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TECHNOLOGIES FOR CONTROLLING

POLLUTANTS FROM COAL COMBUSTION

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Summary

Sulfur dioxide, nitrogen oxides, and particles are the predominant pollutants emitted from the combustion of coal. One goal of current R&D activities is to reduce the costs for controlling these pollutants.

Several technologies have the capability to reduce emissions of one or more of these pollutants. Some of the technologies are currently available. Others will be available over the next 5-10 years, depending on market factors. One problem associated with most of the currently available technologies is high cost. For example, the capital cost of scrubbers can range as high as 30% of the cost of the power plant.

Some of the "advanced technologies" show great promise for more efficient removal of pollutants at lower costs. We are particularly encouraged with the cost saving potential of LIMB, E-SOX, Staged ESP's, and Electrostatic Enhancement of Fabric Filtration which are currently under development by EPA. For example, the application of LIMB (approximately 60% SO_2 removal) as a partial substitute for flue gas desulfurization (approximately 90% SO_2 removal) may result in cost savings as great as $670 per ton SO_2 removed. This estimate is based on a 300 MW utility boiler firing coal which contains approximately 2% sulfur.

Our research findings are encouraging. There is good potential for major breakthroughs that will allow acceptable control of coal-related pollutants at reasonable costs.

Introduction

The Environmental Protection Agency has several programs mandated by Congress to achieve environmental goals related to the combustion of coal. Three of these programs are: (1) the National Ambient Air Quality Standards (NAAQS) program which attempts to set goals for ambient air quality which ensure protection of human health and welfare; (2) the New Source Performance Standards (NSPS) program which attempts to reduce future air quality problems by requiring installation of best emission controls on new or substantially modified pollution sources; and (3) the National Acid Precipitation Assessment Program (NAPAP) which attempts to identify causes and effects of acid precipitation in order to provide a scientific basis for decision making by regulators and legislators.

The NAAQS and NSPS programs have been in place for some time, and their effects have already been factored into the coal use equation. There are no current or near-term actions contemplated under these programs which would alter coal markets. However, should the Congress pass acid rain legislation, the result could be a significant impact upon future use of coal.

At present, the NAPAP program is developing the data base that will improve the ability to make decisions concerning the need for acid rain legislation. Current research efforts are focused on the identification and assessment of acid rain sources and effects and the development of capabilities for evaluating control strategies to mitigate these effects.

If the research on sources and effects of pollutants brings us to the position of being able to make reasonable, defensible decisions concerning control strategies, a number of control technologies will be considered in the strategies.

Some control technologies are currently commercial, and other "advanced technologies" which may help mitigate the adverse effects of pollutant emissions on the environment are being evaluated. At the EPA Office of Research and Development, one of the efforts within NAPAP is to assemble performance and cost data for all applicable control technologies. The technology program is identifying and developing new technologies which may reduce emissions in a more cost-effective manner and will provide this information to Congress and regulatory agencies in a timely manner to ensure that the chosen strategies and legislation follow the most beneficial route (taking costs into consideration).

We at EPA are hopeful that the emission reduction technologies currently being evaluated will meet the dual challenge of reducing emissions and minimizing the potential disruption in coal markets. This paper will focus on the status, effectiveness, and costs of the currently available and advanced technologies for controlling sulfur dioxide, nitrogen oxides, particles, and combinations of these pollutants.

Technologies for Sulfur Dioxide Control

Background

Currently, about 25 million tons of SO_2 are emitted annually into the atmosphere by various utility and industrial sources in the United States. SO_2 has been associated with such environmental concerns as adverse health effects, visibility deterioration, material corrosion, and acid rain. Generally, there are three types of technologies which can reduce the emissions of SO_2:

1. Pre-combustion technologies which remove the sulfur from the coal before it is burned.
2. Combustion technologies which capture or remove the SO_2 during the combustion process.
3. Post-combustion technologies which remove the SO_2 from the combustion gases produced when coal is burned.

Table 1 summarizes these control technologies for SO_2 control.

Commercial Technologies

Flue Gas Desulfurization - The post-combustion technology known as flue gas desulfurization (FGD) is the only technology which has been used extensively by power plants for SO_2 control. To date, more than 120 FGD installations control SO_2 emissions from about 53,000 MW of power plant capacity. By the year 2000, there will be approximately 215 FGD units controlling over 106,000 MW of power plant capacity.

Some FGD processes produce a waste byproduct and some produce a saleable byproduct such as sulfur or sulfuric acid. Almost all current and planned FGD installations are the waste-producing type because they are generally less expensive. The most common FGD processes that produce a waste product are those which use a lime or limestone slurry to remove SO_2. The lime or limestone reagent reacts with the SO_2 and produces a waste byproduct.

Currently available FGD technology is expensive. Capital costs are typically \$200 to \$300 per kW of power plant capacity. These costs amount to as much as 20 to 30% of the cost of a new power plant without an FGD system. Thus, for a new, 500 MW power plant priced at \$1000/kW (\$500 million), the capital costs for FGD would be \$200 to \$300/kW (\$100 to \$150 million). FGD costs can be expected to range from about \$600 per ton of SO_2 removed to more than \$1000 per ton.(1)

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(1) Actual costs will vary depending on site-specific factors. The costs have been determined to be \$670/ton of SO_2 for the following case:

1. FGD unit installed at a new, 500 MW power plant.
2. The capacity factor is 62.8%; i.e., the plant operates 5500 hr/yr.
3. Coal is fired at a rate of 812 lb/MW-hr.
4. The coal contains 3.36% sulfur.
5. Levelized annual revenue requirement is \$41 million (in 1984 dollars).

Source: Economics of Nitrogen Oxides, Sulfur Oxides, and Ash Control Systems for Coal-Fired Utility Power Plants, EPA-600/7-85-006, February 1985.

Since the early 1970's, EPA's research program has played an important role in upgrading the performance and reliability of the lime and limestone FGD technology. Recently, our Laboratory has demonstrated that the performance and reliability of these FGD processes can be significantly improved by the addition of organic acids to the lime or limestone slurry. This process has produced beneficial results in several full-scale utility applications. We continue to seek lower cost FGD processes with particular emphasis on a spray dryer FGD system which offers the potential for significantly lower capital costs than corresponding wet systems.

Physical Coal Cleaning - Physical coal cleaning is generally viewed as a supplement to FGD for SO_2 control. Coal may be "cleaned" by crushing and washing to remove mineral impurities (i.e., ash), including inorganic compounds containing sulfur. The cleaning processes can reduce the SO_2 emissions from the combustion of coal by only 10 to 50%, depending on the composition and characteristics of the coal. Currently, about 30% of coal used in power plants is cleaned. While the cost of coal is increased by 15 to 30% by the cleaning process, part of these costs may be offset by transportation cost savings and reductions in boiler operating costs. Physical coal cleaning costs are likely to be in the range of $300 to $500 per ton of SO_2 removed.[1]

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(1) Actual costs will vary depending on site-specific factors. The costs have been determined to be $450 per ton of SO_2 removed for the following case:

1. Coal cost is $30/ton.
2. Coal cost is increased 25% by cleaning.
3. The cleaning process results in a 25% decrease in SO_2 emissions.

Advanced (Not Commercial) Technologies

Chemical Coal Cleaning - The pre-combustion technology known as chemical coal cleaning has the potential for removal of both inorganic and organically bound sulfur from coal before it is burned, thereby greatly reducing the emissions of SO_2 during combustion. The cost per ton of SO_2 removed is higher for chemical coal cleaning than for existing commercial technologies. Chemical coal cleaning costs are likely to be in the range of $800 to $1500 per ton of SO_2 removed. (1)

Even though the technology is expensive, it may be important in allowing conversion of certain existing oil and gas facilities to coal since the large cost differential between coal and oil or gas may be sufficient to justify the relatively high costs of chemical coal cleaning. The research programs that we have conducted in this area and the ongoing research at DOE are important first steps in bringing the technology to commercialization. However, this can be accomplished only with significant involvement of industry, and market factors will be the ultimate determinant of the extent of industrial participation.

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(1) Actual costs will vary depending on site-specific factors. The cost range specified was calculated from data obtained from the following sources:

1. Evaluation of Physical/Chemical Coal Cleaning and Flue Gas Desulfurization, EPA-600/7-79-250, November 1979.

2. Economic Evaluation of Limestone and Lime Flue Gas Desulfurization Processes, EPA-600/7-83-029, May 1983.

Technologies for Nitrogen Oxide Control

Background

EPA recently estimated that about 20 million tons of nitrogen oxides are emitted annually from stationary and mobile sources in the United States. The combustion of coal by power plants accounted for nearly 30% of these emissions. The family of nitrogen oxide compounds, including NO, NO_2, and other compounds, is usually referred to generically as "NO_x." NO_2 has been designated by EPA as a criteria pollutant because it produces adverse human health effects. It also contributes to the formation of photochemical oxidants and is an acid rain precursor. NO_x control technologies can be divided into two categories: (1) combustion technologies and (2) post-combustion technologies. Table 2 summarizes important NO_x control technologies.

Commercial Technologies

Low Excess Air Firing - For existing coal-fired boilers, one NO_x control technique is the reduction of excess air supplied to the burner. This technique, referred to as low excess air firing, can reduce NO_x emissions by as much as 20% and has the added benefit of increased boiler efficiency. Capital costs average only about $2/kW. All boilers, however, do not have sufficient flexibility to achieve this level of emission reduction.

Staged Combustion (Overfire Air) - A variation of the low excess air approach is to operate the lower burners (utility boilers have multiple rows of burners located on the boiler's vertical walls) at the lowest excess air level possible and provide additional air in the upper regions of the boiler. EPA field tests of 22 pulverized-coal-fired boilers using low excess air combined with staged combustion showed that NO_x emission reductions of about 10-40% can be achieved at a cost of about $300 per ton of NO_x removed.

Reduced Load - Utilities sometimes choose to reduce emissions by reducing load. Obviously, this approach is equally applicable to existing or new units.

First Generation Burner Technology - The major thrust of EPA's NO_x reduction program is to develop the technology for new low-NO_x burners which may be either retrofitted to existing boilers or incorporated into new designs. These burners reduce NO_x by delaying the mixing of fuel and air, thereby limiting the availability of free oxygen in the initial burning process. First generation burner technology has already been applied commercially and was the basis for reducing the New Source Performance Standard (NSPS) for NO_x in 1979 for coal-fired utility boilers. Costs have been estimated at about $185 per ton of NO_x removed.

Thermal De-NO_x (Ammonia Injection) - This process involves the injection of ammonia into the hot flue gas to reduce NO to N_2 and O_2, thereby decreasing NO_x emissions. The process is commercially offered by the Exxon Research and Engineering Company. The process is expensive; recent estimates are in the range of $600 per ton of NO_x removed.

Advanced (Not Commercial) Technologies

Second Generation Burner Technology - While conventional combustion modifications have been used to achieve emissions below NSPS levels, we are exploring advanced combustion techniques to reduce NO_x even further. The most promising technique is second generation low-NO_x burners. Two such concepts developed under EPA sponsorship are the distributed mixing burner (for wall-fired boilers) and the rich fireball (for tangentially fired boilers). In experimental tests, these techniques have shown the potential to reduce NO_x emissions by more than 50% from current NSPS levels for pulverized-coal-fired units. The distributed mixing burner has been installed on an industrial-sized boiler (22 MW) and has achieved up to 70% NO_x reductions under optimal conditions. The rich fireball, installed on a 400 MW utility boiler, has achieved up to 50% reduction in NO_x emissions in long-term operation. For new boilers, NO_x levels of less than 50% of current NSPS levels should be achievable. Although these control systems represent state-of-the-art technologies, no full scale field data exist because market factors and other incentives have not yet generated industrial interest in commercialization of the systems. The costs associated with this technology should be about the same as for first generation low-NO_x burners (about $185/ton NO_x).

Reburning Technology - Studies are underway to reduce NO_x emissions by staged introduction of fuels in the firebox. This combustion technology, referred to as reburning, involves the introduction of coal or heavy oil as the first stage fuel and light oil or gas as the second stage fuel. Bench scale tests have shown that the "reburning" of first stage combustion gases during the second stage combustion under chemically reducing conditions results in 50 to 80% NO_x reductions. Pilot scale studies (10 million Btu/hr or 3 MW) to verify laboratory findings are underway. Although the Japanese have evaluated this technology on commercial size units, no commercial demonstrations have been conducted in the United States. Cost estimates are approximately $300 per ton of NO_x removed.

Flue Gas Denitrification - NO_x emissions from power plants may be reduced by 80 to 90% through the application of selective catalytic reduction (SCR) of NO_x in the flue gas with ammonia as the reactant. For the most part, this SCR technology has been developed and commercially applied in Japan. EPA has sponsored pilot scale tests of an SCR process known as the Hitachi Zosen process. These tests show that the process can remove up to 90% of the NO_x in flue gases which contain the full loading of particles from a coal-fired boiler. Cost estimates for utilizing SCR are very high--approximately $4000 per ton of NO_x removed.

Technologies for Particle Control

Background

Coal-fired power plants are a major source of particle emissions to the atmosphere, and the effect of fine particles on public health and welfare continues to be a major national environmental concern. EPA promulgated both primary (to protect health) and secondary (to protect welfare) National Ambient Air Quality Standards (NAAQS) for Total Suspended Particulate (TSP) in 1971. EPA also set New Source Performance Standards (NSPS) for a number of important sources of particulate matter, including coal-fired power plants.

Although these standards and compliance efforts have produced major reductions in the national TSP over the past 10 years, many regions are still unable to meet primary standards. In these regions industries will not only have to retrofit their existing equipment with particle control devices, but they will also have to institute controls on sources of fugitive particles if primary standards are to be met.

Additionally, there is increasing concern about the health effects of respirable particles. Atmospheric particles appear to be a factor in a worsening visibility problem in many parts of the country. These and other concerns continue to focus attention on fine particle control technologies. Table 3 summarizes information on important particle control technologies. Essentially all effective approaches involve particle removal subsequent to combustion.

Commercial Technologies

Electrostatic Precipitators - A portion of the incombustible portion of the coal is emitted from the boiler as particles (sometimes called flyash). Electrostatic precipitators (ESP's) are the most commonly used device for controlling the emission of these particles. An ESP is basically a large box with many rows of metal collection plates positioned parallel to the direction of flue gas flow through the box. High voltage is applied to wires located between these collection plates. The voltage produces an electric discharge (corona) which electrically charges the particles. The charged particles then move to the collection plates as a result of the electric field that exists between the wires and the plates. Conventional ESP's are capable of efficient particle control (greater than 99%).

ESP costs are likely to be in the range of $70 to more than $300 per ton of flyash removed. (1)

Fabric Filters - Fabric filters (sometimes called baghouses) are the major alternative to ESP's for particle control. These filters work like very large vacuum cleaners. Combustion gases laden with particles are forced through the filters, and the particles are entrapped in the fine mesh structure

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(1) Actual costs will vary depending on site-specific factors. The costs have been determined to be $80/ton of flyash removed for the following case:

1. ESP is installed on a new, 500 MW power plant.
2. ESP is "cold side"; i.e., it is downstream of the flue gas denitrification process.
3. The capacity factor is 62.8%; i.e., the plant operates 5500 hr/yr.
4. Coal is fired at a rate of 812 lb/MW-hr.
5. The coal contains 15.1% ash of which 80% is flyash.
6. Levelized annual revenue requirement is $12.8 million (in 1984 dollars).

Source: Economics of Nitrogen Oxides, Sulfur Oxides, and Ash Control Systems for Coal-Fired Utility Power Plants, EPA-600/7-85-006, February 1985.

of the filter. For most particles, the fabric filtration process is very efficient (99.9%), but the filters are very large and expensive to install, operate, and maintain. Costs may be expected to be in about the same range as costs for ESP's ($70-300/ton of particles removed).

Advanced (Not Commercial) Technologies

The major problems with both ESP's and fabric filters are their high costs and their operational uncertainties. Our research program is directed toward reducing costs by as much as 50% and minimizing the operational uncertainties. EPA engineers have made significant progress toward the achievement of these ambitious goals, and two of the advanced technologies which have resulted from their research are described below.

Multi-Stage Electrostatic Precipitator - This advanced ESP system, developed by EPA, consists of a device for precharging the particles followed by a specially designed downstream collector. Pilot test results of the staged ESP concept have been most encouraging and suggest cost savings in the order of 50% for coals with difficult-to-collect ashes. Experience at a larger facility will be necessary before the commercial potential of this technology can be evaluated. Market factors will control the extent and the timing of the commercialization of this technology.

Electrostatic Enhancement of Fabric Filtration - The most promising concept for reducing the costs of fabric filters is electrostatic enhancement of the filters. Adding an electric field in the fabric filter allows higher gas flow rates through the filter at a given pressue drop without sacrificing collection efficiency. The increased gas flow allows a drastic reduction in the size of the filter required to get the job done, with a corresponding cost reduction. Our research suggests that both capital and operating costs can be reduced by 30-60% over commercial systems. These findings must be evaluated in some larger-scale tests to verify the research results. At present, the research is still underway.

Technologies for Combined Pollutant Control

Background

In addition to separate controls for SO_2, NO_x, and particles, several technologies simultaneously remove two or more of these pollutants. These technologies are in various stages of development, and none has been fully commercialized for power plant operation. Table 4 lists four such technologies that are now or have been components of the EPA R&D program.

Commercial Technologies

Currently, physical coal cleaning is the only commercial technology available for combined control of pollutants from utility boilers.

Advanced (Not Commercial) Technologies

Limestone Injection Through Multi-Stage Burners (LIMB) - This technology evolved from the EPA-sponsored low-NO_x coal burner development work previously discussed. It was recognized that the condition which resulted in reduced NO_x might also promote capture of sulfur compounds if sorbents (e.g., limestone) were added. Both retrofit and new applications of the technique to boilers could be a comparatively simple and inexpensive way to reduce SO_2 and NO_x emissions. The primary objectives of the LIMB R&D program are: (1) for retrofit, 50 to 60% reduction of both NO_x and SO_2 from uncontrolled levels; (2) for new systems, 70 to 80% NO_x reduction and 70 to 90% SO_2 reduction from uncontrolled levels; and (3) cost savings of $224 to $670 per ton of SO_2 removed (depending on coal sulfur content) compared to flue gas desulfurization (FGD). I would like to emphasize that these are objectives of our research and development program and that many technical uncertainties must be clarified before we can claim achievement of these objectives. Further, LIMB will not serve as full substitution for existing technologies like FGD in those applications where high removal efficiency would be required.

The EPA research program has shown that removal efficiencies depend on factors such as coal type, alkali selected, and boiler conditions. However, recent research at the pilot scale has identified techniques that may increase the levels of SO_2 removal in the LIMB process. For example, the presence of metal oxides such as MgO, Fe_2O_3, and MoO_3 shows potential for the promotion of limestone reactivity resulting in increases in SO_2 removal efficiency. Research is continuing in an effort to define the mechanisms by which these and other additives promote limestone reactivity so that SO_2 removal can be maximized.

Our research has also shown that SO_2 removal can be enhanced by the use of high surface area sorbents. The high surface area sorbents are produced by the calcination of limestone ($CaCO_3$) and dolomitic limestone ($CaCO_3 \cdot MgCO_3$) to produce lime (CaO) and dolomitic lime (CaO•MgO). These products can then be hydrated to produce hydrated lime and hydrated dolomitic lime which are also high surface area sorbents. Even though high surface area sorbents are more expensive than limestone, evaluations of the LIMB process using these sorbents suggest that LIMB still may have a cost advantage over FGD for both retrofit and new sources. The first commercial scale demonstration of the LIMB process in the U. S. will be at the 105 MW single-wall-fired unit at the Edgewater Station of the Ohio Edison Company. Long-term testing will begin July 1987. Costs have been projected to be about 50-70% of the costs associated with the use of FGD technology for SO_2 control.

Approximately 90% of utility boilers are either wall-fired or tangentially fired, and the split between the two types is approximately equal. Because of the substantial differences between the firing systems, technology developed for wall-fired boilers is not directly applicable to tangentially fired boilers. EPA's research program will evaluate LIMB-type technology on such boilers up to the small industrial boiler size category.

Fluidized Bed Combustion - Fluidized bed combustion (FBC) is another technology that simultaneously reduces emissions of SO_2 and NO_x. FBC involves the burning of coal in a bed of limestone that has been fluidized with the combustion air. The limestone in the bed reacts with the SO_2 released during the combustion of the coal. The solid material which results from this reaction can be disposed of as a dry solid waste along with the coal ash. Several successful industrial scale (as opposed to utility scale) FBC units are currently in operation. FBC shows promise for removing SO_2 from coal combustion at a lower cost per ton of SO_2 than conventional flue gas desulfurization technologies. Although FBC is generally limited to new units, retrofit may be cost-effective in select cases where a utility may wish to upgrade the capacity of an older unit. EPA does not have an active R&D program for FBC, but we do monitor developments in this area. TVA, EPRI, and DOE have had important FBC development programs in recent years. Three utility FBC units are currently under construction in the U.S.

Electrostatic Precipitator Particle Removal and Spray Dryer SO_x Removal Process (E-SOX) - Laboratory and pilot scale experiments have proven the technical feasibility of combining multi-stage ESP technology and spray dryer technology to collect both particles and SO_2 in an existing ESP. The process uses the multistage ESP to reduce the space requirement in the ESP for particle removal, and the freed space is converted to a spray dryer by adding suitable spray nozzles. Initial experiments with Na_2CO_3 solutions show that the SO_2 removal efficiency ranges from 50 to 80% with inlet SO_2 concentrations up to 1600 ppm. Similar encouraging results have been obtained in experiments with CaO slurry. The process can be retrofitted during a planned outage and has the potential for providing a very low cost option for SO_2 control with no reduction in the level of particle control.

The costs associated with the E-SOX process are expected to be comparable to LIMB costs; i.e., about 50-70% of the costs associated with the use of FGD for SO_2 control.

Conclusion

Table 5 summarizes comparative cost data for all of the technologies discussed. The table indicates that some of the control technologies have the potential for allowing the use of our abundant coal reserves at reasonable costs and without undue environmental degradation. For this reason, the EPA research program will continue to explore the fundamental interactions between combustion products and sorbents in order to increase efficiencies and reduce costs of the control technologies. This work--coupled with related research programs at DOE, TVA, and the private sector (e.g., EPRI)--provides the technical foundation needed should rapid commercialization of the technologies be required in the future to meet energy or environmental incentives.

Table 1. Summary of Technologies for SO_2 Control

Description	Application	State of Development	Effectiveness	Availability
I. Pre-combustion				
1. Physical Cleaning	Retrofit	Commercial	10-50% SO_2 removal	Current
2. Chemical Cleaning	Replace Oil/Gas	Not commercial	Up to 90% SO_2 removal (at an energy penalty of approximately 25%)	After 1990
II. Combustion - Technologies which simultaneously remove SO_2 and other pollutants during the combustion process are summarized in Table 4.				
III. Post-Combustion				
1. Flue gas desulfuri-zation	Retrofit/ New	Commercial	60-95% SO_2 removal Note: The higher removal efficiencies may require the use of organic acids to enhance FGD.	Current

Table 2. Summary of Technologies for NO_x Control

Description	Application	State of Development	Effectiveness	Availability
I. Pre-combustion - None				
II. Combustion				
1. Low Excess Air Firing	Retrofit	Commercial	Research data suggest potential for up to 20% NO_x removal	Current
2. Staged Combustion (Overfire Air)	Retrofit/New	Commercial	10-40% NO_x removal	Current
3. Reduced Load	Retrofit/New	Commercial	Up to 50%	Current
4. First Generation Burner Technology	Retrofit/New	Commercial	Research data suggest potential for up to 50% NO_x removal	Current
5. Second Generation Burner Technology	Retrofit/New	Demonstration	Research data suggest potential for 50-70% NO_x removal	1988
6. Reburning Technology	Retrofit	Experimental	Research data suggest potential for 50-80% NO_x removal	after 1990
III. Post-Combustion				
1. Thermal De-NO_x (Ammonia Injection)	Retrofit/New	Commercial	40-60% NO_x removal	Current
2. Flue Gas Denitrification (Selective Catalytic Reduction)	Retrofit/New	Commercial in Japan; pilot scale in U.S.	80-90% NO_x removal	1990

Table 3. Summary of Technologies for Particle Control

Description	Application	State of Development	Effectiveness	Availability
I. Pre-combustion				
1. Physical Coal Cleaning	Retrofit	Commercial	$\leq$ 50%	Current
II. Combustion -	None			
III. Post-combustion				
1. Electrostatic Precipitator	Retrofit/ New	Commercial	99.5^{+}%	Current
2. Fabric Filter	Retrofit/ New	Commercial	99.5^{+}%	Current
3. Two-Stage Electrostatic Precipitator	Retrofit/ New	Pilot scale	99.5^{+}%	1990
4. Electrostatic Enhancement of Fabric Filtration	Retrofit/ New	Pilot scale	99.5^{+}%	1990

Table 4. Summary of Technologies for Combined Pollutant Control

Description	Application	State of Development	Effectiveness	Availability
I. Pre-combustion				
1. Physical coal cleaning	Retrofit/ New	Commercial	10-50% SO_2 $\leq$ 50% particles	Current
II. Combustion				
1. LIMB	Retrofit/ New	Large scale pilot; commercial demonstration planned	Retrofit: 50-60% NO_x & SO_2 New: 70-80% NO_x 70-90% SO_2	1989
2. Fluidized Bed Combustion	New	Successful application to industrial boilers	90% SO_2 NO_x removal uncertain	Post-1990
III. Post-Combustion				
1. E-SOX	Retrofit/ New	Pilot	50-80% SO_2 99% particles	1990

Table 5. Summary of Costs for Pollutant Removal

Pollutant Removed	Technology	Pollutant Removal Costs, \$/Ton	Removal Efficiency, %
SO_2	Flue Gas Desulfurization	600-1000+	60-95
	Physical Coal Cleaning	300- 500+	10-50
	Chemical Coal Cleaning	800-1500+	up to 90
NO_x	Low Excess Air Firing	< 10	up to 20
	Staged Combustion (overfire air)	300	10-40
	Reduced Load	-	up to 50
	Low-NO_x Burners	185	up to 50
	Second Generation Low-NO_x Burners	185	50-70
	Reburning	200-300+	50-80
	Thermal De-NO_x (ammonia injection)	600	40-60
	Flue Gas Denitrification	4000+	up to 90
Particles	Electrostatic Precipitator	70-300+	99.5+
	Fabric Filtration	70-300+	99.5+
	Multi-Stage Electrostatic Precipitator	35-150+	99.5+
	Electrostatic Enhancement of Fabric Filtration	35-150+	99.5+
SO_2/NO_x	Limestone Injection Multi-Stage Burners	50-70% of FGD	Retrofit: 50-60 New: 70-80 NO_x 70-90 SO_2
SO_2/NO_x	Fluidized Bed Combustion	< FGD	up to 90
SO_2/Particles	E-SO_x	50-70% of FGD	50-80 SO_2 99 particles