

## Chapter 11

### **FOSSIL FUELS: ENVIRONMENTAL EFFECTS**

In air quality, the National Energy Strategy seeks to reduce energy-related emissions to achieve and maintain the National Ambient Air Quality Standards for carbon monoxide and ozone; [and] to develop cost-effective, flexible control strategies to reduce energy-related emissions of sulfur dioxide (SO<sub>2</sub>) and nitrogen oxides (NO<sub>x</sub>). [...] The 1990 Clean Air Act Amendments [...] will limit the major air pollutants from powerplants, vehicles, and industry. In many cases, pollutants will be reduced from current levels – despite economic growth and increased use of energy.

*(National Energy Strategy, Executive Summary, 1991/1992)*

Energy production and use pose significant environmental challenges. Policy approaches must align energy and environmental issues to ensure that economic growth and environmental protection are achieved together. The Administration is reinventing environmental protection, creating regulatory systems that are more flexible and accountable, emphasizing pollution prevention over “end-of-pipe” clean-up, and fostering the development of new energy-efficient technologies to meet both economic and environmental goals.

*(Sustainable Energy Strategy, 1995)*

It is fashionable and easy to say that we are 'environmentalists'. The now famous 1992 Earth Summit in Rio de Janeiro has produced the environmentalist manifesto. *Newsweek* magazine's cover page on June 1, 1992 said the following: "No More Hot Air: It's Time to Talk Sense About the Environment." Indeed, we all are environmentalists, until it comes to making some tough economic and political choices, like proposing or voting for a hefty tax on gasoline. This ambivalence about the environment is clear from the careful political statements quoted on the previous page. You may remember how much time Congress spent debating the ambitious BTU tax in 1993 (see Chapter 21). When the 'dust' settled, this presidential proposal was converted into a 4.3 cent-per-gallon gasoline tax. Any such tax will increase Federal revenues but will hardly do anything for the environment.

Our industrialized society generates an increasing amount of waste. This waste is released into the atmosphere, dumped into the water or buried into the earth. The pollution of the atmosphere is primarily caused by the combustion of fossil fuels in energy conversion devices. Some water and land pollution also occurs during the use of fossil fuels, but this problem is not as severe as that of air pollution and it is similar to that confronted by other industries (such as the chemical industry, to name just one).

A *pollutant* is a substance – usually a harmful one – that is not a natural constituent of the environment. If it does occur naturally, it is present in abnormally high concentrations. The principal air pollutants resulting from fossil fuel combustion are the following: (a) carbon monoxide; (b) the oxides of sulfur,  $\text{SO}_2$  and  $\text{SO}_3$  (represented as  $\text{SO}_x$ ); (c) the oxides of nitrogen,  $\text{NO}$  and  $\text{NO}_2$  ( $\text{NO}_x$ ); and (d) 'particulates', consisting primarily of very fine soot and ash particles. Air pollution may result also from unburned hydrocarbons; these either pass through energy conversion devices without burning or escape into the air by evaporation before they can be burnt. For many years, lead compounds contributed to air pollution, but the nearly complete elimination of 'leaded' gasoline has reduced this problem significantly.

These *primary* pollutants can further interact with the environment to generate additional deleterious effects. Examples of these effects (*secondary* pollutants) are acid rain and smog, the greenhouse effect and the high ozone levels in the air we breathe. (This last effect should not be confused with the ozone layer depletion, which is also becoming an environmental problem but has no direct relationship with fossil fuel utilization.)

## Primary Air Pollutants

**Carbon Monoxide.** Carbon monoxide (CO) is a product of incomplete combustion of any fuel. It is both a highly poisonous gas and the principal constituent of photochemical smog (see below). Table 11-1 summarizes the effects of CO exposure on human health.

The main culprits of CO pollution are the urban automobiles and transportation vehicles in general. This is illustrated in Figure 11-1. It has been estimated that some 100 million tons of CO are emitted every year in the U.S. (see "America Then and Now," *Time* of

1/29/96, p. 38; see also Review Question 11-4). Use of cold engines – the result of frequent short trips – and of improperly tuned engines simply does not allow the carbon in gasoline to burn completely into carbon dioxide. As much as 80% of today's automobile emissions occur during cold starts (see “Corning Introduces System to Cut Emissions as Vehicle Is Started,” NYT of 2/26/96). Electric power plants (stationary sources) that burn fossil fuels cannot be turned off and on so easily (see Chapter 18), and their contribution to this pollution problem is insignificant.

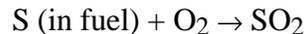
**TABLE 11-1**  
Health effects associated with human exposure to carbon monoxide

CO concentration (parts per million)	Duration of exposure (hours)	Effect
100	10	Headache
300	10	Nausea, unconsciousness
600	10	Death
1000	1	Unconsciousness
1000	4	Death

**FIGURE 11-1**

Typical distribution of carbon monoxide emissions by source.

**Sulfur Oxides.** Sulfur oxides arise during combustion from oxidation of sulfur in sulfur-containing fuels (some coals and some petroleum-based products). The principal product is sulfur dioxide:



Sulfur dioxide has an annoying odor and it irritates the eyes and respiratory tract. Still,  $\text{SO}_2$  itself is not highly dangerous. However, when it is released to the atmosphere, it can react with oxygen in the air to form sulfur trioxide:



Sulfur trioxide irritates the mucous membranes of the respiratory tract. A concentration of 1 volume of  $\text{SO}_3$  in a million volumes of air (one part per million or 1 ppm) is enough to cause coughing and choking. Sulfur trioxide dissolves in water to form sulfuric acid, which is a strong acid capable of corroding or destroying many materials. Sulfur trioxide can absorb moisture from the atmosphere to form very fine droplets of sulfuric acid. Inhalation of these droplets can harm the respiratory system. Chronic exposure leads to a much greater likelihood of suffering from bronchitis. Sulfur trioxide can also dissolve readily in rain drops, and fall to the earth as acid rain (see below).

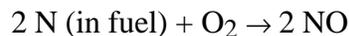
Figure 11-2 shows the principal culprits of  $\text{SO}_x$  emissions in the United States. Figure 11-3 summarizes the recent emission trends in the world and in the U.S.

### FIGURE 11-2

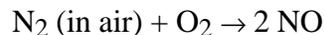
U.S. sulfur dioxide emissions by source.

[Source: *The New York Times*, February 19, 1989.]

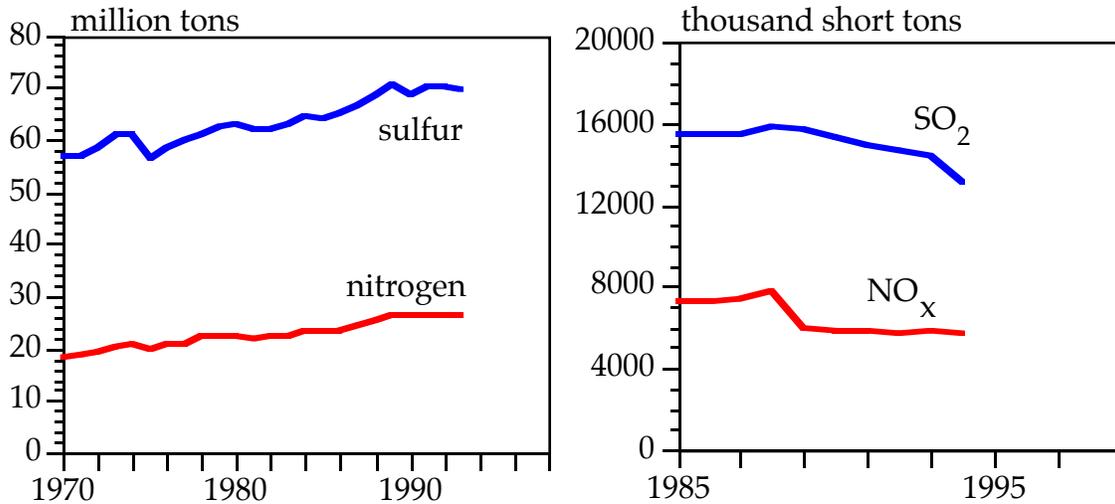
**Nitrogen Oxides.** Nitrogen oxides have two sources. *Fuel  $\text{NO}_x$*  is produced when nitrogen atoms chemically combined with the molecules of the fuel are oxidized during the combustion process to form nitric oxide:



In addition, *thermal  $\text{NO}_x$*  is produced in some combustion processes that operate at such high temperatures that nitrogen molecules in the air are oxidized to nitric oxide:



(Remember that air is 79%  $\text{N}_2$  and 21%  $\text{O}_2$ .) When the nitric oxide is emitted to the environment, it readily reacts with oxygen in the air to form nitrogen dioxide:



**FIGURE 11-3.** Emissions of sulfur oxides and nitrogen oxides in the world (left) and the U.S. (right). U.S. emissions are only from fossil fuel-burning electric power plants. To convert from tons of S and N to tons of SO<sub>2</sub> and NO, multiply by 64/32 and 30/14. [Source: Vital Signs 1996, Worldwatch Institute; Energy Information Administration.]

**Illustration 11-1.** The annual consumption of coal in the United States is about a billion tons (see Figure 7-2). If coal had about 1% sulfur, on average, calculate the annual sulfur dioxide emissions. Compare this number with the information provided in Figure 11-3.

*Solution.*

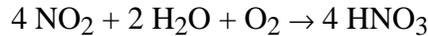
According to the chemical equation shown on page 193, for every 32 grams of sulfur in a fuel, 64 grams of sulfur dioxide are formed (see Table 6-1). Therefore, remembering our “elementary mathematical prelude” (Chapter 2), we have:

$$\begin{aligned} \text{Sulfur dioxide emissions} &= \left( \frac{64 \text{ tons SO}_2}{32 \text{ tons S}} \right) \left( \frac{1 \text{ ton S}}{100 \text{ tons of coal}} \right) \left( \frac{10^9 \text{ tons of coal}}{\text{year}} \right) = \\ &= 20 \text{ million tons of SO}_2/\text{year} \end{aligned}$$

This is more than the number shown in Figure 11-3. Therefore, either the average sulfur content of coals used in U.S. power plants is less than 1% (see Table 7-3) or some of the SO<sub>x</sub> produced is captured before the products of combustion are released to the atmosphere.



Nitrogen dioxide is a noxious gas that can cause inflammation of the lungs and, at high concentrations, even death. In addition, nitrogen oxides will react further with water and oxygen to form nitric acid:



Like sulfuric acid, nitric acid is a very strong acid that easily corrodes or attacks many materials. Nitric acid is also a component of acid rain.

Figure 11-3 shows the trends in  $\text{NO}_x$  emissions in the world and the United States while Figure 11-4 identifies the main culprits in the U.S. Unlike the case of  $\text{SO}_x$  and  $\text{CO}$ , no particular source is to blame, because much of the emissions are thermal  $\text{NO}_x$  from the air and not from the fuel, as discussed above. For this reason, it is much more difficult to reduce  $\text{NO}_x$  emissions than  $\text{SO}_x$  emissions. This is seen in Figure 11-3: for the last five years, not much progress has been made. This issue will be explored further in Chapter 21.

#### FIGURE 11-4

U.S. emissions of  $\text{NO}_x$  by source. [Source: *The New York Times*, February 19, 1989.]

**Particulate Matter.** Particulate matter emissions (soot and fly ash) are a concern because they can contribute to long-term respiratory problems. Many of these particles are extremely small, of the order of 10 micrometer or less, and they are thus suspended in the air we breathe. After inhaling them, they get trapped in the very thin air passages inside the lungs. Over a period of years this reduces the air capacity of the lungs. Reduced air capacity leads in turn to severe breathing and respiratory problems. Chronic asthma or emphysema can result, as well as increased general susceptibility to respiratory diseases. To make things worse, these particles may carry along small amounts of hazardous trace

elements or potentially carcinogenic organic molecules. Particulate matter is also an aesthetic nuisance. Areas with high concentrations of air-borne particulate matter are more likely to experience fogs, because these particles are preferred nucleation sites for water droplets. Smoke and soot are also very undesirable aesthetically.

Soot is formed during combustion when the supply of oxygen is insufficient for complete conversion of carbon to carbon oxides. Its formation is mainly a problem in the combustion of liquid and solid fuels (oil, coal, or wood), because molecular-scale mixing of fuel and oxygen is not as easy here as it is in the combustion of natural gas (see below). The most familiar experience with soot is the powdery “black stuff” inside chimneys. It can also be observed as ‘smoke’ (gas laden with soot and thus rendered visible) which billows from the exhausts of diesel-fueled trucks accelerating on the highway.

Fly ash is the inorganic, non-combustible residue of pulverized coal combustion. These solid particles are very small and very light, and as a result are swept through the boiler into the atmosphere.

Figure 11-5 shows that the industrial consumers of fossil fuels are responsible for almost half of the emissions of particulates, both as fly ash and as soot. Stationary sources that burn pulverized coal produce fly ash mostly, while the soot comes mostly from the transportation sector.

### **FIGURE 11-5**

Typical distribution of emissions of particulate matter by source.

**Unburned Hydrocarbons.** Unburned hydrocarbons represent another source of air pollution associated with the use of fossil fuels (especially gasoline), even though they are not a result of combustion. Much of the emission of unburned hydrocarbons to the air occurs as a result of evaporation from fuel tanks (remember the smell of gasoline during your last fill-up?) and as a result of leaks or spills. Taken individually, these events seem trivially small. But on any given day millions of vehicles are being refilled with gasoline. In addition, if you drive a car whose engine is poorly tuned, a significant fraction of gasoline

sweeps right through the engine and ends up unburned in the exhaust system. To understand how this happens and also to understand the related phenomenon of soot formation, let us consider four possible fates of heptane,  $C_7H_{16}$ , in an engine.

Reaction	Oxygen/fuel ratio
$C_7H_{16} + 11 O_2 \rightarrow 7 CO_2 + 8 H_2O$	11:1
$2 C_7H_{16} + 15 O_2 \rightarrow 14 CO + 16 H_2O$	7.5:1
$C_7H_{16} + 4 O_2 \rightarrow 7 C + 8 H_2O$	4:1
$C_7H_{16} \rightarrow C_7H_{16}$	0:1

As the ratio of oxygen to fuel (or air to fuel) decreases, the products change from the desired carbon dioxide to the undesired carbon monoxide and then to soot (which is almost pure carbon) or unburned heptane. When an engine is operating on a high value of air/fuel ratio, we say the engine is running *lean*. Sometimes we may also speak of a lean-burning engine. When the air/fuel ratio is low, we say that the engine is running or burning *rich*. The carburetor or fuel injector system of an engine can be adjusted, at least to some extent, to change this ratio. It would seem, therefore, that the whole business of carbon monoxide, soot and unburned hydrocarbon emissions could be avoided simply by making the engine run leaner. Unfortunately, as the combustion conditions become leaner, the temperature of the engine increases. This makes the thermal  $NO_x$  emissions go up as we try to reduce CO and soot emissions. So it is quite difficult to tune the engine in a way that minimizes emissions of CO, soot, unburned fuel and  $NO_x$  all at the same time.

The addition to gasoline of a lead-containing compound called tetraethyllead was an attempt to enhance engine performance. The use of this compound was phased out when it was found to destroy the effectiveness of the catalytic converter (described below) which is used to reduce emissions of carbon monoxide, hydrocarbons and  $NO_x$ . Tetraethyllead is just one member of a group of compounds, called *octane boosters*, which can be added to gasoline to increase its octane number. Other compounds that have been used as octane enhancers over the years include methanol ( $CH_3OH$ ) and ethanol ( $C_2H_5OH$ ). Each of these alcohols has an oxygen atom in its molecular structure. For that reason these compounds are called *oxygenates*. Adding oxygenates to gasoline has the effect of making the engine run leaner: since some oxygen is already present in the fuel molecules, the total amount of oxygen (from the air and from the oxygenates) relative to carbon and hydrogen in the fuel is greater. Running the engine leaner reduces the emissions of CO substantially; it also reduces the emissions of unburned hydrocarbons to some extent. Since the largest source of CO emissions is the automobile exhaust, use of oxygenated fuels substantially reduces the emissions of this pollutant. It is for this reason that, since January 1995, the oil companies have to offer this 'reformulated' gasoline in major metropolitan areas (see "More Oxygen, Less Monoxide: A New Mix at the Pump," NYT of 11/9/94). A gallon costs up to 10 cents more but its additional virtue is that it evaporates to a lesser extent. (The politics of reformulated gasoline are complex; they are discussed briefly in Chapter 21.)

## Secondary Air Pollutants

Sulfur oxides and nitrogen oxides combine with water to form *acid rain*. To understand what is meant by this term, we must briefly consider how acidity is defined.

Chemists describe the acidity by means of the *pH scale*. Pure water is neither acidic nor basic; it is neutral with a pH of 7. Acids have a pH less than 7. The lower the pH is, the more acidic a substance will be. The pH scale is logarithmic. That means that if we compare two liquids, one with a pH of 6 and the other with a pH of 3, we cannot say that the former is twice as acidic as the latter. In fact, it is 1000 times more acidic. Each change of 1 pH unit represents a change in acidity of a factor of 10. Natural rainfall, even in pristine areas, is slightly acidic. As rain falls, it dissolves some of the carbon dioxide from the air. A solution of carbon dioxide in water is mildly acidic. Natural rainfall has a pH of 5.6. In contrast, rain falling over much of the eastern United States in the summer typically has a pH of 4 or less. As the acidity of lakes and streams increases, the water can eventually become too acidic to support the life of fish and other aquatic organisms. Acid rain falling on land can acidify the soil, harming crops and forests. For example, more than 50% of the red spruce in the Adirondacks, the Green Mountains in Vermont and the White Mountains in New Hampshire have died in the past 25 years (see *Scientific American* of 8/88, "The Challenge of Acid Rain"). In Europe, the estimated forest damage due to acid rain ranges from less than 10% in Spain and France to more than 50% in the U.K. (see Vital Signs 1993, Worldwatch Institute).

Sulfur oxides are primarily responsible for acid rain. Increases in acid rain correlate with increases in  $\text{SO}_x$  emissions: the highest acidity of acid rain is found in those areas having the highest concentrations of  $\text{SO}_x$ .

*Smog* is another secondary pollutant. This term was developed to describe a substance that is a hybrid of smoke and fog. The  $\text{SO}_x$  aerosols are one source of smog formation. As discussed earlier, sulfuric acid droplets, or sulfuric acid absorbed on the surface of soot and fly ash particles, can attract moisture from the air to form what is often referred to as conventional or 'classical' smog. Such smog, whose principal components are  $\text{NO}_x$ ,  $\text{SO}_x$  and particulates, was prevalent in the heyday of the coal-fueled Industrial Revolution, before the transportation revolution of the 20th century.

Modern-day smog is often referred to as 'photochemical' smog. It is produced by complex, sunlight-stimulated chemical reactions among the components of automobile exhaust. It is responsible for much of today's air pollution in cities such as Los Angeles and Denver. Carbon monoxide from incomplete combustion of automobile engines, particulate matter and  $\text{NO}_x$  all react to generate the noxious brown haze.

An estimated 80% of smog today arises from vehicle exhausts. Not only does smog smell bad and obstructs vision, but both short-term and long-term exposure to it may be hazardous. Eye irritation develops upon short-term exposure. Chronic pulmonary diseases,

asthma, bronchitis and even lung cancer may result from longer-term exposure; in addition, paint and fabrics slowly deteriorate during long-term exposure.

The development of the *catalytic converter* was society's response to smog problems. The installation of this clever device in the exhaust system has been mandatory on all new cars sold in the United States since 1975. It accomplishes three tasks, with varying degree of effectiveness: it converts any CO in the combustion products to CO<sub>2</sub>. It also facilitates the combustion of any unburned hydrocarbons to carbon dioxide and water. Finally, it also helps to reduce the emissions of nitrogen oxides by transforming them into the harmless nitrogen (N<sub>2</sub>). Because the proper functioning of the catalytic converter is destroyed by lead, the adoption of catalytic converters to address smog formation resulted in the phasing out of the so-called leaded gasoline, curtailing at the same time the pollution problems caused by lead emissions.

The problems of smog formation are exacerbated by a meteorological phenomenon known as *thermal inversion*. Under normal atmospheric conditions, warm air in the vicinity of a large city is trapped by an overlayer of cool air. Since warm gases tend to rise, they normally diffuse upward and disperse the smog and other pollutants. A thermal inversion occurs when the upper layer is a layer of warm air, while the polluted air near the ground is relatively cool. In such a situation, the pollutant-laden cool air cannot rise and disperse. Thermal inversion is stabilized by specific geographical features, especially near-by mountains. The local geography of cities like Los Angeles and Denver makes the air pollution problems in these cities much worse than elsewhere (see "L.A. seeks breathing room" in *USA Today* of 3/20/89 and "A Drastic Plan to Banish Smog" in *Time* of 3/27/89).

As mentioned earlier, since carbon monoxide is a major contributor to smog formation, and since oxygenated fuels reduce carbon monoxide emissions, many metropolitan areas are now required by federal law to sell oxygenate-rich or 'reformulated' gasoline. At the time of this writing, the EPA has embarked on the next phase of combatting smog (see, for example, "Smog Alert: The EPA proposes tough new clean-air standards," *Time* of 12/9/96; see also Chapter 21).

Finally, the *ozone* level in the air needs to be mentioned (see Table 11-2). Again, this ground-level ozone should not be confused with the depletion of the ozone layer in the upper atmosphere, which is increasing the exposure of earth's surface (and our skin) to harmful ultraviolet radiation. This depletion is caused primarily by chemicals such as chlorofluorocarbons (CFCs), which are used as refrigerants in air conditioners, refrigerators, etc.

Ground-level ozone (O<sub>3</sub>) is a secondary air pollutant and an important smog constituent. It is formed by complex chemical reactions of primary pollutants with oxygen (O<sub>2</sub>). Its effect depends on its concentration in the air. At low concentrations, it can be beneficial, as in fresh air after a storm. At higher concentrations, it is an irritant. Its concentration rises proportionately with that of primary pollutants and it is often reported as an indicator of smog accumulation in a city (see Investigation 11-11). The energy and fuels

industry (primarily vehicles and fuel filling stations) accounts for about 50% of ground-level ozone; the rest comes from other industrial and nonindustrial uses (see “Ozone: Sources of a Threat on the Ground,” NYT of 4/3/89).

## **Air Pollution Control**

The Clean Air Act of 1970 and its amendments (in 1977 and 1990) are crucial milestones in air pollution control history. They are a political response to the increasing concern of society about the environmental impact of fossil fuel utilization. Ironically, it is precisely this fossil fuel utilization that has provided society – and especially the industrialized nations – with the technical and economic means to achieve air pollution control. (Who was it that said, “Thou shalt bear the seeds of thy own destruction”?)

It is important to emphasize that technological solutions are available today for reducing pollutant emissions from most sources to environmentally acceptable levels. Unfortunately, what actually constitutes “environmentally acceptable” amounts of a pollutant is a matter of some debate. What is much more debatable, of course, is who should pay for these emissions reductions. For example, when the economy falters, these amounts typically tend to increase. On the other hand, as the discharge requirements for a given pollutant are reduced closer and closer to zero, the cost of control rises steeply. There is obviously a trade-off between the costs associated with emission standards and the benefits to the environment and to society.

It would be ideal, of course, if the emission of all pollutants could be reduced to zero, and the technology may indeed be available for doing so. However, the costs of doing this may be prohibitive in some cases. A balance must be found, therefore, between the amount of pollution control that society is both willing and able to pay for and the amount of environmental damage resulting from pollution. Since there are no straightforward measures of the costs associated with environmental damage, the approach to finding a realistic balance involves a great deal of argument. Unquestionably, the regulation of emissions has brought about a significant improvement in air quality in the U.S., especially in large cities. Since the early 1970s, annual emissions of SO<sub>2</sub> have been decreasing and those of NO<sub>x</sub> have not increased (see Figure 11-3). These dramatic consequence of the Clean Air Act are illustrated in Figure 11-6. The improvement has been due, in part, to the efforts of the Environmental Protection Agency (EPA). However, it is not necessary to spend much time in any of our larger cities to realize that much is left to be done regarding air pollution control. Table 11-2 summarizes the current National Ambient Air Quality Standards, which the Environmental Protection Agency has a mandate to enforce.

In the past, a popular approach to reduce the local concentration of pollutants was to build a tall smokestack. With a little luck in the form of favorable wind currents, the emissions would be transported far away from their source. Of course, this ‘solution’ does not destroy the pollutants; it only relocates them. In today’s world air pollution has become

a global problem. A heightened concern for the environment, combined with increasing sophistication in tracking and modelling air currents, has led to the realization that local air and water may be contaminated by pollutants emitted many miles away. Indeed, this realization has resulted in inter-regional and international tensions regarding air pollution. For example, much of the acid rain problem in the northeastern United States is a result of  $\text{SO}_x$  emissions from coal-fired power plants in the Midwest. Similarly, the United States and Canada have a long-standing (and occasionally heated) debate over the issue of which country is exporting its acid rain to the other, while the Scandinavians have been making similar complaints to their southern neighbors. A recently publicized case is that of the Grand Canyon National Park: the Environmental Protection Agency had to intervene to limit the pollution from a power plant in Page, AZ which was found to be the single most important source of pollution there (see Review Question 11-5).

So, today's air pollution control technology is a booming and very competitive business (see "Bush's Nonsense on Jobs and the Environment," NYT of 9/25/92). Only the most important control methods are summarized here briefly.

**Illustration 11-2.** A power plant consumes 10000 tons of coal per day. The coal has 2% sulfur. If the sulfur oxides released are confined during one day to a volume of  $10^{11}$  cubic meters, calculate the concentration of  $\text{SO}_2$  in the air surrounding the power plant.

*Solution.*

Following up on Illustration 11-1, we have that the amount of  $\text{SO}_2$  released is:

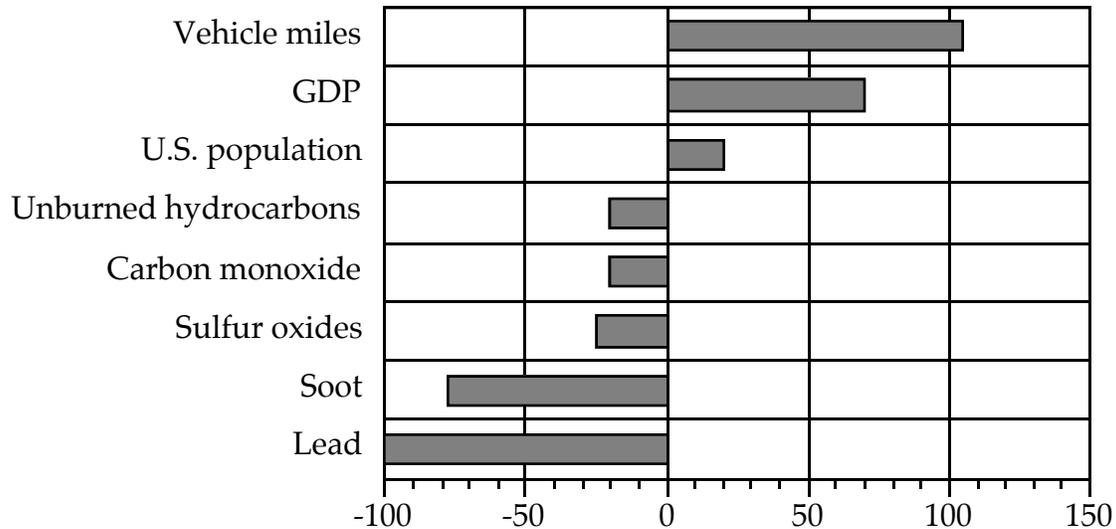
$$\left(\frac{64 \text{ tons SO}_2}{32 \text{ tons S}}\right) \left(\frac{2 \text{ tons of sulfur}}{100 \text{ tons of coal}}\right) \left(\frac{10000 \text{ tons of coal}}{\text{day}}\right) = 400 \frac{\text{tons of SO}_2}{\text{day}}$$

If the volume over which this gas is dispersed is  $10^{11}$  cubic meters, we have:

$$\text{Concentration of SO}_2 = \left(400 \frac{\text{tons of SO}_2}{\text{day}}\right) \left(\frac{1 \text{ day}}{10^{11} \text{ m}^3}\right) \left(\frac{10^{12} \mu\text{g}}{1 \text{ ton}}\right) = 4000 \mu\text{g/m}^3$$

This number is substantially higher than that allowed by NAAQS (see Table 11-2). So this power plant should have the EPA knocking (or banging!) on its doors.

Note that the result depends on the area (or volume) over which the pollutant can spread. If thermal inversion occurs (see above), this area (volume) is much smaller – and the pollutant level much higher – than under normal conditions.



**FIGURE 11-6.** U.S. air pollution decreased as a consequence of the Clean Air Act and its amendments (see Chapter 21), despite the growth in GDP, population and automobile use. The numbers shown are % increases or decreases in 1994 relative to 1970. [Source: *Economist*, 3/4/95, p. 26.]

**TABLE 11-2**  
National Ambient Air Quality Standards (NAAQS)

Pollutant	Averaging time	Primary standard levels
Particulate matter (10 $\mu\text{m}$ in size)	Annual	75 $\mu\text{g}/\text{m}^3$
	24 hours	260 $\mu\text{g}/\text{m}^3$
Sulfur oxides	Annual	80 $\mu\text{g}/\text{m}^3$ (0.03 ppm)
	24 hours	365 $\mu\text{g}/\text{m}^3$ (0.14 ppm)
Carbon monoxide	8 hours	10 $\text{mg}/\text{m}^3$ (9 ppm)
	1 hour	40 $\text{mg}/\text{m}^3$ (35 ppm)
Nitrogen dioxide	Annual	100 $\mu\text{g}/\text{m}^3$ (0.05 ppm)
Ozone	1 hour	240 $\mu\text{g}/\text{m}^3$ (0.12 ppm)
Hydrocarbons	3 hour (6-9 A.M.)	160 $\mu\text{g}/\text{m}^3$ (0.24 ppm)
Lead	3 months	1.5 $\mu\text{g}/\text{m}^3$

Sulfur oxide emissions are most often controlled by a chemical process called *flue gas desulfurization* (FGD). The gaseous combustion products are passed through a slurry of lime, or calcium oxide (CaO), to capture the SO<sub>3</sub>. The device in which FGD takes place is called a *scrubber*. This process can be described by the reaction



The solid product is a wet sludge of calcium sulfate which can be disposed of easily. So FGD does not eliminate pollution. What it does accomplish is to convert a big problem (emission of large volumes of air contaminated by harmful levels of gaseous SO<sub>x</sub>) into a small problem (collection and disposal of scrubber sludge).

Dealing with the problem of air pollution is not cheap. An FGD system installed in a newly constructed power plant represents about one-third of the total cost of building the entire plant. Energy is also required to operate an FGD system, meaning that for two otherwise comparable power plants, one with an FGD system will produce slightly less energy for sale than would be obtained without the FGD system. For example, if the efficiency of a power plant without FGD is 37%, a comparable plant with an FGD system may have an efficiency of 33%. The investment in such a system, its maintenance and operation, as well as the slight decrease in net energy produced are all costs that must either be borne by the utility or be passed on to the consumers.

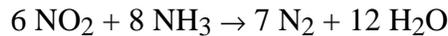
Flue gas desulfurization is an example of a *post-combustion* cleaning process, meaning that it is something done *after* the fuel has been burned. *Pre-combustion* cleaning is also a possible air pollution control strategy. For example coal and petroleum can be treated chemically ('refined') to remove sulfur *before* they are burned. Coal gasification and coal liquefaction (see Chapter 10) represent pre-combustion cleaning as well, because in both processes it is possible to remove sulfur as the synthetic gaseous or liquid fuel is being made from coal.

Yet another control strategy removes pollutants *during* fossil fuel combustion. The most important example here is *fluidized bed coal combustion*. Here coal is neither burned as relatively large lumps on a grate, as in domestic furnaces, nor is it pulverized to very fine particles that are carried through the furnace by the air, as in power plants. It is burned as a 'bed' of medium-size particles (1 cm or so) suspended in a reactor by an upward air stream. Lime or limestone particles are typically added to the bed to mix with the burning coal particles. In contrast to flue gas desulfurization in a scrubber, the SO<sub>x</sub> formed during combustion reacts immediately with CaO to produce solid calcium sulfate, which is easily removed.

Another option for dealing with the problem of SO<sub>x</sub> emissions is *fuel switching*. A fuel with a high sulfur content is replaced by a low-sulfur fuel. This option might involve replacing a high-sulfur coal with a low-sulfur coal, or switching from coal to either fuel oil or natural gas. While fuel switching can reduce SO<sub>x</sub> emissions, it is neither straightforward nor inexpensive. Suppliers of low-sulfur fuels are aware that such fuels are premium commodities because of today's increased concerns about environmental quality. Increased

demand for low-sulfur fuels makes possible their higher price. A single, medium-sized power plant might burn some 3 million tons of coal per year (see Illustration 11-2). Even a small increase in cost for low-sulfur coal has a significant effect on fuel costs for the utility. (For example, a \$2.00 per ton premium for low-sulfur coal will increase coal cost by \$6 million! And this cost will most likely be passed on to the consumers of electricity.) In addition, modern power plants use boilers that have been designed for burning a very specific fuel. A switch from, say, coal to oil or gas means that new burners must be installed in the boiler; a new fuel handling system must also be installed. In a typical 1000-MW electric power plant, such conversion can cost millions of dollars.

Nitrogen oxides are more difficult to deal with than  $\text{SO}_x$ . This is clear from Figure 11-3 which shows the data for the U.S. In the other industrialized nations, the situation is much the same. For example, the *Economist* of 2/17/96 reports that the GDP of OECD nations has increase by 40% since 1980; in the same period,  $\text{SO}_x$  emission have decreased by almost 40% while  $\text{NO}_x$  emissions haven't decreased at all. The EPA has recently announced that the annual average standard of 0.05 ppm (see Table 11-2) will remain unchanged. Some post-combustion methods for their removal by flue gas treatment have been developed. In many processes, the major source of  $\text{NO}_x$  is thermal  $\text{NO}_x$  rather than fuel  $\text{NO}_x$ . Combatting the formation of thermal  $\text{NO}_x$  requires that the combustion process itself be modified. As mentioned earlier, one approach to reducing thermal  $\text{NO}_x$  formation in motor vehicles is to add compounds containing oxygen to the gasoline. Another approach is flue gas denitrogenation, a process analogous to flue gas desulfurization. One way to accomplish this is to inject some substance into the boiler, or into the exhaust gas stream, which will react with and destroy the nitrogen oxides. An example is the use of ammonia:



The products of this reaction, nitrogen and water, are both harmless.

Particulates can be removed using a number of techniques of varying degree of sophistication (and cost!). Cyclones, fabric filters and electrostatic precipitators are the most common ones. Cyclones (see next page) are simple devices, as illustrated below, but are effective for removal of large particles only. Baghouses are somewhat similar in operation to a vacuum cleaner. A stream of gas (in this case, the flue gas from the boiler) is made to pass through fabric bags. The particulate matter is trapped in the pores of the fabric. If the bags were never cleaned, eventually all the pores would plug up with trapped fly ash particles. To prevent this, the ash is removed either by vigorous shaking of the bags, or by occasionally blowing a puff of air backwards through the baghouse, and gently blowing the ash particles loose from the bags. In either case the ash particles fall to the bottom of the baghouse, where they can be collected and removed for disposal.

The use of *electrostatic precipitators* (ESP) is the principal method available to the electric power industry to control fly ash emissions. A centrally mounted wire carries a strong negative electrical charge. The walls of an ESP have a strong positive charge. As fly ash particles are swept through the ESP by the stream of flue gas, the particles acquire a

negative charge from the wire. The negatively charged ash particles migrate to the positively charged walls, where they stick. Periodically, the walls of the ESP are cleaned. The dislodged ash falls to the bottom of the ESP, allowing periodic withdrawal for disposal.

**Illustration 11-3.** In Illustration 11-2 we saw that the cited power plant, using coal with 2% sulfur, does not meet the EPA standards. The management has decided to switch to a low-sulfur coal. How low does the %S in the coal have to be so that the power plant can meet the standard, if all other conditions are the same?

*Solution.*

This is essentially the reverse of the calculation shown in Illustration 11-2. Based on this calculation and using the data in Table 11-2, the maximum production of SO<sub>2</sub> allowed (X) is obtained as follows:

$$\text{Concentration of SO}_2 = \left( X \frac{\text{tons of SO}_2}{\text{day}} \right) \left( \frac{1 \text{ day}}{10^{11} \text{ m}^3} \right) \left( \frac{10^{12} \mu\text{g}}{1 \text{ ton}} \right) = 365 \mu\text{g/m}^3$$

Therefore, X = 36.5 tons of SO<sub>2</sub>/day. For a daily consumption of 10000 tons of coal, the maximum sulfur content in the coal is:

$$\begin{aligned} \text{Sulfur \% in coal} &= \left( \frac{1 \text{ ton of S}}{2 \text{ tons of SO}_2} \right) \left( \frac{36.5 \text{ tons of SO}_2}{\text{day}} \right) \left( \frac{1 \text{ day}}{10000 \text{ tons of coal}} \right) = \\ &= 0.0018 \frac{\text{tons of S}}{\text{ton of coal}} = 0.2\% \end{aligned}$$

Each one of the pollution control strategies discussed here has some cost associated with it. Another ‘strategy’ is available also, of course. It is to take no action at all. In the electric power industry, utilities would not be required to install and operate emission control devices, and would thus be encouraged to burn the most inexpensive fuel. In the Northeast and Midwest this would continue to be high-sulfur coal. If the option of doing nothing were adopted, our energy would be less expensive and we would perceive that we are saving money. This option might especially look like a good deal when we sit down to write the monthly check to the local electric utility. However, this option would increase the amount of money society must spend for other things. The total spending on health care would increase, because almost certainly the incidence of respiratory problems would increase. Costs for mitigating the damage to property, such as limestone buildings, and damage to the environment, such as lakes, caused by acid rain would increase sharply. These costs are not usually as obvious to individual consumers as the monthly electric bills are, but they are real costs nonetheless.

Finally, an ingenious and controversial market-oriented ‘solution’ should also be mentioned here. It is to purchase the ‘right’ to pollute (see Investigation 21-6). As part of the Clean Air Act amendment of 1990 (see Chapter 21), Congress gave polluters – primarily to electric power plants – the option of meeting emission standards by buying and selling allowances that the EPA issues to them on the basis of current emission standards. So they now have three options:

- (a) reduce capacity or close down the plant;
- (b) reduce emissions by installing scrubbers or switching to low-sulfur fuel;
- (c) purchase emissions allowances from companies (electric power plants, primarily) that exceed their emission reduction goals.

The apparent success of these SO<sub>x</sub> pollution permits has stimulated the Chicago area and other communities to attempt to solve some of their smog problems by developing marketable permits for other pollutants (see “Economic Scene: Illinois is looking to market forces to help reduce its smog,” NYT of 3/30/95; “Trying a Market Approach to Smog,” NYT of 3/25/92). Even the United Nations Conference on Trade and Development (UNCTAD) has recently suggested that a similar international trading system for CO<sub>2</sub> emissions be developed as well.

## **Greenhouse Effect**

The burning of all carbon-containing fuels inevitably produces huge quantities of carbon dioxide. With efficient combustion, all of the carbon in the fuel is converted to carbon dioxide. Carbon dioxide is a desired product of fuel combustion. It is also a normal constituent of air, at an average concentration of 0.0315% (315 parts per million). So it is not usually considered to be a primary air pollutant. It better not be, because we drink it all the time, in sodas.

Yet carbon dioxide emissions took over the media headlines in the late 1980s, and especially after the drought and excessive heat in the summer of 1988. *Newsweek* was among the first to sound the alarm, with a special report “Inside the Greenhouse: Heat Waves” on 7/11/88. The popular PBS *Nova* series had a 1-hour special entitled “Hot Enough for You?”. *Popular Science* magazine ran a series of articles on global warming; Part III, in October 1989, was entitled “Saving the Planet.” The NYT's editorial of 1/27/89 was emphatic: “The Greenhouse Effect is For Real.” It should be realized, however, that this issue has been coming and going for some time now.

More than a century ago, the Englishman John Tyndall suggested that changes in water vapor and CO<sub>2</sub> concentrations in the atmosphere could account for “all the mutations of climate which the researches of geologists reveal” (*Philosophical Magazine*, Vol. 22, 1861, p. 277). Exactly 100 years ago, the Swede Svante Arrhenius recalled the words of the French mathematician Joseph Fourier, who in 1827 “maintained that the atmosphere acts like the glass of a hothouse, because it lets through the light rays of the sun but retains the dark rays from the ground” (*Philosophical Magazine*, Vol. 41, 1896, p. 237). At that time Arrhenius was more concerned with explaining the phenomenon of ice ages, so he concluded that as little as a forty percent decrease in CO<sub>2</sub> concentration would account for a 4-5 °C decrease in temperature. A century later, the conclusions of a 1995 United Nations-sponsored study, prepared by more than a thousand scientists, are not that much different (see below). Fossil fuel combustion was not, however, among the possible causes that Arrhenius considered for the changes in CO<sub>2</sub> concentration (see Figure 6-3).

The essence of the greenhouse effect is summarized in Figure 11-7. For every 100 units of radiant energy that reaches the atmosphere, 25 are reflected from the clouds and another 25 are estimated to be absorbed by the clouds. Of the 50 units that reach the Earth's surface, 5 are reflected and 45 are absorbed. The absorbed radiation is re-emitted from the surface back toward space as infrared radiation (heat). However, because of the presence of CO<sub>2</sub> and other infrared-absorbing gases (see Figure 11-9), it is trapped and returned back to the surface, as an estimated 88 units of energy (greenhouse effect). As the CO<sub>2</sub> concentration increases, it may be responsible for an increase in this amount. The result would be that the surface balance – shown in Figure 11-8 as 45 + 88 units (going out) = 29 + 104 (coming in) – is tilted toward a higher quantity of heat reaching the surface and a consequent global temperature increase.

Figure 11-8 shows that burning of fossil fuels is estimated to contribute about 50% of the gases that are thought to be responsible for the greenhouse effect (global warming). Other culprits are methane (that might escape from natural gas reservoirs, or is vented from coal mines, or is produced by anaerobic fermentation in landfills and by cows), nitrous oxide (yet another nitrogen oxide produced during fossil fuel combustion), and chlorofluorocarbons. Deforestation is also a problem because it decreases nature's capacity to absorb, by photosynthesis, the CO<sub>2</sub> already present in the atmosphere.

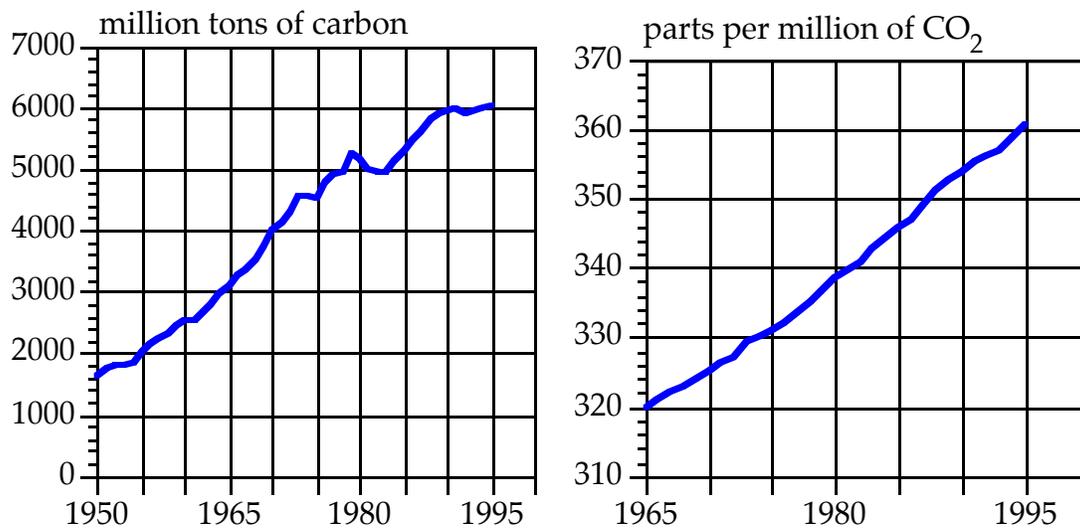
Ordinary window glass has the same behavior as carbon dioxide. It is of course transparent to visible light. However, it traps infrared radiation. We are all familiar with this effect: a car parked in the sunlight on a summer day builds up an inside temperature

that is much higher than the outside temperature. The growth of plants in greenhouses exploits the same effect. This analogy between the behavior of glass in a greenhouse and the behavior of CO<sub>2</sub> in the atmosphere has led to the use of the term *greenhouse effect*.

Abundant evidence exists that the amount of carbon dioxide in the earth's atmosphere is increasing slowly but steadily. Figures 11-9 and 11-10 illustrate this fact along with the more or less parallel trends in world's emissions of carbon dioxide. The industrialized nations in the Northern Hemisphere plus the highly populated nations such as India and China are seen to be the greatest contributors. Some of the data on CO<sub>2</sub> concentration come from the Mauna Loa Observatory in Hawaii, which is quite a distance from world's industrial centers. So we can be sure that we are dealing with a global problem. Whether this increase in CO<sub>2</sub> concentration is the main *cause* of global warming is a matter of continued debate, however. The best data available are shown in Figure 11-11. For example, there have been periods in this century when the average temperature was falling while at the same time the CO<sub>2</sub> concentration was increasing. Also, the concurrent emissions of sulfur oxides seem to complicate the ability of meteorologists to predict temperature variations (see the *Economist* of 4/1/95, "Reading the patterns. The evidence that greenhouse gases are changing the climate is getting stronger. The details of what it means, though, remain blurred"). Finally, the effect of clouds on the absorption of radiation seems to be uncertain (see Figure 11-7). All this makes the predictions of temperature trends in the coming *decades* a difficult task, as all of us who are interested in reliable *weekly* weather forecasts often find out.

**FIGURE 11-7.** The greenhouse effect. [From "The Changing Climate," by S. H. Schneider. Copyright © 1989 by Scientific American, Inc. All rights reserved.]

**FIGURE 11-8.** Estimated contributions to the greenhouse effect.  
 [Source: *Coal and Synfuels Technology*, May 6, 1991, p. 5.]



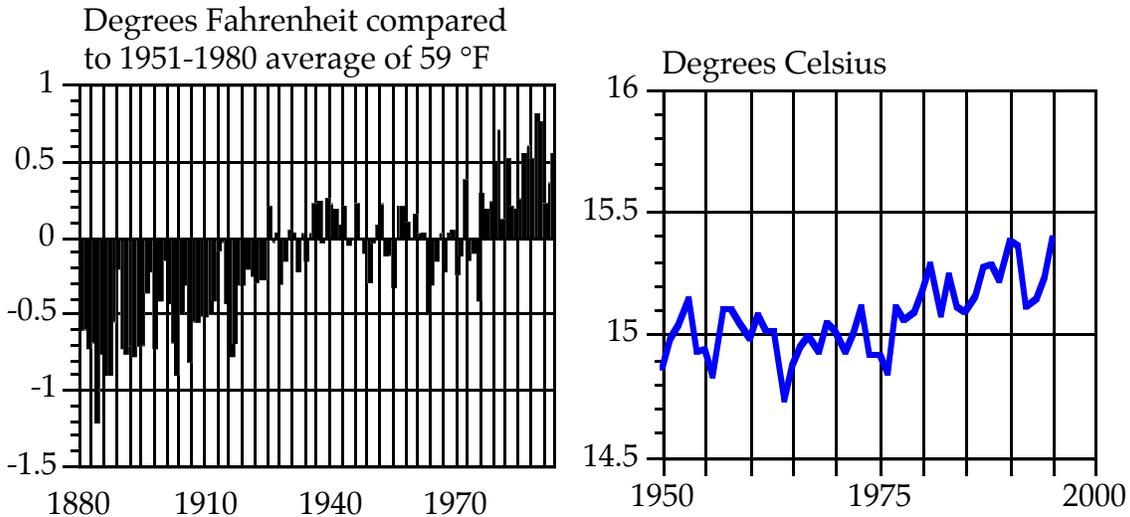
**FIGURE 11-9.** Build-up of carbon dioxide emissions in the world. To convert from carbon emissions to carbon dioxide emissions, multiply by 44/12 (see Chapter 6).  
 [Source: *Vital Signs 1996*, Worldwatch Institute, 1996.]

**FIGURE 11-10.** Carbon emissions around the world in 1990 (in thousand metric tons).  
[Source: Energy Information Administration.]

Despite such uncertainties, more than a thousand scientists members of a UN-sponsored Intergovernmental Panel on Climate Change (IPCC) concluded that “the balance of evidence suggests that there is a discernible human influence on global climate.” This carefully worded statement reflects the uncertainties mentioned above. A less vague part of the report contains the key statement: “Our ability to quantify the magnitude of this effect is presently limited,” and goes on to give estimates of global warming that range from 1 to 3.5 °C by the year 2100. Whether or not these statements will be sufficient for serious political action depends on the possible scenarios for the effects of such global warming. And these abound, especially when (re)interpreted by the media. Here is a sample of headlines in the last two years, which range from the apocalyptic to the cautious to the indifferent:

- Heading for Apocalypse? (*Time*, 10/2/95)
- Experts Confirm Human Role in Global Warming (NYT, 9/10/95)
- Scientists Say Earth's Warming Could Set Off Wide Disruptions (NYT, 9/18/95)
- In Rain and Temperature Data, New Signs of Global Warming (NYT, 9/26/95)
- More Extremes Found in Weather, Pointing to Greenhouse Gas Effect (NYT, 5/23/95)

- Global Warming: The Debate Heats Up. Are tougher CO<sub>2</sub> limits needed? The data are inconclusive (BW, 2/27/95)
- A Global Warming Resumed in 1994, Climate Data Show. After a two-year cooling period, the world gets hotter (NYT, 1/27/95)



**FIGURE 11-11.** Statistical information on the average global temperature of the atmosphere. [Source: Vital Signs 1996, 1993, Worldwatch Institute.]

The pessimistic scenarios suggest that an average temperature increase of 2-3 °C would cause major disruptions in life on Earth. Climate changes caused by this warming would shift the prime agricultural regions closer to the poles. Countries that are now self-sufficient or are exporters of agricultural products might have to become importers of such goods. Similarly, some countries that now must import agricultural products might become exporters in the future. Such changes could affect not only the balance of payments of nations but also their geopolitical power. In addition, most of the world's largest cities are located near seacoasts. Ocean warming of 2-3 °C could melt large amounts of ice at the earth's poles. The increased sea level could submerge coastal areas, requiring relocation of large numbers of people. Extended hot weather conditions caused by global climate changes would increase the demand for personal comfort items, such as air conditioners. Increased use of air conditioning may overload electric power systems, requiring the combustion of more fossil fuels to generate more electricity. Increasing fossil fuel combustion will increase carbon dioxide emissions even further, starting a vicious cycle that would make the greenhouse effect all the worse.

To prevent such calamities, two courses of action are being advocated. In the short term, the efficiency of combustion devices should be improved. A high-impact example is the use of cars providing substantially more miles per gallon than today's average car (see Chapter 20). In the long term, there are two options. One is conservation; this is discussed in Chapters 18-20. The other is a massive shift in the energy economy away from fossil fuels toward energy sources that do not add CO<sub>2</sub> to the atmosphere. Such energy sources include solar, geothermal and nuclear options; they are reviewed in Chapters 12-17.

The optimistic, 'laissez-faire' view is that the greenhouse effect is of no long-term consequence. Throughout history it has seemed that the best standards of living have been enjoyed by those societies with the highest energy consumption levels (see Figure 5-5). For the people living in the less developed countries ever to enjoy standards of living similar to those of the industrialized nations, a massive increase in the consumption of energy must occur. If the earth should warm up in the process, what of it? If the vast Siberian steppes and Canadian prairies could become major agricultural producers, these areas could provide food for most of the world's population. Some analysts have even argued that large cities today have such severe problems of crime and pollution that perhaps it would not be such a bad thing if they were submerged by the rising sea and society could start afresh with new, better-planned cities.

A crystal ball is needed, of course, to say which of these extreme predictions will turn out to be closer to reality. It is certain, however, that society is performing a potentially dangerous experiment. The consequences of our action (or inaction) will only become clear in a few decades. As the economic assessments of the possible courses of action become available, the task in front of the politicians (see Chapter 21) is quite daunting. For example, the *Economist* of 7/7/90 shows here yet another example of exponential growth (see Chapter 5): as the desired cuts in greenhouse gas emissions increase from 10 to 20 to 50 to 80 to 90%, the estimated global costs rise from 5 to 10 to 200 to 1000 to 1400 billion dollars!

The current state of affairs can be summarized as follows. After a long debate, the scientists have given their verdict. Although they are not quite sure about the cause-effect relationship between CO<sub>2</sub> emissions and global warming, the mere possibility of global warming suggests prompt action (see Chapter 21). It is better to be safe than sorry! The economists have made some 'ball-park' estimates for the various options available and their basic message, not surprisingly, is that action will be expensive in the short term, but inaction may be more expensive in the long term. The ball is in the court of the politicians now. While they get their act together, all we can do is assess the relative contributions to the (potential) greenhouse effect of the various fossil fuels and advocate energy policies that minimize them. This is summarized in Table 11-3. Illustration 11-4 shows that only grade-school math is required to come up with these important numbers which will shape energy policies in the coming decades. The other thing that we can do is to conserve energy. But that's more easily said than done, as we know and as we shall document in Chapters 18-20.

**Illustration 11-4.** Show that the greenhouse effect caused by the combustion of methane is indeed 115 pounds of CO<sub>2</sub> for every BTU of burned fuel.

*Solution.*

There is one carbon atom in one molecule of methane. When methane burns, one carbon dioxide molecule is produced for every carbon atom in methane. Therefore, remembering our discussions in Chapter 2 and Chapter 9, we have:

$$\begin{aligned} \frac{1 \text{ atom C}}{1 \text{ molecule CH}_4} &= \frac{1 \text{ mol C}}{1 \text{ mol CH}_4} = \frac{12 \text{ lb C}}{16 \text{ lb CH}_4} = \\ &= \left(\frac{12 \text{ lb C}}{16 \text{ lb CH}_4}\right) \left(\frac{44 \text{ lb CO}_2}{12 \text{ lb C}}\right) \left(\frac{1 \text{ lb CH}_4}{2.4 \times 10^4 \text{ BTU}}\right) \left(\frac{10^6 \text{ BTU}}{10^6 \text{ BTU}}\right) = 115 \frac{\text{lb CO}_2}{10^6 \text{ BTU}} \end{aligned}$$

**TABLE 11-3**  
Contributions to the greenhouse effect from combustion of different fuels

Fuel	Formula	Heating Value (BTU/lb)	lb CO <sub>2</sub> /lb fuel	lb CO <sub>2</sub> /10 <sup>6</sup> BTU
Coal	CH <sub>0.8</sub> O <sub>0.1</sub>	13000	3.06	235
Fuel oil No.6	CH <sub>1.6</sub> S <sub>0.02</sub>	19000	3.09	163
Fuel oil No.2	CH <sub>1.8</sub>	19500	3.19	164
Gasoline	CH <sub>2</sub>	20000	3.14	157
Methanol	CH <sub>3</sub> OH	8500	1.38	162
Ethanol	C <sub>2</sub> H <sub>5</sub> OH	12000	1.91	159
Methane	CH <sub>4</sub>	24000	2.75	115

Note 1. Formulas for coal (bituminous), fuel oils and gasoline are approximate.

Note 2. Heating values for all the fuels are also approximate.

### REVIEW QUESTIONS

11-1. *Popular Science* of October 1989, p. 54, has the following statement: "Brookhaven National Laboratory has ranked different fuels by their greenhouse gas contributions, when burned, in pounds of carbon dioxide generated per million Btu of heat. Natural gas is at the low end of the spectrum, at 0.11. Oil is at 0.16, wood at 0.18, and coal at 0.20." Are these numbers correct?

11-2. A Mobil advertisement in the NYT of 9/17/92 applauds EPA's "Green Lights" initiative (see Investigation 11-9) and says the following: "If everyone in the United States switched to energy-efficient lighting, 202 million metric tons of carbon dioxide, 1.3 million metric tons of sulfur dioxide and 600,000 metric tons of nitrogen oxides could be eliminated every year." Are the numbers cited in the right "ball park"?

11-3. The Worldwatch Institute publication "Vital Signs 1996" (p. 65) shows that the world CO<sub>2</sub> emissions stand at 6 billion tons of carbon and states that "at 1.4 billion tons, the United States remained the world's largest source of carbon emissions in 1995." Using the information in Figure 5-14, show how this number for the U.S. was obtained.

11-4. *Time* magazine of 1/29/96 reports that since the 1970s, CO emissions in the U.S. have decreased from 128 to 98 million tons. The most recent DOE data confirm that the decreasing trend is continuing: the figure for 1993 is 88.1 million metric tons. To get some feel for this number, show that this is roughly equivalent to 2% incomplete combustion of carbon in fossil fuels. Use the 1995 carbon emissions data for the U.S. (1.4 billion tons).

11-5. The Associated Press reported in August 1989 that the 2500-MW Navajo power plant near Page, AZ released as many as 13 tons per hour of sulfur dioxide by burning 24,000 tons of coal per day. These emissions found their way to the Grand Canyon, more than 50 miles to the south, and were responsible for the white haze over the canyon, especially during the winter months. Verify these numbers by seeing whether the efficiency of the plant and the sulfur content of the coal used are reasonable. (Assume that the coal has a heating value of 11,500 BTU/lb.)

11-6. Important policy decisions are made on the basis of how much sulfur is emitted into the atmosphere—in the form of SO<sub>2</sub>. Simple, 'back-of-the-envelope' calculations are often sufficient to understand the numbers being discussed by policy makers. For example, assume that all the coal burnt in the U.S. is a lignite having the following elemental composition: 68.6% C, 4.3% H, 25.6% O, 0.6% S, 0.9% N. These are weight percentages. Show that the "molecular formula" for this coal would then be CH<sub>0.75</sub>O<sub>0.28</sub>S<sub>0.0033</sub>N<sub>0.01</sub>. So for each 'molecule' of coal, 0.0033 molecules of SO<sub>2</sub> are produced. Therefore, 0.012 tons of SO<sub>2</sub> are produced for every ton of coal burnt. Verify this! If all the coal consumed in the U.S. every year (one billion tons) had this sulfur content, then the SO<sub>2</sub> emissions would be some 12 million tons per year. Verify this as well. Is this number reasonable?

11-7. Important policy decisions are also made on the basis of how much carbon is emitted into the atmosphere—in the form of CO<sub>2</sub>. From the information provided in Figure 5-13, show how the 1985 CO<sub>2</sub> emissions of 19.8 billion tons (corresponding to 5.4 billion tons of carbon) can be obtained. (Hint: Assume that coal contains 80% carbon on average, that natural gas contains 75% carbon and that crude oil contains 85% carbon.)

11-8. Indicate whether the following statements are true or false:

- (a) Carbon dioxide from automobile exhausts is one of the principal constituents of photochemical smog.
- (b) If fossil fuels contained no sulfur, the production of  $\text{SO}_x$  during their combustion (in air) would be eliminated.
- (c) If fossil fuels contained no nitrogen, the production of  $\text{NO}_x$  during their combustion (in air) would be eliminated.
- (d) The average concentration of carbon dioxide in the atmosphere has been increasing *steadily* for the last fifty years.
- (e) The global temperature of the atmosphere has been increasing *steadily* for the last fifty years.

### **INVESTIGATIONS**

11-1. Much has been written lately on the air pollution caused by lawn mowers. For example, the *Economist* of 3/4/95, p. 26, states that a lawnmower generates in one hour as much pollution as a new car driven 8500 miles. Find out about some of the recent initiatives to curb lawn mower pollution. See the *Economist* of 3/11/95 ("New fuel: The lawnmower's tale"), *Time* of 7/4/94 ("The Backyard Besieged"), and NYT of 8/6/92 ("Lawn Mower Is New Target in War Against Air Pollution").

11-2. Motor vehicle engines in cars, buses and trucks that use diesel fuel are more efficient than the spark-ignition engines that are mostly used in cars. Unfortunately, they have serious air pollution problems. Find out about some of these problems and about efforts to solve them. See NYT of 9/26/93 ("A Unique Joint Effort Seeks to Reduce Sulfur Levels in Diesel Fuel").

11-3. Coal mining is the principal culprit for the black-lung disease. Find out some of the statistics on this. See NYT of 3/17/91 ("Coal Miners Contend Their Plight Is Worsening").

11-4. The Exxon Valdez oil spill was a highly publicized environmental tragedy. Review the media reports for an update on the clean-up efforts and an account of the damage to Prince William Sound. See *National Geographic* of 8/89 ("Tragedy in Alaska Waters") and 1/90 ("Alaska's Big Spill"); *USA Today* of 10/1/91 ("Alaska Oil Spill Settlement"); *Time* of 9/28/92 ("A battle is raging over how best to spend the settlement money from the Exxon Valdez disaster"); NYT of 7/31/94 ("Exxon Is Right. Alas").

11-5. Increasingly abundant abandoned oil and gas wells can be a pollution problem. Find out more about it. See NYT of 5/3/92 ("Abandoned Oil and Gas Wells Are Now Portals for Pollution"). See also the recent controversy about Shell's idea to abandon an offshore platform in the North Sea: NYT of 6/21/95 ("Shell Abandons Plans to Sink Oil Platform Off Scottish Coast"), 6/23/95 ("A Humbled Shell Is Unsure On Disposal of Atlantic Rig") and 6/29/95 ("Refugee Oil Platform: Hope for Growth Industry?").

11-6. One man's fortune is another's misfortune. Owners of stocks in Wyoming coal mines are the fortunate ones this time around (see Investigation 7-2). The miners of high-sulfur coal in Fairmont, WV are not; find out more about the reasons for their misfortune. See NYT of 2/15/96 ("East's Coal Towns Wither in the Name of Cleaner Air").

11-7. Japan has very strict air pollution control standards. Despite the increase in its energy consumption since 1970s, its emissions of nitrogen and sulfur oxides has decreased very significantly. Compare the 1990 NO<sub>x</sub> emissions in Japan and the U.S. in kilograms per thousand dollars of GDP. See the *Economist* of 4/9/94, p. 114.

11-8. That carbon dioxide emissions are a global problem is clear from the fact that their increase has been detected even in Hawaii (see Figure 11-9). So it makes sense that electric power utilities in the U.S. embark on tree growing projects in places like Guatemala and Malaysia. Find out more about such initiatives. See the *Economist* of 10/24/92 ("Plant a tree").

11-9. Find out more about EPA's voluntary program called "Green Lights," whose goal is to reduce pollution by encouraging businesses, governments and other large organizations to switch to energy-efficient lighting. Look it up on EPA's web site: <http://www.epa.gov>. See also Mobil's advertisement "Change a light bulb: combat air pollution and save some money, too" in NYT of 9/17/92, as well as NYT of 1/16/91.

11-10. An important issue in EPA's new initiatives on smog control is the effect of particulate matter of different sizes. Find out more about regional differences in air pollution from soot and fly ash. See NYT of 3/10/95 ("Dirty-Air Cities Far Deadlier Than Clean Ones, Study Shows"). See also NYT of 7/19/93 ("Studies Say Soot Kills up to 60,000 in U.S. Each Year").

11-11. Find out more about the monitoring of smog (ozone levels) in metropolitan areas. See whether the newspapers that you read regularly report any air pollution information (on the weather page). To find out more about the EPA's Pollution Standards Index, see the NYT of 2/7/94 ("Smog Pulse"). See also WSJ of 7/31/95 ("Highflying Scientists Watch Ozone Drift").

11-12. Find out more about smog control strategies. See "New Tactics Emerge in Struggle Against Smog" in NYT of 2/21/89, "Reducing Pollution From Gasoline" in NYT of 4/26/89, and "We Can Fight Smog Without Breaking the Bank," in BW of 10/3/94.

11-13. It should come as no surprise that some media reports on air pollution are not precise enough. Here is a typical example, from a NYT report of 7/11/95 ("U.S. Will Begin Efforts to Halve Truck Pollution"): "Nitrogen oxides are the essential ingredients in ground-level ozone, a component of smog." What is wrong with this statement? If you were the journalist assigned to (re)write it, what would you say instead?

11-14. Find out about the economics of global warming. See NYT of 10/10/95 (“Price of Global Warming? Debate Weighs Dollars and Cents”); *Economist* of 7/7/90 (“Greenhouse economics: Count before you leap”) and 3/6/93 (“Global warming: Cool costing”).

11-15. One way to boycott the purchases of a right to pollute (see Investigation 21-6) is to follow the example of a group of students at the University of Southern Maine. They have formed the Acid Rain Retirement Fund. Unlike power plants, when they buy pollution ‘shares’ they ‘retire’ them. Explore the Internet to find out about this altruistic initiative. Is it still alive? Start with the ARRF web site: <http://www.usm.main.edu/~pos/arrf.htm>.

11-16. Most large metropolitan areas around the world suffer from at least one form of air pollution. For example, the biggest problem in Los Angeles (population, 10 million) is ozone. In Mexico City (population, more than 20 million) SO<sub>x</sub>, particulates, CO and ozone are all big problems. Find out more about these and other problems of mega-cities and comment on the reasons for the prevalence of one or another air pollutant. See “Take a deep breath: City dwellers are anxious about air pollution. But the causes are complex, its impact on health poorly understood, and most remedies controversial,” in the *Economist* of 9/17/94. See also *Time* of 12/14/92, p. 25.

11-17. The conventional wisdom is that, given the magnitude of CO<sub>2</sub> emissions in the world (see Figure 11-9), there are no cost-effective technologies to capture them once they are released to the atmosphere. Nevertheless, there are some ideas how this might be done. Find out what they are. See “Science gets the CO<sub>2</sub> out” in *Popular Science* of 2/94.

11-18. It is fashionable (and appropriate, for the most part) to point out how polluted the air we breathe is. It is also useful to emphasize how much progress has been made in cleaning up the air since the 1970s. One of the prominent spokesmen for environmental optimists is Gregg Easterbrook, the author of “A Moment on the Earth,” Penguin Books, 1995. Make a list of some success stories. See also *Newsweek* of 8/23/93 (“Winning the War on Smog”), and NYT of 8/13/93 (“From Uncle Smoke to Mr. Clean”).

11-19. Can fly ash be put to some good use? See PI of 10/31/93 (“Finding a home for 150,000 tons of ash”).

11-20. Global warming has even gotten onto the pages of *Consumer Reports* (9/96, pp. 38-40). Read this article and make a list of important facts that are mentioned. Summarize the top 10 CR suggestions on how to “cut your personal energy use” and thus help reduce the greenhouse effect. Comment on how effective these actions can be. Finally, check whether the CO<sub>2</sub> emissions for the U.S. (43,000 lb per person in 1992) agree with the information provided in this chapter.

11-21. Read the article “An Atmosphere of Uncertainty” in *National Geographic* of 4/87, pp. 502-537. List the fossil fuel-related air pollution problems discussed there.