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POTENTIAL EFFECTS OF CLEAN COAL TECHNOLOGIES ON ACID PRECIPITATION, GREENHOUSE GASES, AND SOLID WASTE DISPOSAL

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POTENTIAL EFFECTS OF CLEAN COAL TECHNOLOGIES ON ACID PRECIPITATION, GREENHOUSE GASES, AND SOLID WASTE DISPOSAL

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Acronyms

CAFB	circulating atmospheric fluidized-bed combustion
CCT	clean coal technology
CCTDP	Clean Coal Technology Demonstration Program
DOE	U.S. Department of Energy
FC	fuel cell
FGD	flue gas desulfurization
IGCC	integrated gassifier combined cycle
LIMB	limestone injection multistage burner
NAAQS	National Ambient Air Quality Standards
NAPAP	National Acid Precipitation Assessment Program
NSPS	New Source Performance Standards
PEIS	Programmatic Environmental Impact Statement
PFB	pressurized fluidized-bed combustion

Potential Effects of Clean Coal Technologies on Acid Precipitation, Greenhouse Gases, and Solid Waste Disposal

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EXECUTIVE SUMMARY

The U.S. Department of Energy's Clean Coal Technology Demonstration Program (CCTDP) was initially funded by Congress in December 1985 to demonstrate technologies for increasing the role of coal as an energy option through increased efficiency and flexibility. In January 1986, the joint report of special envoys Drew Lewis of the United States and William Davis of Canada, who had been appointed by their respective governments to assess transboundary air pollution, recommended a 5-year, $5 billion industry/government cost-shared program in the United States to demonstrate technologies that can lead to reductions in emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x). As a result, the CCTDP emerged as a major program to combat acid deposition associated with those pollutants.

Two other environmental issues on which clean coal technologies (CCTs) could have an appreciable impact are the emission of carbon dioxide (CO_2) from fossil fuels and the production of solid waste. Concerns about CO_2 emissions involve climatic changes that could occur as a result of an increasing "greenhouse" effect. Concerns about solid waste reflect the increasing scarcity of land available for waste disposal, potential groundwater impacts, and the expected increase in solid waste from coal-fired power plants due to an increased use of flue gas desulfurization units (scrubbers) that may be necessary as a result of the Clean Air Act Amendments of 1990.

Emissions of SO_2, NO_x, and CO_2, and the production of solid waste stand out as being different when CCTs are compared with conventional technologies. Therefore, emissions of those gases and production of solid waste were addressed in the comprehensive Programmatic

Environmental Impact Statement (PEIS) that was prepared by DOE to comply with the National Environmental Policy Act. The PEIS addressed potential environmental consequences of widespread commercialization of successfully demonstrated CCTs by the year 2010 (DOE 1989). The PEIS evaluated two alternatives: a no-action alternative and a proposed-action alternative. The no-action alternative assumed that the CCTDP was not continued and that conventional coal-fired technologies with flue gas desulfurization controls would continue to be used for new plants or as replacements for existing plants that are retired or refurbished; the proposed-action alternative assumed that CCTDP projects were selected for funding and that successfully demonstrated technologies will undergo widespread commercialization by 2010. Primary emphasis in the PEIS was on changes in emissions of SO_2, NO_x, and CO_2 and in production of solid waste that are projected to occur if the proposed action alternative is realized (as compared to the baseline no-action alternative). In this report we summarize those projected changes and provide an extended examination of their subsequent effects on acid precipitation, climatic change, and solid waste disposal.

An upper bound of change for SO_2, NO_x, and CO_2 emissions and for solid waste production was estimated for each of 22 CCTs individually, assuming full penetration into potential commercial markets. Indirect effects of producing clean coal (e.g., the CO_2 produced by converting coal to fuel gas for the integrated gasification combined cycle technology) as well as direct effects (e.g., the combustion of the fuel gas made from the coal) were included in the calculations.

Clean coal technologies may be divided into two major categories: repowering technologies and retrofit technologies. Repowering technologies are those that replace a major portion of an existing facility. These technologies not only reduce emissions significantly but also may provide for the use of a different fuel form, increase facility capacity, extend facility life, and/or improve system efficiency. Repowering technologies may also be applicable to new facilities. Retrofit technologies are those that reduce emissions of SO_2 and/or NO_x by modifying existing facilities or their present feedstocks or by utilizing new fuel forms.

As a group, the repowering technologies achieve the greatest reductions in both SO_2 and NO_x, compared to projections for the year 2010 in the absence of CCTs. SO_2 reductions range from 29% to 48% for specific repowering technologies, while corresponding NO_x reductions range from 14% to 17%. Some of the retrofit technologies, either singly or in

combinations, are capable of achieving comparable reductions of these pollutants. Individual retrofit technologies that, applied singly, are capable of meeting the New Source Performance Standards (NSPS) required by the Clean Air Act are known as NSPS-capable technologies. Retrofit technologies that cannot, applied singly, meet the NSPS are referred to as partial NSPS-capable technologies. NSPS-capable technologies can reduce national SO_2 emissions by up to 45% of the amount of emissions projected for 2010 in the absence of CCTs. Corresponding reductions in NO_x emissions range as high as 33%. Technologies involving new fuel forms (including coal cleaning) can provide relatively smaller reductions in SO_2 emissions (from 2% to 26%), with very little change in NO_x emissions compared to the amount projected in 2010 in the absence of CCTs. This information is summarized in Table ES-1.

Table ES.1. Comparison of projected national emissions for the proposed action and the no-action alternative for the year 2010

Clean coal technology category	Environmental consequences in 2010 (% change; no-action versus proposed action)			
	SO_2	NO_x	CO_2	Solid waste
Repowering technologies	−29 to −48	−14 to −17	−5 to −12	−16 to +8
Retrofit technologies				
NSPS-capable	−30 to −45	−11 to −33	0 to < −1	−22 to +19
Partial NSPS-capable	0 to −48	0 to −15	0 to < −2	−2 to +9
New fuel forms	< −1 to −26	−3 to +4	0 to +1	0 to +23

Source: DOE 1989.

Repowering technologies are the only CCTs that emit significantly less CO_2 to the atmosphere than do conventional technologies. Complete market penetration of repowering

CCTs could reduce U.S. fossil-fuel CO_2 emissions by amounts up to about 10% of the amount otherwise projected by the year 2010. A 10% reduction in fossil-fuel CO_2 is comparable to reducing U.S. petroleum consumption by about 30% of its current value by 2010. However, because global CO_2 emissions are contributed by a variety of source categories from around the world, such a reduction would amount to only about 2.2% of the world's total fossil-fuel CO_2 emissions and would reduce the global warming potential of all greenhouse gases by less than 2%.

Mandatory emissions reductions required by the 1990 Clean Air Act amendments may increase the use of conventional scrubbers and their resulting solid waste. The largest of these solid waste increases can be expected in the southeastern, south-central, and Great Lakes states, where most of the coal is expected to be consumed by the year 2010. Three of the four repowering technologies and three of the 18 retrofit technologies are projected to reduce solid waste volumes. Clean coal technologies generate solid wastes that for the most part are dry and do not present the sludge disposal problems associated with conventional flue gas desulfurization systems. Most of the technologies that are expected to generate less waste than the conventional flue gas desulfurization systems do so by producing a salable by-product. Technologies that reduce appreciably the amount of solid waste produced can also significantly extend the useful life of a plant where on-site disposal of solid waste is a limiting factor.

From an environmental viewpoint, the best CCTs would appear to be the repowering technologies and the NSPS-capable retrofit technologies. The CCTDP will provide information to revise and refine these initial projections of the environmental effects of CCTs, and will also provide information on the economic impacts of implementing the CCTs.

This report considers potential environmental effects of implementing CCTs only in the United States. Penetration of CCTs into international markets, compared with a continuation of conventional technologies in those markets, would (1) at the global level, amplify CCTs' effects of reducing the concentration of atmospheric CO_2; (2) at the continental level, lead to reductions of acid deposition on continents other than North America; and (3) at the local level, possibly reduce solid waste volumes in individual communities in several countries besides the United States.

ABSTRACT

The U.S. Department of Energy's (DOE's) Clean Coal Technology Demonstration Program (CCTDP) was initially funded by Congress to demonstrate more efficient, economically feasible, and environmentally acceptable coal technologies. Although the environmental focus at first was on sulfur dioxide (SO_2) and nitrogen oxides (NO_x) because of their relationship to acid precipitation, the CCTDP may also lead to reductions in carbon dioxide (CO_2) emissions and in the volume of solid waste produced, compared with conventional technologies. The environmental effects of clean coal technologies (CCTs) depend upon which (if any) specific technologies eventually achieve high acceptance in the marketplace. In general, the repowering technologies and a small group of retrofit technologies show the most promise for reducing CO_2 emissions and solid waste. These technologies also compare favorably with other CCTs in terms of SO_2 and NO_x reductions. The upper bound for CO_2 reductions in the year 2010 is only enough to reduce global "greenhouse" warming potential by about 1%. However, CO_2 emissions come from such a variety of sources around the globe that no single technological innovation or national policy change could realistically be expected to reduce these emissions by more than a few percent. Particular CCTs can lead to either increases or decreases in the amount of solid waste produced. However, even if decreases are not achieved, much of the solid waste from clean coal technologies would be dry and therefore easier to dispose of than scrubber sludge.

1. INTRODUCTION

1.1 OVERVIEW OF THE CLEAN COAL TECHNOLOGY PROGRAM

The U.S. Department of Energy's (DOE's) Clean Coal Technology Demonstration Program (CCTDP) was originally funded by Congress in December 1985 to demonstrate technologies that can increase the role of coal as an energy option through increased efficiency and flexibility. In January 1986, the joint report of special envoys Drew Lewis of the United States and William Davis of Canada, who had been appointed by their respective governments to assess transboundary air pollution, recommended a 5-year, $5 billion industry/government cost-shared program in the United States to demonstrate technologies that can lead to reductions in sulfur dioxide (SO_2) and nitorgen oxides (NO_x) emissions associated with acid rain. As a result, the CCTDP expanded dramatically and emerged as a major program to combat acid deposition and thus mitigate its adverse environmental impacts. The goal of the CCTDP is to demonstrate a new generation of advanced, reliable, more efficient, economically feasible, and environmentally acceptable coal technologies in a series of full-scale "showcase" facilities built across the country (DOE 1990). The best and most promising of these technologies will then be advanced in terms of technical, environmental, and economic performance to the point where the private sector can introduce them into the commercial marketplace. The CCTDP is expected to finance projects totaling more than $5 billion during five (or possibly more) rounds of competition, with at least half of the funding coming from the private sector.

Although environmental considerations of clean coal technologies (CCTs) initially focused on reducing emissions of SO_2 and NO_x to the atmosphere, some CCTs may also contribute appreciably to reducing emissions of carbon dioxide (CO_2). Further, some CCTs may lead to large reductions in solid waste production, although other CCTs would be expected to increase solid waste production by equally large amounts. It is in these three areas of environmental concern—acid precipitation, CO_2 emissions, and solid waste production—that CCTs may produce the greatest changes, when compared with the continued

use of conventional coal technologies. Therefore, this report will focus on those three areas. The following sections of this chapter will summarize the various CCTs and present an approach to assessing their projected environmental effects.

1.2 SUMMARY OF CLEAN COAL TECHNOLOGIES

Clean coal technologies may be divided into two major categories: repowering technologies and retrofit technologies. Repowering technologies are those that, by replacing a major portion of an existing facility, not only reduce emissions significantly but also may provide for the use of a different fuel form, increase facility capacity, extend facility life, and/or improve system efficiency. An example would be replacing a conventional pulverized coal combustion boiler with a fluidized bed combustion unit. Retrofit technologies are those that reduce emissions of SO_2 and/or NO_x by modifying existing facilities or their present feedstocks or by utilizing new fuel forms. For example, retrofitting might add air pollution control equipment to a coal-using facility that was originally designed to function without such equipment.

The repowering technologies include (1) circulating atmospheric fluidized-bed combustion (CAFB), in which the low combustion temperature limits NO_x formation and optimizes sulfur capture by the limestone that is mixed with the coal; (2) pressurized fluidized-bed combustion (PFB), in which the combustor operates at very high pressure, most of the sulfur emissions are captured in the combustion process, and lower operating temperatures reduce NO_x emissions; (3) integrated gasification combined cycle (IGCC), in which coal is converted into a fuel gas which is then cleaned and used to fire a gas turbine generator, and the exhaust heat is then used to produce steam and drive a steam turbine generator; and (4) coal gasification fuel cell (FC), in which a coal gasifier supplies the fuel gas for electrochemical conversion of the chemical energy of the fuel in the cells to electrical energy, thus eliminating a large heat engine and its inherent efficiency limitations. Repowering technologies are among the cleanest of coal-burning options. For example, fluidized-bed combustors can eliminate 90 to 95% of the potential sulfur pollutants during the combustion process, eliminating the need for post-combustion sulfur controls, and combined-

cycle coal gasification systems can remove more than 99% of sulfur emissions from coal-derived gases.

The retrofit technologies are divided into three classes based initially on their ability to meet the New Source Performance Standards (NSPS) required by Clean Air Act. The three retrofit technology classes are NSPS-capable, partial NSPS-capable, and new fuel forms (which include coal-cleaning technologies). The NSPS-capable class includes those technologies that can, when applied singly, control SO_2 *and* NO_x emissions to levels equal to or below the NSPS limits. The partial NSPS-capable class includes technologies that, when applied singly, will control *either* SO_2 *or* NO_x to NSPS levels. (Two or more technologies in this class could conceivably be used in combination to meet the NSPS for both SO_2 and NO_x.) New fuel forms technologies alter the coal physically or chemically so as to reduce emissions of SO_2 and/or NO_x.

The retrofit technologies include advanced slagging combustors, advanced flue gas desulfurization, combined SO_2 and NO_x control, and advanced NO_x control. Although some are less able than conventional flue gas scrubbing to reduce sulfur emissions, these technologies can reduce levels sufficiently to meet possible future requirements for existing plants. Furthermore, many retrofit technologies are capable of being operated as combined systems such that greater reductions in SO_2 and NO_x emissions are achieved at lower cost. For example, advanced flue gas desulfurization, which removes only SO_2, can be used in conjunction with NO_x control technologies that remove only NO_x.

The CCTDP is expected to provide data on the economic aspects of each technology that is demonstrated. Retrofitting may be the only economically feasible way for some existing coal-fired power plants to meet emission standards. However, repowering may be economically or logistically attractive for one or more of the following reasons: (1) repowering can significantly extend the useful life of an existing plant by increasing capacity and thermal efficiencies; (2) increasing the capacity of an existing plant (as opposed to expanding to a new site) may require fewer facilities needed per unit of power generated; (3) demand centers are often closer to existing sites than to land available for new sites; (4) increasing the capacity at an already existing plant may streamline certain aspects of permitting procedures. The repowering CCTs also provide additional options for consideration when designing new plants.

1.3 AN APPROACH TO SUMMARIZING ENVIRONMENTAL EFFECTS OF CLEAN COAL TECHNOLOGIES

As part of complying with the National Environmental Policy Act, a comprehensive Programmatic Environmental Impact Statement (PEIS) was prepared for the CCTDP to address the potential environmental consequences of widespread commercialization of successfully demonstrated CCTs by the year 2010 (DOE 1989). The PEIS evaluated (1) a no-action alternative, which assumed that the CCTDP was not continued and that conventional coal-fired technologies with flue gas desulfurization controls would continue to be used for new plants or as replacements for existing plants that are retired or refurbished, and (2) a proposed action which assumed that CCTDP projects were selected for funding and that successfully demonstrated technologies will undergo widespread commercialization by 2010. Neither alternative included the reductions of SO_2 and NO_x mandated by the Clean Air Act Amendments of 1990.

For the no-action alternative, conventional coal technologies were assumed to be pulverized-coal firing with wet lime/limestone flue gas desulfurization technology. A typical new plant has particulate matter control, such as an electrostatic precipitator or a baghouse with fabric filters, and a flue gas desulfurization system capable of removing 70 to 90% of the SO_2 generated. Utilities have historically selected flue gas desulfurization systems that use wet slurry processes: the SO_2 in the flue gas comes in contact with and reacts with a recirculating lime or limestone slurry, removing the SO_2 for disposal as calcium sulfite or calcium sulfate in a sludge having the consistency of toothpaste. Disposal of the sludge is difficult, and the amount generated is large. For example, solid wastes from a typical 500 MW plant using 2.5% sulfur, 12% ash, bituminous coal include about 145,000 Mg (160,000 tons) per year of ash and 123,000 Mg (135,000 tons) per year (on a dry basis) of sludge (NAPAP 1987).

In the PEIS, the analysis of environmental consequences of the proposed action focused on changes in SO_2, NO_x, CO_2, and solid wastes. An upper bound of change for each of these four parameters was estimated for each of 22 CCTs individually, assuming full penetration into potential commercial markets. This information is summarized in Table 1. It should be noted that the numbers within each column are obtained independently of each other and therefore should not be added to arrive at a total percentage. External effects of producing

Table 1. Change in national SO_2 and NO_x emissions with implementation of 22 clean coal technologies (compared with no action)

	Change in national emissions (%)			
	SO_2	NO_x	CO_2	Solid Waste
Repowering technologies				
CAFB	-44	-17	-5	+8
PFB	-48	-17	-8	-4
IGCC	-37	-17	-6	-5
Fuel cell	-29	-14	-12	-16
NSPS-capable technologies				
Advanced slagging combustor	-45	-18	0	+17
Copper oxide process	-45	-33	0	-22
Dual-alkali scrubber	-30	-11	0	-5
Partial NSPS-capable technologies				
Advanced FGD with salable by-product	-48	0	0	+9
Spray dryer with lime	-45	-5	0	+8
LIMB	-30	-11	0	+8
Sorbent injection	-38	0	0	+8
Selective catalytic reduction	0	-15	0	0
Low NO_x burner	0	-11	0	0
Gas reburning	-10	-11	-2	-2
New fuel forms				
Mild gasification	-5	-2	+1	+14
Direct liquefaction	-9	-3	+1	+9
Indirect liquefaction	-5	+4	+1	+4
Coal/oil coprocessing	-4	< +1	+1	+3
Coal/water mixtures	-2	0	0	+4
Coal-cleaning technologies				
Ultrafine coal cleaning	-16	0	0	+12
Advanced physical coal cleaning	-3	0	0	+10
Advanced chemical coal cleaning	-26	0	0	+23

Source: DOE, 1989.

clean coal (e.g., the CO_2 produced by converting coal to fuel gas for the IGCC technology) as well as direct effects (e.g., combustion of fuel gas made from the coal) have been included in the calculations. However, secondary effects such as reduced petroleum production and use, resulting from increased energy efficiency, are not considered.

Chapter 2 of this report presents background material on SO_2, NO_x, and their environmental effects. This is followed by a discussion of the effects of CCTs on emissions of SO_2 and NO_x. Chapters 3 and 4 discuss the greenhouse effect and solid waste issues, respectively, in a format similar to that of Chapter 2. Chapter 5 summarizes the conclusions about the environmental effects of CCTs that can be drawn from the material in Chapters 2, 3, and 4.

2. EFFECTS OF CLEAN COAL TECHNOLOGIES ON ACID PRECIPITATION

2.1 BACKGROUND

Acid rain, the popular name for acid deposition, occurs when SO_2 and NO_x are chemically transformed and transported in the atmosphere and deposited on the earth's surface in the form of wet (rain, snow, fog) or dry (particle, gas) deposition. Much of the SO_2 is emitted by coal-fired electric utilities, while NO_x is emitted primarily by motor vehicles and utilities. The SO_2 and NO_x are readily oxidized in the atmosphere to form acidic sulfates and nitrates. Subsequently, the sulfates and nitrates may form sulfuric acid and nitric acid when combined with water unless neutralized by other chemicals present. The acids can be formed while the sulfates and nitrates are in the air or following deposition on the earth's surface (i.e., the acidic compounds may join with water droplets and be deposited during fog, fall as acid rain or snow during precipitation events, or attach to dust or other dry airborne particles and fall as dry deposition). The SO_2 and NO_x can also be transformed after dry deposition in their unaltered state. Fig. 1 illustrates the deposition process schematically. Other substances—including hydrocarbons, chlorides, ozone, and trace metals—also contribute to the formation of acid deposition (Placet, Streets, and Williams 1986).

About 20 Tg (22 million tons) of SO_2 and 19 Tg (21 million tons) of NO_x were emitted in the United States in 1987 (EPA 1989a). Approximately two-thirds of the SO_2 emissions were from electric utilities (especially coal-burning power plants), while electric utilities and transportation sources contributed about 30% and 45%, respectively, of the NO_x emissions. Major centers of SO_2 emissions are located in geographical regions having high densities of coal-fired power plants, such as the Ohio River Valley in the Midwest; centers of NO_x emissions include the above regions and large urban areas. As depicted in Fig. 2, for both SO_2 and NO_x it is estimated that, overall, about 30% of these emissions are deposited by precipitation, about 25% by dry deposition, and about 5% by fog, with the remaining 40% persisting in the atmosphere beyond the North American continent (NAPAP 1990a). Dry deposition occurs at a fairly constant rate over time, in contrast to the episodic wet deposition during precipitation events. Generally, areas near emission sources receive substantial

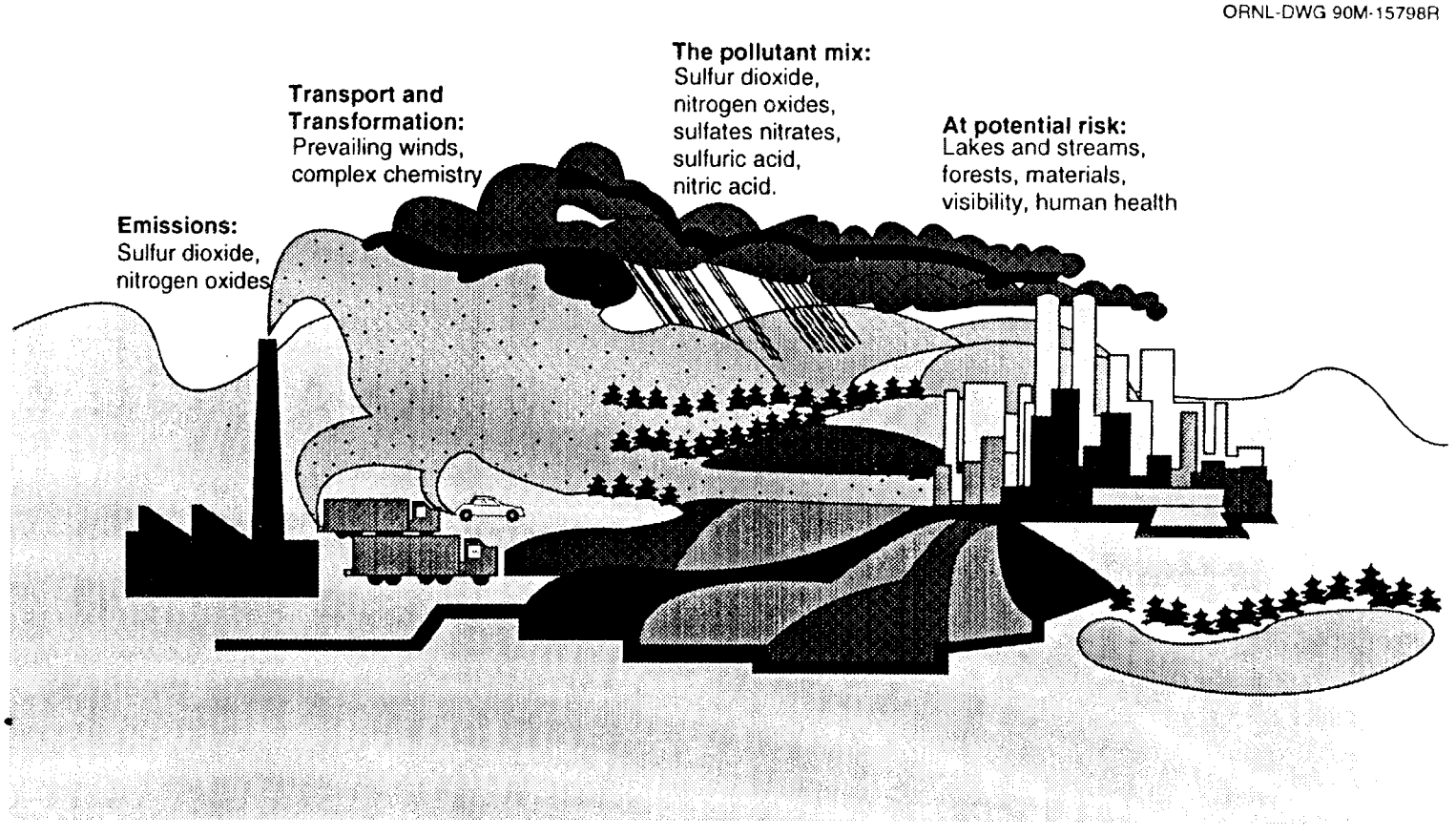

Fig. 1. Transported air pollutants: emissions to effects. The transported air pollutants result from emissions of SO_2 and NO_x. As these pollutants are carried away from their sources, they form a complex pollutant mix leading to acid deposition. These transported air pollutants pose potential risks to surface waters, forests, materials, visibility, and human health (from OTA 1984).

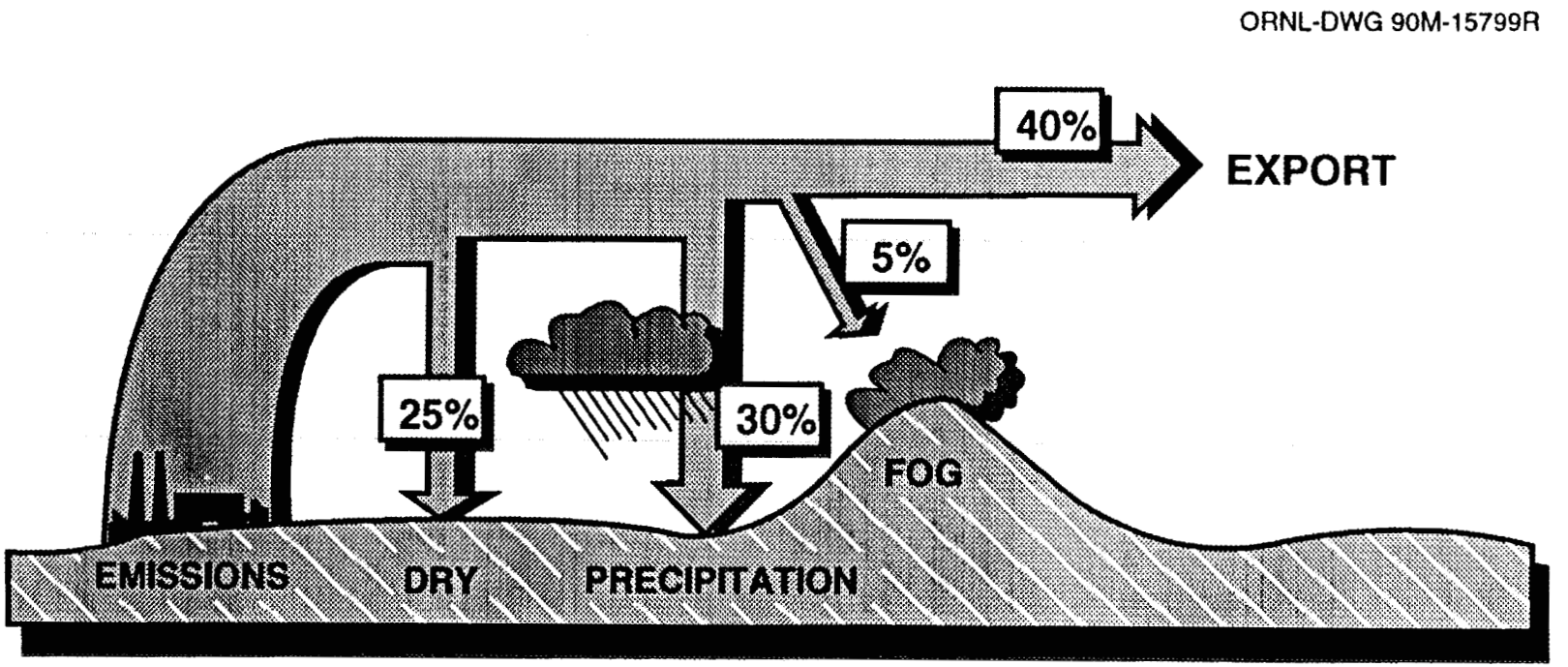

Fig. 2. Overall fate of SO_2 and NO_x emissions (from NAPAP 1990a).

proportions of acid deposition in dry form, while areas removed from emission sources obtain most acid deposition in wet form (OTA 1984).

Acidic compounds formed from NO_x emissions are deposited somewhat closer to the source than those from SO_2 emissions for two reasons (NAPAP 1990b). First, NO_x in the atmosphere is transformed to nitric acid, which is removed very quickly by wet and dry deposition (more quickly than sulfuric acid formed from SO_2 emissions). Second, in contrast to SO_2, more NO_x emissions are emitted near ground level than from tall stacks. For that reason, and because of lighter winds near the earth's surface, NO_x emissions tend to travel shorter distances than do SO_2 emissions.

While natural sources such as carbonic acid, salt spray, dust, and volcanic emissions lower the pH of rain to about 5.0 to 5.2 in some eastern U.S. areas (a pH of 7 is neutral), the additional acidity of precipitation in parts of North America where annual average pH is as low as 4.15 (NAPAP, 1991) results from products of fossil fuel combustion, especially coal combustion. However, establishment of a clear relationship between specific SO_2 and NO_x sources and downwind locations experiencing acid rain is hampered by long travel times between the sources and occurrence of acid rain. The long travel times translate into long distances between sources and receptors (acid rain locations) because emissions can be transported hundreds of miles by the wind from one region to another. Air over any given area will contain some residual emissions from distant areas and infusions received from areas recently passed. This continuing depletion and replenishment of emissions along the path of an air mass makes source-receptor relationships difficult to determine (OTA 1984).

Fig. 3 depicts the annually averaged pH of precipitation in North America in 1989. As the figure indicates, acid rain in North America currently is occurring in the eastern United States (roughly east of the Mississippi River) and southeastern Canada. The phenomenon is widespread throughout this large area, with the greatest acidity found in a continuous area consisting of eastern Ohio, western and central Pennsylvania, western and northern New York, southeastern Ontario, and the southern edge of Quebec. The major SO_2 source region is suspected to be in the Midwest, centered around Illinois, Indiana, and Ohio. Indeed, over 80% of SO_2 emissions in the United States originate in the 31 states east of the Mississippi River, especially in states within or adjacent to the Ohio River Valley (EPA 1988a). Prevailing winds at levels of pollutant transport are generally from the southwest or west-southwest during periods prior to precipitation, suggesting a general transport of pollutants in

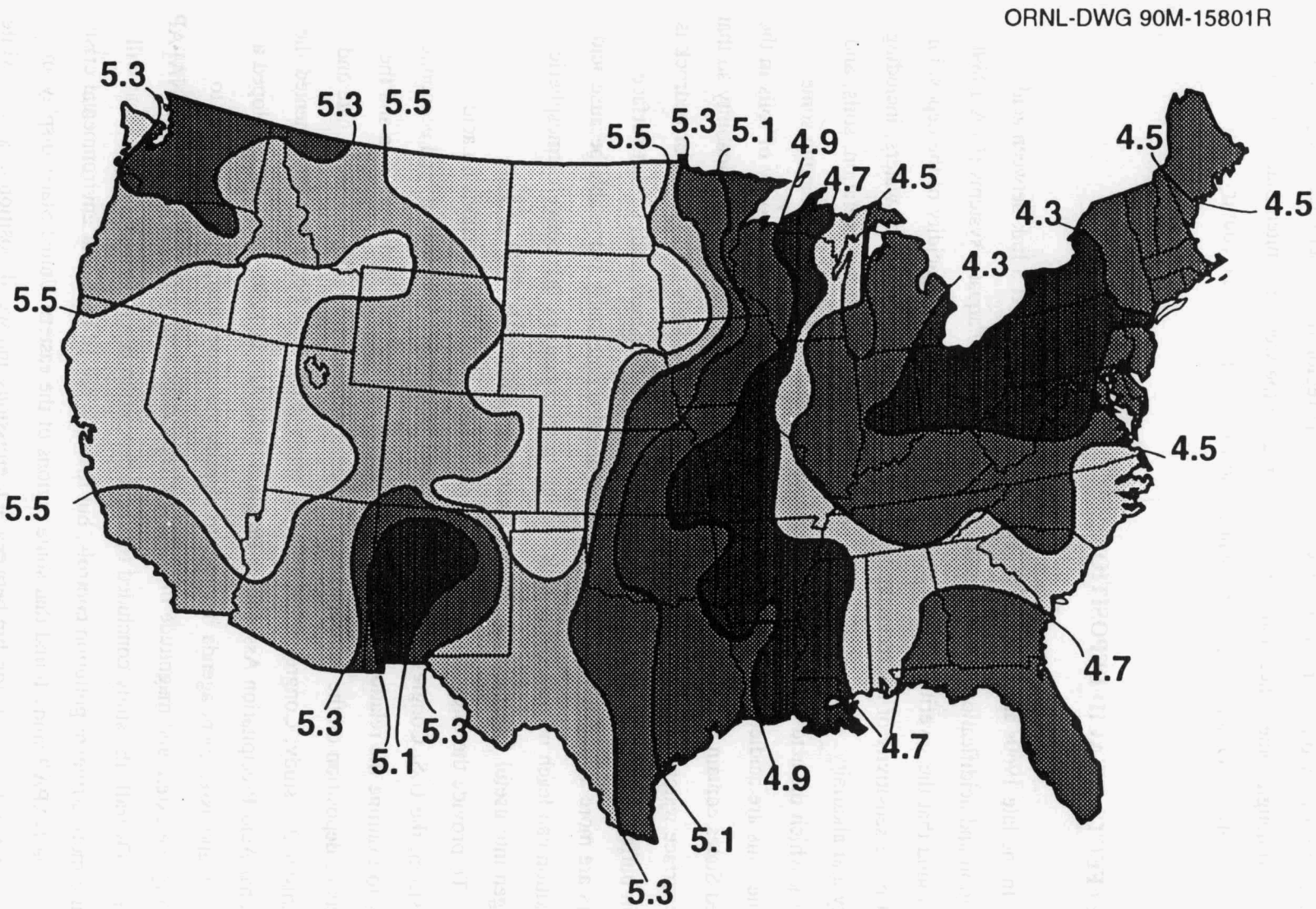

Fig. 3. Precipitation-weighted mean pH in precipitation in 1989 (from Simmons 1990).

an east-northeasterly direction from the Midwest to the region that experiences the greatest acidity. Although some concern also exists for areas in the western United States, lower emission levels of SO_2 and NO_x are present in most of this part of the country.

2.2 EFFECTS OF ACID DEPOSITION

In the late 1960s and early 1970s, scientists began to suspect a link between acid deposition and acidification of lakes and subsequent damage to aquatic systems (EPA 1989b). They found that the severity of the damage depends on not only the acidity of the deposition but also the sensitivity of the receiving location. The chemistry of surface waters, including acidity and alkalinity, is determined primarily by the chemistry of the vegetation, soils, and bedrock which the acid deposition contacts on its path to a water body. Although some organic soils are acidic, leading to naturally acidic surface waters, the majority of soils in the United States contain sufficient neutralizing compounds to provide buffering capability so that most surface waters are neutral or alkaline. However, where soils are thin and/or bedrock is low in buffering capacity, acid deposition is less likely to be neutralized, so that surface waters are more acidic. Forests and agriculture are also potentially vulnerable because acid deposition can leach nutrients from soils, inhibit microorganisms that convert atmospheric nitrogen into useful fertilizers for plants, and release toxic metals (EPA 1988a).

To provide the information needed for policy and regulatory decisions on acid deposition, the U.S. Congress authorized a 10-year scientific, technological, and economic study to examine the relationships between energy production and acid deposition and the effects of deposition on the environment, economy, and human health. To coordinate and administer this study, Congress established an Interagency Task Force that implemented the National Acid Precipitation Assessment Program (NAPAP) in 1980. NAPAP developed a research and assessment agenda intended to identify the causes and, where possible, to quantify the extent and magnitude of adverse effects associated with acid deposition (NAPAP 1990b). Overall, the study concluded that acid deposition is a long-term problem that will require more stringent pollution controls, but that it is not an imminent environmental crisis.

The NAPAP study found that some regions of the eastern United States display an approximately linear relationship between SO_2 emissions and wet deposition of sulfur, while

other regions are more complicated, particularly within about 200 km (about 120 mi) of large SO_2 emissions regions during winter (NAPAP 1990b). Atmospheric models indicate that, following a decrease in emissions, reductions in wet deposition at these locations during winter may be as low as 80% of the emissions reduction. For example, a 50% reduction in SO_2 emissions may result in only a 40% decrease in wet deposition of sulfur. Historically, SO_2 emissions in the United States decreased by 18% from 1979 [24.5 Tg (27 million tons)] to 1987 [20 Tg (22 million tons)], reflecting the installation of flue gas desulfurization systems at power plants and a reduction in the average sulfur content of coal consumed (EPA 1989a). Fig. 4 displays this trend, including the contributions by transportation, fuel combustion, and industrial processes to the total. During this same period, most of the 39 wet deposition monitoring stations in the United States and Canada showed a decrease in the concentration of sulfate in precipitation. The median trend in sulfate concentration over the 39 sites indicates a decrease of about 20% over the period (NAPAP 1990b). Thus, sulfate concentration trends in general show a decrease corresponding to a reduction in SO_2 emissions. Furthermore, an analysis of regional trends was consistent with the overall pattern and suggested that annual source-receptor relationships in the eastern United States have been approximately linear, although uncertainties in these relationships preclude their direct use for predicting future levels of sulfur deposition.

Because nitrogen compounds experience many complex chemical reactions in the atmosphere, relationships between sources and receptors have been even more difficult to establish than for sulfur compounds. Consequently, potential changes in acid deposition resulting from reducing NO_x emissions are unclear. In the United States, as indicated in Fig. 5, NO_x emissions decreased by 8% from 1979 [21 Tg (23 million tons)] to 1987 [19 Tg (21 million tons)], primarily because of a decrease in emissions by motor vehicles (EPA 1989a). Data from the 39 wet deposition monitoring stations during this same period indicate no overall change in nitrate concentration and no clear regional trends (NAPAP 1990b). These results, while consistent with the relatively small reduction in NO_x emissions, are insufficient to establish a relationship for predicting future levels of nitrogen deposition.

One significant finding from the NAPAP study is that acidic surface waters are concentrated in specific geographical regions rather than widely spread throughout the United States. Overall, less than 5% of the lakes and 10% of the streams examined in the National Surface Water Survey are chronically acidic (NAPAP 1990b). In specific regions, such as the

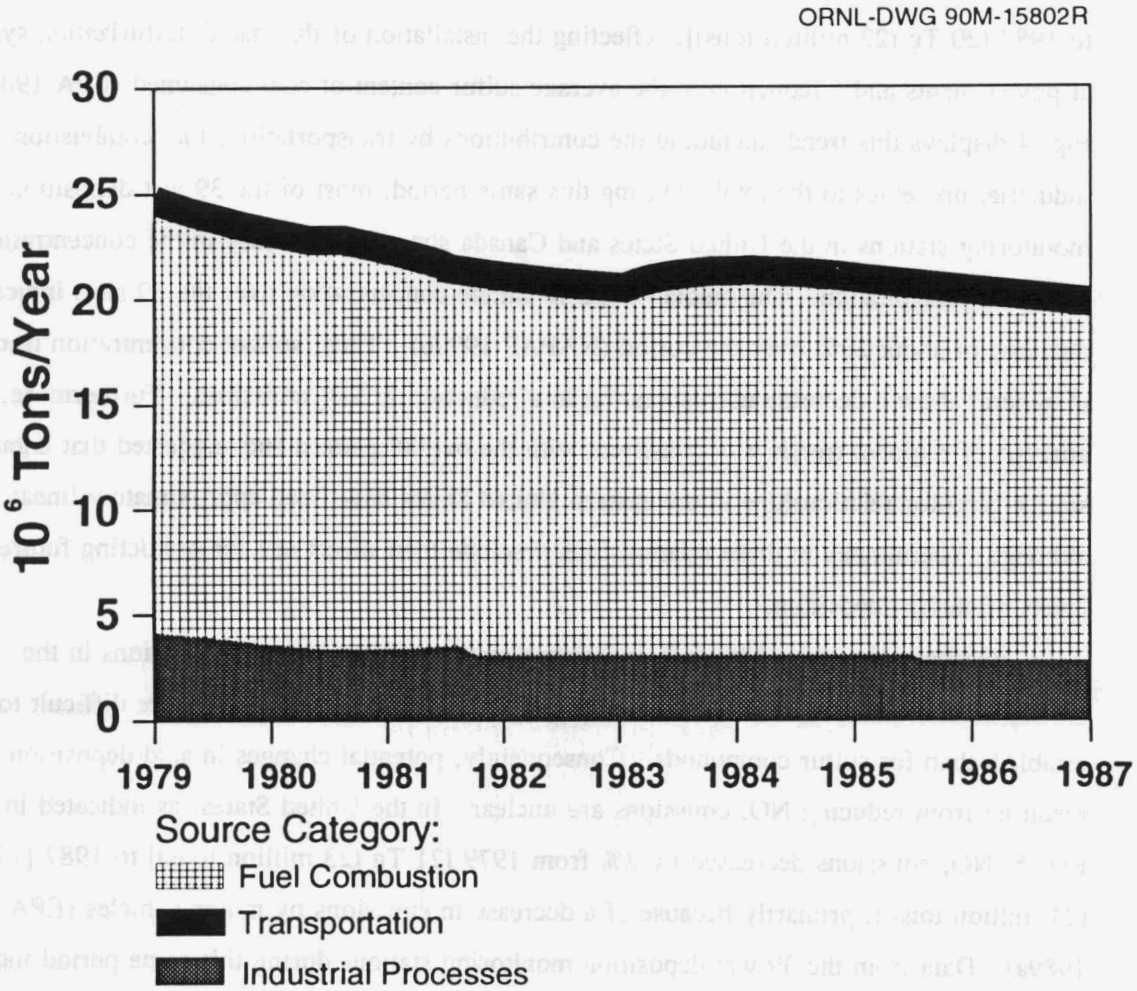

Fig. 4. National trend in SO_2 emissions (from EPA 1989a).

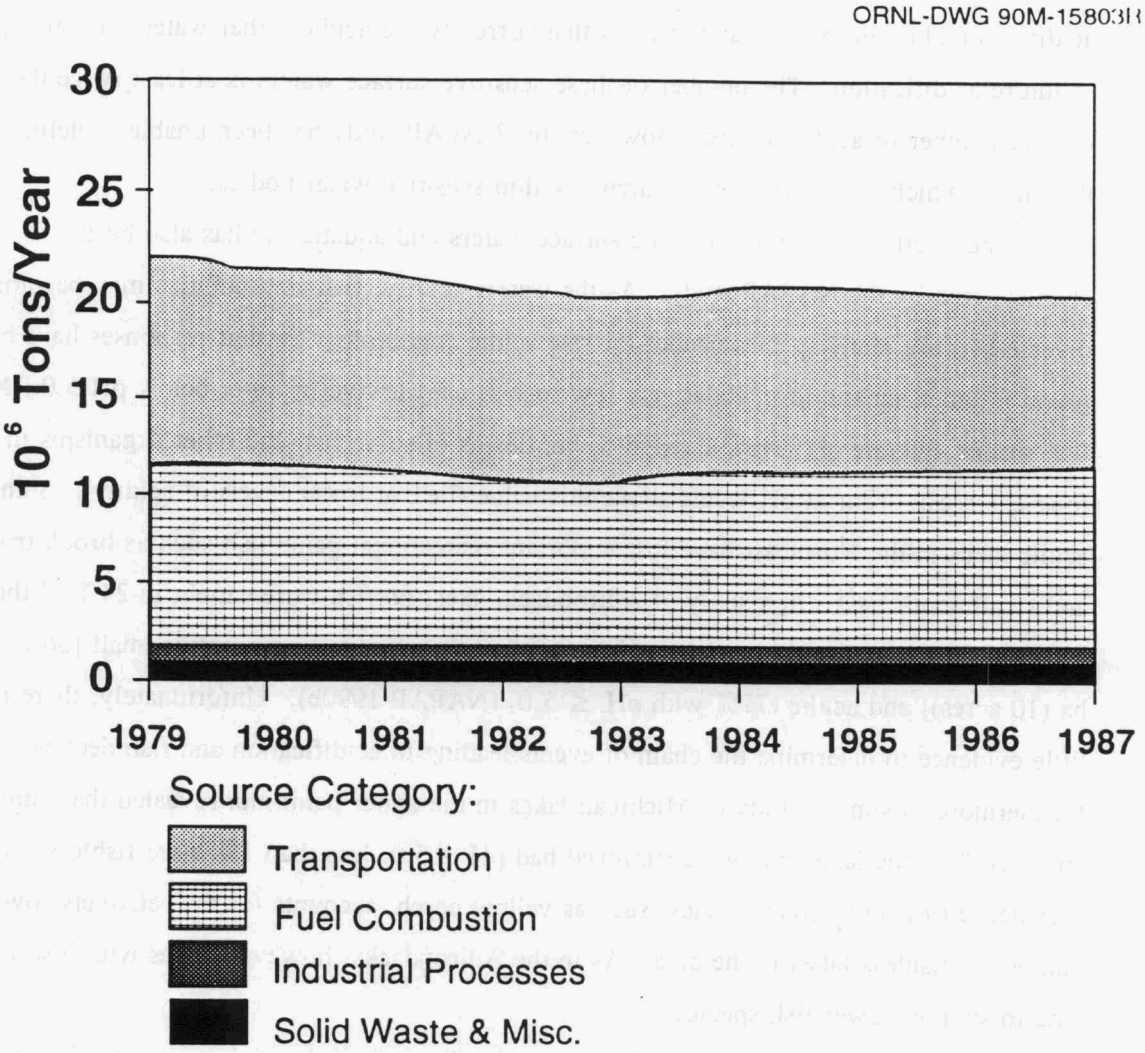

Fig. 5. National trend in NO_x emissions (fror

Adirondack region of New York, up to 15% of the lakes greater than 4 ha (10 acres) in size and up to 30% of small lakes [0.8 to 4 ha (2 to 10 acres)] are chronically acidic. However, the relative importance of acid deposition however is not clear for many of these small lakes because natural organic acids are often abundant and may contribute substantially to lake acidity. In addition to lakes and streams that currently are acidic, other waters are susceptible to future acidification. The number of these sensitive surface waters is at least twice the current number of acidic waters. However, the NAPAP study has been unable to delineate the rate at which acidification is occurring within sensitive water bodies.

The relationship between acidic surface waters and aquatic life has also been characterized by the NAPAP study. As the waters acidify, fish communities may become less diverse because many species cannot tolerate acidic conditions. Similar responses have been found in other aquatic life. Relatively few species can survive in water below pH 5.0. Most fish species tolerate pH levels above 5.5, but deaths of some fish and other organisms in the food chain can occur at pH levels above this value (i.e., at lower levels of acidity). Some acidic lakes in the Northeast have lost important recreational game fish such as brook trout and smallmouth bass. In a study of Adirondack lakes, no fish were caught in 24% of the lakes that were surveyed; the fishless lakes were discovered to be primarily small [66% <4 ha (10 acres)] and acidic (77% with pH $\leq$ 5.0) (NAPAP 1990b). Unfortunately, there is little evidence to determine the chain of events leading to acidification and fish decline. Furthermore, a similar study of Michigan lakes in the upper peninsula revealed that although about 10% of the lakes that were surveyed had pH ≤ 5.0, less than 1% were fishless. The prevalence of acid-tolerant species, such as yellow perch, accounts for the relatively low number of fishless lakes in the area. As in the Adirondacks, however, lakes with lower pH tend to support fewer fish species.

Vegetation is directly exposed to wet acidic deposition via rain, snow, and fog, but there is currently no widespread forest or crop damage in the United States resulting from wet deposition alone (NAPAP 1990b, 1993). However, cloud acidity in conjunction with a complex combination of other factors (i.e., ozone concentrations, soil acidification, insects, and climate) contributes to reduced cold tolerance in high-elevation spruce in the eastern United States, which can result in damage to trees above cloud level during winters with especially low temperatures (NAPAP 1993). In addition, acid deposition may increase leaching rates of magnesium and calcium in forest soils and thus be a contributing factor in

sugar maple decline in some areas. However, no correlations have been found between the distribution of wet sulfate deposition and maples with unhealthy crowns (NAPAP 1993). Trees and crops in some areas may actually benefit from nutrient enrichment by nitrogen and sulfur deposition.

Human health also may be affected indirectly by pollutants related to acid deposition. For example, people who eat large amounts of fish from acidic lakes or streams may experience exposure to methylmercury in some areas of the country. However, considerable uncertainty currently exists regarding indirect effects.

Acid deposition also contributes to the corrosion of metals and deterioration of stone in buildings, statues, and other cultural resources. Impacts from acid deposition on materials are difficult to quantify (NAPAP 1990b, 1991). However, projects begun during the 1980s are beginning to produce some quantitative relationships between acidic deposition and damage to metals and stone materials (NAPAP 1993). It has been estimated that wet and dry acidic deposition accounts for 31 to 78% of the dissolution of galvanized steel and copper in outdoor exposures (NAPAP 1993).

2.3 EFFECTS OTHER THAN ACID DEPOSITION

Sulfur dioxide and nitrogen dioxide are capable of causing direct adverse human health effects, primarily via the respiratory system. Sensitive populations with existing respiratory problems, such as those with asthma, are particularly susceptible. National Ambient Air Quality Standards (NAAQS) have been established by the U.S. Environmental Protection Agency to protect the public health, as well as the public welfare (e.g., animals, forests, crops, and building materials), from exposure to these and other pollutants. The NAAQS for SO_2 and NO_2 are exceeded in only a few areas of the country. Therefore, for most of the United States, there is minimal concern that these pollutants are directly responsible for human health risk. Although the current knowledge of health effects from exposure to sulfates and nitrates (oxidation products of SO_2 and NO_2) is quite limited and NAAQS have not been established, there is some concern that these compounds alone, or in conjunction with other compounds, may currently be contributing to adverse health effects (NAPAP 1990b).

Air pollutants associated with acid deposition also interfere with light transmission in the atmosphere. Fine particles in the atmosphere containing sulfate have been the primary factor in the reduction of visibility in rural and urban areas in the eastern United States since the early 1900s: the natural background visual range is estimated to be about 100 to 200 km (often given as 60 to 120 miles), but the current visual range is 19 to 35 km (12 to 22 miles) in rural areas and 14 to 26 km (9 to 16 miles) miles in urban areas (NAPAP 1990b). Sulfate particles and NO_x emissions are estimated to account for about 60% and 10%, respectively, of the visibility reduction in the eastern United States caused by air pollutants. In the western United States, the estimated natural background visual range is about 200 to 260 km (about 120 to 160 miles), but current visual range is about 130 to 200 km (about 80 to 120 miles) in rural areas, and varies from 14 to 26 km (9 to 16 miles) in Los Angeles to 20 to 80 km (12 to 50 miles) in other western cities. Sulfates are responsible for about 15 to 30% of the western visibility degradation, and NO_x emissions contribute 10 to 25%. Fig. 6 summarizes the current visual range for rural and suburban areas of the United States, and Table 2 lists the contribution of sulfates and NO_x to visibility reduction.

While this section has addressed the direct effects of NO_x and SO_2, it should also be noted that NO_x is a precursor of ozone, and therefore control of NO_x could also contribute to reductions in ozone concentration near the earth's surface. Although ozone has the beneficial effect of absorbing ultraviolet radiation from the sun, this effect takes place primarily at high altitudes. Ozone is a strong oxidant that can be harmful to living things with which it comes in contact, so near-surface ozone is considered a pollutant.

In spite of its harmful effects and the resulting efforts to reduce its concentration, sulfur in the atmosphere may have some beneficial effects. The role of sulfur as a soil nutrient has already been noted. Sulfur particles from natural sources (e.g., volcanoes) and from anthropogenic sources may be reflecting sunlight directly, or causing clouds to reflect sunlight more effectively, thereby cooling the lower atmosphere and thus acting counter to the greenhouse effect (Kerr 1992). The same effect may also be reducing harmful ultraviolet radiation that reaches the earth's surface.

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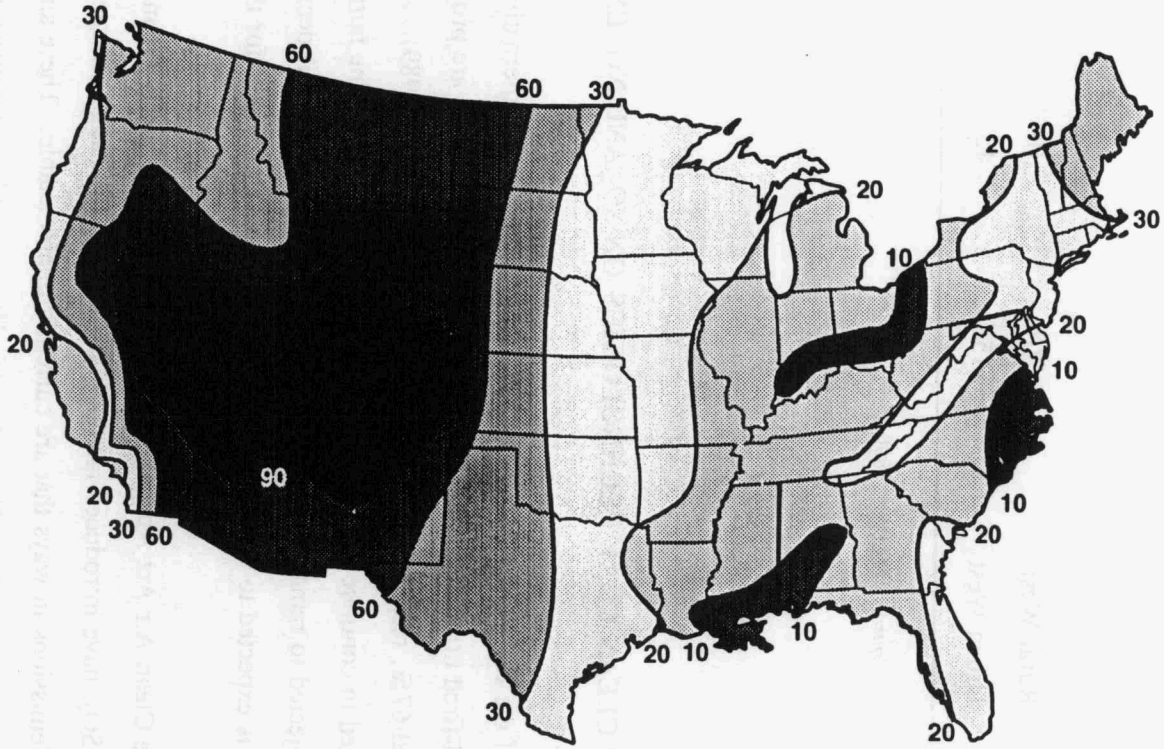

Notes:

- **Values are based on airport median visual ranges factored by 1.3 to account for differences in detection thresholds in estimating visual range. Data included for all days (all weather conditions).**
- **Data are for 1974-1976, but recent studies indicate that current conditions are approximately the same as shown here.**

Fig. 6. Estimated median visual range in miles (1 mile = 1.609 km) for rural (suburban/nonurban) areas of the United States (from OTA 1984).

Table 2. Contribution of sulfates and NO_x to visibility reduction (% of total contribution)

Location	Sulfates	NO_x
Rural East	60	7
Urban East	55	10
Rural West	30	10
Urban West	15	15

Source: NAPAP ,1990.

2.4 EFFECTS OF CLEAN COAL TECHNOLOGIES ON SO_2 AND NO_x EMISSIONS

The results of the PEIS analysis indicate that under the no-action alternative, national emissions from coal-fired utilities and industrial boilers for SO_2 and NO_x are projected to increase by 16% and 67%, respectively, between 1985 and 2010 (DOE 1989). Acid deposition is expected to continue at current or slightly elevated levels. The northeastern United States is projected to remain the most affected area, although a small decrease in SO_2 and NO_x emissions is expected to occur. Increased emissions are projected for the rest of the country.

However, the Clean Air Act Amendments of 1990, and particularly the marketing of allowances to emit SO_2, have introduced factors that are likely to change the geographic distribution of SO_2 emissions in ways that are currently unpredictable. These amendments, signed into law by President Bush on November 15, 1990, include a two-phase reduction in pollutants contributing to acid rain. The law would reduce annual SO_2 emissions nationwide by 4.5 Tg (5 million tons) below 1980 levels by 1995 and another 4.5 Tg (5 million tons) by 2000. A 4-year extension of the latter deadline will be granted to power plants that elect to

use CCTs to decrease their emissions. Utilities, however, are concerned that acid rain legislation will divert funds from clean coal research and demonstration by forcing immediate expenditures on currently proven but expensive emissions controls because the limited extension period will not be sufficient for utilities to incorporate CCTs into their compliance plans. This would be an unfortunate occurrence because CCTs can help decrease compliance costs and reduce other environmental residuals, such as hard-to-handle sludge waste and carbon dioxide emissions. Considerable uncertainty currently exists regarding the extent of market penetration by CCTs in time to meet the deadlines for compliance with the Clean Air Act amendments. However, CCTs may still contribute to the mandated SO_2 emissions reductions by providing an alternative to conventional flue gas desulfurization. Less expensive CCTs combined with purchase of emissions allowances may still, in some cases, be an economically effective way to comply with the provisions of the Clean Air Act as amended. The extent to which that will happen will depend to a large extent on the relative costs of installing a scrubber versus implementing a particular CCT and/or purchasing emissions allowances.

The PEIS analysis determined the percentage change in SO_2 and NO_x emissions for the 22 CCTs as compared to the no-action alternative. Results are displayed in Table 1. As mentioned above, the emissions changes represent maximum projected changes for the technologies because each technology was applied independently and assumed to penetrate 100% of its possible commercial market. It is not known what effect the Clean Air Act Amendments of 1990 will have on the validity of this assumption. The PEIS found that the commercialization of CCTs by the year 2010 would have a substantial beneficial effect on air quality compared to no action. Furthermore, the northeastern United States, the region currently most impacted by acid deposition, was projected to receive the greatest potential benefits. For SO_2, the repowering and some of the retrofit technologies could lead to a significant reduction in national emissions (relative to no action). The decrease for the repowering technologies ranges from about 30 to 50%, and the reduction for the retrofit technologies spans from 0 to 50%. With respect to NO_x, the repowering technologies could lead to a reduction of about 15%, while projections for the retrofit technologies range from an increase of about 5% to a decrease of about 35%. No change in emissions levels by some of the retrofit technologies reflects their intended function of controlling one pollutant only.

While the PEIS evaluated SO_2 and NO_x emissions, the results can be used to estimate changes in levels of acid deposition. Because reductions in SO_2 emissions associated with many CCTs are substantial compared with the projected increase under the no-action alternative, their widespread commercialization should reduce sulfur deposition (the predominant form of acid deposition), especially in the northeastern United States and southeastern Canada. However, because projected decreases in NO_x emissions are less than expected increases under no action, the impact of the new technologies would be to reduce the rate of increase of NO_x concentrations and nitrogen deposition that is predicted under no action.

Reduction in SO_2 and NO_x emissions should lead to improvements in water quality, and some aquatic life recovery should occur, although the degree and timing of the improvement are uncertain. It also is unclear whether recovery would result in the same biological community that existed prior to acidification. However, preliminary evidence indicates an increase in fish population at some previously low-pH lakes that are recovering naturally in the Sudbury, Ontario, area (Keller, Pitblado, and Conroy 1986; Beggs and Gunn 1986). Similarly, reduction in sulfur deposition should improve the cold tolerance of high-elevation spruce in the eastern United States and may reverse the decline of sugar maples in some areas. Finally, a decrease in fine particles containing sulfate, the primary factor in visibility degradation in rural and urban areas in the eastern United States, should result in overall improved visibility.

3. EFFECTS OF CLEAN COAL TECHNOLOGIES ON THE GREENHOUSE EFFECT

3.1 BACKGROUND

The earth's atmosphere allows a large percentage of incoming solar radiation to pass through to the earth's surface. There, it is converted to heat energy (infrared radiation), which does not pass back through the atmosphere as easily. The result is that heat energy is "trapped" near the earth's surface. This phenomenon, diagrammed in Fig. 7, is commonly called the *greenhouse effect*.

The greenhouse effect is related to the wavelengths of the radiation involved. Incoming solar radiation is primarily in the wavelengths between 0.2 and 2 μm (1 μm = 10^{-6} m). The visible spectrum of light lies within this range, between (shorter-wave) ultraviolet radiation and (longer-wave) infrared radiation. The earth radiates energy in the infrared portion of the electromagnetic spectrum, primarily between about 5 and 50 μm. Certain trace gases in the atmosphere, such as CO_2 and water vapor, absorb some of this infrared radiation as it travels upward from the earth. The energy thus absorbed is re-radiated in all directions including back down toward the earth. In this way, some heat energy is recycled through the lower atmosphere. The infrared absorbing gases involved are often referred to as <u>greenhouse gases</u>.

The naturally occurring greenhouse gases in the atmosphere are mainly water vapor and CO_2. Ozone (O_3) is also a strong absorber in a narrow wave band around 10 μm, and methane and nitrous oxide absorb terrestrial radiation in wavelengths near 8 μm. Greenhouse gases are only a small percentage of the earth's atmosphere, whether considered individually or collectively. However, their collective effect is to keep the temperature of the air in which we live about 33°C (59°F) warmer, on average, than the earth's surface would be if there were no atmosphere.

Each greenhouse gas has its own particular absorption spectrum, or set of wavelengths which it selectively absorbs. Some of the more important of these absorption spectra are shown in Fig. 8. Water vapor absorbs radiation at wavelengths around 5 to 8 μm, and also at wavelengths greater than about 18 μm. Carbon dioxide absorbs radiation at wavelengths around 12 to 18 μm. The naturally occurring greenhouse gases are not particularly effective in absorbing radiation between 8 and 12 μm, except for a very narrow ozone absorption band

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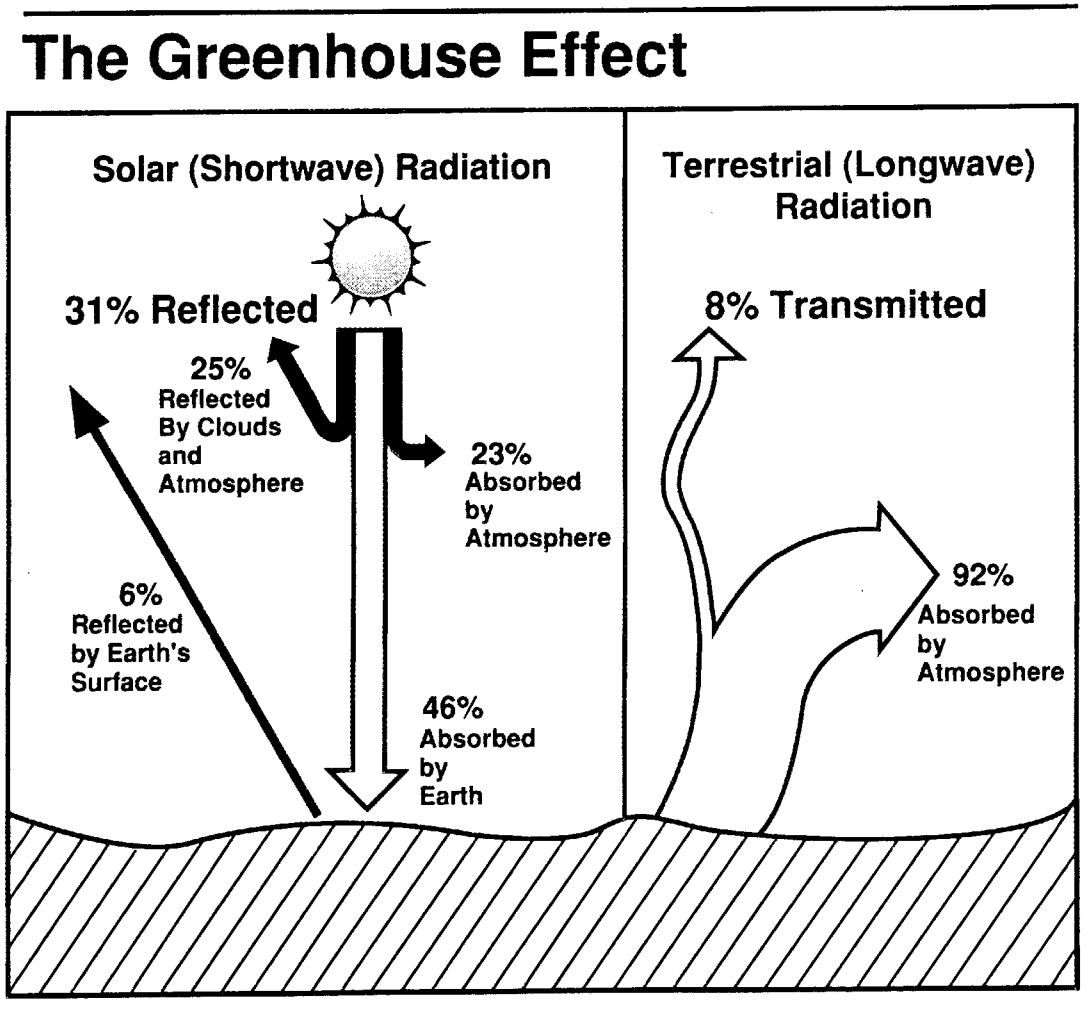

Fig. 7. Absorption, transmission, and reflection of solar and terrestrial radiation.

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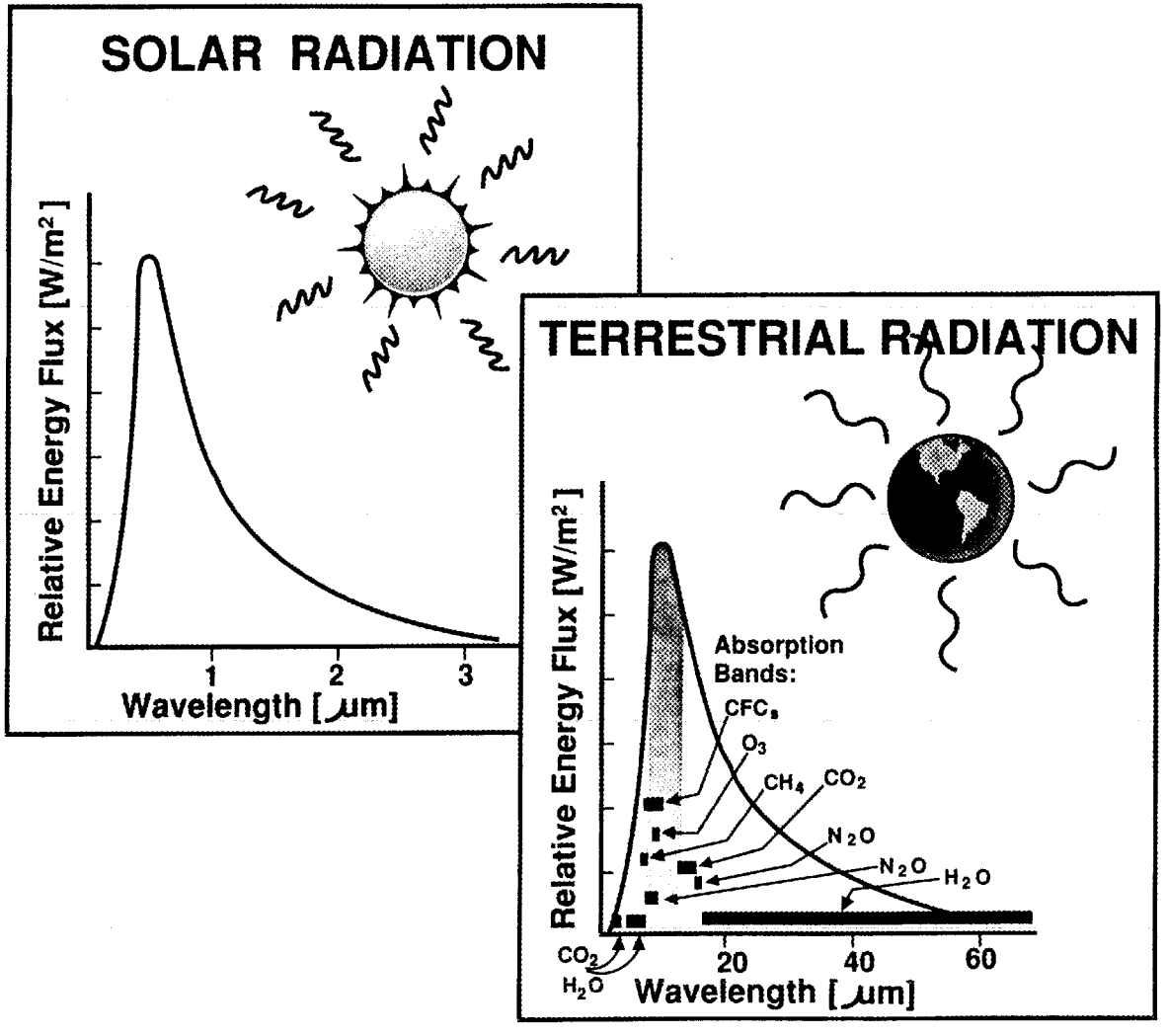

Fig. 8. Solar radiation spectrum and terrestrial radiation spectrum showing major greenhouse gas absorption bands.

around 10 μm. However, many greenhouse gases are emitted to the atmosphere each year as a result of agricultural or industrial activities, and some of these gases are effective absorbers in the 8- to 12-μm band—the wavelengths at which they can add most effectively to the natural greenhouse effect.

In addition to water vapor, CO_2, and O_3, the greenhouse gases include methane (CH_4), nitrous oxide (N_2O), and several chlorofluorocarbons (CFCs, or freons). Notable among the CFCs are CFC-11 ($CFCl_3$) and CFC-12 (CF_2Cl_2), which have atmospheric lifetimes of more than 50 years (Ramanathan et al. 1985) and strong absorption bands in the 8- to 12-μm band (Ramanathan 1988). Although CFCs are greenhouse gases, they have counteracting influences on the greenhouse effect because they destroy O_3 in the stratosphere (where the density of O_3 is greatest). Current thinking is that, for the CFCs, these counteracting influences on the total greenhouse effect have been roughly comparable over the last decade (Ramaswamy et al. 1992), and that therefore CFCs have had only a small, if any, net greenhouse effect.

3.2 INDIVIDUAL GREENHOUSE GASES

3.2.1 Water Vapor

Water vapor is the most abundant greenhouse gas in the atmosphere. Concentrations of water vapor can vary from less than 0.05% arctic air to as high as 4% in the humid tropics. Because of the variability of water vapor concentration in the atmosphere, it is difficult to measure global trends. Inputs from human activities are small compared to evaporation from the world's oceans and other natural sources. If the temperature of the lower atmosphere increases and the relative humidity does not change, the amount of water vapor in the lower atmosphere will also increase and contribute to further increases in the greenhouse effect.

3.2.2 Carbon Dioxide

After water vapor, the most abundant greenhouse gas in the atmosphere is CO_2. Like most greenhouse gases except water vapor, the residence time of CO_2 in the atmosphere is

long enough to allow it to be dispersed homogeneously at the global scale. Measurements of CO_2 in air bubbles trapped in cores of polar and glacial ice (Neftel at al. 1985; Wahlen et al. 1990) indicate that the "pre-industrial" CO_2 concentration in the atmosphere was between 275 and 285 parts per million by volume (ppmv). Atmospheric CO_2 concentration has increased by about 25% over the last century. Recent (1990) CO_2 concentrations measured at several locations around the world were in the range of 351 to 357 ppmv (Conway et al. 1991; Keeling 1991; Keeling and Whorf 1991). Most of the CO_2 increase in the last century has been attributed to the burning of fossil fuels. Therefore, CCTs, by virtue of burning coal more efficiently, can contribute to reductions in CO_2 emissions for a given amount of energy production. Biomass burning may also have contributed a substantial amount of CO_2 to the atmosphere. Estimates of the current annual contribution of CO_2 emissions contributed by biomass burning are about 30% of the fossil-fuel contribution (World Resources Institute 1992). However, estimates of CO_2 emissions from biomass burning are characterized by a wide range of uncertainty.

3.2.3 Methane

After water vapor and CO_2, the next most abundant greenhouse gas is methane, which is present in the atmosphere in concentrations of about 1.6 to 1.7 ppm. Over the last decade it has increased by about 1% per year (Blake and Rowland 1988), but during the last 4 years the rate of increase may have slowed to about 0.8% per year (National Oceanic and Atmospheric Administration 1990). A large percentage of atmospheric methane is produced by bacteria breaking down organic matter in the absence of oxygen. Major sources of atmospheric methane include wetlands, lakes, rice paddies, cattle and other cud-chewing animals, fossil fuel production, biomass burning, and landfills (Taylor et al. 1990).

3.2.4 Nitrous Oxide

Nitrous oxide is also a greenhouse gas. Its current concentration is about 0.31 ppm and has been increasing by about 0.2% to 0.25% per year (Weiss 1981; National Oceanic and Atmospheric Administration 1990). Nitrous oxide is produced by biological processes in soils and in natural waters (Weiss 1981). Increased nitrogen inputs to the soil, via fertilizers or in

the form of acid rain, may be leading to an increase in the amount of N_2O released to the atmosphere by these natural processes.

3.2.5 Ozone

Ozone is a greenhouse gas that varies in concentration from almost zero at night near the ground to as high as 10 ppmv at about 20 km (12 miles) altitude. Most ozone is found in the stratosphere, which extends from about 13 to 50 km (8 to 31 miles) altitude. There, it is formed by chemical processes requiring the presence of ultraviolet radiation. In the troposphere, which extends from the ground to the stratosphere, O_3 is produced via different reactions involving nitrogen oxides and hydrocarbons in the presence of visible light.

3.2.6 Chlorofluorocarbons

These gases are not a natural component of the atmosphere, but are entirely the result of human technology. They are currently present in the atmosphere in concentrations of less than one part per billion (Ramanathan 1988), and were increasing at rates of 4 to 5% per year until about 1989 (National Oceanic and Atmospheric Administration 1990; Mitchell 1989). The relatively small concentrations of CFCs can be deceptive because CFCs are particularly effective greenhouse gases on a molecule-by-molecule basis (Mitchell 1989; Shine et al. 1990). CFCs have long atmospheric lifetimes and eventually ascend into the stratosphere, where they lead to the destruction of ozone. Recent international agreements (e.g., the Montreal Protocol of 1987) to phase out production of CFCs are likely to reduce the rate of atmospheric CFC increase in the next few decades and are intended to eventually lead to a decreasing trend in atmospheric CFC concentrations. Recent evidence (Elkins et al. 1993) indicates a significant decrease in the atmospheric growth rates of CFC-11 and CFC-12 (the two most abundant CFC species) beginning about 1989. If atmospheric growth rates of those two species continue to decrease as expected, their concentrations will begin to decline before the turn of the century (Elkins et al. 1993). As noted above, CFCs can cause reductions in stratospheric ozone (which is also a greenhouse gas). These counteracting influences of CFCs on the total greenhouse effect appear to have been roughly comparable over the last decade (Ramaswamy et al. 1992).

3.3 EFFECTS OF GREENHOUSE GASES ON CLIMATIC FORCING

Carbon dioxide accounts for about 99%, by volume, of the greenhouse gases in dry air (water vapor being neglected because its concentration is variable and, on average, is many times that of CO_2). The contribution of CO_2 to the *current* greenhouse effect is also many times higher than the combined effects of other greenhouse gases except for water vapor. However, in terms of *increasing* the greenhouse effect, the relatively rare greenhouse gases are often much more effective on a molecule-by-molecule basis. One reason for this is that the CO_2 absorption bands in the electromagnetic spectrum are closer to radiative saturation. That is, there is enough CO_2 already absorbing in those bands to reduce the effect of a given amount of additional CO_2. By contrast, the absorption bands of CFC molecules are not saturated because CFCs are present in low concentrations and there is little overlap with absorption bands of other gases (Mitchell 1989). The addition of one molecule of CFC-12 can have the same greenhouse effect as the addition of 10,000 or more molecules of CO_2 (Mitchell 1989). However, one CFC molecule can also cause the destruction of several molecules of ozone via mechanisms discussed by Panofsky (1978) and Levi (1988).

Table 3 shows the contributions of particular gases to increases in greenhouse warming, as projected by Mitchell (1989) for the period 1985 to 2035. Stratospheric ozone is expected to decrease, rather than to increase, because of the presence of the CFCs. This decrease in stratospheric ozone will reduce the greenhouse effect, thereby tending to counteract the increased greenhouse effect due to increased CFCs. The extent to which the ozone decrease will counteract the greenhouse effect of the corresponding CFC increase is not known but is believed to be significant (Isaksen et al. 1992). This, in turn, would reduce the projected amount of CFC-induced greenhouse effect shown in Table 3, thereby reducing the total greenhouse effect and increasing the percentage due to CO_2. A further complication in projecting the greenhouse effect of future CFC increases is that the effects of the Montreal Protocol and subsequent international agreements for phasing out CFC production are not known.

In any case, CO_2 is responsible for over half of the projected global warming, and it is CO_2 emissions that would be most affected by CCTs.

Table 3. Estimated contributions of increases in particular greenhouse gases to global warming for the period from 1985 to 2035

Gas	Estimated contribution (W/m^2)
Carbon dioxide	1.8
Methane	0.5
Nitrous oxide	0.15
CFC-11	0.35
CFC-12	0.69
TOTAL	3.49

Source: Mitchell, 1989.

3.4 CARBON DIOXIDE TRENDS

The increase in atmospheric CO_2 concentrations over the last 100 years is well documented and reasonably well quantified. Measurements of atmospheric CO_2 concentrations at Mauna Loa, Hawaii, go back to March 1958 (Keeling and Whorf 1991), and a less continuous record from the South Pole began in June 1957 (Keeling 1991). Present and projected future anthropogenic source terms for atmospheric CO_2 are presented in Table 4. Coal burning in the United States contributes about 8.4% of the global total. However, this percentage is projected to rise to about 11% by 2010 (Edmonds et al. 1989).

After reviewing studies of projected fossil-fuel growth, Mitchell (1989) selected a value of 1.4% per year for growth in global emission rates of CO_2. This leads to global CO_2 emissions of about 29 Tg (32,000 tons) per year from fossil fuels alone by 2010 (Table 4).

3.5 POSITIVE AND NEGATIVE EFFECTS OF ATMOSPHERIC CO_2

Photosynthesis requires CO_2, and recent evidence indicates that increases in atmospheric CO_2 concentration can enhance the water-use efficiency of plants. Also, CO_2 contributes to the natural greenhouse effect, which makes the earth warm enough for human

Table 4. Recent and projected sources of atmospheric CO_2 in millions of (short) tons

	Year		
	1986	1989[a]	(Projected) 2010[a]
Coal only, USA	1,763	2,014(8)	3,637(11)
All fossil fuel, USA	4,803	5,370(22)	7,100(22)
	4,867		6,990(22)
Coal only, global	9,104	9,665(40)	NI[b]
All fossil fuel, global	22,430	24,111	32,286[c]

[a]a Numbers in parentheses indicate the percentage of the world fossil fuel total due to each source category.)

[b] NI indicates no information.

[c] Calculated assuming a 1.4% per year increase in global CO_2 emissions, as per Mitchell, 1989.

habitation. Nonclimatic effects of increasing CO_2 would generally be considered good for living things. However, while increased CO_2 might be favorable to beneficial plants such as cereals, it would also be favorable to weedy pests such as crabgrass. Rapid environmental changes would be expected to favor species with fast evolutionary response times, such as insects. The species composition of ecosystems could be upset in unpredictable ways. Climatic changes that could result from an increase in greenhouse gases are highly uncertain, as are the direct and indirect effects of such climatic changes on other aspects of the environment. Beneficial and harmful effects would both be expected, but it is not possible to specify the nature, timing, or location of either type of effect.

3.6 EFFECTS OF CLEAN COAL TECHNOLOGIES ON CO_2 EMISSIONS

Environmental considerations of CCTs initially focused on reducing emissions of SO_2 and NO_x to the atmosphere. More recently, however, the effects of CCTs on CO_2 emissions have also been considered (DOE 1989). Recent concern that an increase in the greenhouse effect could lead to a rapid climatic change, with a related rise in sea level and potential

upsets to major ecosystems, has led to consideration of the possibility of reducing CO_2 emissions, at least until we learn more about their effects. CCTs could thus have an added side benefit. By virtue of higher coal-use efficiency (more energy produced per unit of coal burned), certain CCTs could, with full commercialization, reduce U.S. CO_2 emissions from coal burning by 20% or more of what they would otherwise be by 2010 and thereby reduce U.S. CO_2 emissions from all fossil fuel sources by around 10% of what they would otherwise be. The effects of CCTs on concentrations of other greenhouse gases are expected to be negligible. Reductions in NO_x resulting from the use of CCTs could lead to corresponding reductions in tropospheric ozone. However, these reductions would be small, and most ozone is in the stratosphere. The contribution of increased tropospheric ozone concentration to any greenhouse warming in the next few decades is expected to be negligible.

As Table 1 indicates, the repowering technologies, which can increase the amount of energy produced per unit of coal burned, are the only CCTs that can contribute appreciably to reducing CO_2 emissions to the atmosphere. Fuel cell technology is seen to be the most effective of these technologies in reducing CO_2, and circulating fluidized-bed combustion is least effective. In the following discussion, an optimistic assumption of a 10% reduction (as compared to the no-action alternative) in total U.S. fossil fuel CO_2 emissions (from all sources) by the year 2010 will be made to represent an approximate best-case result for market penetration of repowering CCTs. Because the U.S. contribution to global fossil-fuel CO_2 emissions is projected to be about 22% of the total in the year 2010, a 10% reduction in the U.S. contribution by that year is equivalent to a 2.2% reduction in global fossil-fuel CO_2 emissions, as compared to the no-action alternative. This is equivalent to reducing CO_2 emissions by about 635 Tg (700 million tons) per year by 2010.

The 2.2% reduction only applies to global CO_2 increases contributed by fossil fuels. Because biomass burning also contributes CO_2 to the atmosphere, the percentage reduction of total CO_2 emissions to the atmosphere may be lower than 2.2%. It should also be noted that CO_2 is expected to contribute about 50 to 75% (depending upon the *net* contribution of the CFC increases and corresponding ozone reductions) of the increase in greenhouse effect experienced by 2010. Only negligible reductions in emissions of industrially produced greenhouse gases other than CO_2 are expected from CCTs. Therefore, full implementation of CCTs in the United States would be expected to decrease human-induced global warming by only about 1 to 1.5%. Even if CO_2 from biomass burning could be reduced to zero and the

net effect of CFCs were zero, the decrease in any human-induced global warming due to full implementation of CCTs in the United States would probably be less than 2%. Such a percentage might at first seem insignificant. However, when considered in the context of other means of reducing greenhouse gases in the atmosphere, CCTs compare favorably. The following discussion considers the role of CCTs in reducing greenhouse gas emissions in the context of other possible mechanisms to accomplish the same purpose.

Because the residence time of CO_2 and most other greenhouse gases in the atmosphere is long compared to the time required for global dispersion by wind patterns, emissions from any location on earth contribute to the global average concentrations. The current buildup of CO_2 and other greenhouse gases is therefore the result of contributions by many technologies within a variety of industries or practices serving virtually all sectors of society in every inhabited region of the world. Even in the most industrialized countries, no single technology produces more than a few percent of the global fossil-fuel CO_2. Therefore, a significant reduction, or even elimination, of any single fossil-fuel technology in any particular country would have little effect on the overall amount of global fossil-fuel consumption and resulting CO_2 emissions.

For example, Wolff and Frosch (1991) have estimated that a complete elimination of emissions from cars, trucks, and buses in the United States would result in a 3.5% reduction in the anthropogenic contribution to increases in the greenhouse effect. This percentage is in terms of *current* greenhouse gas emissions. The corresponding percentage of greenhouse gas emissions in the year 2010 (for comparison with the percentages given above) is only about 2.5%. Wolff and Frosch account for emissions of CO_2 and other greenhouse gases (methane and nitrous oxide) resulting from the production of motor fuel as well as from its consumption. They noted that it could be argued that the elimination of all U.S. vehicles would have only a negligible effect on global greenhouse forcing. Other examples of large-scale reductions in CO_2 emissions contributing only a small percentage of the global total are readily available from CO_2 emission data (see, for example, Marland and Boden 1991), and some of these examples are shown in Table 5. There is no single CO_2 source category in any country of the world for which drastic reduction or elimination of emissions would realistically be expected to reduce worldwide CO_2 emissions by more than 5% (or to reduce the anthropogenic component of the greenhouse effect by as much as 2% to 3%) by the year 2010. Reduction of global CO_2 emissions is therefore a process that must involve several

Table 5. Comparison of the potential effect of clean coal technologies with effects of other scenarios for reduction of global emissions of CO_2

Scenario for year 2010	Millions of tons of CO_2
Favorable market penetration of repowering clean coal technologies in the U.S.	700
Reducing U.S. oil consumption by 30%[a]	700
Reducing U.S. coal burning by 35%[a]	700
Reducing coal burning in the People's Republic of China by 33%[a]	700
Reducing coal burning in the USSR by 40%[a]	700
Reducing world oil consumption by 5%[a]	500

[a]Units are millions of short tons of CO_2, per year, injected into the atmosphere.

[b]Basis of comparison is the amount for 1989.

participants, none of which individually can reduce greenhouse gases by more than a few percent of the global total.

On a more positive note, CO_2 reductions could be achieved by simultaneous measures that would have a nontrivial cumulative effect. Several options are available to reduce CO_2 emissions in the next generation. These include alternative (nonfossil) energy sources and energy conservation, as well as CCTs. It should be noted that these alternative energy sources and energy conservation may lead to a reduction in coal use, so that by 2010 the actual amount of coal burned may be less than the projections given in Table 4. In that case, the CO_2 savings attributable to CCTs may be less, because those savings are determined by the amount of coal that is actually used in CCTs.

In any case, the repowering CCTs add one more option to the list of ways to reduce future CO_2 emissions to the atmosphere. The CCTs are comparable quantitatively with other individual measures considered specifically for reducing CO_2 emissions, although CCTs were

initiated for a different purpose. Further, CCTs would have less drastic effects on people's life styles than would some of the other measures that have been considered for reducing CO_2 emissions. Finally, this analysis considers only the potential implementation of CCTs in the United States. The extent to which such technologies could penetrate international markets would amplify their potential effectiveness in reducing global CO_2 emissions.

4. EFFECTS OF CLEAN COAL TECHNOLOGIES ON SOLID WASTE

4.1 BACKGROUND

Most of the concern regarding solid waste disposal has been focused on the approximately 180 Tg (about 200 million tons) of municipal solid wastes generated annually in the United States (World Resources Institute 1992) because municipal waste landfills are usually located near cities to minimize haulage costs. This practice often leads to conflicts over the aesthetic, environmental, and land-use effects of waste disposal. Disposal of coal combustion wastes is usually of less concern to the public because it generally occurs at some distance from highly populated areas and often occurs on land owned by a utility or industry.

Currently, about 90 Tg (about 100 million tons) of coal combustion waste is generated annually in the United States. Generation of these wastes is expected to increase to over 236 Tg (over 260 million tons) per year by the year 2010. Coal combustion wastes are important because the cost of waste disposal increases the cost of energy and because disposal of these wastes requires commitment of land that could be put to other uses. Local conditions determine the significance of coal combustion waste as a land-use problem. Coal plants located in rural areas or on large sites may anticipate fewer problems with waste disposal. However, coal plants in or near urban areas frequently face the same problems as the municipalities they serve.

In addition to the aesthetic and land-use problems of waste disposal, there is concern for potential groundwater contamination from constituents in wastes disposed of in landfills. Hazardous wastes in landfills can contaminate groundwater, which is a pathway of concern for human health. Leachate from other wastes can have significant ecological effects where groundwater discharges to surface water bodies. Coal combustion has the potential to generate hazardous materials either as products of incomplete combustion or from trace contaminants in the coal.

4.2 COAL COMBUSTION WASTES

Coal-fired combustion facilities generate bottom ash, fly ash, scrubber waste, and waste from water treatment processes. The amount of waste from water-treatment processes is less than 1% of the amount from the other three sources; therefore, so only solid wastes from bottom ash and fly ash removal and from flue gas scrubbers are discussed here.

Coal ash is the noncombustible solid residue that remains after coal is burned. In a coal-fired boiler, some of the ash remains inside the boiler and is known as bottom ash. Fly ash is the fraction that is too small to settle out in the combustion chamber; it becomes suspended in the high-velocity flue gas. Air pollution regulations require electric-utility and industrial boilers to be equipped with particulate control devices to prevent most (usually 99% or more) fly ash from entering the ambient air. Except for its small particle size, fly ash is not usually considered significantly different than bottom ash.

The control of SO_2 emissions from stationary sources required under the Clean Air Act of 1970 has led to the installation of flue gas desulfurization (FGD) systems (scrubbers) at many electric power and industrial plants. At present, a large majority of FGD units in the country are of the lime or limestone wet scrubbing type, which produces calcium sulfite or calcium sulfate in a sludge having the consistency of toothpaste. The proportions of calcium sulfite and calcium sulfate vary widely. FGD sludge also contains a myriad of trace elements originating in the coal.

The three main methods used to dispose of coal combustion wastes are landfills, ponds (primarily for wet slurries), and mine disposal (Soholt et al. 1980). Wastes from over half the coal-fired electric utility generating units in the United States are placed in off-site landfills. Landfill configurations are adapted to fit topographic and geologic constraints (Fig. 9). Side-hill and valley-fill landfills are generally preferred because they can blend with existing terrain and may provide valuable property if properly constructed. Ponds are generally configured like landfills (Fig. 9), but because the contents are wet, seepage through the sides or bottom is inevitable. Mine disposal is conceptually attractive but used almost exclusively by mine-mouth plants. It is not more widely used because the problems of transporting and handling coal wastes, especially sludges, are formidable.

The current generation of ash at coal-fired electric utility power plants in the United States is about 75 Tg (83 million tons) per year, and generation of FGD waste is about 14.5

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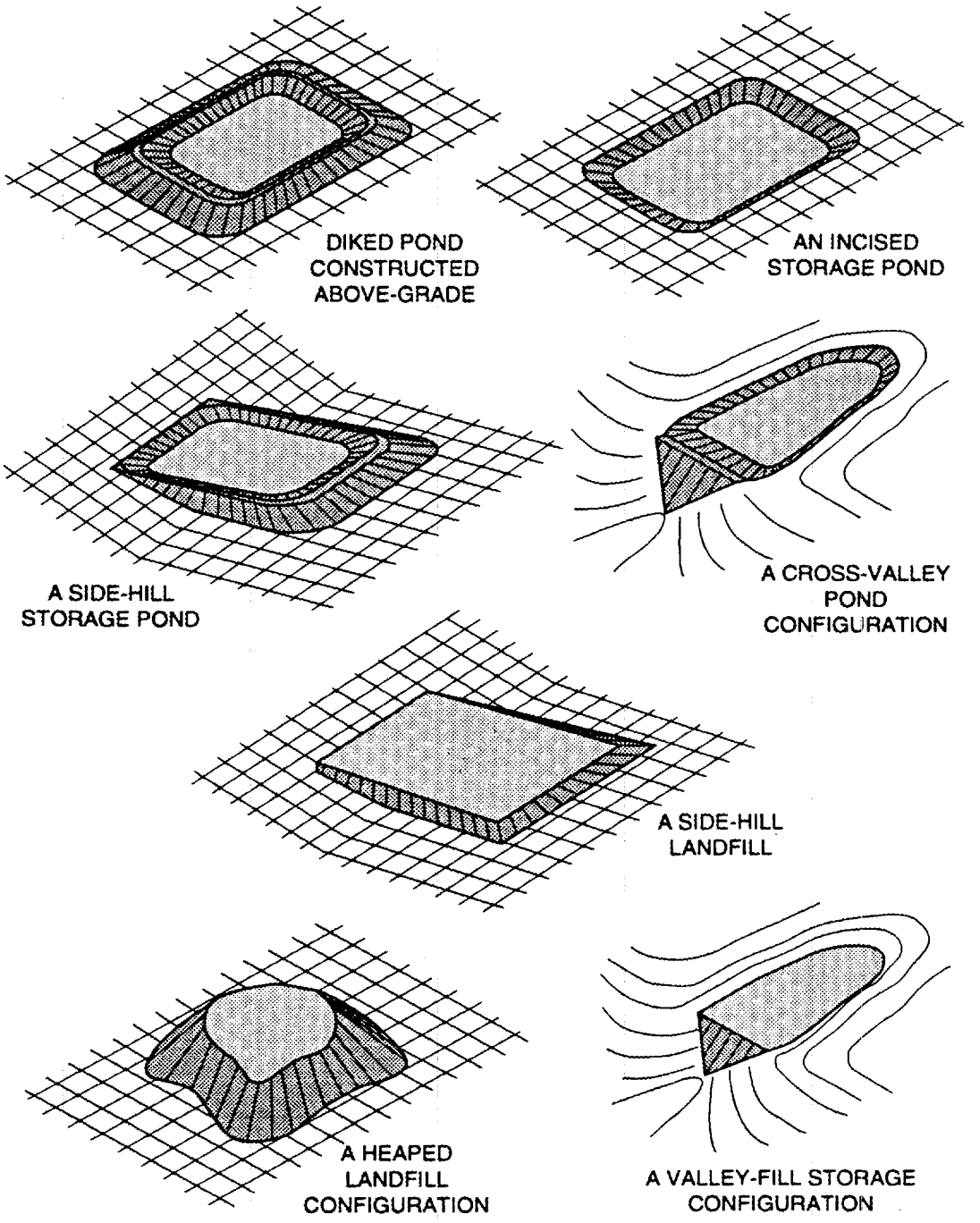

Fig. 9. Typical landfill and pond configurations (from Duvel et al. 1979, as reproduced in Soholt et al. 1980).

Tg (16 million tons) per year. Land requirements for solid waste disposal have been estimated to be 8.5 ha per Tg (19 acres per million tons) of ash and 17 ha per Tg (38 acres per million tons) of FGD waste (Robeck et al. 1980). Using this information, current land disposal requirements in the United States are estimated to be about 650 ha (about 1,600 acres) per year for ash disposal and about 240 ha (about 600 acres) per year for FGD waste disposal.

Ash and FGD sludge generation rates are not evenly distributed across the federal regions (Fig. 10). Ash generation is roughly proportional to coal-fired electric power generation, but FGD sludge generation is not. Scrubber-equipped power plants burning low-sulfur western coal may produce as little as 15% of the amount of FGD sludge produced at a comparable plant burning eastern coal. In addition, many older power plants produce little, if any FGD sludge because they are not required to remove sulfur dioxide from flue gas to comply with the New Source Performance Standards (NSPS) of the Clean Air Act of 1970. Eventual replacement or repowering of these old facilities will require compliance with NSPS, which could increase the use of conventional FGD units thereby increasing the amount of FGD sludge to be disposed of. Estimated land requirements for ash and FGD sludge disposal in 1990 for each of the ten federal regions are presented in Table 6. Although landfills are located throughout the country, most are found in the northeast quadrant [Federal Regions 3 and 5 (Fig. 10)], a region of high coal consumption. While landfills increasingly are being built on the power plant site, nearly all (95%) of the off-site disposal is in landfills.

Ponds, used for about 44% of the generating units nationwide, are most frequently found in the northeast and southeast quadrants (Federal Regions 4 and 5). Such impoundments are used for nearly 70% of the generating units practicing on-site waste disposal. Because facilities in the southeast quadrant rely heavily on surface impoundments, the highest percentage of on-site waste disposal is found in this quadrant.

Mine disposal of wastes, used for only 3% of the generating units, is most frequently encountered in the northwest quadrant (Federal Region 8). The mines used for waste disposal tend to be located adjacent to or near the power plant sites (EPA 1988b).

Wastes and waste by-products from coal-fired power plants can be recovered and reused. Recovered wastes may be used on the power plant site or sold for off-site use; prior to such use, these wastes may be stored at the site. Utilities commonly use captured fly ash and bottom ash for structural fills. External uses are diverse; the largest uses are fly ash in

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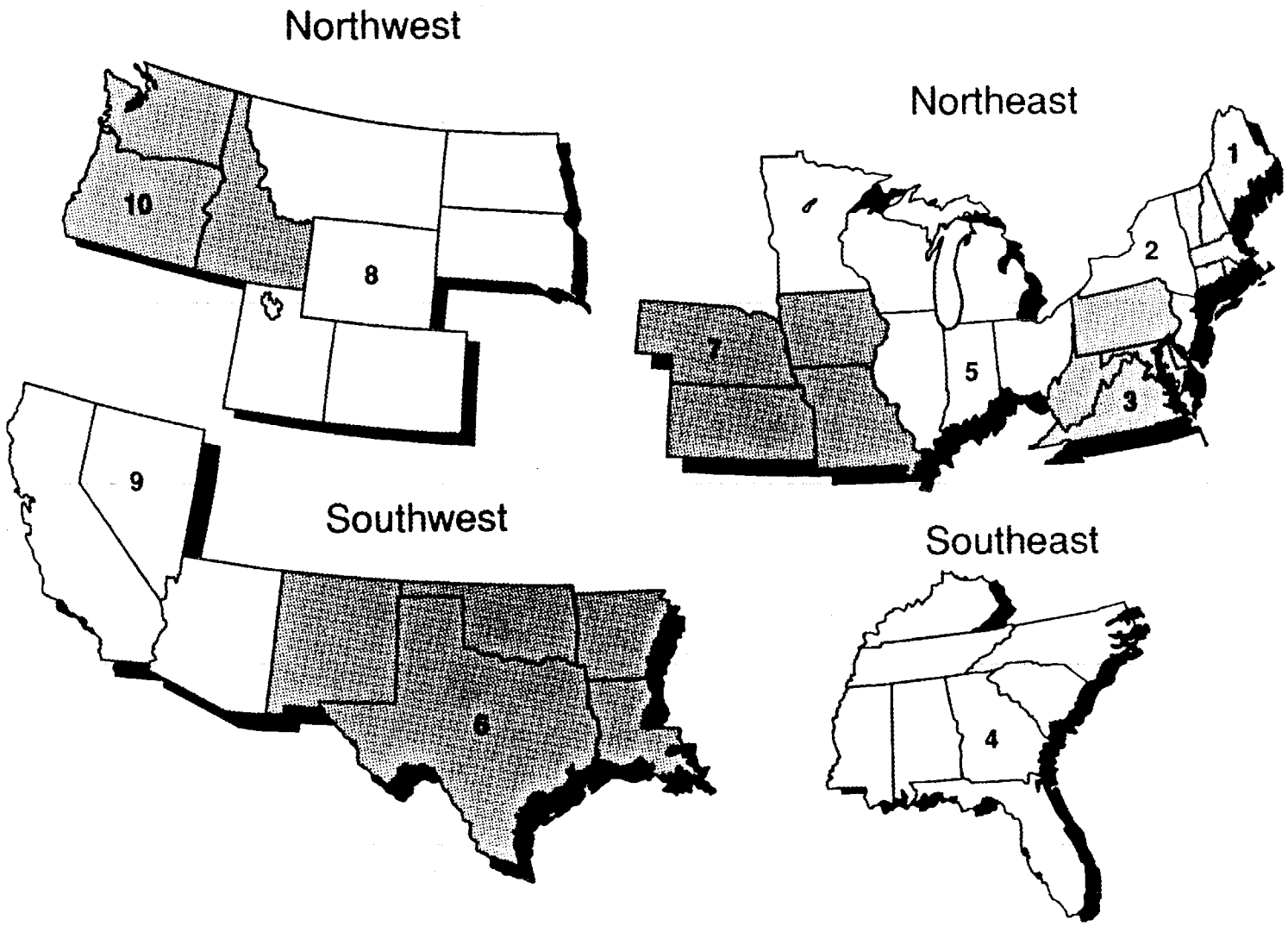

Fig. 10. Quadrants and federal regions for the conterminous United States.

Table 6. Estimated 1990 land requirements for disposal of ash and flue gas desulfurization sludge from coal-fired electric power plants

Quadrant and Federal Region (FR)	Ash		Sludge	
	Quantity[a] (10^6 tons/yr)	Land[b] (acres/yr)	Quantity[a] (10^6 tons/yr)	Land[b] (acres/yr)
Northeast	1.0	19	0.3	8
FR 1	1.3	25	1.0	38
FR 2	10.8	205	2.0	76
FR 3	19.2	365	2.6	99
FR 5	5.7	108	1.0	38
FR 7	38.0	722	6.8	259
Subtotal				
Southeast				
FR 4	19.3	367	2.7	103
Southwest				
FR 6	15.4	293	5.2	198
FR 9	3.0	57	0.3	11
Subtotal	18.4	350	5.5	209
Northwest				
FR 8	6.4	122	0.4	15
FR 10	0.8	15	0.1	4
Subtotal	7.2	137	0.5	19
National total	82.9	1,596	15.5	590

[a]*Source:* EPA 1988 and Placet et al. 1986.

[b]Landfill requirement estimates are based on 19 acres/10^6 tons for ash and 38 acres/10^6 tons for FGD sludge (Robeck et al. 1980).

cement and concrete products and boiler slag as blasting grit and roofing granules. Recent trends indicate that reuse of wastes are increasing. For instance, while 18% of all coal ash generated annually was reused between 1970 and 1980, over 27% of the coal ash generated in 1985 was recycled (American Coal Ash Association, Inc. 1987). About 21% of the combination of fly ash, bottom ash, boiler slag, and FGD sludge from coal combustion wastes

was reused or recovered in 1985. However, current FGD sludge waste recovery processes are inefficient; less than 1% of the volume of such wastes produced was recycled in 1985.

4.3 EFFECTS OF CLEAN COAL TECHNOLOGIES ON SOLID WASTE GENERATION

4.3.1 No-Action Alternative

For the no-action alternative, conventional coal technologies were assumed to be pulverized-coal fired boilers with wet lime/limestone FGD technology. A typical new plant has particulate matter control, such as an electrostatic precipitator or a baghouse with fabric filters, and a flue gas desulfurization system capable of removing 70 to 90% of the SO_2 generated. Utilities have historically selected FGD systems that use wet slurry processes: the SO_2 in the flue gas comes in contact and reacts with a recirculating lime or limestone slurry, removing the SO_2 for disposal as calcium sulfite or calcium sulfate in a sludge. Disposal of the sludge is difficult because of these physical properties and the large quantities that are generated. For example, solid wastes from a typical 500-MW plant using bituminous coal with 2.5% sulfur and 12% ash include about 145 Gg (160,000 tons) per year of ash and 118 Gg (130,000 tons) per year of sludge (dry basis) (NAPAP 1987).

The expected distribution of land needed for disposal of ash and FGD sludge for the no-action alternative is shown in Table 7. Comparison of Table 7 with Table 6 shows that the largest increases in ash generation are expected in Federal Regions 4, 5, and 6, and that the largest increases in sludge generation is expected in Federal Regions 3, 4, 5, and 6. These estimates indicate that on a national basis, about 60% more land would be needed for disposal of sludge than for disposal of ash. This reflects the assumption of nearly universal use of FGD scrubbers. It is also a reversal of the present situation, in which about 2.7 times as

Table 7. Estimated 2010 land requirements for disposal of ash and flue gas desulfurization sludge from coal-fired electric power plants for the no-action alternative

Quadrant and Federal Region	Ash		Sludge	
	Quantity (10^6 tons/yr)	Land[a] (acres/yr)	Quantity (10^6 tons/yr)	Land[a] (acres/yr)
Northeast				
1	1.4	30	0.8	30
2	6.8	130	6.7	250
3	11.4	220	18.8	710
5	35.5	670	27.2	1,030
7	8.8	170	5.1	190
Subtotal	63.9	1,220	58.6	2,210
Southeast				
4	33.9	610	18.4	700
Southwest				
6	32.9	590	34.8	1,320
9	4.8	90	0.9	30
Subtotal	37.7	680	35.7	1,350
Northwest				
8	7.3	130	1.0	40
10	1.9	30	0.5	20
Subtotal	9.2	170	1.5	60
National total	144.7	2,680	114.2	4,320

[a]Land requirement estimates are based on 19 acres/10^6 tons for ash and 38 acres/10^6 tons for FGD sludge (Robeck et al. 1980).

much land is used for ash disposal as for sludge (Table 6). A greater need of land for disposal of FGD sludge than for disposal of ash is characteristic of those regions where a large proportion of the power plants must meet NSPS while burning medium- or high-sulfur coal. Federal Region 6 and much of the northeast quadrant fit this pattern because most

plants there were built after NSPS went into effect in 1970. The southeast quadrant (Federal Region 4) would have a lower proportion of FGD sludge to ash generated because this region would have a relatively high proportion of pre-NSPS power plants in 2010. The northwest quadrant and part of the southwest quadrant (Federal Region 9) would have a low proportion of FGD sludge to ash because these regions use predominately low-sulfur coals.

4.3.2 Assessment of Effects of CCTs on Solid Waste Volumes

A major environmental trade-off of reducing atmospheric emissions by retrofitting or repowering coal-fired boilers with CCTs is the generation of additional solid wastes. Table 1 lists the estimated changes in total national solid waste generation in 2010 for each CCT if it were implemented to the maximum extent without competition from other technologies.

Total national generation of solid waste is expected to be about 540 Tg (600 million tons) per year in 2010 (DOE 1989). Many of the changes indicated on Table 1 would represent only a modest percentage change in waste generation when considering national statistics. At the local level, however, many coal-fired facilities are presently disposing of their solid wastes on the plant site using ponds and landfills that are reaching the end of their operational lifetimes and cannot be expanded to accommodate additional wastes, so CCTs may provide additional options for prolonging the life of these plants.

Operators of utility and industrial coal-fired boilers who adopt clean coal repowering technologies that would extend the lifetime of their plants would frequently need to find new disposal sites for their solid wastes. Similarly, plants that adopt retrofit technologies might generate wastes at an increased rate. Location of new landfills for disposal of wastes would be especially difficult in areas in the northeast quadrant, where suitable landfill sites are scarce, particularly in urban areas. Similar problems would exist in urban areas in the other quadrants.

While use of most of these CCTs leads to increased solid waste generation, several technologies produce by-products that might be usable if a market for them exists. Some technologies produce elemental sulfur or some industrial sulfur compound (e.g., liquid SO_2). Some technologies produce solids that are expected to be useful for construction or road building. The hurdles these byproducts must overcome to be put to beneficial use include purity requirements, transportation costs, and competition from current suppliers of the

materials. Most of the technologies are expected to produce dry granular wastes that are easier to handle and dispose of than FGD sludges.

4.3.2.1 Repowering Technologies

In addition to reducing atmospheric emissions, repowering technologies may increase a facility's efficiency and generating capacity. Increasing power plant efficiency reduces solid waste generation by reducing the amount of coal burned to produce a given amount of electricity. On the other hand, increasing a facility's generating capacity would increase coal combustion and waste generation, which may cause local problems.

Fluidized-bed combustion systems use more limestone to remove SO_2 than the conventional FGD systems. Circulating atmospheric fluidized-bed (CAFB) systems would produce more solid waste per unit of energy than conventional systems, but pressurized fluidized-bed systems would produce less because they are substantially more energy efficient than conventional power plants.

Integrated gasification combined cycle and fuel cell systems do not use limestone or lime to remove SO_2, so they produce less waste than either conventional power plants or fluidized-bed systems. The high energy efficiency of fuel cells combined with their waste-generating characteristics results in sizeable solid waste reductions.

All of these technologies would have smaller land-use impacts than the no-action alternative. Even CAFB, which produces more solid waste than the no-action alternative, would require less land area for disposal because the waste would not be in the form of a sludge and would, therefore, be easier to dispose of.

4.3.2.2 NSPS-Capable Retrofit Technologies

The NSPS-capable retrofit technologies would have land-use effects that range from substantially negative for the advanced slagging combustor to quite positive for the copper oxide process. All except the copper oxide process use lime or limestone to remove the SO_2. The lime or limestone ends up as calcium sulfate/sulfite waste. The principal residue of the copper oxide process is elemental sulfur, or other sulfur compounds if required by the available markets. The dual-alkali scrubber uses sodium hydroxide as well as limestone to

remove SO_2 from combustion gases. Use of the advanced slagging combustor would result in a substantial increase in solid waste, but the waste would be a dry solid instead of a sludge, as is produced by conventional FGD systems.

4.3.2.3 Partial NSPS-Capable Retrofit Technologies

Partial NSPS-capable retrofit technologies are also mixed in their effects on solid waste. Gas reburning, low NO_x burner, and selective catalytic reduction are NO_x-control technologies, and they also produce no solid waste. Gas reburning results in slightly reduced solid waste generation because the natural gas burned in the process displaces some coal that would otherwise be burned. Sorbent injection and limestone injection multistage burner (LIMB) produce sizable quantities of solid waste. Both of these technologies produce dry solid wastes which are easier to dispose of than sludges. For either technology, up to 285 ha (about 700 acres) per year nationwide would be needed to dispose of the waste. The spray dryer would generate about the same increase in solid waste, but the waste would be a sludge much like that produced by conventional FGD systems. Most of the increase for this technology is the result of applying it to plants that do not presently meet NSPS for SO_2 and NO_x. The salable-by-product advanced FGD technology also uses limestone to remove SO_2, but the process produces gypsum, which is widely used in plasterboard. If this technology were used, the projected small increase in solid waste (Table 1) could turn into a substantial decrease as the gypsum it produces is made into useful products.

4.3.2.4 Coal-Cleaning Retrofit Technologies

Coal-cleaning technologies include advanced chemical and physical processes. Chemical coal cleaning can remove over 90% of the sulfur from the coal. This level of cleaning allows the cleaned coal to be burned without any sulfur emission controls while meeting NSPS. The solid wastes from chemical coal cleaning would require up to about 800 ha (about 2000 acres) per year for disposal nationwide. Neither of the two physical coal-cleaning technologies would allow the coal to be burned in new power plants without additional sulfur controls. Maximal use of either technology would require about 400 additional ha (about 1000 additional acres) per year nationwide for landfilling the wastes.

Ultrafine coal could be mixed with water to form a coal/water mixture that could be burned in some utility and industrial boilers. An additional 120 to 160 ha (300 to 400 acres) per year nationwide would be needed to dispose of the solid wastes from this use of ultrafine coal. One distinctive feature of the coal-cleaning technologies is that most of their solid wastes are generated near the mine; consequently, mine disposal of solid wastes is more feasible than for most CCTs.

4.3.2.5 New-Fuel-Form Retrofit Technologies

The five new-fuel-form technologies produce liquid or gaseous fuels that could be used in both new and old residual oil-fired boilers and in modified coal plants. These technologies generate increased amounts of solid waste primarily because of the inefficiencies involved in converting coal from a solid to a liquid or gaseous form. They would generate 13.6 to 63.5 additional Tg (15 to 70 million additional tons) of waste per year. Nationally, these wastes would require 120 to 520 additional ha (300 to 1300 additional acres) per year for solid waste disposal. Because of the high-value fuels these technologies produce, they are also likely to be located near the coal mines, which may make mine disposal of solid wastes feasible.

4.4 UNCERTAINTIES ABOUT CLEAN COAL TECHNOLOGY WASTES

The chemical and physical properties of the solid wastes from most CCTs are not well known at present. In general, the analysis in the PEIS recognized that there is some uncertainty about the chemical properties of these wastes and their potential toxic effects. Some technologies involve novel chemical technologies that may have the potential of generating hazardous wastes. One of the purposes of the CCTDP is to develop new information about the physical, chemical, and toxicological properties of solid wastes generated by the CCTs.

5. SUMMARY, CONCLUSIONS, AND IMPLICATIONS

5.1 SUMMARY

Environmental considerations of CCTs initially focused on reducing emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) to the atmosphere. With increased public awareness of the possibility of global warming due to increased greenhouse effect, potential reduction in CO_2 emissions associated with certain CCTs has received increased attention. Further, as suitable landfill sites become increasingly scarce, the effects of new technologies on solid waste production are becoming more important. The PEIS for the Clean Coal Program (DOE 1989) provided an upper bound for reductions in SO_2, NO_x, and CO_2 emissions, and for reductions in solid waste generation, for each of 22 CCTs, assuming full market penetration of each technology. That information is used in this report to assess possible environmental effects of the various classes of CCTs, and of some noteworthy individual CCTs.

The greatest potential reductions in both SO_2 and NO_x are associated with the repowering technologies and the NSPS-capable retrofit technologies. Comparable reductions in one or the other of those pollutants can be achieved by individual technologies in the partial NSPS-capable category, although either the LIMB technology or certain combinations of other partial NSPS-capable technologies can provide reductions in both SO_2 and NO_x that are comparable to CCTs in the repowering or NSPS-capable categories. Coal cleaning technologies and new fuel forms can provide relatively smaller reductions in SO_2 emissions, with very little change in NO_x emissions.

Reductions in CO_2 emissions are associated primarily with the repowering technologies. Although these reductions could represent up to 10% of United States fossil-fuel CO_2 emissions, the U.S. produces only about 22% of the global CO_2 emissions, and therefore the corresponding global reduction in fossil-fuel CO_2 emissions would be only about 2.2%. Further, because CO_2 from nonfossil sources and greenhouse gases other than CO_2 are likely to be responsible for a substantial fraction of any increase in greenhouse effect that would occur by 2010, full implementation of CCTs in the United States would be expected to reduce the overall effects of greenhouse gas increases by only about 1 to 2%. Although these percentages are small, it should be remembered that CO_2 emissions are a global issue because

of the numerous sources around the world that each contribute a small percentage to that total, and therefore no single technology or policy is likely to result in any greater reduction.

CCTs generate solid wastes that for the most part are dry and do not present the sludge-disposal problems associated with current flue gas desulfurization systems. Most of the technologies that are expected to generate less waste than the conventional flue gas desulfurization systems do so by producing a salable by-product. Solid waste volumes are projected to be reduced for three of the four repowering technologies (by amounts ranging from 4 to 16%) and for two of the three NSPS-capable retrofit technologies (by amounts ranging from 5 to 22%) when compared with the amount of solid waste expected to be generated under the no-action alternative. Gas reburning is the only partial NSPS-capable CCT that is projected to reduce the generation of solid waste. Coal-cleaning and new-fuel-form technologies would increase the amount of solid waste per unit energy produced, but they are likely to generate this waste near the coal mine, making mine disposal a feasible option.

The CCTs can be loosely ranked from an environmental viewpoint as shown in Table 1. Four technologies (PFB, IGCC, fuel cell, and gas reburning) are projected to reduce emissions of SO_2, NO_x, and CO_2, and also to reduce production of solid waste. Three of these technologies are repowering technologies that are capable of reducing SO_2, NO_x, CO_2, and solid waste by relatively large amounts. Gas reburning, a partial NSPS-capable technology, is also capable of reducing all three gaseous emissions and solid waste, but by smaller amounts. The only repowering CCT that reduces SO_2, NO_x, and CO_2 but increases solid waste is CAFB. Two of the three NSPS-capable retrofit technologies are projected to reduce SO_2, NO_x, and solid waste production without increasing CO_2 emissions. Other CCTs are projected to decrease emissions of only one gas, to decrease emissions of one or two gases at the expense of increasing solid waste production, or to decrease emissions of at least one gas at the expense of increasing emissions of at least one other while also increasing solid waste volumes.

5.2 CONCLUSIONS AND IMPLICATIONS

From an environmental viewpoint, the repowering technologies would appear to be the most broadly beneficial. Repowering technologies may also be economically or logistically attractive for one or more of the following reasons: (1) repowering can significantly extend the useful life of an existing plant by increasing capacity and thermal efficiencies; (2) increasing the capacity of an existing plant (as opposed to building a plant at a new site) may translate into fewer facilities needed per unit of power generated; (3) demand centers are often closer to existing sites than to land available for new sites; (4) increasing the capacity at an existing plant may streamline certain aspects of permitting procedures. The repowering CCTs also provide additional options for consideration when designing new plants.

While it is not possible to specify precisely the decreases of SO_2 and NO_x required to reduce acid deposition to acceptable levels, it is obvious that sizeable reductions will be required, and the CCTDP can play an important role by demonstrating new technologies to assist the United States in achieving that goal. Mandatory reductions of SO_2 and NO_x emissions, required by the 1990 Clean Air Act amendments, may increase the use of conventional scrubbers as the technology of choice for reducing emissions of those gases. However, conventional scrubbers produce large amounts of solid waste—a consideration which may provide added incentive to develop CCTs that reduce solid waste production. Technologies that reduce appreciably the amount of solid waste produced can significantly extend the useful life of a plant where on-site disposal of solid waste is a limiting factor.

Emissions of CO_2 come from numerous sources around the world, and each source contributes only a small percentage to the total. A large-percentage reduction in global CO_2 emissions will require several small-percentage contributions from the implementation of a variety of policies and practices in many nations. It appears that the repowering CCTs have the potential to be among the more important options for reducing CO_2 emissions in the United States. For example, favorable market penetration of repowering CCTs is projected to have about the same effect as reducing petroleum consumption in the United States by 30%, which could be considered a significant reduction.

Environmental considerations are seldom simple and straightforward. For example, environmental effects of sulfur and CO_2 in the atmosphere are not always bad, and effects of sulfur may to some extent counteract the greenhouse effect. Further, some CCTs that could

reduce the amount of SO_2 or NO_x in the atmosphere also involve novel chemical aspects that may have the potential to generate hazardous wastes. Many CCTs are projected to decrease emissions of only one gas, to decrease emissions of one or two gases at the expense of increasing solid waste production, or to decrease emissions of at least one gas at the expense of increasing emissions of at least one other while also increasing solid waste volumes. Such tradeoffs might be environmentally advantageous in some cases, but the environmental benefits of many partial NSPS-capable technologies are more limited than those of the repowering or NSPS-capable technologies. New fuel forms, including coal cleaning, would appear to be the most limited technologies in terms of environmental benefits. However, such technologies may still be appropriate in individual cases, especially where solid waste disposal is not a limiting factor.

The CCTDP will provide information on actual performance of CCTs, to revise and refine the initial projections of their environmental effects and of their economic and technical feasibility. This information will be useful to regulatory agencies, utilities, and industry in the selection of technologies for responding to the Clean Air Act amendments and for providing new coal-fired energy supplies.

This report has considered only the potential effects of implementing CCTs in the United States. Penetration of CCTs into international markets would (1) at the global level, amplify their effects of reducing the concentration of atmospheric CO_2, (2) at the continental level, extend their effects of reducing acid deposition to continents beyond North America, and, (3) at the local level, potentially lead to reduction of solid waste volumes in individual communities in countries outside the United States.

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