them undisturbed for 4 days. Another brand requires that the device be left undisturbed for 8 days. These devices are monitoring the same space at the same time for the same length of time. The concentration of radon in the home is determined by the average of the two devices.

As an example, imagine two devices with the following readings:

Device 1 reading after 8 days: 5.0 pCi/L

Device 2 reading after 4 days: 1.2 pCi/L

What is the concentration of radon in the home?

We will take the average of 5 pCi/L and 1.2 pCi/L, weighted by their respective measurement times by splitting the 8-day measurement to two 4-day measurements:

$$(5.0 \text{ pCi/L [for 4 days]} + 5.0 \text{ pCi/L [for 4 days]} + 1.2 \text{ pCi/L [for 4 days]}) \div 3 = 3.73 \text{ pCi/L}$$

There are two significant figures in the measurements, so we round the answer to 3.7 pCi/L.

3.7 pCi/L is less than 4.0 pCi/L so radon abatement is not recommended by the EPA.

**YOUR TURN** A homeowner uses two different short-term radon collection devices to measure the same space. One device measured the air for 4 days and the result was 1 pCi/L. The other device measured the air for 8 days and the result was 6 pCi/L. Calculate an estimate of the radon concentrations in the home, taking into consideration the different measurement periods.

## Volatile Organic Compounds

Many volatile organic compounds are used in building materials, furniture, and other home products such as glues and paints. One of the most toxic of these compounds is formaldehyde, which is used widely to manufacture a variety of building products such as particle board and carpeting glue. Formaldehyde is common in new homes and new products made from pressed wood, such as certain bookcases. Bookcases made from actual wood and most hardwood flooring do not contain formaldehyde. The pungent smell that you may have noticed in a new home or one with new carpeting comes from formaldehyde, which is volatile and emits gases over time. A high enough concentration in a confined space can cause a burning sensation in the eyes and throat, and breathing difficulties and asthma in some people. There is evidence that people develop a sensitivity to formaldehyde over time; though they may not be very sensitive at first, with continued exposure they can experience irritation from increasingly smaller exposures. Formaldehyde has been shown to cause cancer in laboratory animals and has recently been suspected of being a human carcinogen.

Many other consumer products such as detergents, dry-cleaning fluids, deodorizers, and solvents may contain VOCs and can be harmful if inhaled. Plastics, fabrics, paints, construction materials, and synthetic carpets may also release VOCs over time. In response to concerns over manufactured products in the home, some homeowners choose to utilize wood flooring rather than carpeting, or natural fiber carpeting rather than synthetics. While such actions will not ensure zero exposure to VOCs, it will decrease the likelihood of exposure. VOC exposure can also come from outside if the building is in a neighborhood with a source of high VOC emissions such as a chemical plant or waste facility that releases VOCs into the air.

## Lead

We have already discussed lead as an outdoor air pollutant in Module 42. It is also an indoor air pollutant. The greatest exposure to lead in buildings comes from leaded paint, which was last used in the United States in the 1960s. Certain older buildings have lead paint on the walls and if that paint is sanded or scraped, there may be some lead mobilized and dispersed into the air. This mobilized lead can be inhaled by human occupants. Lead from outside can be introduced to a building in air pollution or contaminated soil brought inside. However, the greatest potential lead exposure comes from lead in paint chips that can be ingested by young children, as we discussed in Module 42.

## Other Pollutants

Other pollutants that occur outside such as nitrogen oxide and sulfur dioxide can also be present in indoor air pollution. In buildings that are not well insulated and tightly air sealed, which includes most older buildings, outdoor air pollution can be a source of indoor air pollutants such as nitrogen oxide and sulfur dioxide. Nitrogen oxide can also be present inside buildings as a result of combustion from cooking. But proximity to outdoor sources of air pollution is an important driver of indoor air pollution, not just for nitrogen and sulfur oxides but for many other pollutants as well.

**44-2** How does indoor air pollution differ in the developing and developed world?

# Indoor air pollution in the developing world comes mostly from indoor combustion while in the developed world tightly sealed buildings and VOCs are a bigger problem

Although it generally receives less attention than outdoor air pollution, indoor air pollution is a hazard all over the world. The World Health Organization estimates that indoor air pollution is responsible for approximately 3.8 million deaths annually worldwide. Pneumonia, heart disease, and pulmonary disease are the top three causes of death. Most of the deaths attributable to indoor air pollution occur in lower- and middle-income countries, though the reasons for indoor air pollution differ between the developing world and the developed world.

**Sick building syndrome** A buildup of toxic pollutants in weatherized spaces, such as newer buildings in the developed world.

## Developing Countries

We have discussed the use of wood, animal manure, or coal indoors for heat and cooking in the developing world in Module 39 and earlier in this module. Because the source of these air pollutants is a combustion source from inside the home and usually in close proximity to the occupants, the World Health Organization estimates that indoor particulate matter concentrations can be 100 times higher than acceptable levels. Because many buildings in developing countries may not be well insulated and sealed from the outside, there may be some ventilation that occurs, allowing indoor air pollutants to escape. However, if outdoor air quality is also poor, ventilating with outside air might only improve the situation slightly.

## Developed Countries

There are a number of factors that have caused the quality of air in homes in developed countries to take on greater importance in recent decades. First of all, people in much of the developed world have begun to spend more and more time indoors. Secondly, improved insulation and tightly sealed building envelopes have been constructed or retrofitted to reduce energy consumption. This is beneficial for energy savings due to the increased efficiency of the building but it can have adverse health effects as well. The tightly sealed buildings also keep existing air in contact with the inhabitants of homes, schools, and offices for greater amounts of time, exposing them for longer periods to any indoor air pollutants that may be present. Finally, an increasing number of materials in the home and office are made from volatile organic compounds including formaldehyde, as we discussed earlier in this module. In addition, plastics and other petroleum-based materials can give off chemical vapors harmful to our health. As **FIGURE 44.5** illustrates, all of these factors combine to allow many possible sources of indoor air pollution to impact occupants. In fact, a phenomenon has been observed often enough in new or renovated buildings for it to be given a name: **sick building syndrome**, which describes a buildup of toxic pollutants in weatherized spaces such as newer buildings in the developed world. Because new buildings contain many products made with synthetic

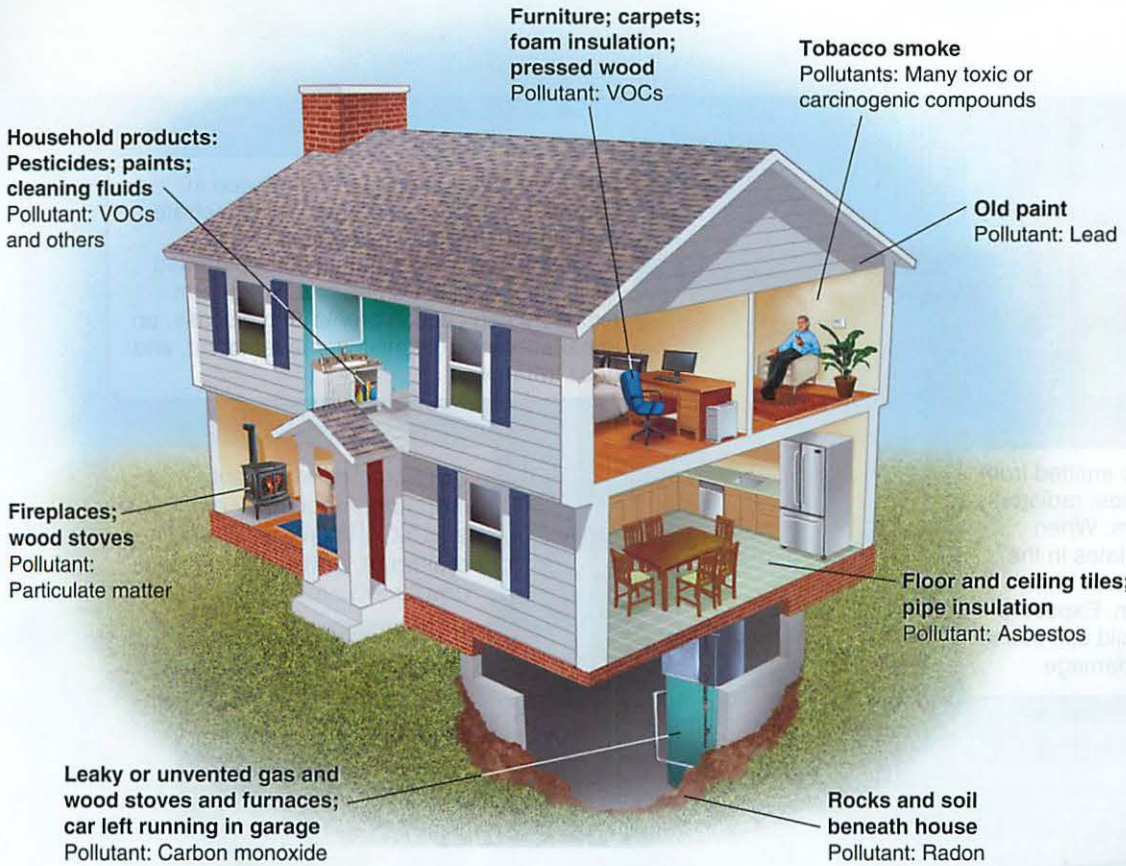



**FIGURE 44.5 Some sources of indoor air pollution in the developed world.** A typical home in the United States may contain a variety of chemical compounds that could, under certain circumstances, be considered indoor air pollutants.

materials and glues that may not have fully dried out, a significant amount of off-gassing occurs, which usually means that the indoor levels of VOCs, hydrocarbons, and other potentially toxic materials are quite high. Sick building syndrome has been observed particularly in office buildings, where large numbers of workers have reported a variety of maladies such as headaches, nausea, throat or eye irritations, and fatigue. The EPA has identified four specific reasons for sick building syndrome: inadequate or faulty ventilation; chemical contamination from indoor sources such as glues, carpeting, furniture, cleaning agents, and copy machines; chemical contamination in the building from outdoor sources such as vehicle exhaust transferred through building air intakes; and biological contamination from inside or outside, such as molds and pollen.

In this module we examined indoor air pollutants and observed that some, such as carbon monoxide and particulates, are the same pollutants that we considered in outdoor air pollution. Others, such as radon and asbestos, are specifically pollutants of concern indoors. Both radon and asbestos cause serious health problems including cancer. Sources of indoor air pollution include combustion within the building, and the release of gases and compounds from materials within the building; other indoor air pollutants occur after transfer of gases and compounds from outside into the building or structure. These can be both natural and anthropogenic compounds. Review the Unit 7 Visual Representation feature to continue your study of the specific human health effects of atmospheric pollutants. (pages 518-519).

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**Visual Representation 7 Sources of Atmospheric Pollution** According to the World Health Organization, 91 percent of the world's population lives in locations where atmospheric pollution exceeds



guidance limits. Atmospheric pollution can come from natural sources such as volcanoes or from anthropogenic sources. It can occur both outdoors and indoors. The effects of air pollution on human health can be severe and long-lasting.

## Indoor Air Pollution



Building materials emit VOCs and in older construction might consist of asbestos or lead.

Poor ventilation and malfunctioning exhaust systems can lead to a buildup of CO, radon, and PM which affect people working and living in these spaces.

**Asbestos** is formed from minerals in metamorphic rocks and was formerly used for insulation in buildings. When disturbed, the fibers can become airborne and enter the respiratory tract. This can lead to respiratory diseases such as asbestosis and mesothelioma.

**Volatile organic compound (VOC)** emissions come from both natural and human-made sources, such as cleaning supplies, personal care products, combustion, office equipment, smoking, woodstoves, and many other substances and activities. They are associated with cancer in humans. Short-term exposure can irritate the eyes, nose, throat, and mucus membranes.



**Radon** is a radioactive gas that occurs naturally from the decay of uranium. It exists in granitic and some other rocks and soils in many parts of the world. Exposure to radon gas can lead to lung cancer.



**Particulate matter** ($PM_{10}$ and $PM_{2.5}$) can penetrate deep into the lungs and enter the bloodstream. Particulates include smog, soot, tobacco smoke, fly ash, cement dust, and various gaseous contaminants. Exposure can lead to heart and respiratory problems, and stroke.

**Carbon monoxide (CO)** is produced by incomplete combustion of fossil fuels. Exposure can cause reduced delivery of oxygen in the body with headache, dizziness, loss of consciousness and death. Long-term exposure causes cardiovascular disease.

In the developing world, cooking with wood, manure, and coal in enclosed spaces exposes adults and children to high levels of PM. Children are particularly susceptible to the effects of indoor air pollution.

# Module 44 AP® Review

Preparing for the AP® Exam

## Learning Goals Revisited

### 44-1 What are the major indoor air pollutants and where do they come from?

Indoor air pollutants are compounds that adversely affect the quality of air in buildings and structures. Indoor air pollutants can come from natural, human-made, and combustion sources. Carbon monoxide is perhaps the most dangerous indoor air pollutant because when concentrations are high enough, it can cause asphyxiation and death. Smoke from fire and from burning tobacco are sources of particulate matter in buildings. Dust contributes to a variety of conditions including asthma and skin and respiratory allergic reactions. The greatest health risks from asbestos have been respiratory diseases such as asbestosis, a chronic lung condition, and lung cancer. Humans can receive significant exposure to radon, a naturally occurring gas, in buildings if sources of radon below the building are present.

### 44-2 How does indoor air pollution differ in the developing and developed world?

Indoor air pollution is a problem around the world, but its presence in the developing and the developed worlds differ. In the developed world, houses sealed up for greater energy efficiency are often the causes of exposure to radon, carbon monoxide, and volatile organic compounds for people who spend substantial amounts of time indoors. In the developing world, combustion sources from inside the house are the largest problem.

## Practice Math and Graphing

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Answer the following questions. Be sure to show all your work.

**1. Practice Math**

Radon in homes is believed to cause approximately 21,000 cancer deaths in the United States each year. The EPA has established an action level for home radon: If concentrations of 4.0 pCi/L (picoCuries per liter) or greater are found, the homeowner should install abatement equipment to lower radon concentrations.

(a) Use the information from five homes presented below to determine the average radon concentration and a maximum concentration found in each home. Complete the table with your calculations.

(b) For each row of the table, determine if the house should have radon abatement based on

(i) whether the average is the most important indicator.

(ii) whether the maximum is the most important indicator.

| Home radon concentration | First reading pCi/L | Second reading pCi/L | Third reading pCi/L | Average | Max | Abatement yes or no if average most important | Abatement yes or no if maximum most important |
|---|---|---|---|---|---|---|---|
| 1 | 3.2 | 3.5 | 3.9 | | | | |
| 2 | 3.8 | 3.5 | 4.9 | | | | |
| 3 | 4.5 | 6.5 | 12.7 | | | | |
| 4 | 5.5 | 3.3 | 1.9 | | | | |
| 5 | 9.6 | 4.4 | 8.3 | | | | |

**2. Practice Graphing**

The table lists $PM_{2.5}$ air concentrations in Beijing, China, from 2011 through 2021. Plot the data on a graph with year on the $x$ axis and $PM_{2.5}$ concentrations on the $y$ axis. Then describe the trend of $PM_{2.5}$ over time.

| Year | $PM_{2.5}$ air concentration $\mu g/m^3$ |
|---|---|
| 2011 | 99 |
| 2012 | 91 |
| 2013 | 100 |
| 2014 | 98 |
| 2015 | 83 |
| 2016 | 73 |
| 2017 | 59 |
| 2018 | 51 |
| 2019 | 43 |
| 2020 | 39 |
| 2021 | 41 |

## AP® Practice Questions

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### Multiple-Choice Questions

1. Carbon monoxide is an important indoor air pollutant because
   (a) it binds with hemoglobin causing asphyxiation.
   (b) it comes from complete combustion.
   (c) it is related to carbon dioxide.
   (d) it doesn't occur in outdoor air pollution.

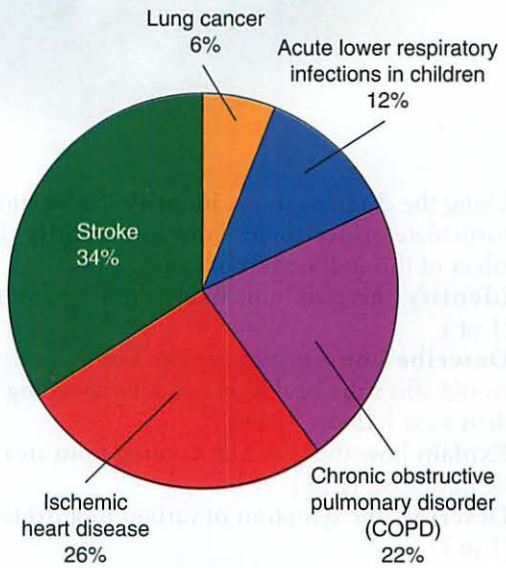
2. New furniture and carpeting may release which indoor air pollutant?
   (a) sulfur dioxide
   (b) nitrogen oxides
   (c) carbon monoxide
   (d) formaldehyde

3. The primary source of radon is
   (a) electronics.
   (b) indoor fires.
   (c) household chemical fumes.
   (d) rocks and soils.

4. Which of the following would be a viable solution for indoor air pollution of radon?
   (a) reduction of asbestos in homes
   (b) use of a wet scrubber on residential chimneys
   (c) addition of an electrostatic precipitator
   (d) increasing ventilation

5. Asbestos
   (a) causes respiratory ailments and cancer.
   (b) can be easily removed and treated.
   (c) can be a problem in new construction.
   (d) causes skin irritation, nausea, and fatigue.

*Use the graph below to answer questions 6 & 7:*




6. In 2020, indoor air pollution led to approximately 4 million deaths worldwide. The data above show the causes of death. How many people died of lung cancer due to indoor air pollution?
   (a) 240,000 (4 million × 0.06)
   (b) 840,000
   (c) 2,380,000
   (d) 1,820,000

7. What percent of indoor air pollution deaths were caused by direct effects on the lungs?
   (a) 60 percent
   (b) 40 percent
   (c) 18 percent
   (d) 48 percent

## Free-Response Question

Indoor air pollutants come from many different sources. The diagram below shows some of these sources.




(a) Using the diagram above, **identify** the location where particulate matter comes from and **identify** the health effect of this indoor air pollutant. (2 pts.)

(b) **Identify** the pollutant likely coming from area A. (1 pt.)

(c) **Describe** how volatile organic compounds (VOCs) would affect the health of someone spending much of their time indoors. (1 pt.)

(d) **Explain** how the pollutant coming from area D could be mitigated. (1 pt.)

(e) **Describe** one symptom of carbon monoxide indoors. (1 pt.)

(f) Individuals in developed and developing nations tend to deal with different forms of indoor air pollution. **Identify** one indoor air pollutant that is more prevalent in a developing nation. **Explain** why this is the case. (2 pts.)

(g) Individuals in developed nations tend to set up their homes for greater energy efficiency. **Make a claim** to support or refute how this affects indoor air pollution, and **justify** the claim using evidence. (2 pts.)

# Module 45



# Reduction of Air Pollutants

The previous modules in this unit have identified the sources of both outdoor and indoor pollutants. Here, we'll examine methods of reducing outdoor air pollution. For air pollution reduction, the most sustainable solutions utilize conservation and efficiency first. It requires less energy and resources to clean up pollution if we seek ways to avoid creating it in the first place. Preventing pollution is usually much less expensive and energy intensive then controlling it. Unfortunately, pollution prevention is not always possible. In this module we will examine a variety of methods for reducing and controlling outdoor air pollution.

**Learning Goals**

After reading this module you should be able to

**45-1** explain how air pollutants can be reduced.

**45-2** describe the various air pollution control devices and how they are used.

**45-1** How can air pollutants be reduced?

## Air pollution can be controlled by prevention, conservation, fuel switching, and regulatory practices

As with other types of pollution, the best way to decrease air pollution emissions is to avoid them in the first place. Pollution prevention can be achieved in a number of ways and the first one is by using less fuel. So, any technique that utilizes conservation and increasing efficiency, topics we discussed in Module 41, will result in less air pollution. Switching to an alternative fuel is also a method for reducing air pollution. In general, oil is cleaner than coal. The sulfur concentrations of both coal and oil vary with type of fuel and location in the world. In addition, during refining and processing, the concentration of sulfur can be lowered in both fuels.

Choosing an alternative fuel can also involve switching from bituminous coal to anthracite coal, or from coal from one region to another, or from one type of oil to another type of oil.

Use of a low-sulfur coal or oil is certainly one of the best means of controlling sulfur dioxide pollution, although typically low-sulfur coal or oil is more expensive to purchase than coal or oil containing higher sulfur concentrations. While these measures reduce emissions by a certain amount, wherever fuel is combusted, pollutants such as nitrogen oxides, carbon monoxide, and carbon dioxide will be emitted. Depending on the fuel, particulates and sulfur dioxide may be emitted as well. So ultimately, no matter what measures are implemented to reduce air pollution, there will ultimately be a need to control the exhaust stream after combustion has occurred. That is the focus of the next section of this module. But first, let's consider regulatory practices that can be implemented.

### Regulatory Practices

Regulatory practices at the city, state, and national levels have reduced air pollution. Municipalities and counties have passed measures, for example, to reduce the amount of gasoline spilled at gasoline stations by requiring a **vapor recovery nozzle** on all gasoline pumps at filling stations. This device prevents VOCs from escaping into the atmosphere while a person is fueling their vehicle (**FIGURE 45.1**). Other measures include regulations to restrict the evaporation of dry-cleaning fluids (a VOC) or restrict the use of lighter fluid (a VOC) for starting charcoal barbecues. All of these regulations have resulted in less VOC emissions into the atmosphere and less photochemical smog formation. Both urban and suburban areas around the United States have taken additional actions such as calling for a reduction in the use of wood-burning stoves or fireplaces that would reduce emissions of not only nitrogen oxide but also particulate matter, VOCs, and carbon monoxide. A number of California municipalities have even discussed reducing the number of bakeries within certain areas, as the emissions from rising bread contain VOCs. This proposal was not very

**Vapor recovery nozzle** A device that prevents VOCs from escaping into the atmosphere while a person is fueling their vehicle.



**FIGURE 45.1 Vapor recovery nozzle at a gasoline filling station.** This control device on the nozzle of a gasoline dispenser reduces VOC fumes that escape to the atmosphere at a gasoline fueling station. *(Radharc Images/Alamy Stock Photo)*

popular, as you can imagine, but emissions from bakeries along with many other businesses are sometimes regulated by local air-quality ordinances.

Since cars are responsible for large emissions of nitrogen oxides and VOCs in urban areas, and these two compounds are the major contributors to smog formation, some municipalities have tried to achieve lower smog concentrations by restricting automobile use. A number of cities, including Mexico City, have instituted plans permitting automobiles to be driven only every other day—for example, those with license plates ending in odd numbers may be used on one day and those with even-numbered license plates on alternate days. In Mexico City, as of 2020, the plan had not had much of an impact. In China, during the 2008 Beijing Summer Olympics, the government successfully expanded public transportation networks, imposed motor vehicle restrictions, and temporarily shut down a number of industries as a way to reduce photochemical smog and improve visibility. For a short period, the air pollution control measures were successful. However, long-term improvements in air quality in China have been harder to achieve. Just prior to the 2022 Beijing winter Olympics, levels of smog and particulate matter reached unhealthy levels (**FIGURE 45.2**).

In 1990 and again in 1995, scientists, policy makers, and academics collaborated on amendments to the Clean Air Act that would allow the free market to determine the least expensive ways to reduce emissions of sulfur dioxide. The free-market program was implemented in two phases between 1995 and 2000, and each phase has led to significant reductions in sulfur emissions. One of the most innovative aspects of the Clean Air Act amendments is "Cap and Trade," which we discuss in "Science Applied 7: Can Cap-and-Trade Reduce Pollution Emissions Equitably?" This is a program that institutes the buying and selling of allowances that authorize the owner of power plants and factories to release a certain quantity of sulfur dioxide ($SO_2$). Each allowance authorizes a power plant or industrial source to




**FIGURE 45.2 Reducing photochemical smog.** The photos show the same locations in Beijing, China, (a) during the Beijing Summer Olympics in 2008 and (b) after the pollution restrictions were removed. *(PETER PARKS/Getty Images)*

emit one ton of $SO_2$ during a given year. Sulfur allowances are awarded annually to existing sulfur emitters proportional to the amounts of sulfur they were emitting before 1990, and the emitters are not allowed to emit more sulfur than the amount for which they have permits. At the end of a given year, the emitter must possess a number of allowances at least equal to its annual emissions. In other words, a facility that emits 1,000 tons of $SO_2$ must possess at least 1,000 allowances that are usable in that year. Facilities that emit quantities of $SO_2$ above their allowances must pay a financial penalty.

Sulfur allowances can be bought and sold on the open market by anyone. If emitters wanted to exceed their allowance level—say, because they intended to increase their industrial output—they would be required to purchase more allowances from another source. If, on the other hand, a company decreased its sulfur emissions more than it needed to in order to comply with its allowance amount, it could sell any unused sulfur emission allowances. Over time, the number of allowances distributed each year were gradually reduced so, ultimately, sulfur dioxide emissions have gone down considerably. "Do the Math: Calculating Annual Sulfur Reductions" shows you how to calculate these decreases as percentages of the original value.

## DO THE MATH Calculating Annual Sulfur Reductions

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$SO_2$ emissions from all sources in the United States declined from 23.5 million metric tons (26 million U.S. tons) in 1982 to 10.3 million metric tons (11.4 million U.S. tons) in 2008. Calculate the total percentage reduction and the annual percentage reduction of $SO_2$ emissions.

23.5 million metric tons – 10.3 million metric tons = 13.2 million metric tons total reduction

Divide the reduction by the original amount and multiply by 100 to obtain a percent reduction:

13.2 million ÷ 23.5 million metric tons × 100% = 56%

The total reduction was 56 percent between 1982 and 2008.

To calculate the reduction per year, divide 56 percent by the number of years from beginning to end:

2008 – 1982 = 26 years

56% ÷ 26 years = 2.2%/year

**YOUR TURN** In the United States, $SO_2$ emissions continued to decrease from 10.3 million metric tons (11.4 million U.S. tons) in 2008 to 1.8 million metric tons (2 million U.S. tons) in 2020. Calculate the total percentage reduction and the annual percentage reduction for $SO_2$ from 2008 to 2020.

Even with regulations, there is still going to be pollution emissions. Therefore, air pollution control devices are necessary to further reduce air pollution.

**45-2** What are the various air pollution control devices and how are they used?

## Control devices convert pollutants to less harmful compounds or remove them from the exhaust stream

Once combustion has occurred, pollution control devices function in two basic ways: by converting pollutant compounds to other, less harmful compounds, or by removing the pollutant compounds from the waste stream. Let's examine the first method.

### Converting Pollutants to Less Harmful Compounds

One of the most common air pollution control devices is the **catalytic converter**, a device that uses chemicals to convert pollutants such as nitrogen oxide and carbon monoxide to nitrogen gas and carbon dioxide. They have been in the news in recent years mostly because they are expensive and relatively easy for thieves to steal by crawling under an unattended car or truck and cutting the converter out. An internal combustion engine emits combustion products, including pollutants, into the exhaust system that is mounted underneath the chassis of the car. Until 1975, the exhaust system consisted of a pipe with a muffler, which is designed to reduce the noise of the engine. Beginning in 1975, as part of the Clean Air Act, a catalytic converter was required to be added before the muffler in all new cars. It contains a metal such as platinum that serves as a catalyst; it increases the rate of a chemical reaction without itself undergoing a change (**FIGURE 45.3**). The catalytic

**Catalytic converter** A device that uses chemicals to convert pollutants such as nitrogen oxide and carbon monoxide to nitrogen gas and carbon dioxide.

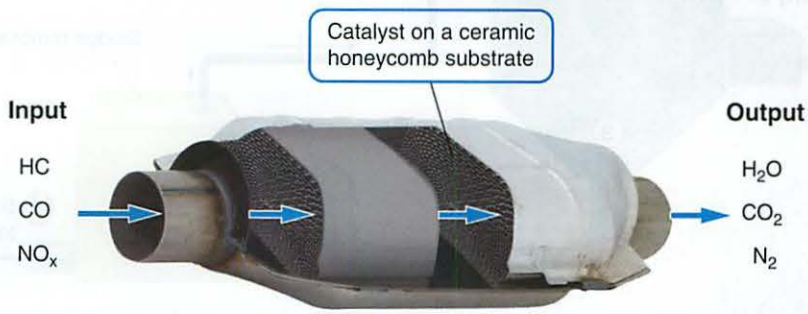



**FIGURE 45.3 Catalytic converter.** This honeycomb device coated with a metal such as platinum, treats pollutant gases from the engine such as nitrogen oxides, carbon monoxide, and hydrocarbons and converts them into nitrogen gas, carbon dioxide, and water. Because the device can be damaged by the metal lead, Clean Air Act legislation that required the catalytic converter also mandated that lead no longer be added to gasoline.

converter in cars and trucks removes oxygen from nitrogen oxides resulting in the formation of nitrogen gas and oxygen gas. It also adds oxygen to carbon monoxide, resulting in the formation of carbon dioxide. Catalytic converters also treat hydrocarbons. The net result of all three reactions is a reduction in nitrogen oxides, carbon monoxide, and hydrocarbons and an increase in nitrogen gas, carbon dioxide, oxygen, and water. This is an example of converting pollutants to less harmful compounds. Catalytic converters are effective. In fact, nitrogen oxide emissions from automobiles have decreased significantly in the United States over the last 45 years. Figure 42.4 shows the decrease from 1990 to 2020. During this same time period, improvements in the combustion technology of power plants and factories also contributed to reduced emissions of nitrogen oxides.

**Scrubber** A device that uses a combination of lime and or water to separate and remove particles from industrial exhaust streams.

## Removing Pollutants from Waste Streams

A substantial number of air pollution control measures have been directed toward removal of particulates, sulfur oxides, and nitrogen oxides in stationary sources of air pollution such as coal-burning power plants and factories. A **scrubber** is an air pollution control device that uses a combination of air and lime (dry scrubber) or air and water (wet scrubber) to separate and remove particles and sulfur dioxide from industrial exhaust streams (**FIGURE 45.4**). Particles and gases coalesce in the scrubber in a liquid or sludge form and relatively cleaner gas exits through the smokestack. Scrubbers are used on industrial plants and coal-burning power plants. In a scrubbing process known as fluidized bed combustion, granulated coal is burned in close proximity to calcium carbonate. The heated calcium carbonate absorbs sulfur dioxide and produces calcium sulfate, which is removed from the exhaust stream and can be used in the production of gypsum wallboard, also known as sheetrock, for houses.

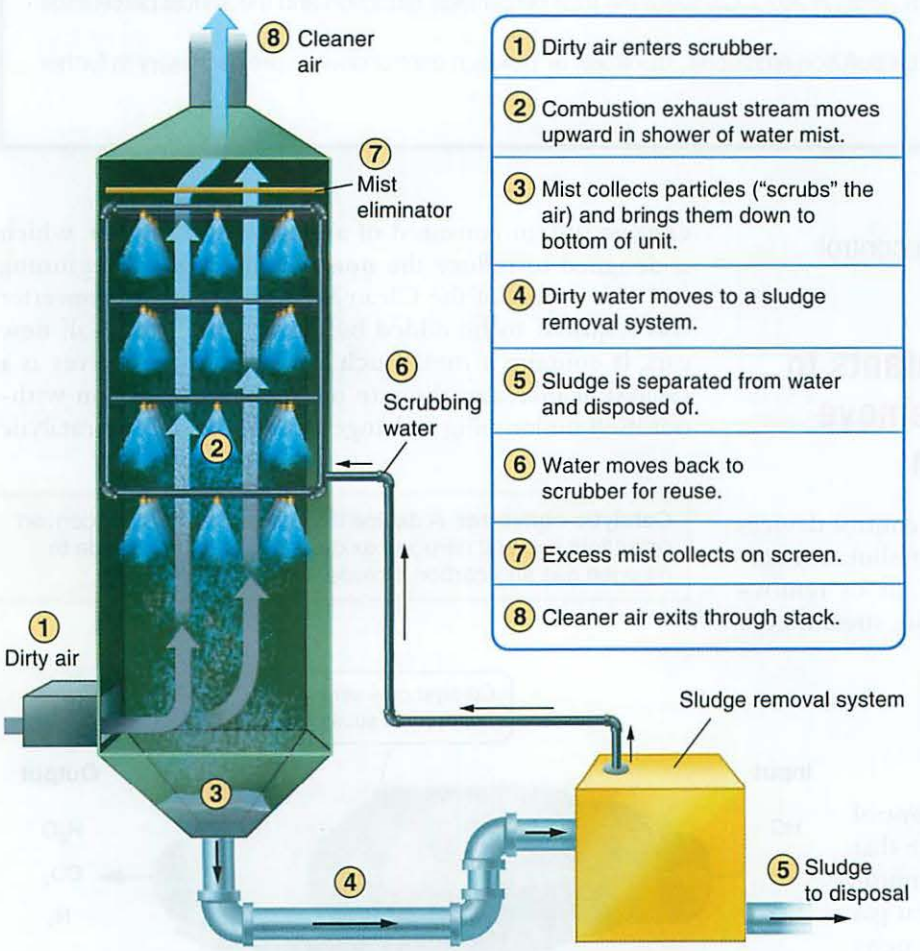
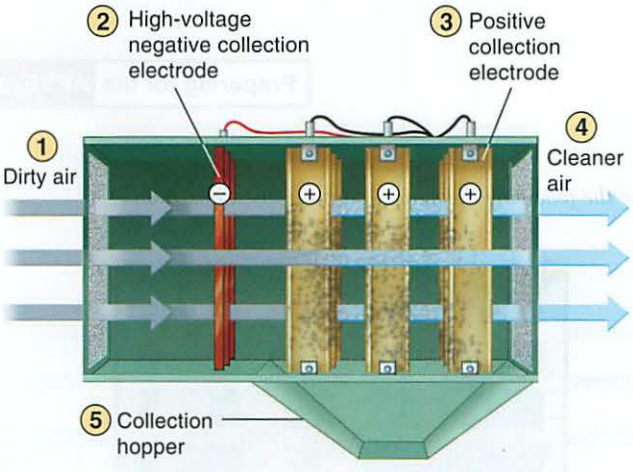



**FIGURE 45.4 The scrubber, wet variety.** In this air pollution control device, particles and sulfur dioxide are "scrubbed" from the exhaust stream by water droplets and air. A water-particle "sludge" is collected and processed for disposal. Another variation, the dry scrubber, uses compounds such as lime and air to remove particles.

There are a variety of methods used to remove particulate matter. Sometimes the process of removing particulate matter incidentally also removes sulfur. The simplest method is gravitational settling, which relies on gravity as the exhaust travels through the smokestack. The particles simply settle out to the bottom. The ash residue that accumulates must be disposed of in a landfill. Depending on the fuel that was burned, the ash may contain sufficiently high concentrations of metals that require special disposal.

Fabric filters are a type of filtration device that allow gases to pass through them but remove particulate matter. Often called baghouse filters, certain fabric filters can remove almost 100 percent of the particulate matter emissions. **Electrostatic precipitators** remove particulate matter by using an electrical charge to make particles coalesce so they can be removed from the exhaust stream (**FIGURE 45.5**). Polluted air enters the precipitator and the electrically charged particles within are attracted to negative or positive charges on the sides of the precipitator. The particles collect on the collection electrodes and relatively clean gas exits the precipitator. Electrostatic precipitators are common in industrial plants and coal-burning power plants.




1. Dirty air enters precipitator unit.
2. Particles in combustion exhaust stream pass by negatively charged plates, which gives them a negative charge.
3. The negatively charged particles are attracted to positively charged collection plates.
4. Cleaner air moves out of the unit.
5. The positive collection plates are periodically discharged, which causes the particles to fall off so that they can be removed from the system.

**FIGURE 45.5 The electrostatic precipitator.** In this air pollution control device, particles are given a negative charge. This causes them to be attracted to a positively charged plate, where they are held. Periodically, the particles are removed from the plate and collected for disposal.

Nitrogen can also be removed from combustion exhaust in stationary sources. As you know, the atmosphere of Earth is 78 percent nitrogen gas and, as a result, nitrogen oxides are produced in virtually all combustion processes. Hotter burning conditions and the presence of oxygen allow proportionally more nitrogen oxide to be generated per unit of fuel burned. In order to reduce nitrogen oxide emissions, burn temperatures must be reduced and the amount of oxygen must be controlled—a procedure that is sometimes utilized in factories and power plants by means of certain air pollution control technologies. However, lowering temperatures and oxygen supply can result in less-complete combustion, which reduces the efficiency of the process and increases the number of particulates and carbon monoxide. Finding the exact mix of air, temperature, oxygen, and other factors is a challenge being met by the introduction of computer-based controls that regulate these factors.

All pollution control devices, because they use additional energy and increase resistance to air flow in the factory or power plant, require the use of more fuel and result in a slight increase in carbon dioxide emissions. And it is much harder—if not impossible—to remove pollutants from the environment after they have been dispersed over a wide area. That is why it is preferable to conserve, increase efficiency, and switch to fuels that contain fewer contaminants.

## AP® Exam Tip

When describing solutions to reducing emissions from combustion sources, don't use the word "filter." Describe a specific technology such as catalytic converters for cars or scrubbers and electrostatic precipitators on smokestacks. Be familiar with what these technologies remove.

In this module we have seen that the best approach for decreasing air pollution emissions is by avoiding them in the first place. This can be done by conservation, efficiency, and switching fuels. It can also be achieved by regulatory practices. When those methods have been utilized, additional air pollution reduction can be achieved by treating the pollutants immediately after combustion. Air pollution control devices such as the catalytic convertor, scrubber, and electrostatic precipitator use a variety of methods to remove sulfur dioxide and particulates from the waste stream.

**Electrostatic precipitator** A device that removes particulate matter by using an electrical charge to make particles coalesce so they can be removed from the exhaust stream.

# Module 45 AP® Review

Preparing for the AP® Exam

## Learning Goals Revisited

### 45-1 How can air pollutants be reduced?

Air pollution is best treated by preventing it or reducing it before combustion occurs. This can be achieved by conservation, increasing efficiency, and choosing fuels that contain fewer impurities. Regulatory practices can reduce air pollution by requiring implementation of devices, such as the vapor recovery nozzle at gasoline filling stations or restricting vehicle use on certain days for certain drivers.

### 45-2 What are the various air pollution control devices and how are they used?

Once combustion occurs, pollution control devices are used to prevent pollutants from entering the atmosphere. The catalytic converter in cars and trucks removes oxygen from nitrogen oxides resulting in the formation of nitrogen gas and oxygen gas. It also adds oxygen to carbon monoxide, resulting in the formation of carbon dioxide. The scrubber literally scrubs the exhaust stream, creating a sludge that can be collected and removed. The electrostatic precipitator uses an electrical charge to coalesce particles so they can be removed.

## AP® Practice Questions

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### Multiple-Choice Questions

1. Which method is used to reduce nitrogen oxide emissions?
   (a) installation of catalytic converters
   (b) increased temperature of combustion
   (c) the addition of oxygen to combustion processes
   (d) the use of fluidized bed combustion

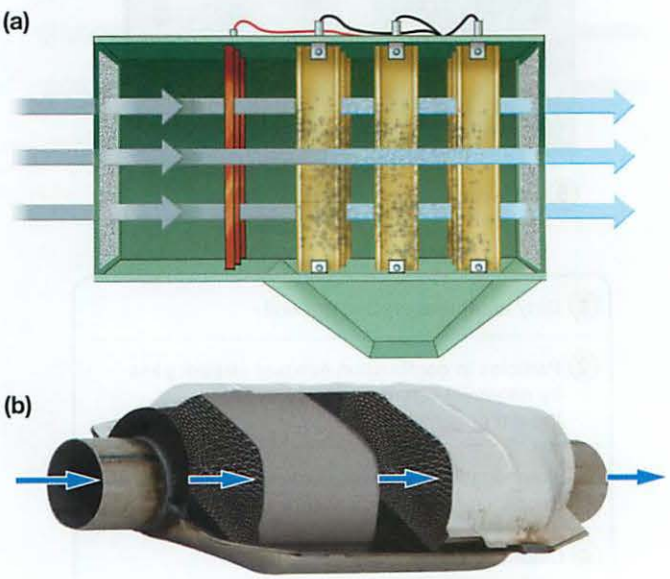
2. Which is used to prevent the emission of particulate matter?
   (a) automotive mufflers
   (b) increased ventilation
   (c) electrostatic precipitators
   (d) catalytic converters

3. A vapor recovery nozzle is commonly found at
   (a) coal-burning power plants.
   (b) factories.
   (c) gasoline stations.
   (d) natural-gas power plants.

4. If carbon monoxide emissions decreased from 145 million tons annually to 80 million tons annually, by what percentage have emissions been reduced?
   (a) 41 percent
   (b) 45 percent
   (c) 47 percent
   (d) 52 percent

5. The main purpose of an electrostatic precipitator is to remove
   (a) carbon monoxide.
   (b) nitrogen oxide.
   (c) particulates.
   (d) sulfur dioxide.

*Use the following diagrams to answer questions 6 & 7:*




6. Figure A represents an electrostatic precipitator and Figure B represents a catalytic converter. Which of the following is the product of a catalytic converter?
   (a) carbon monoxide
   (b) nitrogen
   (c) particulate matter
   (d) nitrogen oxides

7. Which statement is true about the two figures?
   (a) Figure A is found on vehicles to alter pollutants before they reach the atmosphere.
   (b) Figure B removes particulate matter from the air.
   (c) Figure A uses electrodes to remove particulates.
   (d) Figure B is placed on a smokestack of coal-burning factories.

### Free-Response Question

Industrial processes and fossil fuel-burning tend to lead to different air pollutants being released into the atmosphere. One of these pollutants is sulfur dioxide ($SO_2$).

(a) **Identify** a method or device that removes air pollution from the exhaust stream of an industrial process. (1 pt.)
(b) **Identify** a piece of legislation that regulates emissions of sulfur dioxide. (1 pt.)
(c) **Describe** one by-product of removing air pollution through the method identified in part (a). (1 pt.)
(d) **Explain** one reason why air pollution removal strategies are not typically used unless there is legislation requiring them. (1 pt.)
(e) A smokestack emits 31 micrograms of particulate matter each hour. After a wet scrubber is installed this number drops to 2 micrograms of particulate matter each hour.
   (i) **Calculate** how much particulate matter is released in 24 hours before the scrubber is added. Show all work. (2 pts.)
   (ii) **Calculate** how much particulate matter is released in 24 hours after the scrubber is added. Show all work. (2 pts.)
   (iii) **Calculate** the percent decrease in particulate matter released in the two 24 hour periods. Show all work. (2 pts.)

# Module 46





# Acid Rain and Noise Pollution

As we saw in the last module, there are a variety of methods for controlling air pollution and many methods have been successful. In this module we will examine acid rain, also known as acidic deposition, which is caused by the air pollutants sulfur dioxide and nitrogen oxide, and describe its causes and effects. We will also describe noise pollution and its effects on humans and marine life.

**Learning Goals**

After reading this module you should be able to

**46-1** describe acid rain and its effects.

**46-2** explain the sources and effects of noise pollution.

**46-1** What is acid rain and what are its effects?

## Acid rain is acidified precipitation derived from air pollutants, which adversely affects terrestrial and aquatic systems and buildings

You may recall that acidified rainfall and snow, or acid rain, was first defined in Module 20 as rain or snow containing sulfuric and nitric acid. In order to discuss acid rain further, we must first examine the pH scale. The **pH** indicates the relative strength of acids and bases in a substance. A water molecule, $H_2O$, is made up of two hydrogens (2 H+) and one oxygen (O). Many substances dissolve easily into water, which can be represented in solution as one hydrogen ion (H+) and one hydroxide ion (OH–). A pH value of 7—the pH of pure water—is neutral, meaning that the number of hydrogen ions is equal to the number of hydroxide ions.

**pH** The relative strength of acids and bases in a substance. It is a logarithmic scale, meaning that each number on the scale represents a change by a factor of 10.

Anything above 7 is basic, or alkaline, and anything below 7 is acidic. Another way to define acids and bases is to state that an **acid** is a substance that contributes hydrogen ions to a solution. A **base** is a substance that contributes hydroxide ions to a solution. Both acids and bases dissolve in water. The pH scale tells us that the lower the number, the stronger the acid, and the higher the number, the stronger the base. The pH scale is logarithmic, meaning that each number on the scale represents a change by a factor of 10. For example, a substance with a pH of 5 has 10 times the acidity or 10 times the hydrogen ion concentration of a substance with a pH of 6—or in simpler terms, it is 10 times more acidic. Water in equilibrium with Earth's atmosphere typically has a pH of 5.65 because carbon dioxide from the atmosphere dissolves in it, which makes it weakly acidic. **FIGURE 46.1** lists the pH of many familiar substances on the pH scale, which ranges from 0 to 14.

As you can see from Figure 46.1, normal rainwater is naturally somewhat acidic; the reaction between water and atmospheric carbon dioxide lowers the pH of precipitation on the pH scale from a neutral 7.0 to 5.6. We'll explain this idea in further detail when we discuss ocean acidification in Module 58. What's important to know now, is that the increase in carbon dioxide in the atmosphere has led to more carbon dioxide in ocean water, which has led to acidification of ocean water. When an acid is dissolved in water, it dissociates or breaks apart into positively charged hydrogen ions ($H^+$) and negatively charged ions. When air pollution mixes with rainwater, it creates additional acidity. The two acids that comprise **acid rain**, also known as **acid deposition**, are nitric acid ($HNO_3$) and sulfuric acid ($H_2SO_4$), both of which dissociate to contribute hydrogen ions to water and soil. Acid deposition is largely the result of human activity, although natural processes, such as volcanoes, may also contribute to its formation. Let's examine how acid deposition forms and how it travels in the atmosphere.

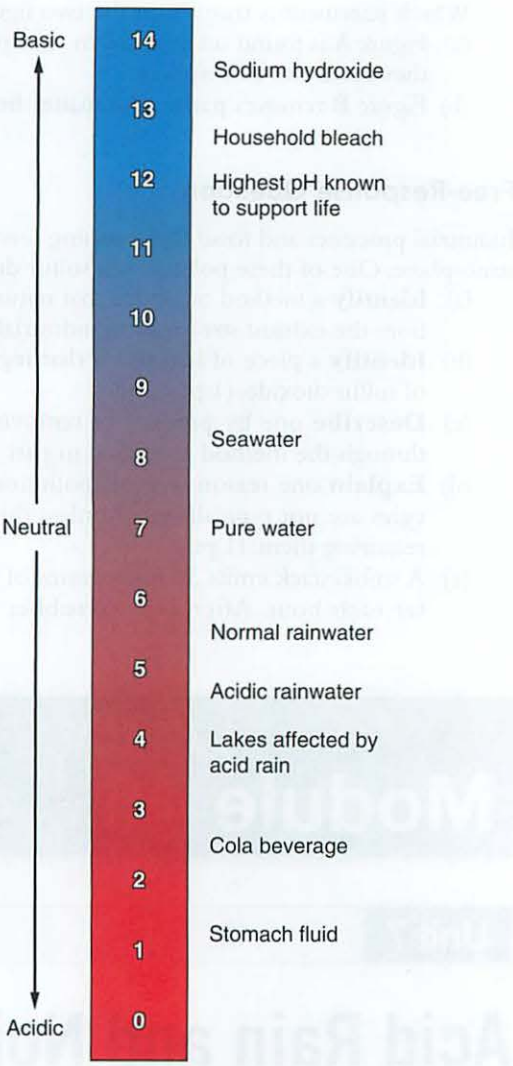



**FIGURE 46.1 Acid rain and the pH scale.** The pH scale indicates how acidic or how basic a solution is. The pH scale is logarithmic, meaning that each number on the scale represents a change by a factor of 10. Acid rain is more acidic than normal rainwater.

### AP® Exam Tip

You are expected to understand pH on the AP® Environmental Science Exam and to know the pH of water — rainwater, acid rain, and ocean water — as shown in Figure 46.1. You should also be able to recognize some common acids and bases.

**Acid** A substance that contributes hydrogen ions to a solution.

**Base** A substance that contributes hydroxide ions to a solution.

**Acid rain** Precipitation high in sulfuric acid and nitric acid. *Also known as* **acid deposition**.

## How Acid Deposition Forms and Travels

**FIGURE 46.2** shows how acid deposition forms. Nitrogen oxides (NO and $NO_2$) and sulfur oxides (primarily $SO_2$) are released into the atmosphere by natural and anthropogenic combustion processes. Volcanoes emit sulfur oxides and nitrogen oxides and are a natural source of acid rain. Automobile and truck exhaust from gasoline and diesel fuels as well as stationary combustion of coal and oil are important human sources of nitrogen oxides and sulfur dioxide. Through a series of reactions with atmospheric oxygen and water, these primary pollutants are transformed into the secondary pollutants nitric acid ($HNO_3$) and sulfuric acid ($H_2SO_4$). Sulfuric acid breaks down into $2\,H^+$ and $SO_4^{2-}$ (sulfate) and nitric acid breaks down into $H^+$ and $NO_3^-$ (nitrate). The sulfate and nitrate are inorganic

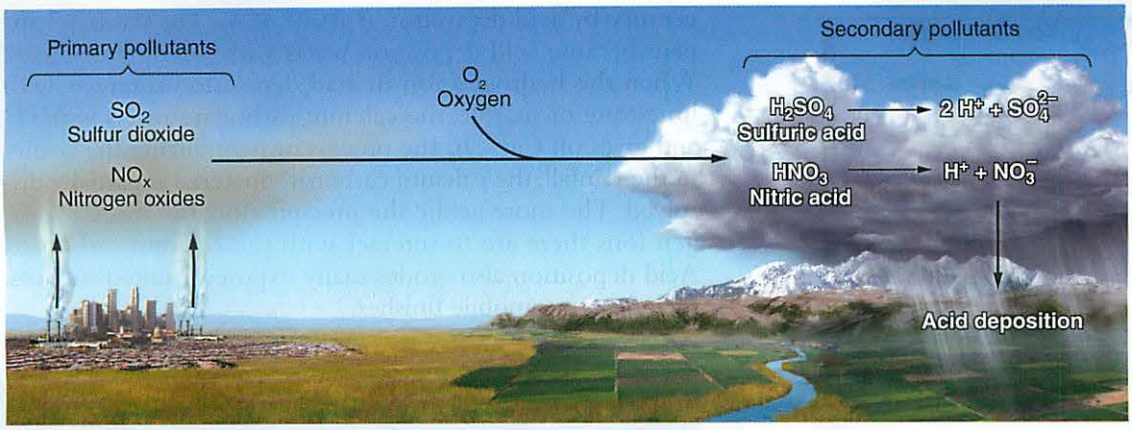



**FIGURE 46.2 Formation of acid deposition.** The primary pollutants sulfur dioxide and nitrogen oxides are precursors to acid deposition. After transformation to the secondary pollutants — sulfur acid and nitric acid — dissociation occurs in the presence of water. The resulting ions — hydrogen sulfate and nitrate — cause the adverse ecosystem effects of acid deposition.

compounds and the hydrogen ions ($H^+$) generate the acidity in acid deposition. These transformations occur over several days, and during this time, the pollutants may travel a thousand kilometers (600 miles) or more. Eventually, these secondary acidifying pollutants are washed out of the air and deposited either as precipitation or in dry form on vegetation, soil, or water.

Acid deposition has been reduced in the United States as a result of lower sulfur dioxide and nitrogen oxide emissions, as we saw in Figure 42.4. As we discussed in Module 42, much of this improvement is a result of the Clean Air Act Amendments that were passed in 1990 and implemented in 1990 and 1995. Prior to the implementation of the Clean Air Act Amendments, acid rain from midwestern states was carried by the prevailing westerlies to New York and New England where it was deposited in lakes and forests.

In addition to locations in the United States, studies have documented regional acid deposition in West Africa, South America, Japan, China, and many areas in eastern and central Europe. Acid deposition crosses international borders between the United States and Canada and is carried from England, Germany, and the Netherlands to Scandinavia. Because of this mobility, the precursors to acid deposition emitted in one region may have a significant impact on another region or another country. For example, over the years, there have been legislative and legal attempts to restrict emissions from coal-burning power plants in the midwestern United States that fall as acid deposition in Canada. Many of the regions that once received high amounts of acid deposition are receiving less deposition today. However, recently observed acid deposition documented along the West Coast of the United States is believed to be the result of coal combustion in China; sulfur and nitrogen oxides are released in China and elsewhere in Asia and are carried by the prevailing westerlies from one continent to another, across the Pacific Ocean. When they reach the western United States, they are deposited on the ground in rain and snow and intercepted by vegetation in California, Oregon, and Washington State.

## Effects of Acid Deposition on Terrestrial and Aquatic Ecosystems

Acid deposition in the United States increased substantially from the 1940s through the 1990s due to the combustion of coal and oil and other industrial activities. It leads to acidification and degradation of building materials and automobiles, on agricultural lands, and on both aquatic and terrestrial natural habitats. News reports from the United States and Europe in the 1980s and 1990s contained frequent reports about adverse effects of acid deposition on forests, lakes, and streams.

Effects of acid deposition may be direct, such as a decrease in the pH of lake water, or indirect, such as when acid deposition acidifies a soil (direct) and mobilizes a toxic metal (indirect) that adversely affects fish. When soils are high in calcium and magnesium, usually because of limestone bedrock underlying the soil, acid rain can be partially neutralized or "buffered." This will reduce the impact of acid rain on plants growing in that soil, and on aquatic systems that are adjacent to the limestone bedrock. Regional differences in vegetation and bedrock can mitigate acidification but they can also make the situation worse.

In locations without underlying limestone bedrock, the lower pH from acid deposition can lead to mobilization of metals, an indirect effect. When this happens, metals bound in organic or inorganic compounds in soils and sediments are released into surface water. Because metals such as aluminum and mercury can impair the physiological functioning of aquatic organisms, exposure can lead to species loss. Decreased pH can also affect the food sources of aquatic organisms, creating indirect effects at several trophic levels. On land, at least one species of tree, the red spruce (*Picea rubens*), at high elevations of the northeastern United States, was shown to have been harmed by acid deposition. It is likely that these trees

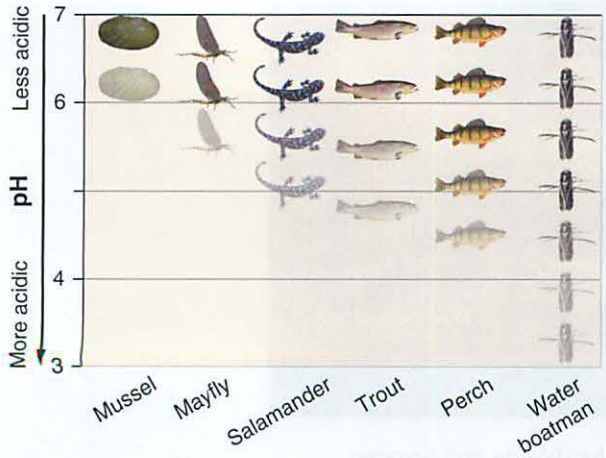



**FIGURE 46.3 Aquatic organisms and the pH ranges in which they survive and reproduce.** For each organism, the solid color represents the pH range in which they thrive, meaning they survive and reproduce. The lighter colors for each organism represents the pH range in which they survive but cannot reproduce. When the organism is absent below a certain pH, it indicates they cannot survive.

have been harmed by a combination of the acidity of the deposition as well as by the nitrate and sulfate ions.

The greatest effects of acid deposition have been on aquatic ecosystems. Lower pH of lakes and streams in areas of northeastern North America, Scandinavia, and the United Kingdom has caused decreased species diversity of aquatic organisms. As we saw in Unit 2, many species are able to survive and reproduce only within a narrow range of environmental conditions, called range of tolerance. Many amphibians, including salamanders, for instance, will survive when the pH of a lake is 6.5, but when the lake acidifies to pH 6.0 or 5.5, the same organism will begin to have developmental or reproductive problems. In water below pH 5.0, most salamander species cannot survive. **FIGURE 46.3** shows a variety of aquatic organisms and the pH range in which they survive and reproduce, the range in which they survive only but cannot reproduce, and the pH below which they cannot survive. As you can see, the pH range in which each organism thrives is different.

## Effects of Acid Deposition on Humans and Infrastructure

People are not harmed by direct contact with acid rain at the pH levels of acid rain commonly experienced in the United States and elsewhere in the world because human skin is a sufficiently robust barrier. Acid deposition mainly affects ecosystems and materials that are downwind from sources of acids such as coal-burning power plants and factories. Acid deposition can harm human-built structures such as statues, monuments, and buildings. For example, buildings from ancient Greece such as those on and near the Acropolis in Athens, many of which have stood for approximately 2,000 years, have been seriously eroded over the last half century by acid deposition (**FIGURE 46.4**). The damage happens because acid deposition reacts with building materials. When the hydrogen ion in acid deposition interacts with limestone or marble, the calcium carbonate reacts with $H^+$ and gives off $Ca^{2+}$. In the process of neutralizing the acidity in the rainfall, the calcium carbonate material is partially dissolved. The more acidic the precipitation, the more hydrogen ions there are to interact with the calcium carbonate. Acid deposition also erodes many exposed painted surfaces, including automobile finishes.

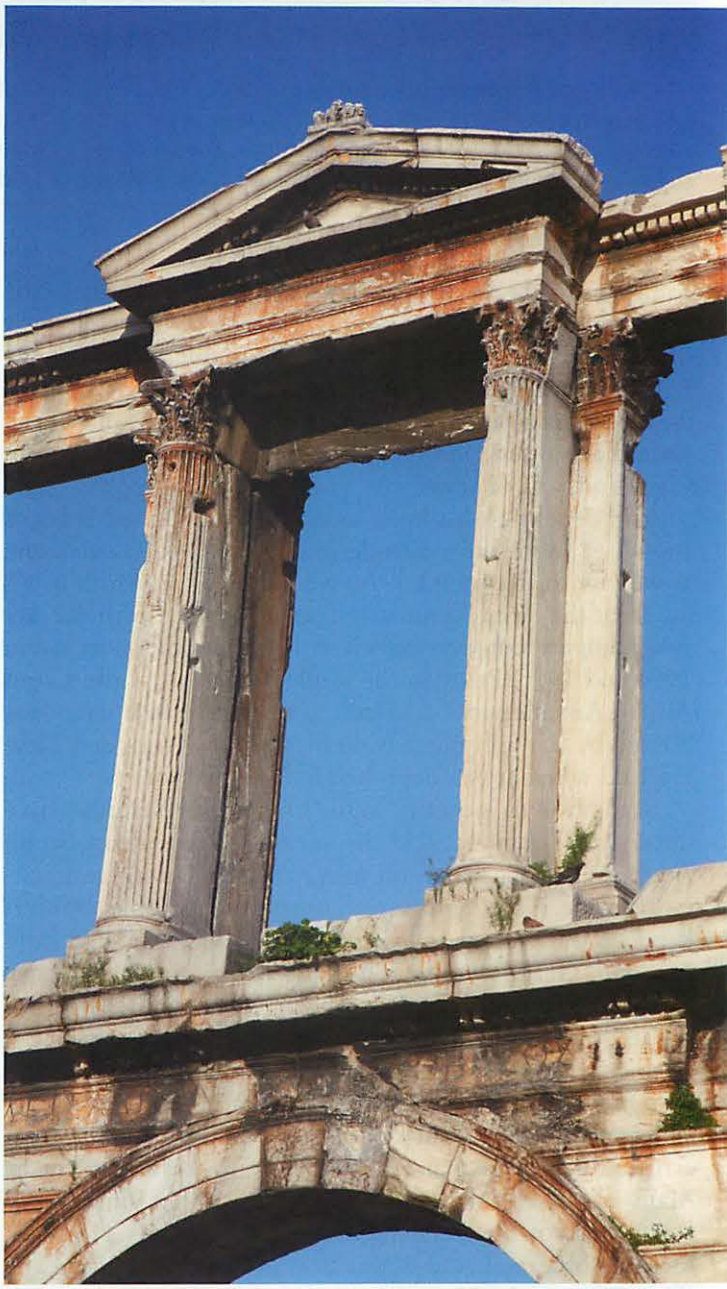


**FIGURE 46.4 Material damage from acid deposition.** Hadrian's Arch, near the Acropolis in Athens, Greece, has been damaged by acid deposition. It is made of marble, which contains calcium carbonate, and is susceptible to deterioration from acid deposition and acids in the air. *(Heritage Image Partnership Ltd/Alamy Stock Photo)*

Acid rain comes from sulfur dioxide and nitrogen oxide pollutant emissions. A portion of the legislation that addresses acid rain is contained within the Clean Air Act Amendments of 1990, Title IV. When those amendments were passed, Congress did not repeal the previously existing Title IV, which covered noise pollution. So although seemingly disconnected, it is appropriate to cover these concepts together since they are both regulated by Title IV of the Clean Air Act.

**46-2** What are the sources and effects of noise pollution?

## Noise pollution in the air can affect human health and behavior; noise pollution in water may interfere with animal communication

**Noise pollution** is unwanted sound that interferes with normal activities such as sleeping or conversation, or sound that is loud enough to cause physiological stress and other health issues including hearing loss. You might be aware that noise pollution affects humans, although disproportionately more in low-income communities, but did you know it also affects wildlife? We'll explore how it affects all life below.

### Noise Pollution and Humans

Noise pollution is measured in two ways: loudness and frequency, which is also known as pitch. The standard unit for measuring loudness is the decibel (db), which is one-tenth (0.1 or deci) of a bel. Like the pH scale, it is logarithmic. Therefore, a sound that is 10 db higher than another is perceived by the average listener as twice as loud. A sound that is 20 db higher is perceived as four times as loud. Frequency or pitch is measured in hertz (Hz). Humans can hear in the frequency range of 20 Hz to 20,000 Hz. People are more sensitive to some frequencies than others, and as people age, some lose hearing in the higher frequency ranges. The lowest frequency range that people can hear is called low-frequency noise (20 Hz to 200 Hz) and is a sound range sometimes emitted by wind turbines. There is more than one decibel scale, but the most commonly reported decibel scale is the **decibel A scale (db(A))**, a logarithmic scale that measures both the loudness of sound, and the frequency combined with the way that the human ear perceives that sound. **FIGURE 46.5** shows the db(A) scale with some common sounds and their db(A) ratings. This rating incorporates both the loudness and the frequency of the sound. If you have ever heard the sound of a leaf blower used by gardeners and cleanup crews, or the whine of a garbage truck compressing garbage, you may be able to appreciate how

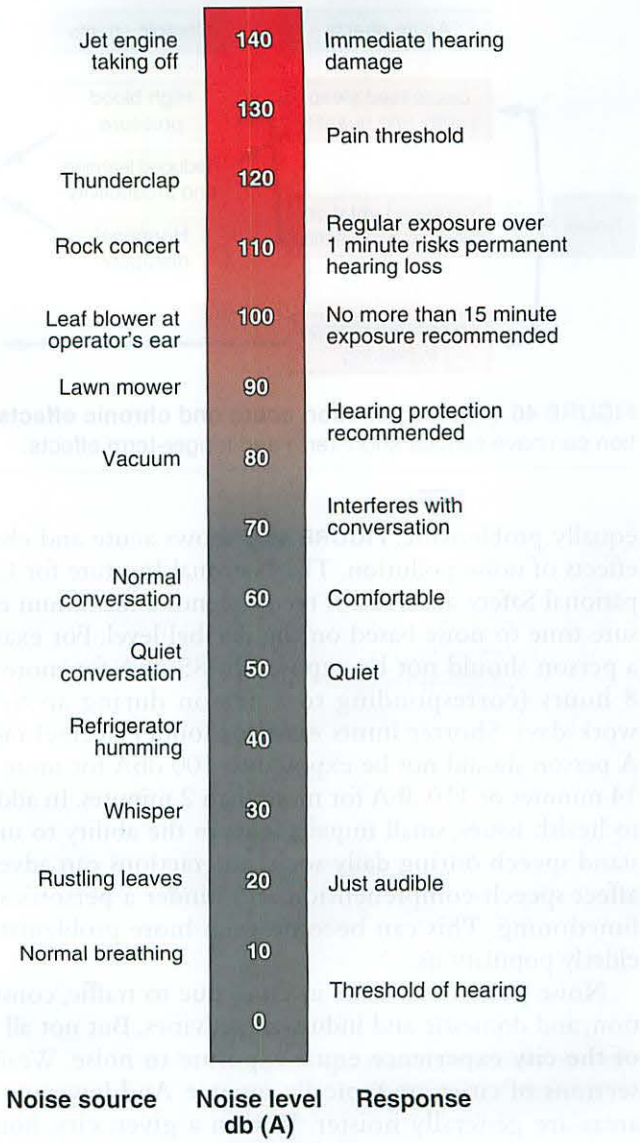



**FIGURE 46.5 The decibel scale.** Like the pH scale, the decibel scale is logarithmic. So a normal conversation at 60 db is perceived as twice as loud as a quiet conversation at 50 db.

the frequency as well as the loudness affects perception of sound.

In humans, unwanted noise and long-term exposure to noise can lead to hearing loss but can also lead to stress-related illnesses, sleep disruption, high blood pressure, and difficulty with concentration. Noise Induced Hearing Loss is probably the most common and commonly recognized effect from noise pollution, but other conditions can be

**Noise pollution** Unwanted sound that interferes with normal activities that is loud enough to cause health issues including hearing loss.

**decibel A scale (db(A))** A logarithmic scale that measure both the loudness of sound and the frequency.

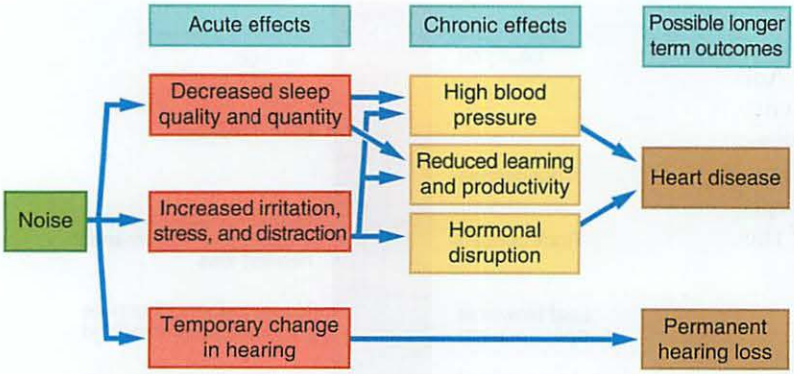



**FIGURE 46.6 Noise pollution acute and chronic effects.** Noise pollution can have serious short-term and longer-term effects.

equally problematic. **FIGURE 46.6** shows acute and chronic effects of noise pollution. The National Institute for Occupational Safety and Health recommends a maximum exposure time to noise based on the decibel level. For example, a person should not be exposed to 85 dbA for more than 8 hours (corresponding to a person during an 8-hour work day). Shorter limits exist for louder decibel ratings. A person should not be exposed to 100 dbA for more than 14 minutes or 110 dbA for more than 2 minutes. In addition to health issues, small impairments in the ability to understand speech during daily social interactions can adversely affect speech comprehension and hinder a person's social functioning. This can become even more problematic in elderly populations.

Noise pollution occurs in cities due to traffic, construction, and domestic and industrial activities. But not all parts of the city experience equal exposure to noise. Wealthier sections of cities are typically quieter. And lower-income areas are generally noisier. Within a given city, housing adjacent to elevated rail lines, for example, experiences noise that is much louder and the cost of the housing is less expensive than housing that is closer to a park (**FIGURE 46.7**). Suburban and rural areas are also subject to the same noise pollution sources but perhaps traffic noise is not as loud as in more densely populated, congested areas. Industries such as factories and waste treatment facilities such as landfills, incinerators, and recycling centers can all be sources of noise pollution.



**FIGURE 46.7 Noise pollution in urban areas.** Transportation infrastructure, such as this city street with an elevated train structure above it, can be a major source of noise pollution in urban areas. *(Franck Michel, CC)*

### Noise Pollution and Environmental Justice

People of color, lower income communities, and recent immigrants are more likely than Caucasians to live in proximity to solid waste incinerators, chemical production plants, petroleum refineries, toxic waste plants, and other so-called loud and dirty industries. In a number of now-famous studies in the 1980s and 1990s, investigators used the distribution of minority residents by postal zip code to relate race and class to the location of hazardous chemical and waste facilities and sites. In Atlanta, 83 percent of the Black population lived within the same zip code as the 94 uncontrolled toxic waste sites, while only 60 percent of Caucasians lived in those areas. In Los Angeles, roughly 60 percent of Hispanics lived in the same areas as the toxic waste sites, while only 35 percent of the Caucasian population lived in those areas. One study in five southern states compared the size of specific landfill facilities with the percentage of minorities in the zip code in which the landfill was located. The study concluded that the largest landfills are located in areas that have the greatest percentage of minorities. Not only are people who work or live near these facilities subjected to unwanted noise, but they may also be subjected to outdoor or indoor air pollution as well.

## Noise Pollution and Wildlife

Noise pollution can adversely affect animal species in multiple ways. Amphibians, birds, mammals, fish, and reptiles are all affected. As it does with humans, excess anthropogenic noise can cause stress in animal populations and it can damage hearing. Traffic noise has been shown to reduce the hunting efficiency of bats. Noise can interfere with warning signals and mating calls being heard by birds and amphibians. Noise has also been shown to alter migratory routes of certain animals. A 2019 comprehensive review of noise pollution and wildlife suggested that rather than just a few sensitive species being affected, it is more likely that most species are affected by anthropogenic noise.

Noise pollution may also occur in the oceans. Sounds emitted by propellers and mechanical systems on ships and submarines can interfere with underwater animal communication. Sonar, which is underwater sound propagation for use in navigation and map making, can negatively affect species such as whales that rely on low-frequency, long-distance



**FIGURE 46.8 Aquatic noise pollution.** Noise from navy sonar and oil exploration may interfere with the normal behavior of whales. *(Lazareva/Getty Images)*

communication (**FIGURE 46.8**). Several instances of beached whales in the Bahamas, the Canary Islands, and the Gulf of California have been connected to the use of military sonar and the use of loud, underwater air guns by energy companies searching for oil deposits under the oceans.

In 2003, a federal judge rejected the U.S. Navy's request to install a network of long-range sonar systems across the ocean floor to detect incoming submarines because of suspected negative impacts on endangered whales and other species of marine animals. In 2008, however, the U.S. Supreme Court ruled that the president of the United States could exempt the Navy from environmental laws that were related to potential sonar effects on ocean life. To better understand noise pollution in the ocean, the U.S. National Oceanic and Atmospheric Administration (NOAA) announced in 2012 that it had completed the first step in mapping the noises across different regions of the ocean. By 2014, NOAA concluded that the Navy's activities would have a negligible effect on fish and whales in the ocean. At the same time, an increased awareness of noise pollution in the ocean has inspired some ship builders to design ships equipped with quieter propellers.

In this module we described acid rain and its formation from nitrogen oxides and sulfur dioxide. We identified that the major sources of acid rain are vehicle exhaust and stationary combustion. Acid rain can potentially affect forests, soils, and aquatic communities downwind from the location where acid rain precursors are released. Aquatic ecosystems are the most adversely affected. If a soil is underlain by limestone bedrock, the impact of acid rain on terrestrial and aquatic systems can be partially neutralized. Noise pollution is unwanted noise at levels high enough to cause hearing damage and other health effects. Transportation, construction, and industry are sources of noise pollution. People of color, lower income communities, and recent immigrants are more likely to experience anthropogenic noise pollution than Caucasians. Many different animal populations are also subject to noise pollution including marine mammals that rely on sound for long-distance communication. Outdoor air pollution, indoor air pollution, acid deposition and noise are all components of atmospheric pollution that require assessment and mitigation for the safety of humans, animals, and ecosystems.

# Module 46 AP® Review

Preparing for the AP® Exam

## Learning Goals Revisited

### 46-1 What is acid rain and what are its effects?

The pH indicates the relative strength of acids and bases in a substance and is a logarithmic unit of measure. Acid rain is rain or snow containing nitric and sulfuric acids that come from the release of the primary pollutants nitrogen oxides and sulfur dioxide. Motor vehicles and stationary combustion such as from coal-burning power plants are two important sources of acid rain. Volcanoes are a natural source of acid rain. Vegetation, soils, and aquatic communities are potentially affected by acid rain. Watersheds underlain by limestone bedrock may have the capacity to partially neutralize acid rain. Structures such as buildings and automobiles can be degraded by acid rain. The acidity of rainfall in the United States has decreased due to legislation passed with the Clean Air Act and subsequent amendments.

### 46-2 What are the sources and effects of noise pollution?

Noise pollution is unwanted sound that causes hearing loss, stress, and other health issues in humans. Amphibians, birds, mammals, fish, and reptiles are also affected by unwanted noise. Noise pollution in air is measured in decibels, which is a logarithmic unit of measure. Transportation, construction, and industrial activity generate noise pollution. Urban areas can be major sources of anthropogenic noise. People of color, lower income people, and recent immigrants are more likely to experience anthropogenic noise pollution than Caucasians.

# AP® Practice Questions

## Multiple-Choice Questions

1. Acid deposition
   (a) is caused by combustion of fossil fuels.
   (b) is made worse by limestone.
   (c) occurs as a result of mining.
   (d) leads to photochemical smog.

2. The pH scale and the decibel scale are both
   (a) logarithmic.
   (b) range from 0 to 100.
   (c) increase with increasing harmful impact.
   (d) measured in air and water.

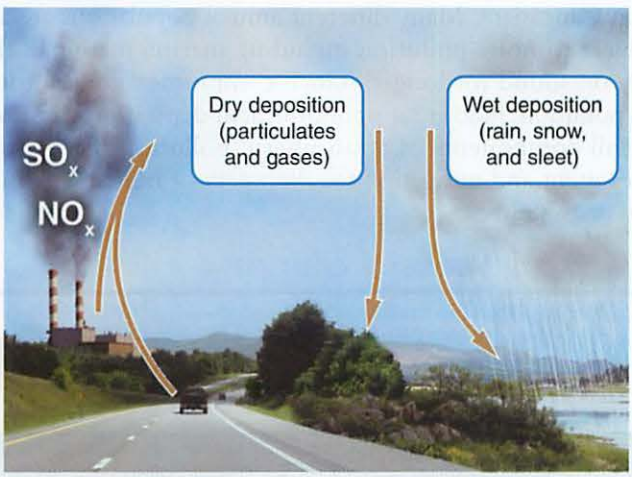
3. Lakes affected by acid rain could have a pH of approximately
   (a) 2.
   (b) 4.
   (c) 10.
   (d) 12.

4. Noise pollution can cause which of the following health effects?
   (a) heart disease
   (b) hair loss
   (c) diabetes
   (d) cancer

5. Which of the following is an acute effect of noise pollution?
   (a) high blood pressure
   (b) sleep loss
   (c) reduced productivity
   (d) hormonal disruptions

## Free-Response Question

The diagram below shows the formation of acid rain with anthropogenic sources.




(a) **Identify** one type of acid that forms in the atmosphere. (1 pt.)

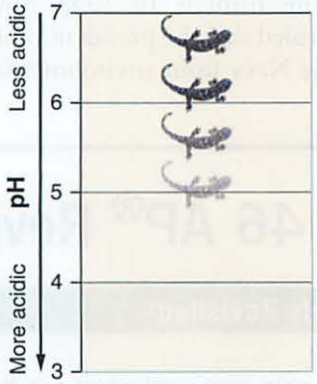
(b) **Describe** one effect of acid rain on human-made structures. (1 pt.)

(c) **Describe** one effect of acid rain on ecological systems. (1 pt.)

(d) **Explain** what occurs to the pH of aquatic ecosystems when acid rain falls. (1 pt.)

(e) Local scientists suggest that when acid rain falls, and enters a lake, one method for remediation is to add limestone to the lake. **Justify** whether you support or refute this method. (2 pts.)

(f) The data table below shows the pH preference of salamanders in a freshwater ecosystem. Scientists measured the abundance of salamanders at different pH levels in the ecosystem.




Salamander

(i) **Identify** the independent variable for this data collection. (1 pt.)

(ii) **Identify** a likely hypothesis for this data collection. (1 pt.)

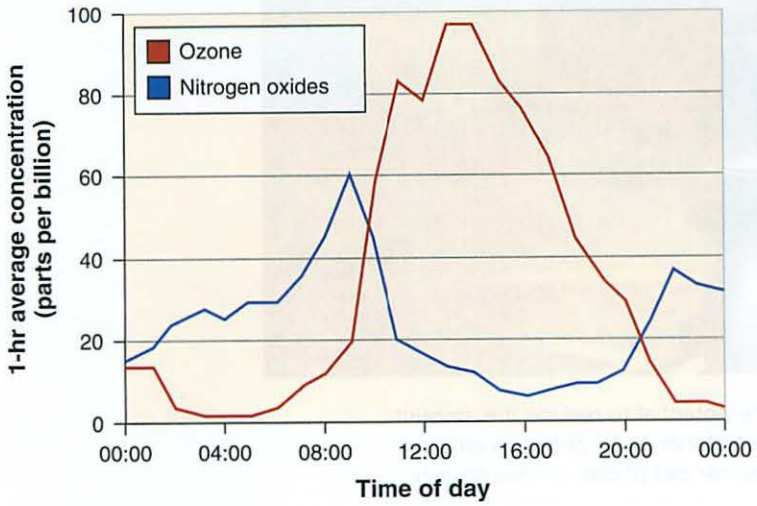
(iii) **Identify** the dependent variable for this data collection. (1 pt.)

(iv) **Describe** a modification to this data collection that would clarify the data. (1 pt.)

# UNIT 7
# Practice Your Science Skills

Preparing for the AP® Exam

## Data Analysis




### Questions

1. **Describe** the pattern of ozone over the course of the day.
2. **Explain** why this pattern of ozone occurs.
3. **Identify** one source of $NO_2$ emissions that most likely contributes to the pattern of $NO_2$ seen in the graph.
4. **Explain** how this graph would change on a typical day in winter.

## Pursuing Environmental Solutions

### Better Indoor Cook Stoves

In China, India, and sub-Saharan Africa, people in 80 to 90 percent of households cook food using wood, animal manure, and crop residues as their fuel. Since women do most of the cooking, and young children are with the women of the household for much of the time, it is the women and young children who receive the greatest exposure to carbon monoxide and particulate matter. When biomass is used for cooking, concentrations of particulate matter in the home can be 200 times higher than the exposure limits recommended by the U.S. Environmental Protection Agency. A wide range of diseases has been associated with exposure to smoke from cooking. Earlier in this unit, we described that indoor air pollution is responsible for 3.8 million deaths annually around the world, and indoor cooking is a major source of indoor air pollution.

There are hundreds of projects and business ventures underway around the world to enable women to use more efficient cooking stoves, ventilate cooking areas, cook outside whenever possible, and change customs and practices that will reduce their exposure to indoor air pollution. The use of an efficient cook stove will have the added benefit of consuming less fuel. This improves air quality and reduces the amount of fuel needed, which reduces the amount of nearby vegetation that must be collected and also reduces the amount of time that a woman must spend searching for fuel.

Increasing the efficiency of the combustion process requires the proper mix of fuel and oxygen. One effective method of ensuring a cleaner burn is the use of a small fan to facilitate greater oxygen delivery. However, because most homes in developing countries with significant indoor air pollution problems do not have access to electricity, some sort of internal source of energy for the fan is needed.

Two innovators from the United States developed a cook stove for backpackers and other outdoor enthusiasts who needed to cook a hot meal with little impact on the environment. The BioLite CampStove, which works by burning



**BioLite HomeStove.** This small stove and others like it have the potential to reduce the amount of firewood needed to cook a meal, as well as lower the amount of indoor air pollution emitted. This woman in a village in Kenya is also using the stove to charge her cell phone. *(Courtesy BioLite Inc.)*

solid biomass and weighs only 935 grams (2 pounds), needs no gasoline or batteries—a desirable feature for people carrying all their belongings on their backs. The stove utilizes two small wires made from different metals to generate electricity from the heat of the stove. The electricity can be used to charge a battery or phone.

The inventors of the CampStove soon realized that the same technology could make an important contribution to improving indoor air quality in the developing world. For home use in the developing world, they created the BioLite HomeStove, which weighs 8 kg (17.6 lbs). Like the CampStove, it physically separates the solid fuel from the gases that form when the fuel is burned, which allows the stove to burn the gases. In addition, a small electric fan, located inside the stove, harnesses energy from the heat of the fire and moves air through the stove at a rate that ensures complete combustion. The result is a more efficient burn, less fuel use, and less release of carbon monoxide and particulate matter. BioLite states that its HomeStove uses "less than half the fuel and produces 90% fewer emissions." The stove generates enough electricity to power the fan and has additional capacity to power a small USB port suitable for charging a cell phone or flashlight.

The BioLite CampStove stove is readily available on consumer goods websites; the BioLite HomeStove is sold in Kenya and Uganda. The manufacturer estimates that three-quarters of a million people have benefitted from the use of their stove. BioLite stoves won awards in 2009, 2012, 2014, and 2021 for low emissions, innovative design, and promoting social good. There are many other small stoves under development and in use around the world that increase combustion efficiency and reduce carbon monoxide and particulate emissions. The challenge is to make them affordable, available, and locally manufactured so that large numbers of people in the developing world will have access to them and use them. They also need to be easily and simply repairable. Other promising ways to reduce fuel use and improve indoor air quality include the solar cooker shown in Figure 39.5 on page 449.

## Critical Thinking Questions

1. Why are women and children exposed more often to indoor air pollution than men in developing countries?
2. How can technology offer solutions to cooking over open fires?

### References


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https://www.bioliteenergy.com/, homepage of BioLite stove.

https://youtu.be/mV1MRlhLnWQ Biolite Mission, Everyone Plays A Part. Posted on YouTube on February 10, 2016.

# Science Applied 7: Concept Explanation

## Can Cap-and-Trade Reduce Pollution Emissions Equitably?

Throughout this unit we have identified the need for reducing pollutant emissions. Pollutant reductions have been achieved in the United States for just about every major pollutant except carbon dioxide. As we identified in Module 42 and will further explore in Unit 9, a current challenge for human civilization is the need to reduce carbon dioxide concentrations in the atmosphere. There are even international protocols agreed to by almost every nation calling for specific carbon dioxide reductions through 2050. While there is something of a consensus on the need for further carbon reduction, there has been a great deal of debate regarding the most effective and fair way to achieve these reductions.

### Can successes controlling sulfur translate to carbon emission reductions?

As we described in Module 45, the cap-and-trade approach has been used for the control of sulfur dioxide emissions from coal-burning power plants since enactment of the Clean Air Act Amendments (CAAA) of 1990 to reduce acid precipitation (**FIGURE SA7.1**). In effect, the CAAA was a nation-wide experiment to see if controls of sulfur dioxide emissions at power plants could result in reductions in the acidity of rainfall. Motivated by the newly instituted cost of buying



(a)



(b)



(c)



(d)

**FIGURE SA7.1 Carbon cap-and-trade approach.** A diversity of industries emits large amounts of $CO_2$, including (a) coal-fired electricity-generating power plants, (b) automobiles, (c) airplanes, and (d) steel manufacturers. Under cap-and-trade, all of these industries could be involved in buying and selling permits for $CO_2$ emissions. *(a: RGB Ventures/Alamy Stock Photo; b: NadyGinzburg/Shutterstock; c: Dmitry Marchenko/Alamy Stock Photo; d: Andrey Radchenko/Alamy Stock Photo)*

pollution permits, companies that owned coal-fired electricity generation plants were required to retrofit existing facilities, construct new facilities that polluted less, or buy pollution permits from other companies that had already reduced their emissions. Even though some older power plants were exempt from certain provisions of the act, the CAAA had achieved a 50 percent reduction in sulfur emissions by 2021. The cap-and-trade system encouraged investment in new technologies, which is one of the underlying reasons for the success of this program. For example, an air pollution control system from coal-burning power plants was developed that recovers sulfur from sulfur dioxide emissions and converts it to synthetic gypsum (calcium sulfate that is used to make sheetrock, a building material). Because gypsum is a valuable product used in construction, the economic incentive to reduce sulfur emissions motivated new research and development that produced a profitable commercial product as part of the solution. Furthermore, the reductions in sulfur dioxide emissions were accompanied by reductions in particulate matter and carbon dioxide as additional benefits.

## What were the implications of sulfur cap-and-trade for the environmental justice movement?

The substantial decreases in emissions that were achieved did not benefit everyone equally. While the total amount of sulfur dioxide emitted by coal-burning power plants was reduced, certain communities were subjected to even higher rates of pollution. By design, the CAAA created a market for emissions credits that allows heavily polluting plants to continue polluting or even increase their annual emissions, as long as they purchase the right to do so. Through this system, plants can pay to pollute and the nearby communities that are downwind of the plants experience the adverse consequences—they experience increased air pollution. A number of studies have shown that the negative impacts of pollution disproportionately fall on lower-income communities and people of color. Critics of the sulfur dioxide cap-and-trade regulations argue that the program has exacerbated these inequalities, by leading to higher emissions downwind of certain plants and exposing communities of color to more pollution, not less.

A core concern of environmental justice is the importance of finding solutions to environmental challenges that distribute the benefits and costs equitably. Environmental justice examines whether there is equal enforcement of environmental laws and elimination of disparities—intended or unintended—in the exposure to pollutants and other environmental harms affecting different ethnic and socioeconomic groups within a society (**FIGURE SA7.2**). Some environmental injustices occur because wealthier communities sometimes have residents with time and financial resources to object to a proposed landfill or incinerator through protests, letter writing campaigns, social media posts, and legal action. When a landfill or incinerator is proposed in a lower-income community, the local residents may not possess



**FIGURE SA7.2 An oil refinery located near a community of color in Port Arthur, Texas.** Residents are exposed to a variety of pollutants including sulfur dioxide, volatile compounds, particulates, and noise. *(AP Photo/LM Otero)*

the same resources to successfully prevent the proposed entity from being permitted and constructed. Delegates to the First National People of Color Environmental Leadership Summit in 1991 established a total of 17 principles of environmental justice. Professor Robert Bullard of Texas Southern University is probably best known for his 1990 book *Dumping in Dixie*, which demonstrated that minority and lower socioeconomic groups were often the recipients of pollution from dumping of municipal solid waste and hazardous waste. Newer studies have reassessed the unequal distribution of hazardous waste dumping in the United States and found that the situation is worse than previously reported.

Sulfur dioxide and other pollutants from coal-burning plants are of special concern to environmental justice activists because of their direct implications for human health. A 2012 study determined that 78 percent of Black Americans lived within 30 miles of a coal-fired power plant and, as a result, Black children were significantly more likely to have asthma and require emergency department visits for an asthma attack than white children. The concentration of coal-burning power plants in lower-income communities has also been implicated in higher rates of lung disease and stroke. As more and more coal-burning power plants have been shutting down, the situation has improved but there is still a disproportionate exposure of communities of color to coal-burning power plant emissions. A 2017 study based on EPA data found that almost 8 million Black Americans live within a half-mile of oil and gas facilities including refineries where they are exposed to air pollution, noise, and groundwater contamination. Overall, they found that Black Americans were 75 percent more likely than white Americans to live in communities that were next to commercial facilities that had harmful levels of emissions, odors, noise, and/or vehicular traffic.

## Could cap-and-trade be used to reduce carbon dioxide emissions in the United States?

The inequitable distribution of air pollution did not improve from sulfur cap-and-trade regulations, but cap-and-trade has the potential to yield better results in other situations. In fact, many environmental scientists and economists argue that carbon dioxide is an ideal pollutant to be managed through cap-and-trade. One of the reasons for this is the fact that the need to reduce carbon dioxide emissions is due to its greenhouse warming potential rather than its health effects. Carbon dioxide does express indirect implications for human health—climate change increases the vulnerability of at-risk populations to natural disasters, can exacerbate the spread of infectious diseases, and may reduce the availability of fresh produce in some areas—but living near a large carbon dioxide emitter does not directly threaten health in the same way that living near sulfur dioxide or particulate polluters does. The cap-and-trade approach gives companies the freedom to choose the carbon-reduction approach that is most affordable while also offering an economic incentive to reduce pollution. The rate at which the carbon dioxide reduction occurs would depend on how quickly one government or an international treaty reduced the number of pollution permits. In 2005, a carbon cap-and-trade system was instituted in the European Union (EU). The system started slowly and was criticized for not lowering the number of permits quickly enough. In 2010, the European Union started to lower the cap and more companies, including electric generating plants and airlines began paying for the permits. A study in the Proceedings of the National Academy of Science estimated that the EU carbon cap-and-trade program had avoided more than 1 billion tons of carbon dioxide emissions between 2008 and 2016. This amounted to an almost 4 percent reduction of what would have been emitted in the EU had the program not been enacted. However, there are differences between controlling sulfur and carbon dioxide. As we discussed in Modules 37 and 42, sulfur is an impurity found in coal and oil. Sulfur can be removed before or after burning and certain fuels can be selected that have a lower sulfur content. Chemical bonds from carbon, on the other hand, are the source of the energy in fossil fuels and carbon dioxide is the actual end product of combusting that carbon, so it is much more difficult to control.

If carbon cap-and-trade is used in the United States, energy companies will probably be targeted including those that produce petroleum products and those that generate electricity. A recent study by Point Carbon, a market research company, found that the major oil companies including ExxonMobil and Chevron would likely pay hundreds of millions of dollars in $CO_2$ permits while electric generating companies that have diversified their electricity generation portfolios to include hydroelectric and nuclear energy will pay substantially less. Ultimately, if cap-and-trade is successful in the European Union, it could serve as an effective model for other locations in the world and help reduce the growing problem of excessive $CO_2$ emissions and the resulting global change.

### Questions

1. In general, is cap-and-trade an acceptable pollution control approach? When is it not such a desirable approach?
2. What is a difference between controlling emissions of sulfur dioxide versus carbon dioxide?

### Practice AP® Free-Response Question

Cap-and-trade controls on air pollution can be general, or they can be very specifically designed to control one specific pollutant. Cap-and-trade measures can also result in certain pollutant emitters purchasing pollution permits and emitting large amounts of pollution in one specific location.

(a) **Describe** one method of reducing air pollution that is general, meaning it will control virtually all air pollutants at the same time. (2 pts.)

(b) There are also very specific air pollution control methods that target one or a few air pollutants. **Explain** how one air pollution control technology will reduce or remove only specific air pollutants, but not usually all air pollutants. (2 pts.)

(c) Fuel switching is a term for achieving the same work or activity in an environmentally less harmful way by switching from one fuel to another.

(i) **Describe** an example of fuel switching that will result in lower sulfur emissions. (2pts.)

(ii) **Describe** an example of fuel switching that will result in lower carbon dioxide emissions. (2 pts.)

(d) When considering human health effects, critics of cap-and-trade express concern about localized areas of high pollutant emissions that will occur during a properly designed cap-and-trade pollution reduction system. **Explain** how a cape-and-trade program may result in an increase in adverse human health effects in specific geographic locations. (2 pts.)

#### References


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*Food and Water Watch*. 2019. Cap and Trade: More Pollution for the Poor and People of Color. https://foodandwaterwatch.org/wp-content/uploads/2021/04/ib_1911_rggicaptradeej-web.pdf.

Toomey, D. 2013. Coal Pollution and the Fight for Environmental Justice. *Yale Environment 360*, June 19. https://e360.yale.edu/features/naacp_jacqueline_patterson_coal_pollution_and_fight_for_environmental_justice.

# UNIT 7 Review

## Key Terms to Remember

Air pollution (p. 495)
Sulfur dioxide ($SO_2$) (p. 496)
Haze (p. 498)
Photochemical oxidant (p. 498)
Smog (p. 498)
Lead(Pb) (p. 498)
Hydrocarbons (p. 498)
Primary pollutant (p. 499)
Secondary pollutant (p. 499)
Photochemical smog (Los Angeles–type smog; Brown smog) (p. 504)
Sulfurous smog (London-type smog; Gray smog; Industrial smog) (p. 504)
Evaporate (p. 505)
Sublimate (p. 506)
Formaldehyde (p. 506)
Thermal inversion (p. 507)
Inversion layer (p. 507)
$PM_{10}$ (p. 509)
$PM_{2.5}$ (p. 509)
Indoor air pollutants (p. 512)
Asbestos (p. 513)
Radon-222 (p. 514)
Sick building syndrome (p. 516)
Vapor recovery nozzle (p. 523)
Catalytic converter (p. 525)
Scrubber (p. 526)
Electrostatic precipitator (p. 527)
pH (p. 529)
Acid (p. 530)
Base (p. 530)
Acid rain (Acid deposition) (p. 530)
Noise pollution (p. 533)
decibel A scale (dbA) (p. 533)

**Unit 7 AP® Environmental Science Practice Exam** Preparing for the AP® Exam

## Section 1: Multiple-Choice Questions

1. Which of the following is an example of a secondary pollutant?
   (a) sulfur dioxide
   (b) carbon dioxide
   (c) tropospheric ozone
   (d) nitrogen oxide

2. The accumulation of tropospheric ozone during the middle of the day depends mainly upon the atmospheric concentration of nitrogen oxides and
   (a) carbon dioxide.
   (b) volatile organic compounds.
   (c) chlorofluorocarbons.
   (d) sulfates and nitrates.

3. Air pollution generally refers to pollution in the
   (a) stratosphere.
   (b) troposphere.
   (c) lithosphere.
   (d) mesosphere.

4. Which of the following is an effect of acid deposition?
   (a) mobilization of metal ions from the soil into surface water
   (b) increased numbers of salamanders in ponds and streams
   (c) increased food sources for aquatic organisms
   (d) increased incidence of photochemical smog

5. Two major factors involved in the conversion of primary pollutants into secondary pollutants are the presence of
   (a) sunlight and water.
   (b) sulfates and sunlight.
   (c) water and volatile organics.
   (d) nitrogen oxides and sulfates.

6. The pollutant least likely to be emitted from a smokestack would be
   (a) carbon monoxide.
   (b) carbon dioxide.
   (c) ozone.
   (d) sulfur dioxide.

7. Which of the following is a source of particulate matter in the atmosphere?
   (a) the chemical by-products of acid rain formation
   (b) incomplete natural gas combustion
   (c) runoff from irrigation
   (d) volcanoes

8. Which air pollutant is sourced from bedrock typically in foundations of homes?
   (a) ozone
   (b) radon-222
   (c) volatile organic compounds
   (d) particulate matter

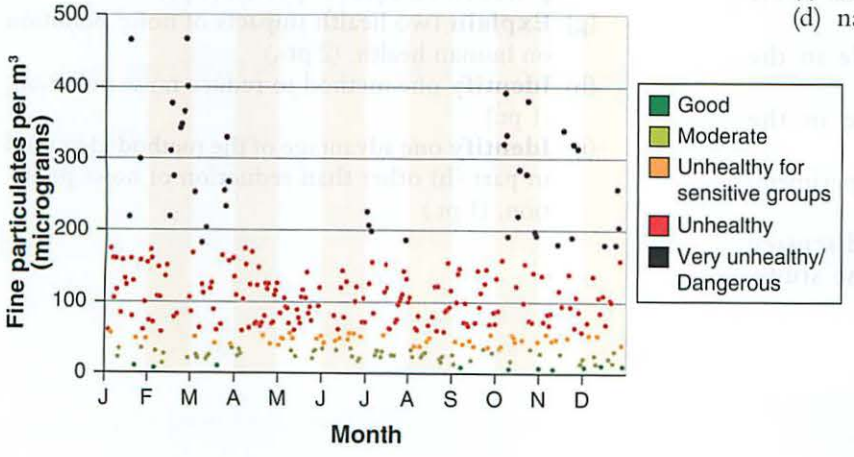
9. Pollutants can be categorized as primary or secondary. Which pairing is correct?
   (a) primary: ozone
   (b) primary: sulfate
   (c) secondary: nitrate
   (d) secondary: carbon monoxide

10. A thermal inversion
   (a) occurs when cool and warm air are intermixed throughout the year.
   (b) occurs when air pollution from China reaches the West Coast of the United States.
   (c) occurs when cool air is present through the troposphere.
   (d) occurs when a warm air layer overlies a cooler layer.

11. The juvenile Western Bluebird (*Sialia mexicana*) is a small thrush that has been found to be affected by noise pollution. A study showed that a small increase of 10-decibels can reduce the juveniles ability to hear background noise by as much as 90 percent. Birds can't hear predators or mating calls, and have drastically different migratory patterns due to background noises. One solution to reducing noise pollution would include
   (a) increased transportation.
   (b) decreased use of pesticides on crops.
   (c) increase in protected habitats.
   (d) decreased use of fossil fuels.

12. In the troposphere, $O_3$ is formed by the combination of _____ and _____ in the presence of sunlight due to fossil fuel combustion.
   (a) carbon dioxide, particulate matter ($PM_x$)
   (b) sulfur oxides, carbon dioxide
   (c) photochemical smog, acid rain
   (d) volatile organic compounds (VOCs), nitrogen oxides ($NO_x$)

*Use the graph below to answer questions 13–15:*




13. Using the graph, which month had the widest range of particulate matter around the U.S. Embassy in Beijing?
   (a) November
   (b) June
   (c) February
   (d) August

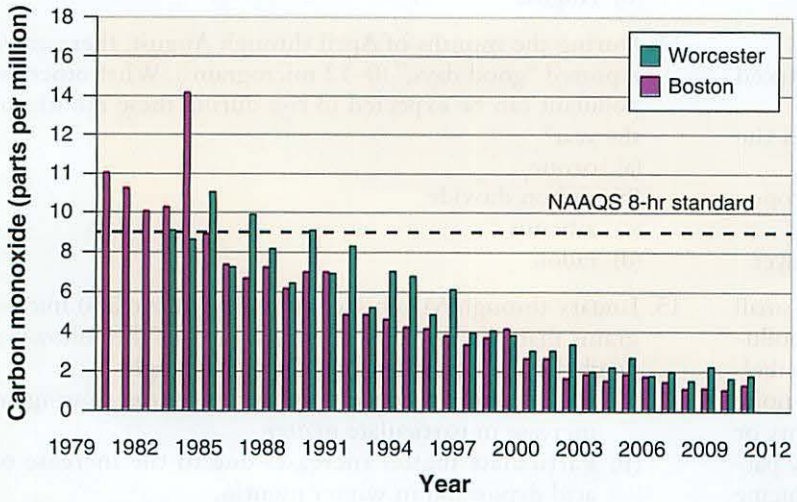
14. During the months of April through August, there are 0 reported "good days," (0–12 micrograms). What other air pollutant can be expected to rise during these months of the year?
   (a) ozone
   (b) carbon dioxide
   (c) asbestos
   (d) radon

15. January through March saw more days above 250 micrograms than the rest of the year. Which of the following would be a good explanation for this finding?
   (a) Respiration and decomposition increase, causing an increase in particulate matter.
   (b) Particulate matter increases due to the increase of acid deposition in winter months.
   (c) Coal is burned during winter months, increasing particulate matter.
   (d) During the winter months, trees release more particulate matter.

16. Migrant farm workers picking fruit on a farm would not have to worry as much about which of the following pollutants?
   (a) asbestos
   (b) photochemical smog
   (c) particulate matter
   (d) sulfur dioxide

17. A city has been experiencing rain with a pH of 5.5. Given this information, which is the likely source of energy used in this city?
   (a) tidal energy
   (b) wind turbines
   (c) coal power plant
   (d) natural gas power plant

18. The graph below shows carbon monoxide levels in the period of 1979 to 2011 in the city of Boston and surrounding areas. Which of the following is most likely responsible for the trend in carbon monoxide in this area?




(a) catalytic converters in vehicles
(b) wet scrubbers in factories
(c) vapor recovery nozzles on fuel nozzles
(d) electrostatic precipitators in factories

*Use the following passage to answer questions 19 & 20:*

The Clean Air Act established criteria for air pollution and limits how much of certain air pollutants can be released. Further amendments also created programs to reduce acid rain, creating cap-and-trade programs for $SO_2$. The CAAA has been found to reduce emission by 77 percent since 1970, and prevented an estimated 2.3 million premature deaths, 17 million lost workdays, and 5.4 million lost school days.

19. Which of the following best describes the author's claim?
    (a) The Clean Air Act has had a positive effect on ecosystems.
    (b) the Clean Air Act has had a negative impact on ecosystems.
    (c) The Clean Air Act has had a positive impact on health and safety in the United States.
    (d) The clean Air Act has had no impact on health and safety in the United States.

20. Which of the following is a method to determine the accuracy of the author's claim?
    (a) analyzing data to see if deaths from respiratory and cardiovascular causes have decreased since the implementation of the law
    (b) measuring amounts of nitrates and phosphates in water systems
    (c) testing soils for sand, silt, and clay particles
    (d) obtaining data to measure the amount of solid waste in ponds and lakes

## Section 2: Free-Response Questions

1. A study counted the number of bird nests found around a small city. The number of nests was counted around three different areas: a park without a forest, an area of land near a small airport, and an area of land around a small nature center at the edge of the city.
    (a) **Identify** the independent variable in the experiment. (1 pt.)
    (b) **Identify** the dependent variable in the experiment. (1 pt.)
    (c) **Identify** a likely hypothesis for the experiment. (1 pt.)
    (d) **Describe** one variable that isn't discussed that might affect the results of the study. (1 pt.)
    (e) **Describe** an environmental effect of noise pollution on terrestrial species. (1 pt.)
    (f) **Describe** an environmental effect of noise pollution on aquatic species. (1 pt.)
    (g) **Explain** two health impacts of noise pollution on human health. (2 pts.)
    (h) **Identify** one method to reduce noise pollution. (1 pt.)
    (i) **Identify** one advantage of the method identified in part (h) other than reduction of noise pollution. (1 pt.)

2. The table below shows the ambient air data collected for Pittsburgh, Pennsylvania, in 2008. Examine the data and answer the following questions.

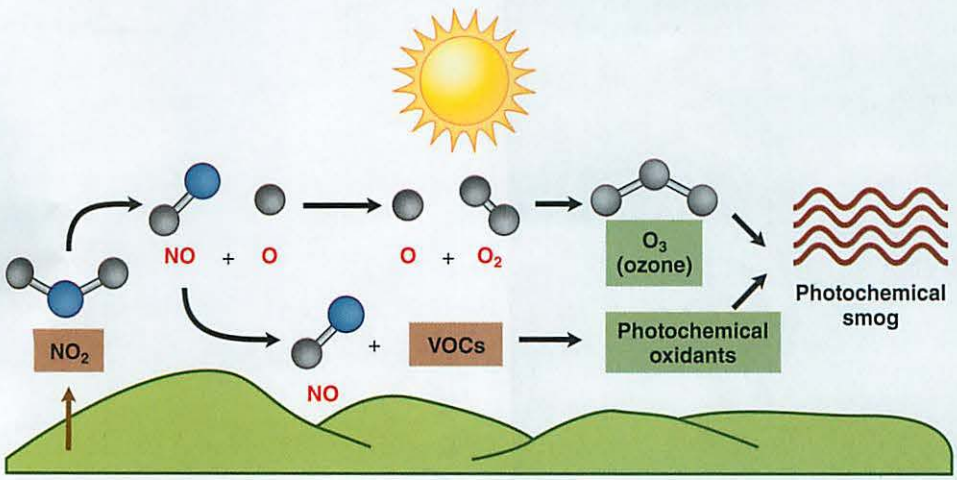
**2008 Monthly ambient air monitoring report, Pittsburgh**

| Month | Monthly maximum ozone concentration (ppb) | Monthly average ozone concentration (ppb) | Monthly average solar radiation |
|---|---|---|---|
| January | 37 | 14 | 65 |
| February | 49 | 15 | 63 |
| March | 56 | 23 | 86 |
| April | 76 | 31 | 81 |
| May | 75 | 27 | 152 |
| June | 77 | 32 | 208 |
| July | 95 | 31 | 215 |
| August | 92 | 27 | 204 |
| September | 89 | 20 | 153 |
| October | 48 | 14 | 109 |
| November | 57 | 12 | 64 |
| December | 30 | 14 | 45 |

Data from http://www.ahs.dep.pa.gov/aq_apps/aadata/

(a) **Identify** the month that had the highest average ozone concentration. (1 pt.)
(b) **Describe** why the month in part (a) was likely the highest. (1 pt.)
(c) Based on the National Ambient Air Quality Standards (NAAQS), average ozone concentrations are not to exceed 0.075 ppm (75 ppb) in any 8-hour period. **Describe** how this NAAQS may not truly reflect the overall air quality. (1 pt.)
(d) Ozone is classified as a secondary pollutant. **Identify** one of the primary pollutants necessary for its formation and **describe** how tropospheric ozone is formed. (2 pts.)
(e) **Explain** one environmental effect ozone can have on ecosystems. (1 pt.)
(f) **Describe** one method to reduce tropospheric ozone. (1 pt.)
(g) **Explain** how ozone can contribute to other secondary pollutant formation. (1 pt.)
The same sources that contribute to ozone formation can also contribute to other secondary pollution.
(h) **Identify** another secondary pollutant formed by the same sources that form ozone. (1 pt.)
(i) **Propose a solution** to the source mentioned in part (f). (1 pt.)

3. The diagram below shows the typical formation and buildup of photochemical smog.




(a) **Identify** one primary pollutant in the diagram. (1 pt.)
(b) **Identify** one secondary pollutant formed in the accumulation of photochemical smog. (1 pt.)
(c) Volatile Organic Compounds (VOCs) have many anthropogenic as well as natural sources.
(i) **Describe** one natural source of VOCs. (1 pt.)
(ii) **Describe** one anthropogenic source of VOCs. (1 pt.)
(d) Nitrogen dioxide is a gas that occurs naturally and can be released anthropogenically into the atmosphere. In 2000, the national average air concentration of nitrogen dioxide was 98 ppb, and in 2015, the average concentration had changed to 76 ppb.
(i) **Calculate** the average decrease of nitrogen dioxide per year. (2 pts.)
(ii) **Calculate** the percent change in nitrogen concentrations from 2000 to 2015. (2 pts.)
(iii) **Calculate** the estimated concentration of nitrogen in 2030 if the rate remains the same as in part (i). (2 pts.)

UNIT 8

# Aquatic and Terrestrial Pollution



A diversity of alternatives for household products. Single-use and multiple-use products differ in their environmental costs and benefits, including the amount of energy, water, and global warming impact needed to manufacture the items, the water and energy used to wash the items, and the environmental impact of disposal. *(ARISTIDIS VAFEIADAKIS/Alamy Stock Photo)*